The following supplement accompanies the article

Effects of sea temperature and stratification changes on seabird breeding success

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Supplement.

Supplement 1. sensitivity analysis of threshold values used to define foraging areas

When turning GPS data into estimated foraging areas, thresholds were applied to remove records unlikely to be associated with foraging. It was therefore necessary to examine whether subsequent analyses were sensitive to the threshold values used. An initial threshold value was selected for both travel speed and distance from colony, and then three other values for each were trialled in a sensitivity analysis.

A distance-from-colony threshold was applied to remove records associated with behaviours at or around the nest. A threshold of 1 km was used, as kittiwakes are rarely observed foraging within 1 km of the nest (Irons 1998). Values of 0.2, 0.5 and 2 km were trialled in the sensitivity analysis. A travel speed threshold was also applied. Speed between GPS records follows a bimodal distribution, with the two parts of the distribution representing different behaviours (e.g., Weimerskirch et al. 2002, Guilford et al. 2008); for kittiwakes, the slower speeds are likely to be associated with foraging (Kotzerka et al. 2010). A preliminary analysis of FAME project data from 2010 and 2011, covering colonies at Bardsey Island, Flamborough Head and Bempton Cliffs, Isle of Colonsay, Fair Isle, Orkney (Copinsay, Muckle Skerry and Swona), Puffin Island and the Isles of Scilly, indicated that the trough between the two modes was wide, and that a speed of 14 km h^{-1} represented a reasonable threshold (Fig. S1.1; A. Butler & E. Owen, *unpublished*). As the distribution of speeds in the full dataset was similar to that from this earlier analysis (Fig. S1.2), 14 km h^{-1} was selected as the primary threshold in the full analysis; values of 11, 17 and 20 km h^{-1} were trialled in the sensitivity analysis.

Each threshold was applied in turn to the data. First, the proportion of points found in each POLCOMS grid cell (the grid on which all environmental data were based) was calculated. This was designed to indicate whether areas would be over- or under-represented. Second, the oceanographic variables used in the full analyses (sea surface temperature, stratification onset date and potential energy anomaly) were extracted from the record locations and a mean calculated. This was designed to indicate whether environmental variable values would be biased by threshold selection. Resulting values were correlated against those produced using the 1 km and 14 km h^{-1} thresholds (Figs. S1.3 – S1.6); Pearson correlations were calculated for each comparison.

Selection of the speed threshold made little or no difference to resulting values; Pearson correlations for both the proportion of time in each cell and for all three environmental variables were > 0.999

(Figs. S1.3 – S1.6, parts a, c, e). The distance threshold had a greater impact on the proportion of time spent in each cell, with the correlation dropping to 0.873 when a 200 m threshold was used, and 0.751 when a 2 km threshold was used (Fig. S1.3, parts b, d, f), most probably because well-used grid cells near the colony were being included or excluded depending on the threshold value. However, mean environmental variables were still highly correlated (Figs. S1.4 – S1.6, parts b, d, f), with correlation coefficients ranging from 0.929 – 0.999.

In conclusion, the speed threshold had almost no impact on the analysis, and although the distance threshold had a slightly greater impact, its effect on oceanographic variable values was limited. Therefore, further analyses should be robust to threshold specification, with the thresholds of 14 km h^{-1} and 1 km suitable for use in the full analysis. It must be noted, however, that the findings of this analysis are only relevant to the grid from which the environmental data are drawn; if environmental data were at a finer resolution or analyses conducted at a finer spatial scale, impacts of threshold specification could increase.

Figure S1.1. Distribution of speed values from initial analysis of subset of tracking data (see text for details of sites and years), showing a) full histogram, and b) histogram with truncated y axis for improved view of second distribution mode. Vertical line indicates 14 km h^{-1} speed threshold used in subsequent analyses.

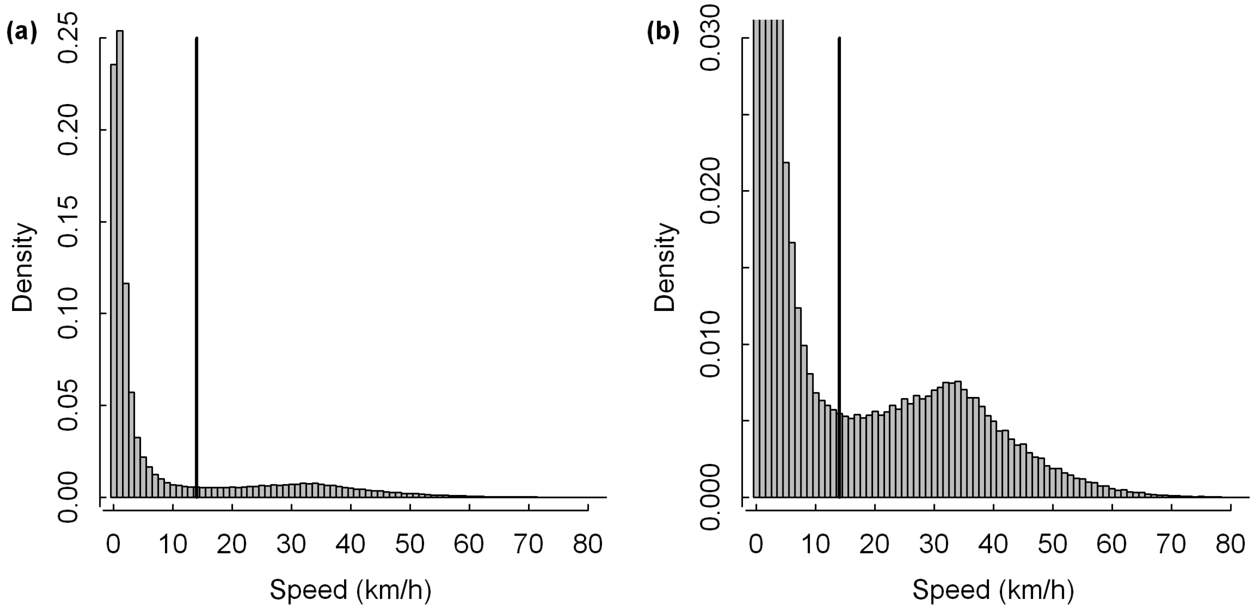


Figure S1.2. Distribution of speed values from full dataset used in analysis showing a) full histogram, and b) histogram with truncated y axis for improved view of second distribution mode. Vertical lines indicate thresholds used (solid line = 14 km h^{-1}) and trialled in the sensitivity analysis (dashed lines = 10, 17 and 20 km h^{-1})

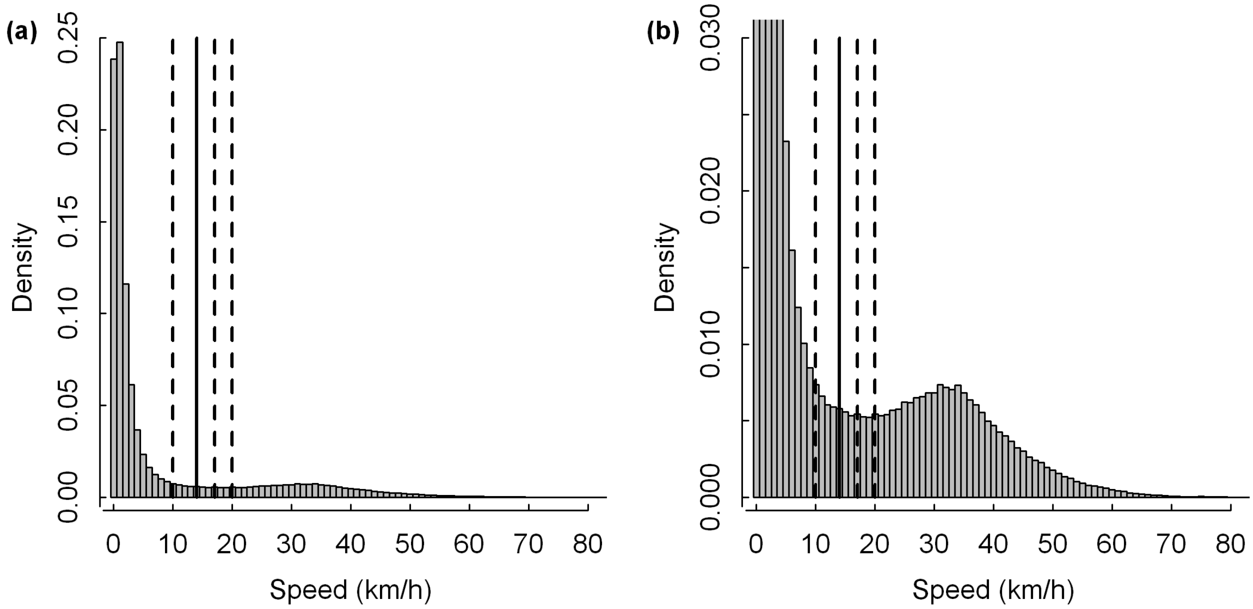


Figure S1.3. Comparison of the proportion of time spent in each POLCOMS grid cell for the standard distance and speed thresholds (i.e., 1 km and 14 km h^{-1}), and that for different possible speed threshold values ((a) 11 km h^{-1}; (c) 17 km h^{-1}; (e) 20 km h^{-1}) and distance threshold values ((b) 200 m; (d) 500 m; (f) 2 km). Plots show Pearson correlation coefficient between the two sets of values.

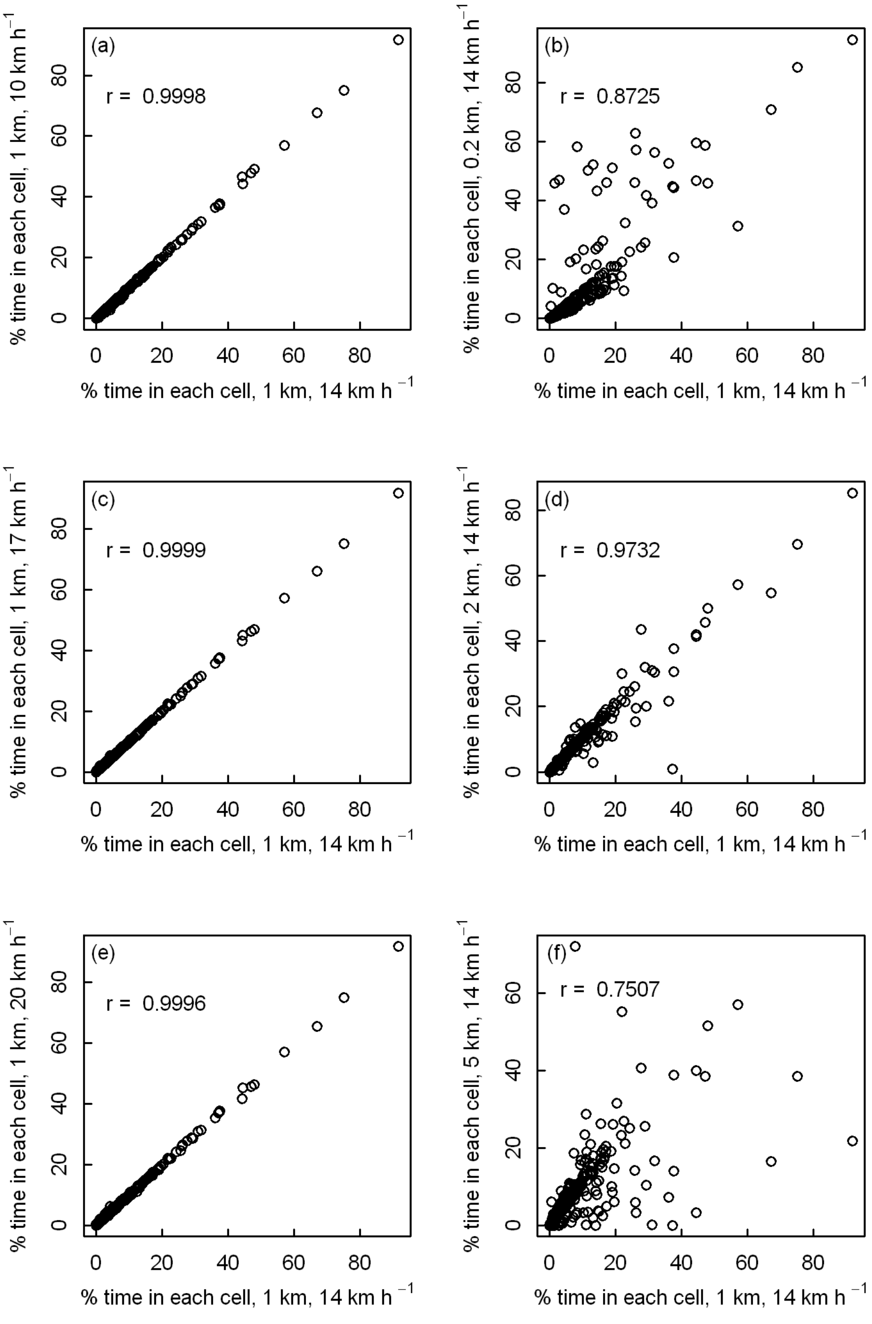


Figure S1.4. Comparison of the mean sea surface temperature extracted from filtered points for the standard distance and speed thresholds (i.e., 1 km and 14 km h^{-1}), and that for different possible speed threshold values ((a) 11 km h^{-1}; (c) 17 km h^{-1}; (e) 20 km h^{-1}) and distance threshold values ((b) 200 m; (d) 500 m; (f) 2 km). Plots show Pearson correlation coefficient between the two sets of values.

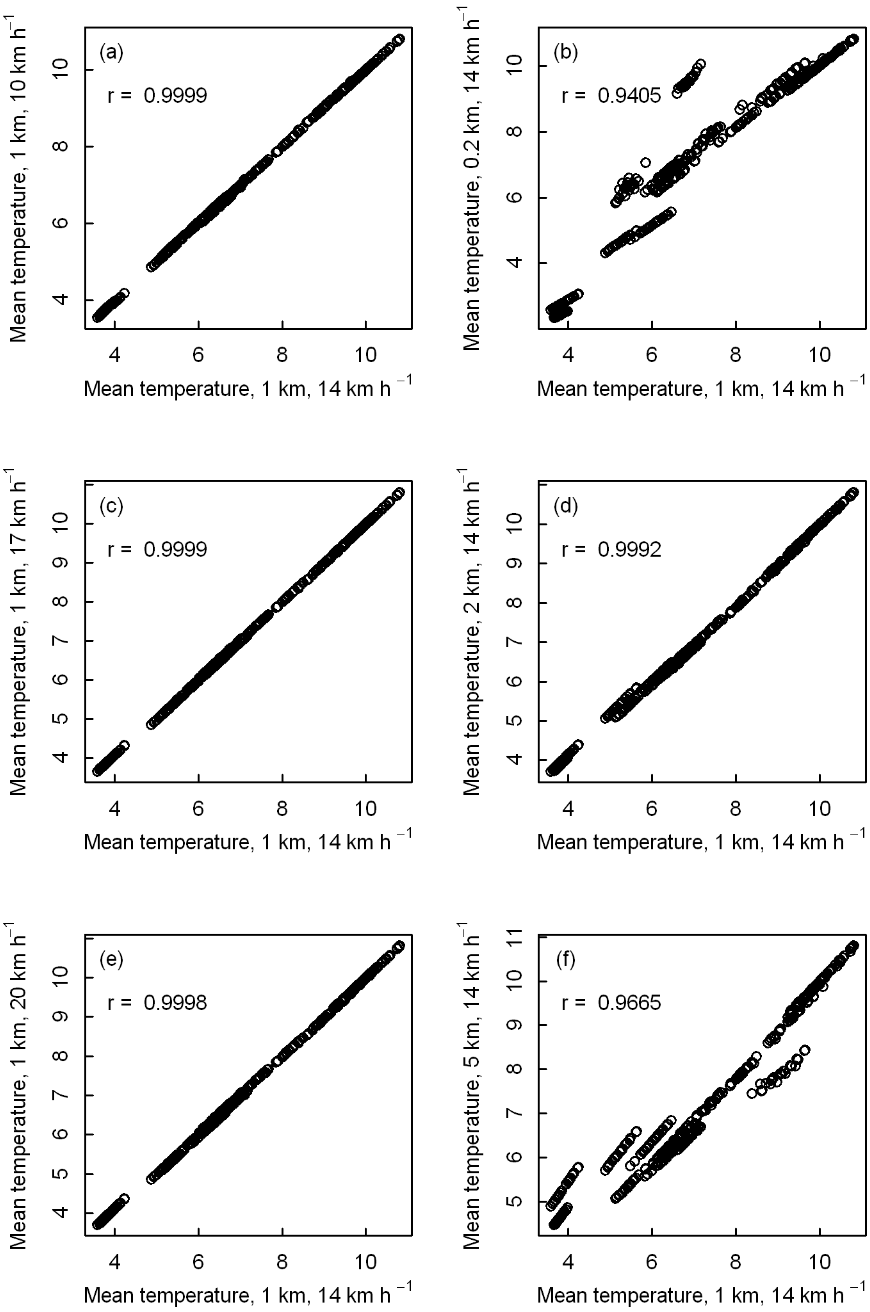


Figure S1.5. Comparison of the mean potential energy anomaly extracted from filtered points for the standard distance and speed thresholds (i.e., 1 km and 14 km h^{-1}), and that for different possible speed threshold values ((a) 11 km h^{-1}; (c) 17 km h^{-1}; (e) 20 km h^{-1}) and distance threshold values ((b) 200 m; (d) 500 m; (f) 2 km). Plots show Pearson correlation coefficient between the two sets of values.

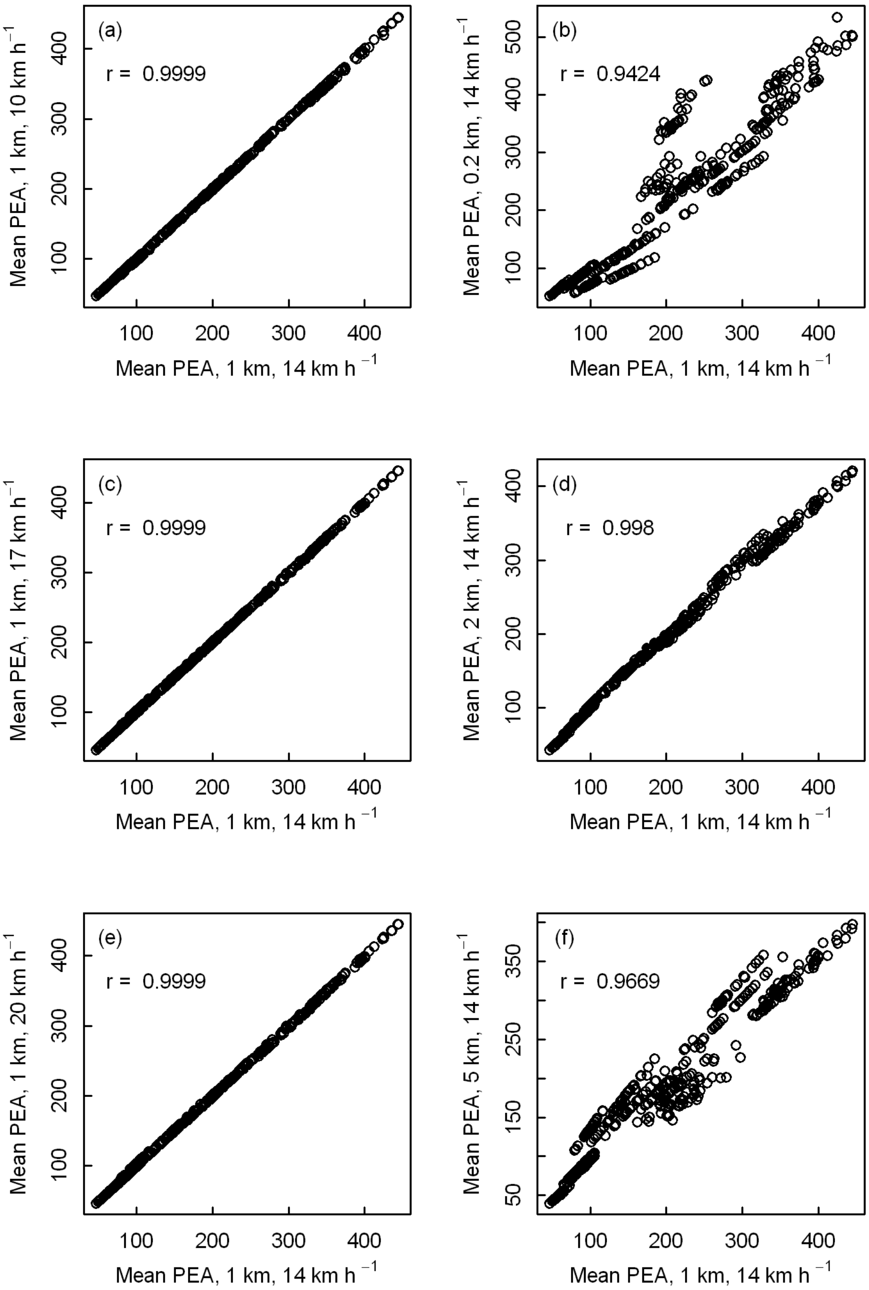
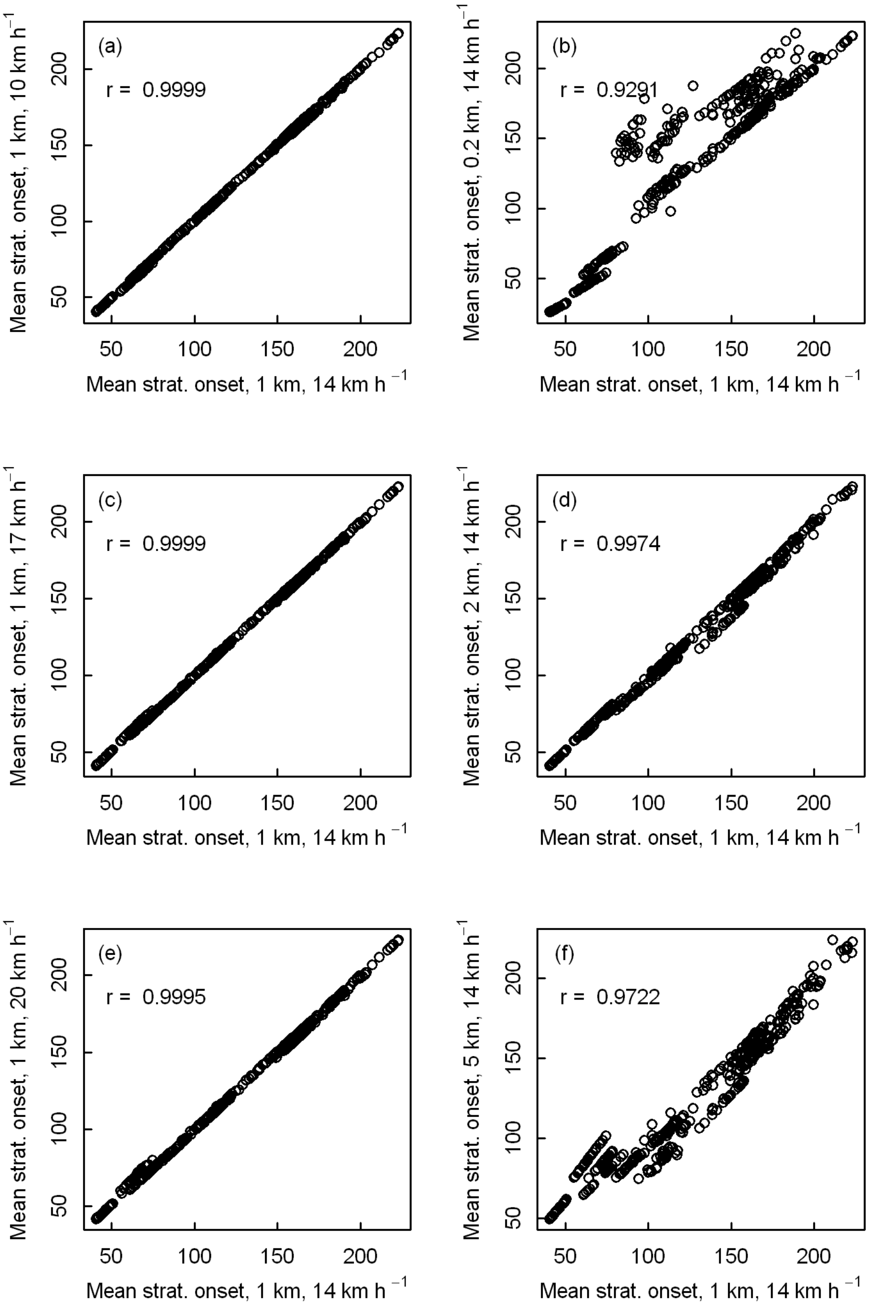


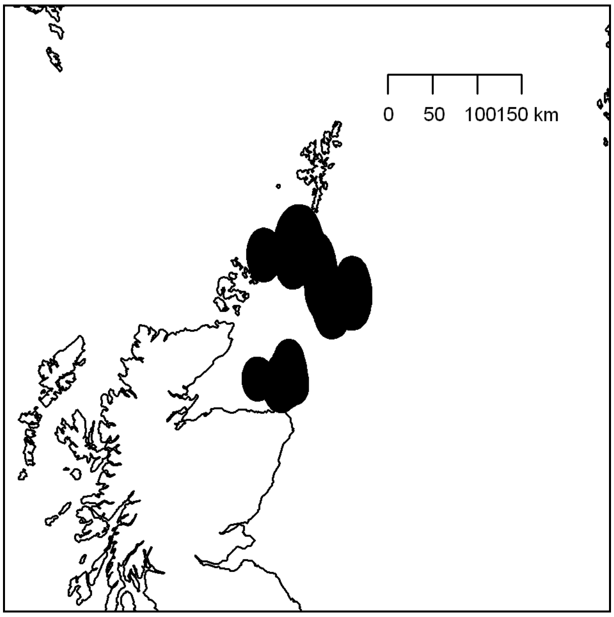
Figure S1.6. Comparison of the mean stratification onset date extracted from filtered points for the standard distance and speed thresholds (i.e., 1 km and 14 km h^{-1}), and that for different possible speed threshold values ((a) 11 km h^{-1}; (c) 17 km h^{-1}; (e) 20 km h^{-1}) and distance threshold values ((b) 200 m; (d) 500 m; (f) 2 km). Plots show Pearson correlation coefficient between the two sets of values.



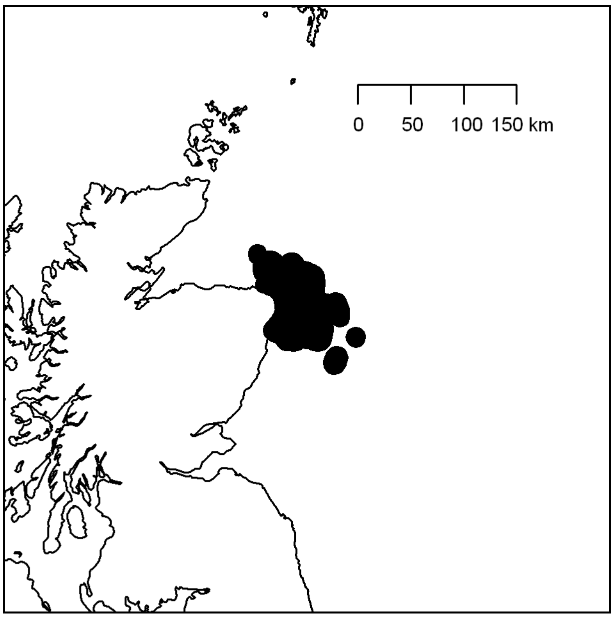
Supplement 2. Maps of foraging area kernels used in analyses

Fig. S2.1. Final foraging areas used in analyses

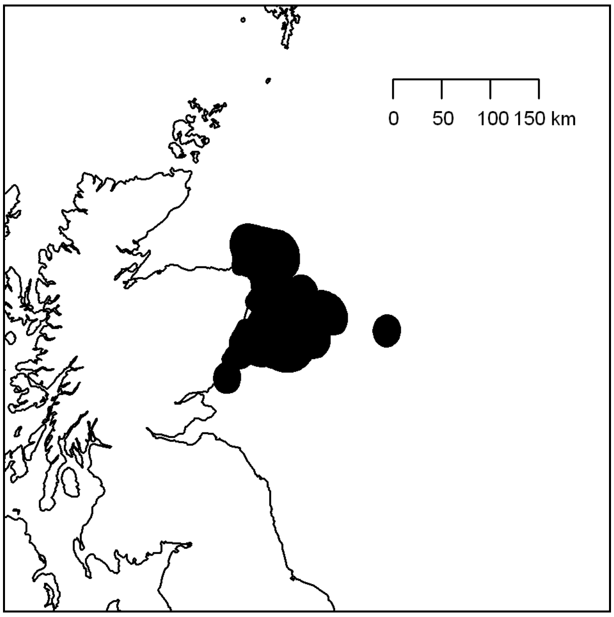
Fair Isle



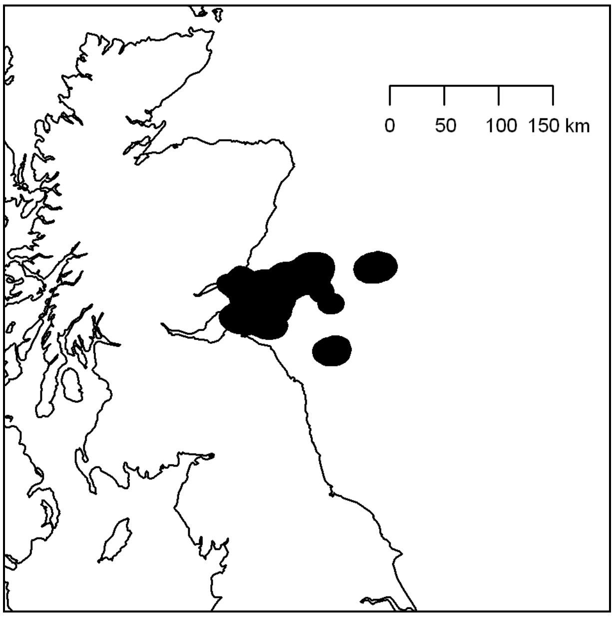
Boddam to Collieston



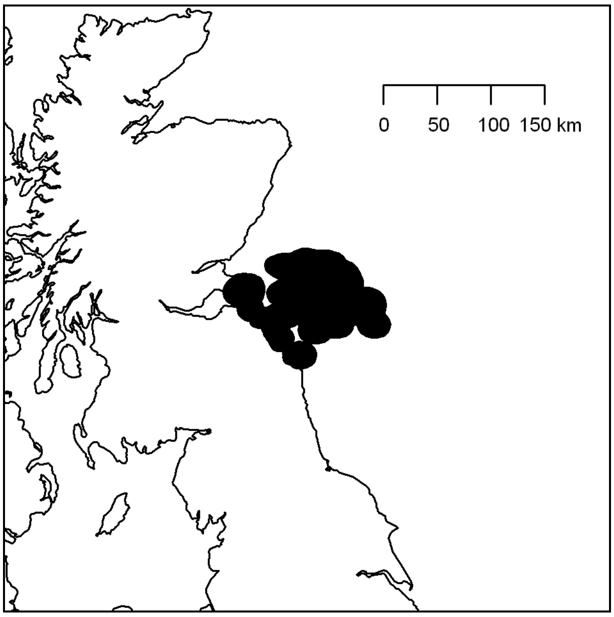
Fowlsheugh



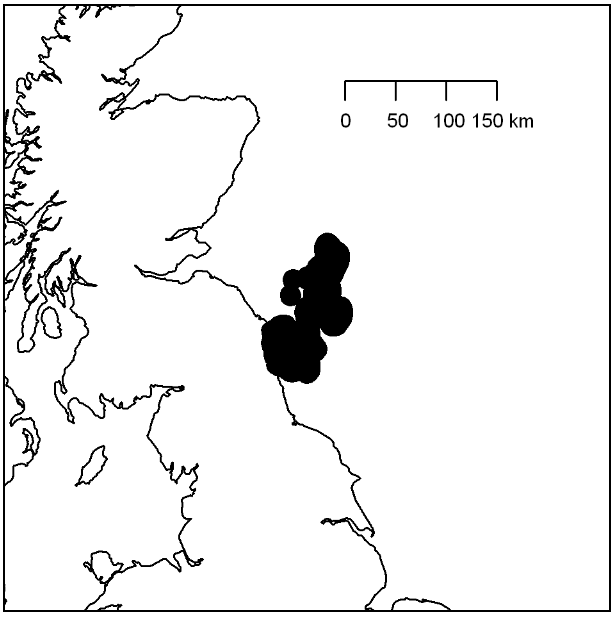
Isle of May NNR



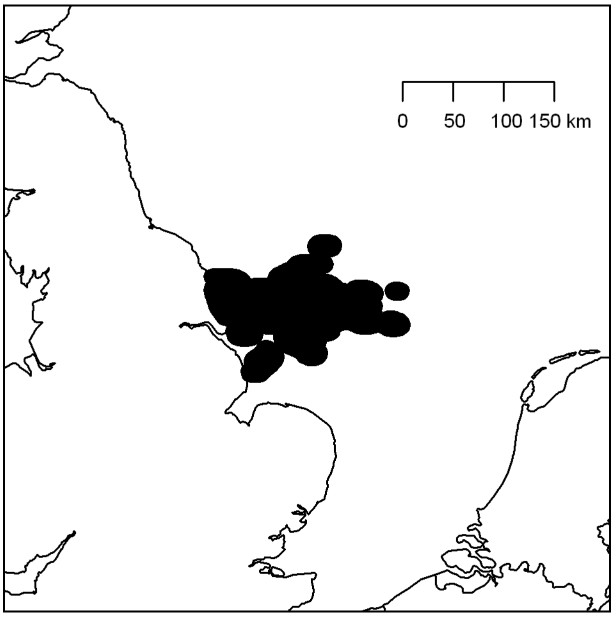
St Abb's Head NNR



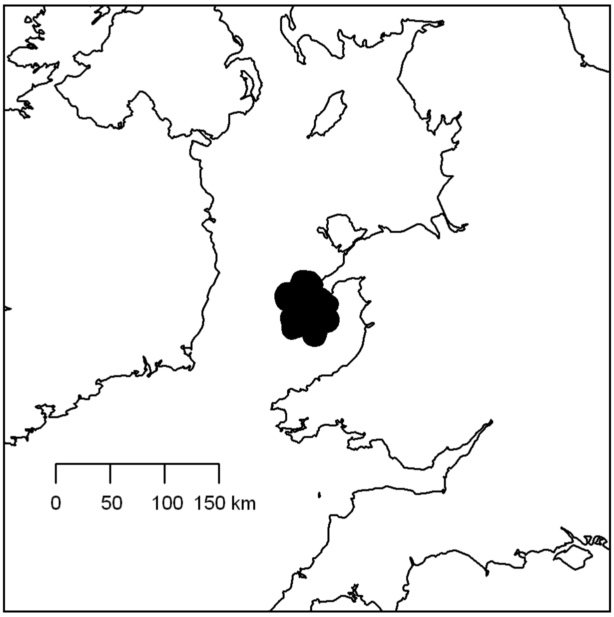
Coquet Island



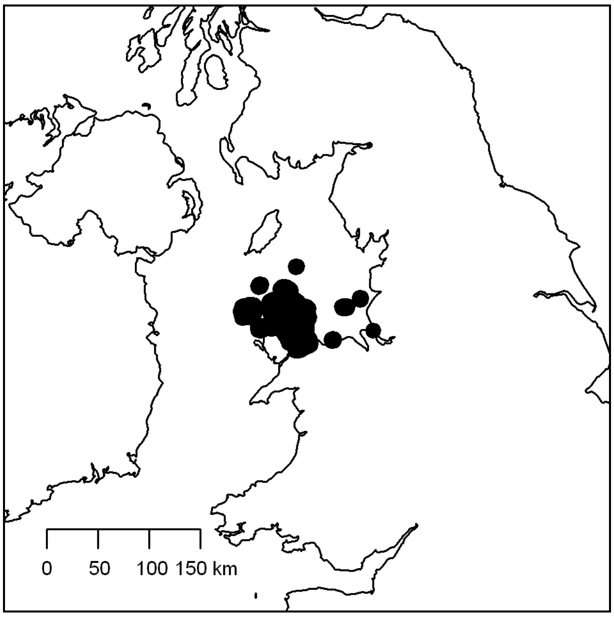
Flamborough Head and Bempton Cliffs



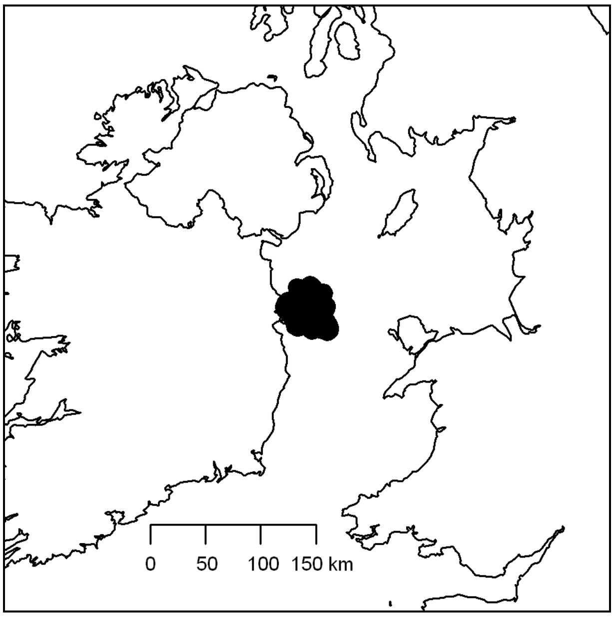
Bardsey Island NNR



Puffin Island



Lambay



Isle of Colonsay

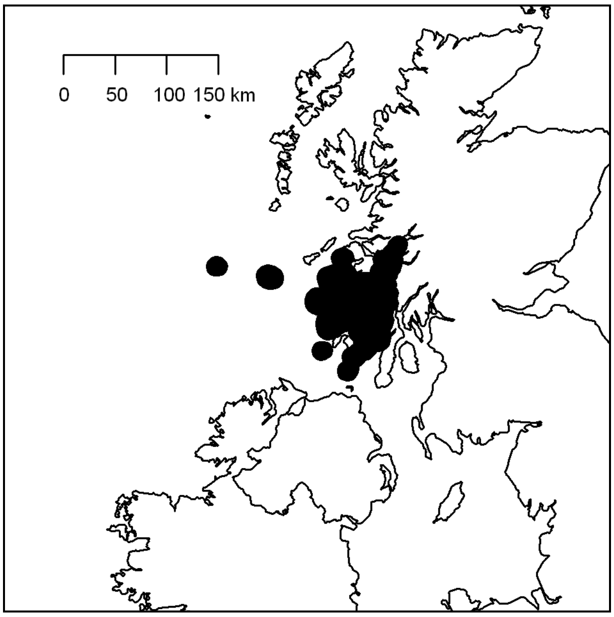
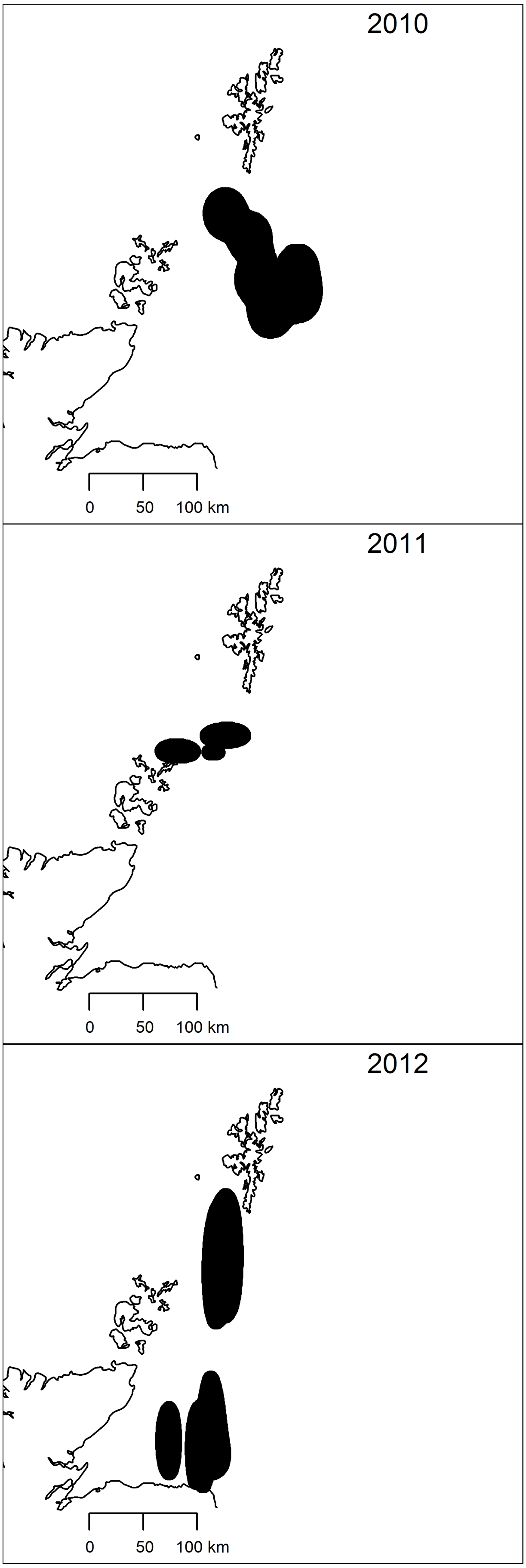
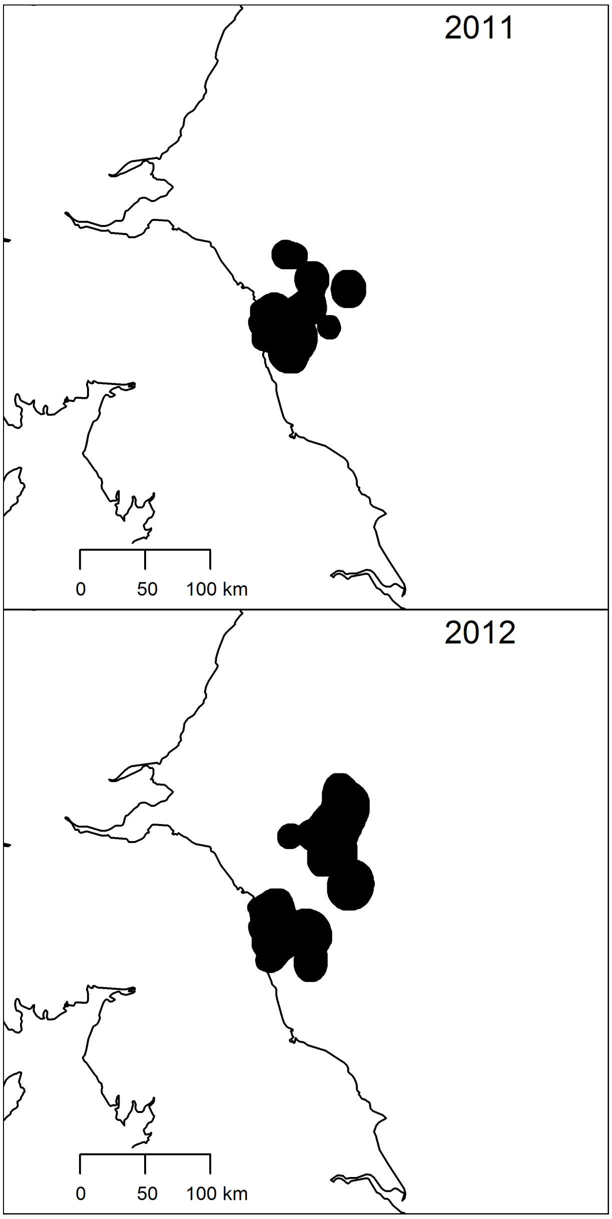


Fig. S2.2. Foraging areas from individual years for sites with multiple years of data

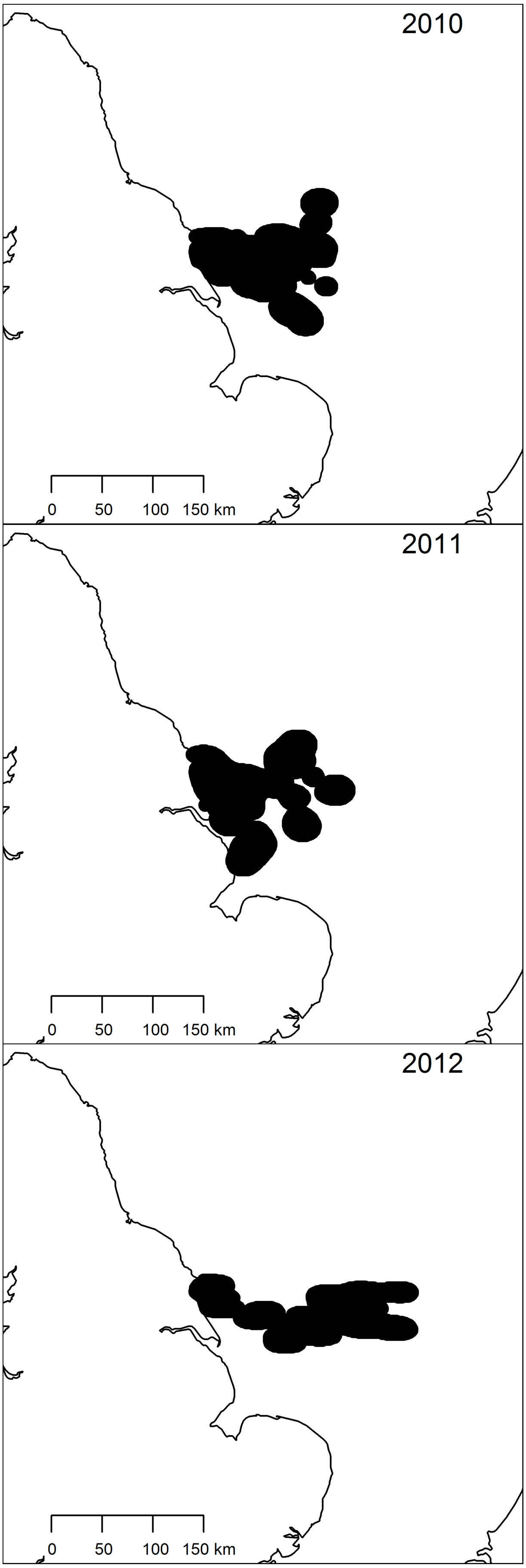
Fair Isle



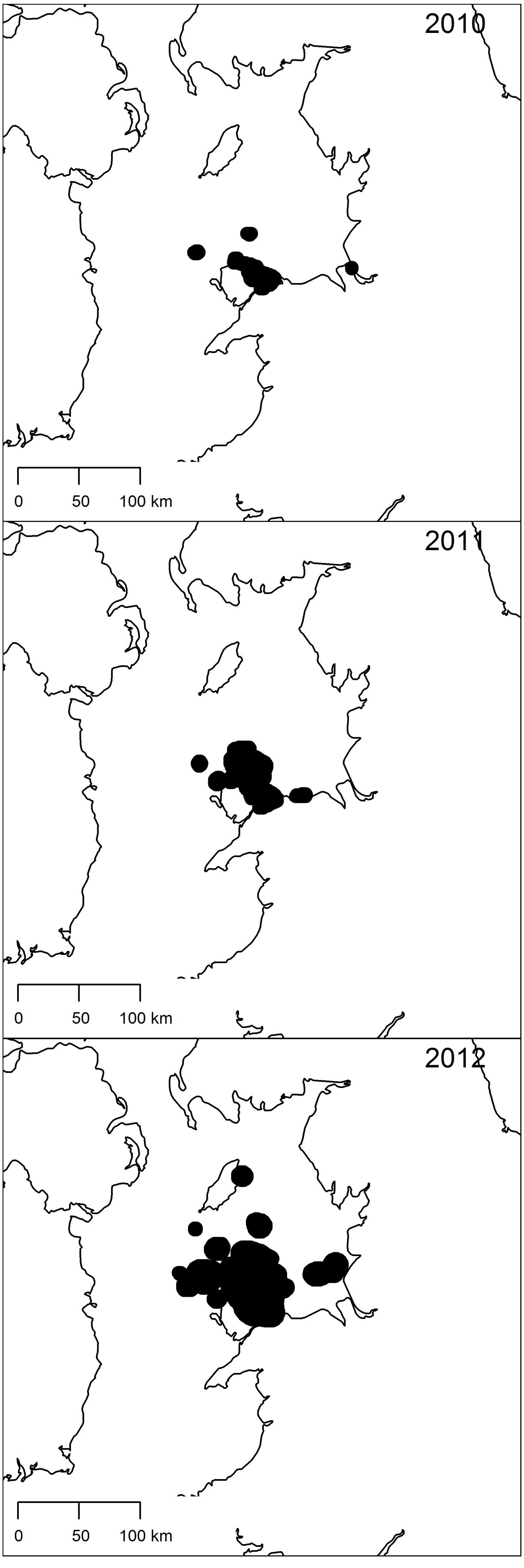
Coquet Island



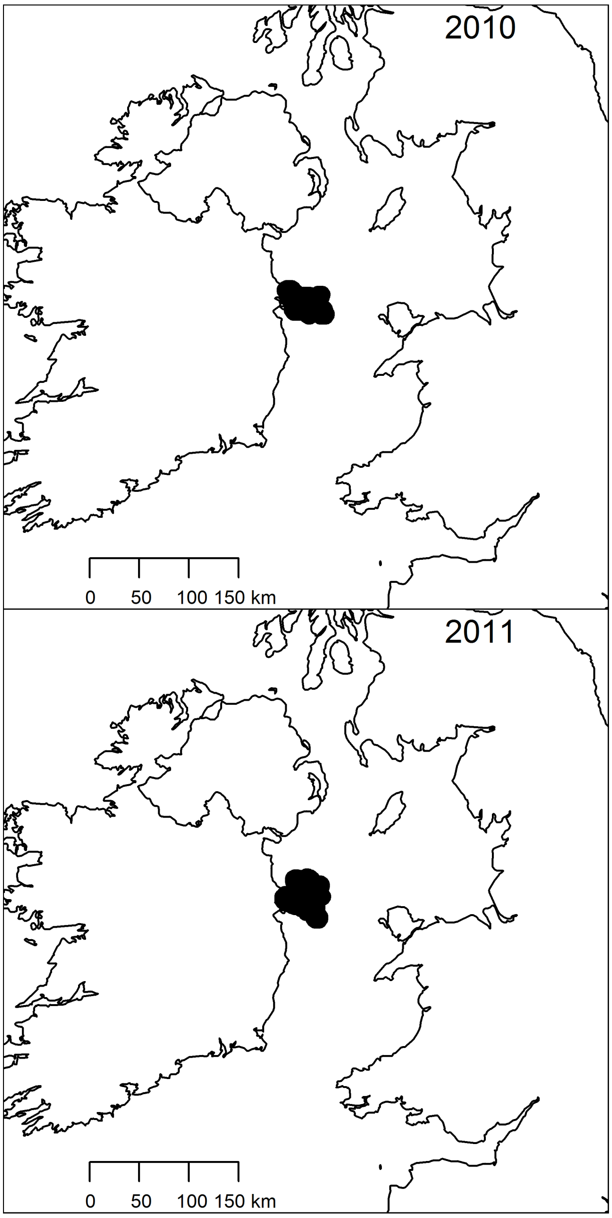
Flamborough Head and Bempton Cliffs



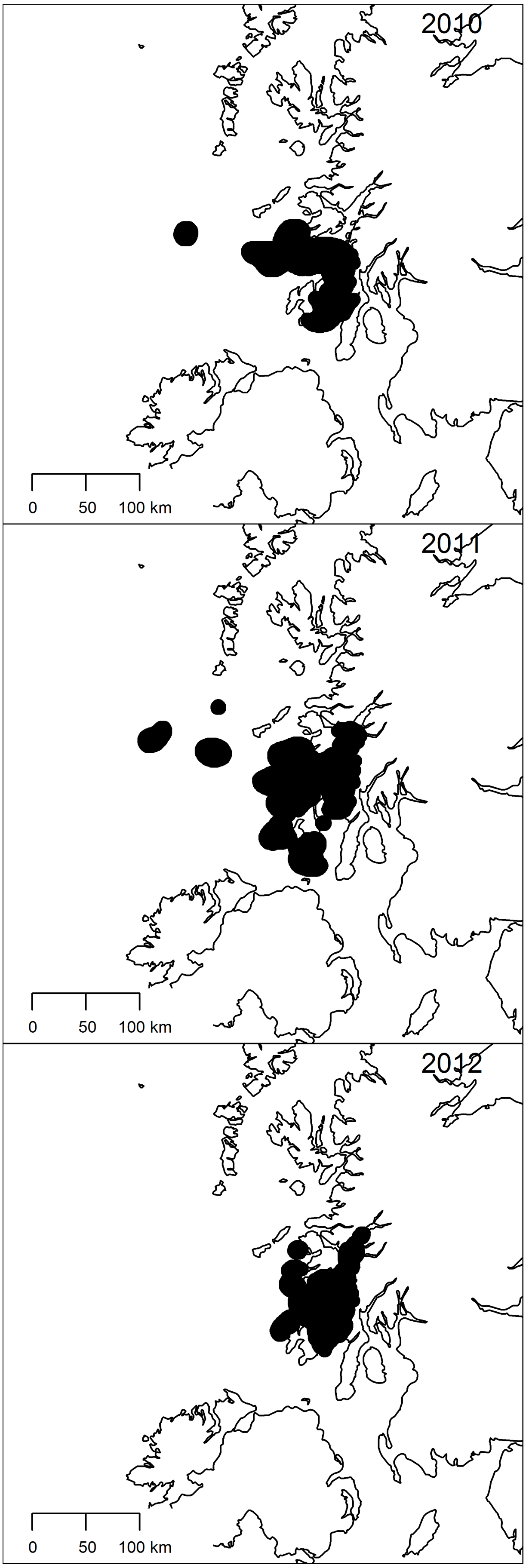
Puffin Island



Lambay



Isle of Colonsay



Supplement 3. Results from generalised linear mixed models with Poisson error structure

To understand whether the selected modelling framework affected the results of main analyses (i.e., Binomial error, assumption of 2 eggs per nest), GLMMs were also specified with the number of fledged chicks as the response, with a Poisson error distribution, log link function, and an offset of log(nests); remaining elements of the analysis (e.g., random effects structure, AIC comparisons) remained identical to the main analysis. Results from single-predictor models for single sites are presented in Table S3.1 (comparable to results presented in Table S6.1). Results from all-sites models with single predictor variables are presented in Table S3.2; those with multiple predictor variables are presented in Table S3.3 (comparable to results presented in Table S6.2).

For single-site models, all sites showed the best model to be the same as that identified in the main analysis, and other variables identified as important via ΔAICc were the same as those in binomial models. Fixed effect parameter estimates were similar to those from the binomial models. The best model with multiple predictor variables was the same in both frameworks, with strong negative effects of both spring temperature and winter PEA; ΔAIC of the best model relative to the null model was highly similar in both cases. When considering other models with some empirical support (ΔAIC ≤ 2 relative to the best model), there the order of the top-ranked models differing somewhat between modelling frameworks. The 4th-ranked model under the binomial framework (spring PEA, spring temperature, winter PEA) becoming 3nd-ranked under the Poisson framework. However, other highly-ranked models retained their relative rankings. Outside of the top-ranked models, there was further variation in model performance, but the strong negative effects of spring temperature and winter PEA remained the main feature of all highly-ranked models. Climate change projections were similar to those from the binomial analysis, with projected declines across all sites (Table S3.4). However, the magnitude of declines was larger, and the proportion of simulations not showing a decline was larger than in the binomial analysis.

Given the high similarities between results from the two different approaches, it can be concluded that there is little impact of modelling breeding success in a binomial framework instead of a Poisson framework. The best models were the same in both analyses, and relationships identified were highly similar, although there were some differences in the ranking of multiple-predictor models and the magnitude of climate change projections. Therefore, the results identified in the main analyses appear to be robust to the modelling framework used.

Table S3.1. Parameter estimates, AIC and ΔAIC from model fitting for single-site models with a Poisson error and log link. Fixed effects are reported as estimate (± standard error); the 'year' random effect is reported as the standard deviation of the effect. ΔAIC and ΔAICc were calculated relative to the null model for each site. Fixed effects highlighted in bold are those for which Wald Z tests indicated the parameter estimate was significantly different from 0; italics highlight parameter estimates approaching significance ($0.05 \leq P < 0.1$). See text for model fitting details.

Site	Predictor variable	Intercept	Parameter estimate	Year RE	AIC	ΔAIC	AICc	ΔAICc
	Null model	**-0.680 (± 0.282)**	–	1.134	196.679	–		–
	Spring PEA	2.299 (± 4.549)	-1.124 (± 1.715)	1.120	198.252	1.573	200.098	2.562
	Lagged spring PEA	6.800 (± 4.954)	-2.837 (± 1.880)	1.051	196.526	-0.153	198.372	0.836
	Spring SST	*-11.027 (± 6.575)*	1.044 (± 0.662)	1.070	196.222	-0.457	198.068	0.532
	Lagged spring SST	1.668 (± 5.087)	-0.239 (± 0.517)	1.129	198.466	1.787	200.312	2.776
Bardsey Island	Stratification onset	**-3.986 (± 1.646)**	**0.031 (± 0.015)**	1.025	194.573	-2.106	196.419	-1.117
	Lagged strat. onset	2.183 (± 2.710)	-0.025 (± 0.024)	1.100	197.571	0.892	199.417	1.881
	Winter PEA	-0.104 (± 0.339)	**-1.217 (± 0.528)**	0.975	193.776	-2.903	195.622	-1.914
	Lagged winter PEA	-0.073 (± 0.385)	**-1.614 (± 0.800)**	1.022	194.768	-1.911	196.614	-0.922
	Winter SST	*-6.915 (± 3.859)*	0.713 (± 0.439)	1.060	196.108	-0.571	197.954	0.418
	Lagged winter SST	-0.262 (± 4.162)	-0.048 (± 0.477)	1.135	198.669	1.990	200.515	2.979
	Null model	**-0.787 (± 0.194)**	–	0.742	180.033	–	181.033	–
	Spring PEA	-1.064 (± 3.123)	0.094 (± 1.059)	0.742	182.025	1.992	184.207	3.174
	Lagged spring PEA	-4.468 (± 2.731)	1.239 (± 0.917)	0.701	180.302	0.268	182.484	1.450
	Spring SST	-1.193 (± 3.806)	0.047 (± 0.443)	0.742	182.022	1.989	184.204	3.170
	Lagged spring SST	-1.187 (± 3.896)	0.046 (± 0.453)	0.742	182.023	1.989	184.205	3.171
Boddam to Collieston	Stratification onset	*-2.528 (± 1.431)*	0.017 (± 0.014)	0.707	180.596	0.562	182.777	1.744
	Lagged strat. onset	0.745 (± 1.501)	-0.015 (± 0.014)	0.717	181.010	0.977	183.192	2.159
	Winter PEA	**-0.789 (± 0.193)**	-0.149 (± 0.364)	0.738	181.867	1.833	184.048	3.015
	Lagged winter PEA	**-0.787 (± 0.194)**	-0.028 (± 0.402)	0.742	182.029	1.995	184.210	3.177
	Winter SST	-1.454 (± 2.907)	0.086 (± 0.374)	0.741	181.981	1.947	184.163	3.129
	Lagged winter SST	2.508 (± 2.939)	-0.423 (± 0.377)	0.713	180.818	0.785	183.000	1.967

Table S3.1 (cont.)

Site	Predictor variable	Intercept	Parameter estimate	Year RE	AIC	ΔAIC	AICc	ΔAICc
Coquet Island	Null model	0.081 (± 0.074)	–	0.214	102.258	–	103.592	–
	Spring PEA	-1.796 (± 1.483)	0.515 (± 0.405)	0.199	102.713	0.454	105.713	2.121
	Lagged spring PEA	-1.253 (± 1.578)	0.368 (± 0.434)	0.201	103.585	1.326	106.585	2.993
	Spring SST	0.655 (± 1.322)	-0.065 (± 0.149)	0.214	104.070	1.811	107.070	3.478
	Lagged spring SST	0.428 (± 1.343)	-0.040 (± 0.153)	0.214	104.192	1.933	107.192	3.600
	Stratification onset	-0.482 (± 0.401)	0.008 (± 0.006)	0.198	102.253	-0.006	105.253	1.661
	Lagged strat. onset	-0.067 (± 0.432)	0.002 (± 0.006)	0.214	104.137	1.879	107.137	3.545
	Winter PEA	**0.266 (± 0.118)**	*-0.256 (± 0.142)*	0.182	101.308	-0.950	104.308	0.716
	Lagged winter PEA	0.005 (± 0.153)	0.100 (± 0.174)	0.209	103.939	1.680	106.939	3.347
	Winter SST	0.440 (± 1.030)	-0.048 (± 0.138)	0.214	104.137	1.878	107.137	3.545
	Lagged winter SST	-0.155 (± 1.024)	0.032 (± 0.139)	0.214	104.205	1.947	107.205	3.613
Fair Isle	Null model	**-1.564 (± 0.603)**	–	2.586	292.324	–	293.074	–
	Spring PEA	**43.710 (± 17.285)**	**-11.908 (± 4.557)**	2.204	287.716	-4.609	289.316	-3.759
	Lagged spring PEA	32.916 (± 20.510)	*-9.112 (± 5.427)*	2.422	291.513	-0.811	293.113	0.039
	Spring SST	**29.875 (± 8.858)**	**-3.661 (± 1.037)**	1.934	283.073	-9.252	284.673	-8.401
	Lagged spring SST	**21.916 (± 10.217)**	**-2.755 (± 1.202)**	2.291	289.155	-3.169	290.755	-2.319
	Stratification onset	-6.145 (± 5.706)	0.041 (± 0.050)	2.557	293.680	1.356	295.280	2.206
	Lagged strat. onset	-7.820 (± 5.889)	0.055 (± 0.052)	2.517	293.212	0.888	294.812	1.738
	Winter PEA	-0.589 (± 1.659)	-0.705 (± 1.128)	2.548	293.942	1.618	295.542	2.468
	Lagged winter PEA	0.577 (± 1.569)	-1.526 (± 1.053)	2.447	292.302	-0.022	293.902	0.828
	Winter SST	**21.915 (± 10.082)**	**-3.023 (± 1.300)**	2.232	289.485	-2.839	291.085	-1.989
	Lagged winter SST	12.997 (± 11.566)	-1.883 (± 1.495)	2.493	292.770	0.446	294.370	1.296

Table S3.1 (cont.)

Site	Predictor variable	Intercept	Parameter estimate	Year RE	AIC	ΔAIC	AICc	ΔAICc
Flamborough Head and Bempton Cliffs	Null model	-0.182 (± 0.137)	–	0.577	233.190	–	233.990	–
	Spring PEA	**3.389 (± 1.332)**	**-1.519 (± 0.565)**	0.485	229.072	-4.119	230.786	-3.205
	Lagged spring PEA	1.868 (± 1.520)	-0.882 (± 0.652)	0.551	233.436	0.245	235.150	1.160
	Spring SST	**3.489 (± 1.597)**	**-0.423 (± 0.184)**	0.506	230.504	-2.686	232.218	-1.772
	Lagged spring SST	1.060 (± 1.871)	-0.145 (± 0.218)	0.571	234.752	1.561	236.466	2.476
	Stratification onset	1.247 (± 1.733)	-0.015 (± 0.018)	0.566	234.518	1.327	236.262	2.242
	Lagged strat. onset	-0.929 (± 1.796)	0.008 (± 0.018)	0.575	235.018	1.827	236.732	2.741
	Winter PEA	-0.018 (± 0.325)	0.174 (± 0.313)	0.572	234.883	1.692	236.597	2.607
	Lagged winter PEA	-0.303 (± 0.325)	-0.122 (± 0.298)	0.575	235.023	1.833	236.737	2.747
	Winter SST	1.750 (± 1.618)	-0.289 (± 0.241)	0.556	233.806	0.616	235.520	1.530
	Lagged winter SST	0.427 (± 1.773)	-0.092 (± 0.266)	0.576	235.072	1.881	236.786	2.796
Fowlsheugh	Null model	**-0.472 (± 0.132)**	–	0.539	215.509	–	216.366	–
	Spring PEA	2.117 (± 2.534)	-0.829 (± 0.811)	0.523	216.490	0.982	218.336	1.971
	Lagged spring PEA	-0.865 (± 2.598)	0.126 (± 0.833)	0.538	217.486	1.977	219.332	2.966
	Spring SST	1.014 (± 2.282)	-0.173 (± 0.266)	0.532	217.088	1.579	218.934	2.568
	Lagged spring SST	1.677 (± 2.261)	-0.252 (± 0.265)	0.524	216.627	1.118	218.473	2.107
	Stratification onset	-1.338 (± 1.261)	0.009 (± 0.013)	0.531	217.038	1.529	218.884	2.518
	Lagged strat. onset	0.223 (± 1.236)	-0.007 (± 0.013)	0.534	217.192	1.683	219.038	2.672
	Winter PEA	**-0.495 (± 0.131)**	-0.261 (± 0.294)	0.526	216.737	1.228	218.583	2.217
	Lagged winter PEA	**-0.495 (± 0.133)**	-0.210 (± 0.277)	0.530	216.943	1.434	218.789	2.423
	Winter SST	0.965 (± 1.842)	-0.187 (± 0.239)	0.530	216.906	1.398	218.753	2.387
	Lagged winter SST	0.962 (± 1.889)	-0.188 (± 0.247)	0.529	216.940	1.431	218.786	2.420

Table S3.1 (cont.)

Site	Predictor variable	Intercept	Parameter estimate	Year RE	AIC	ΔAIC	AICc	ΔAICc
Isle of May	Null model	**-1.034 (± 0.236)**	–	0.997	258.389	–	259.189	–
	Spring PEA	0.141 (± 6.755)	-0.337 (± 1.939)	0.995	260.359	1.970	262.073	2.884
	Lagged spring PEA	0.712 (± 6.779)	-0.503 (± 1.953)	0.995	260.322	1.934	262.037	2.848
	Spring SST	2.700 (± 4.233)	-0.432 (± 0.489)	0.977	259.622	1.233	261.336	2.148
	Lagged spring SST	**7.168 (± 2.976)**	**-0.960 (± 0.348)**	0.831	254.011	-4.377	255.726	-3.463
	Stratification onset	**-4.353 (± 1.072)**	**0.076 (± 0.024)**	0.800	252.328	-6.061	254.042	-5.147
	Lagged strat. onset	-1.516 (± 1.309)	0.011 (± 0.029)	0.992	260.249	1.860	261.963	2.774
	Winter PEA	1.402 (± 1.830)	-1.297 (± 0.967)	0.952	258.666	0.277	260.380	1.191
	Lagged winter PEA	-0.679 (± 1.877)	-0.189 (± 0.993)	0.995	260.353	1.964	262.067	2.878
	Winter SST	0.758 (± 3.067)	-0.256 (± 0.437)	0.989	260.048	1.659	261.762	2.573
	Lagged winter SST	1.161 (± 2.974)	-0.316 (± 0.427)	0.980	259.850	1.461	261.564	2.376
St Abb's Head	Null model	**-0.502 (± 0.116)**	–	0.485	231.157	–	231.957	–
	Spring PEA	2.416 (± 2.910)	-0.829 (± 0.826)	0.472	232.176	1.019	233.890	1.933
	Lagged spring PEA	0.865 (± 3.046)	-0.390 (± 0.869)	0.482	232.956	1.799	234.670	2.714
	Spring SST	-0.155 (± 2.137)	-0.039 (± 0.240)	0.485	233.130	1.974	234.845	2.888
	Lagged spring SST	*2.783 (± 1.621)*	**-0.375 (± 0.185)**	0.437	229.428	-1.729	231.142	-0.815
	Stratification onset	**-1.998 (± 0.587)**	**0.023 (± 0.009)**	0.412	227.447	-3.709	229.162	-2.795
	Lagged strat. onset	-0.741 (± 0.679)	0.004 (± 0.010)	0.483	233.029	1.872	234.743	2.786
	Winter PEA	0.351 (± 0.487)	*-0.730 (± 0.408)*	0.445	230.208	-0.948	231.922	-0.034
	Lagged winter PEA	0.112 (± 0.495)	-0.528 (± 0.415)	0.464	231.607	0.450	233.321	1.365
	Winter SST	0.333 (± 1.594)	-0.115 (± 0.219)	0.482	232.882	1.725	234.596	2.639
	Lagged winter SST	0.702 (± 1.557)	-0.167 (± 0.216)	0.477	232.566	1.409	234.280	2.323

Table S3.2. Parameter estimates, AIC and ΔAIC from all-sites models with single predictor variables, fitted with Poisson error and log link. Fixed effects are reported as estimate (± standard error); random effects are reported as the standard deviation of the effect. ΔAIC was calculated relative to the null model. Fixed effects highlighted in bold are those for which Wald Z tests indicated the parameter estimate was significantly different from 0; italics highlight parameter estimates approaching significance (0.05 ≤ *P* < 0.1). See text for model fitting details.

Predictor variable	Intercept	Parameter estimate	Site RE	Region RE	Year RE	Site * year RE	Region * year RE	AIC	ΔAIC
Null model	**-0.532 (± 0.202)**	–	0.244	0.263	0.182	0.601	0.904	1885.454	–
Spring PEA	0.960 (± 0.674)	-0.485 (± 0.213)	0.332	0.000	0.114	0.574	0.932	1881.685	-3.769
Lagged spring PEA	0.836 (± 0.676)	**-0.446 (± 0.214)**	0.326	0.000	0.119	0.577	0.934	1882.769	-2.685
Spring SST	**4.323 (± 1.865)**	**-0.546 (± 0.207)**	0.244	0.429	0.000	0.574	0.907	1880.231	-5.223
Lagged spring SST	**3.793 (± 1.746)**	**-0.491 (± 0.196)**	0.247	0.398	0.000	0.582	0.901	1880.978	-4.477
Stratification onset	**-1.536 (± 0.546)**	*0.011 (± 0.006)*	0.326	0.338	0.134	0.558	0.939	1881.849	-3.605
Lagged strat. onset	-0.751 (± 0.458)	0.002 (± 0.004)	0.223	0.304	0.190	0.601	0.901	1887.186	1.731
Winter PEA	-0.284 (± 0.195)	**-0.444 (± 0.147)**	0.355	0.000	0.217	0.539	0.920	1874.959	-10.495
Lagged winter PEA	**-0.355 (± 0.176)**	**-0.354 (± 0.129)**	0.303	0.280	0.197	0.580	0.880	1878.297	-7.157
Winter SST	0.926 (± 1.311)	-0.188 (± 0.168)	0.303	0.173	0.000	0.594	0.920	1886.337	0.883
Lagged winter SST	0.302 (± 1.437)	-0.108 (± 0.185)	0.282	0.199	0.116	0.601	0.910	1887.133	1.678

Table S3.3 Parameter estimates, AIC, ΔAIC and Akaike weights from all-sites models fitted with multiple predictor variables, using Poisson error distribution and log link. Fixed effects are reported as estimate (± standard error); random effects are reported as the standard deviation of the effect. Fixed effects highlighted in bold are those for which Wald Z tests indicated the parameter estimate was significantly different from 0; italics highlight parameter estimates approaching significance ($0.05 \leq P < 0.1$). See text for model fitting details.

Intercept	Spring PEA	Spring temperature	Stratification onset	Winter PEA	Winter temperature	Site RE	Region RE	Year RE	Site * year RE	Region * year RE	AIC	delta	weight
3.320 (± 1.685)	–	**-0.408 (± 0.189)**	–	**-0.424 (± 0.140)**	–	0.372	0.000	0.000	0.532	0.922	1872.433	–	0.243
3.245 (± 1.686)	–	*-0.507 (± 0.260)*	–	**-0.429 (± 0.141)**	0.125 (± 0.225)	0.385	0.001	0.000	0.531	0.918	1874.117	1.684	0.105
3.753 (± 1.863)	-0.138 (± 0.252)	**-0.412 (± 0.189)**	–	**-0.379 (± 0.163)**	–	0.380	0.000	0.000	0.531	0.923	1874.130	1.696	0.104
3.135 (± 1.744)	–	**-0.415 (± 0.190)**	0.003 (± 0.006)	**-0.392 (± 0.159)**	–	0.398	0.001	0.003	0.528	0.923	1874.236	1.803	0.099
-0.284 (± 0.195)	–	–	–	**-0.444 (± 0.147)**	–	0.355	0.000	0.217	0.539	0.920	1874.959	2.526	0.069
3.627 (± 1.865)	-0.127 (± 0.253)	*-0.498 (± 0.258)*	–	**-0.386 (± 0.165)**	0.113 (± 0.225)	0.388	0.001	0.004	0.531	0.920	1875.869	3.436	0.044
0.962 (± 1.276)	–	–	–	**-0.432 (± 0.143)**	-0.164 (± 0.166)	0.345	0.000	0.154	0.539	0.927	1875.999	3.566	0.041
3.540 (± 1.954)	-0.125 (± 0.258)	**-0.415 (± 0.189)**	0.002 (± 0.006)	**-0.358 (± 0.174)**	–	0.398	0.001	0.004	0.528	0.924	1876.009	3.576	0.041
3.145 (± 1.741)	–	*-0.495 (± 0.266)*	0.002 (± 0.006)	**-0.408 (± 0.013)**	0.103 (± 0.242)	0.400	0.001	0.001	0.529	0.920	1876.053	3.620	0.04
0.034 (± 0.773)	-0.110 (± 0.258)	–	–	**-0.412 (± 0.165)**	–	0.368	0.000	0.208	0.538	0.923	1876.774	4.340	0.028
-0.445 (± 0.629)	–	–	0.002 (± 0.006)	**-0.428 (± 0.160)**	–	0.377	0.000	0.208	0.535	0.926	1876.885	4.452	0.026
3.068 (± 1.896)	–	**-0.505 (± 0.201)**	*0.009 (± 0.005)*	–	–	0.302	0.430	0.000	0.548	0.918	1877.424	4.991	0.020
0.910 (± 1.297)	–	–	0.004 (± 0.006)	**-0.377 (± 0.167)**	-0.212 (± 0.180)	0.385	0.000	0.097	0.531	0.940	1877.537	5.104	0.019
1.441 (± 1.577)	-0.138 (± 0.260)	–	–	**-0.391 (± 0.163)**	-0.175 (± 0.168)	0.362	0.000	0.136	0.537	0.930	1877.713	5.279	0.017
3.545 (± 1.948)	-0.119 (± 0.258)	*-0.492 (± 0.264)*	0.001 (± 0.007)	**-0.375 (± 0.179)**	0.099 (± 0.242)	0.398	0.000	0.000	0.529	0.921	1877.841	5.407	0.016

4.880 (± 1.813)	**-0.480 (± 0.206)**	**-0.444 (± 0.189)**	–	–	–	0.343	0.001	0.000	0.559	0.926	1878.006	5.573	0.015

Table S3.3 (cont.)

Intercept	Spring PEA	Spring temperature	Stratification onset	Winter PEA	Winter temperature	Site RE	Region RE	Year RE	Site * year RE	Region * year RE	AIC	delta	weight
3.882 (± 1.976)	-0.344 (± 0.241)	**-0.451 (± 0.191)**	0.007 (± 0.006)	–	–	0.408	0.000	0.000	0.544	0.930	1878.248	5.815	0.013
-0.116 (± 1.026)	-0.105 (± 0.261)	–	0.001 (± 0.006)	**-0.399 (± 0.176)**	–	0.384	0.000	0.201	0.535	0.927	1878.722	6.289	0.010
1.337 (± 1.587)	-0.124 (± 0.263)	–	0.004 (± 0.006)	*-0.343 (± 0.183)*	-0.217 (± 0.180)	0.393	0.000	0.079	0.531	0.941	1879.313	6.880	0.008
3.063 (± 1.894)	–	*-0.525 (± 0.272)*	*0.009 (± 0.005)*	–	0.027 (± 0.240)	0.299	0.436	0.000	0.548	0.918	1879.412	6.979	0.007
4.765 (± 1.817)	**-0.473 (± 0.021)**	**-0.502 (± 0.253)**	–	–	0.08 (± 0.216)	0.343	0.008	0.003	0.559	0.926	1879.866	7.432	0.006
4.322 (± 1.865)	–	**-0.545 (± 0.207)**	–	–	–	0.244	0.429	0.000	0.574	0.907	1880.231	7.798	0.005
3.881 (± 1.977)	-0.343 (± 0.241)	-0.435 (± 0.266)	0.007 (± 0.006)	–	-0.021 (± 0.239)	0.407	0.001	0.000	0.544	0.930	1880.241	7.807	0.005
0.690 (± 1.321)	–	–	**0.013 (± 0.005)**	–	*-0.313 (± 0.173)*	0.421	0.000	0.000	0.548	0.944	1880.814	8.381	0.004
1.898 (± 1.560)	-0.332 (± 0.242)	–	*0.009 (± 0.006)*	–	*-0.296 (± 0.173)*	0.403	0.000	0.000	0.547	0.943	1880.926	8.492	0.003
4.023 (± 1.855)	–	**-0.688 (± 0.251)**	–	–	0.203 (± 0.209)	0.216	0.465	0.000	0.574	0.904	1881.323	8.889	0.003
0.959 (± 0.674)	**-0.485 (± 0.213)**	–	–	–	–	0.332	0.000	0.114	0.574	0.932	1881.685	9.252	0.002
-1.536 (± 0.546)	–	–	*0.011 (± 0.006)*	–	–	0.326	0.338	0.134	0.558	0.939	1881.849	9.416	0.002
-0.094 (± 1.078)	-0.362 (± 0.244)	–	0.008 (± 0.006)	–	–	0.408	0.000	0.089	0.552	0.951	1881.870	9.437	0.002
2.645 (± 1.487)	**-0.504 (± 0.215)**	–	–	–	-0.213 (± 0.164)	0.343	0.000	0.000	0.571	0.930	1881.973	9.540	0.002
-0.532 (± 0.202)	–	–	–	–	–	0.244	0.263	0.182	0.601	0.904	1885.454	13.021	0.000
0.926 (± 1.311)	–	–	–	–	-0.188 (± 0.168)	0.303	0.172	0.000	0.594	0.920	1886.337	13.904	0.000

Table S3.4. Projections of mean fledged chicks under the UKCP09 climatic baseline period of 1961-90 and for 2070-99 under the SRES A1B scenario. Reported values are the mean of 100,000 randomisation runs, where each run produces a mean number of fledged chicks across all years in the time period. The standard deviation of the 100,000 projections is also given. Proportional change is calculated as ((future - baseline)/baseline), based on the mean for each period. To indicate the probability of decline, the difference between the baseline and future projections was calculated for each run, and the proportion of these differences > 0 (i.e. those not showing a decline) was calculated.

Site	Mean predicted 1961 – 1990 fledged chicks (± st. dev.)	Mean predicted 2070 – 2099 fledged chicks (± st. dev.)	Proportional change	Proportion of projections not showing decline
Bardsey Island	1.498 (± 0.818)	0.665 (± 0.543)	-55.6%	0.032
Boddam to Collieston	2.875 (± 1.728)	1.369 (± 0.772)	-52.4%	0.136
Coquet Island	6.506 (± 3.883)	2.768 (± 1.778)	-57.5%	0.100
Fair Isle	1.407 (± 0.718)	0.557 (± 0.246)	-60.4%	0.016
Flamborough Head and Bempton Cliffs	3.087 (± 1.900)	1.141 (± 0.678)	-63.0%	0.056
Fowlsheugh	3.256 (± 1.927)	1.539 (± 0.875)	-52.7%	0.143
Isle of Colonsay	2.674 (± 1.747)	1.097 (± 0.672)	-59.0%	0.054
Isle of May	1.953 (± 1.042)	0.798 (± 0.374)	-59.2%	0.088
Lambay	1.882 (± 0.811)	0.899 (± 0.704)	-52.3%	0.079
Puffin Island	3.990 (± 3.126)	1.783 (± 1.748)	-55.3%	0.035
St Abb's Head	3.047 (± 1.542)	1.262 (± 0.617)	-58.6%	0.082
Across all sites	2.925 (± 1.290)	1.261 (± 0.638)	-56.9%	0.063

Supplement 4. Results from models including population size to account for density-dependence

Introduction

The main analyses in this study examined the effects of environmental conditions on kittiwake breeding success. However, seabird breeding success could be also influenced by intrinsic processes. Notably, in larger populations, greater local competition could reduce breeding success through processes such as food depletion or availability of high quality nest sites, thus producing density-dependent population regulation (e.g., Furness & Birkhead 1984, Kokko et al. 2004). To test for such a relationship here, we ran all models considered in the main analyses, but also took into account population size.

Methods

Generalised linear mixed models relating kittiwake breeding success to oceanographic variables were fitted following the methods described in the main text. Here, however, $\log_{10}$(population size) was entered as another predictor to examine for density-dependent effects. Breeding population size data were acquired from the seabird monitoring programme (SMP), describing the number of apparently occupied nests at each colony. However, breeding population size data were not available for all years for which breeding success data were available. Hence, 78 site-by-year combinations were available (Table S4.1); due to a lack of data, Lambay and Colonsay were not retained in analyses. For single-site models, four sites had the requisite ten years of data (Bardsey Island, Coquet Island, Isle of May and St Abb's Head). The reduced dataset meant that results could not be compared with those from the main analysis, so models without log(population) were also run on this reduced dataset to allow the effects of including population size to be identified.

First, two 'null' models were fitted: one had no fixed effects, and one had only log(population) as a fixed predictor. The model with population as a predictor allowed examination of the relationship between population size and breeding success. Further, these models were used as baselines against which the AIC (or AICc) value of models could be compared.

Next, models with single oceanographic predictors were fitted; for each variable, one model was fitted including population size, and one was fitted excluding population size. AIC (or AICc) values were compared against the appropriate null model. Finally, models including multiple predictors were fitted using data from all sites. One set of models included log(population), whilst the other contained only oceanographic predictors. As in the main analysis, these models were assessed by comparing AIC values to that from the best model.

Results

Across all sites (Table S4.2), and at three of the four sites considered individually (Tables S4.3 – S4.5) breeding success had no significant relationship with population size. Only St Abb's Head (Table S4.6) showed a significant relationship between population size and breeding success, but instead of the expected negative relationship, a positive relationship was found. There was therefore limited evidence of a relationship between breeding success and population size.

In models including all sites (Table S4.2), population size was always non-significant, and relationships with oceanographic variables did not differ between models including or excluding population size. In both sets, the best model showed a negative relationship with winter PEA, the second-ranked model showed a positive relationship with stratification onset, and the third-ranked model showed a negative relationship with spring PEA. Unlike in the main analysis, no significant relationship was found with spring SST, but this was attributable to the reduced dataset rather than the inclusion of population size. All models including population size displayed larger AIC values than the equivalent model without population size. Therefore, density-dependence did not affect relationships with oceanographic variables.

For individual sites, there was limited evidence of density-dependence influencing results. At Bardsey Island (Table S4.3), population size was always non-significant, and models with and without population size showed the best model to be a significant negative relationship with winter PEA. At Coquet Island (Table S4.4), population size was again non-significant. Winter PEA was weakly significant when population size was excluded ($P = 0.044$), but only approached significance when population size was included ($P = 0.079$). However, neither model performed better than the null model, so conclusions were identical regardless of the inclusion of population size. At Isle of May (Table S4.5), population size was non-significant, and both model sets showed stratification onset to be the only variable that performed better than the null model, again indicating identical conclusions. Finally, at St Abb's Head (Table S4.6), although population size performed better than the null model (population AICc = 228.6; null AICc = 230.5), the best model was that with stratification onset only (AICc = 227.9); when both stratification onset and population size were included in the same model, a larger AICc was produced (AICc = 228.4). Therefore, the inclusion of population size did not influence the conclusions drawn about oceanographic drivers of breeding success in any site tested.

In models including multiple predictors (Table S4.7), population size remained non-significant, although did achieve $P < 0.1$ in some models (smallest $P = 0.086$). Relationships with oceanographic variables showed the same form and similar significance regardless of whether population size was included. The six top-ranked models were the same in each set, but the relative ranking varied: the best model without population size became fourth-ranked when population size was included, whilst the best model including population size became third-ranked without population included. However, relationships that could be inferred were the same regardless of the inclusion of population size, with the negative PEA relationship present in all highly-ranked models, and negative winter SST and positive spring PEA (likely due to the correlation with winter PEA) relationships also present in highly-ranked models. The top-ranked model overall was that with winter PEA only.

Discussion

Here, population size appeared to have little effect on kittiwake breeding success. There was no evidence of the expected negative relationship between breeding success and population size; other than at St Abb's Head, there was no evidence of any relationship with population size. When population size and oceanographic variables were included in the same model, parameter estimates and model performance were similar to models without population size. Consequently, inferences made about the effects of oceanography on kittiwake breeding success were not affected by density-dependence.

The lack of a strong relationship between population size and breeding success or population growth has been reported previously for kittiwake colonies in the UK and Norway (Frederiksen et al. 2005, Sandvik et al. 2014), whilst similar findings have also been reported for gannets (Lewis et al. 2001). Hence, in some seabird populations, extrinsic factors may be more important drivers of breeding success. It may, of course, be possible that density-dependence is manifested through other processes such as chick growth, nest-site availability or breeding propensity (Lewis et al. 2001, Kokko et al. 2004, Crespin et al. 2006) that could still lead to population-level impacts. Alternatively, the only measure of population size available here may not adequately represent total population size, as it excludes non-breeders and failed breeders, and the proportion of breeders may vary over time (Frederiksen et al. 2004). Further, multiple seabird species are likely to be competing for the same prey resource in a given area, with many species relying on sandeels (Furness & Tasker 2000), so interspecific competition may also be relevant. However, although density dependence is likely to have some influence on seabird populations, it appears that in the present study, its influence is sufficiently limited that results of the main analyses can be considered to be robust.

Table S4.1. Sites included in analysis, showing number of years of overlapping breeding success, population and oceanography data available.

Site	Map site number (main text Fig. 1)	Region	Coordinates	Years with overlapping breeding success, population and oceanography data
Fair Isle	1	Shetland	1.65° W, 59.52° N	6
Boddam to Collieston	2	East Scotland	1.85° W, 57.42° N	3
Fowlsheugh	3	East Scotland	2.20° W, 56.92° N	2
Isle of May NNR	4	East Scotland	2.57° W, 56.18° N	18
St. Abb's Head NNR	5	East Scotland	2.13° W, 55.91° N	18
Coquet Island	6	East England	1.52° W, 55.34° N	12
Flamborough Head and Bempton Cliffs	7	East England	0.08° W, 54.12° N	1
Bardsey Island NNR	8	Irish Sea	4.83° W, 52.76° N	17
Puffin Island	9	Irish Sea	4.03° W, 53.32° N	1
Lambay	10	Irish Sea	6.03° W, 53.50° N	0
Isle of Colonsay	11	West Scotland	6.21° W, 56.08° N	0

Table S4.2. Parameter estimates, AIC and ΔAIC from all-sites models with single oceanographic predictor variables. Fixed effects are reported as estimate (± standard error); random effects are reported as the standard deviation of the effect. ΔAIC was calculated relative to the relevant null model (i.e., containing no fixed effects, or containing only population size as a fixed effect). Fixed effects highlighted in bold are those for which Wald Z tests indicated the parameter estimate was significantly different from 0; italics highlight parameter estimates approaching but not attaining significance (0.05 ≤ P < 0.1).

	Predictor variable	Intercept	Population parameter estimate	Parameter estimate	Site RE	Region RE	Year RE	Site * year RE	Region * year RE	AIC	ΔAIC
Excluding log(population)	Null model	*-0.499 (± 0.302)*	–	–	0.561	0.079	0.550	0.688	0.719	957.769	–
	Stratification onset	**-2.739 (± 0.676)**	–	**0.024 (± 0.005)**	0.000	0.960	0.495	0.643	0.647	946.026	**-11.743**
	Spring SST	-0.329 (± 2.964)	–	-0.019 (± 0.333)	0.553	0.119	0.548	0.688	0.720	959.766	1.997
	Spring PEA	*2.070 (± 1.210)*	–	**-0.811 (± 0.365)**	0.422	0.372	0.557	0.575	0.832	954.015	**-3.754**
	Winter SST	-0.676 (± 1.965)	–	0.023 (± 0.256)	0.566	0.026	0.550	0.686	0.722	959.761	1.992
	Winter PEA	0.056 (± 0.271)	–	**-0.749 (± 0.134)**	0.000	0.354	0.413	0.618	0.719	940.139	**-17.630**
With log(population)	Null model	0.099 (± 0.834)	-0.184 (± 0.238)	–	0.501	0.000	0.583	0.698	0.696	959.230	–
	Stratification onset	**-2.527 (± 0.944)**	-0.087 (± 0.275)	**0.024 (± 0.005)**	0.000	0.935	0.508	0.645	0.639	947.927	**-11.303**
	Spring SST	1.297 (± 3.223)	-0.224 (± 0.252)	-0.122 (± 0.317)	0.471	0.000	0.574	0.698	0.707	961.086	1.856
	Spring PEA	*2.377 (± 1.236)*	-0.160 (± 0.232)	**-0.744 (± 0.308)**	0.493	0.000	0.597	0.572	0.823	955.634	**-3.596**
	Winter SST	0.386 (± 2.323)	-0.194 (± 0.248)	-0.034 (± 0.256)	0.495	0.000	0.585	0.701	0.692	961.213	1.983
	Winter PEA	0.530 (± 0.647)	-0.149 (± 0.185)	**-0.768 (± 0.137)**	0.000	0.337	0.456	0.618	0.694	941.499	**-17.731**

Table S4.3. Parameter estimates, AICc and ΔAICc from models with single predictor variables for Bardsey Island. Interpretation of table as for Table S4.2.

	Predictor variable	Intercept	Population par. estimate	Parameter estimate	Year RE	AICc	ΔAICc
Excluding log(population)	Null model	**-0.888 (± 0.373)**	–	–	1.507	187.621	–
	Stratification onset	**-5.369 (± 2.133)**	–	**0.041 (± 0.019)**	1.351	186.266	*-1.356*
	Spring SST	-13.877 (± 8.709)	–	1.311 (± 0.877)	1.431	188.428	0.807
	Spring PEA	3.668 (± 6.012)	–	-1.719 (± 2.266)	1.483	190.042	2.420
	Winter SST	*-8.998 (± 5.082)*	–	0.928 (± 0.579)	1.412	188.137	0.516
	Winter PEA	-0.111 (± 0.449)	–	**-1.645 (± 0.693)**	1.295	185.531	**-2.090**
With log(population)	Null model	-1.935 (± 0.437)	0.437 (± 4.323)	–	1.507	190.600	–
	Stratification onset	-10.187 (± 9.980)	1.941 (± 3.917)	**0.043 (± 0.019)**	1.340	189.509	*-1.091*
	Spring SST	-12.984 (± 12.334)	-0.426 (± 4.156)	1.324 (± 0.886)	1.432	191.905	1.305
	Spring PEA	0.966 (± 10.790)	1.316 (± 4.379)	-1.890 (± 2.331)	1.478	193.439	2.839
	Winter SST	-8.543 (± 10.574)	-0.200 (± 4.080)	0.931 (± 0.582)	1.412	191.622	1.022
	Winter PEA	-7.697 (± 9.042)	3.195 (± 3.804)	**-1.802 (± 0.707)**	1.266	188.326	**-2.274**

Table S4.4. Parameter estimates, AICc and ΔAICc from models with single predictor variables for Coquet Island. Interpretation of table as for Table S4.2.

	Predictor variable	Intercept	Population par. estimate	Parameter estimate	Year RE	AICc	ΔAICc
Excluding log(population)	Null model	0.233 (± 0.178)	–	–	0.579	103.824	–
	Stratification onset	-0.999 (± 0.940)	–	0.018 (± 0.014)	0.538	105.816	1.992
	Spring SST	0.775 (± 3.109)	–	-0.061 (± 0.352)	0.578	107.460	3.636
	Spring PEA	-4.245 (± 3.532)	–	1.228 (± 0.968)	0.541	105.964	2.140
	Winter SST	0.791 (± 2.343)	–	-0.075 (± 0.315)	0.577	107.433	3.610
	Winter PEA	**0.742 (± 0.297)**	–	**-0.697 (± 0.346)**	0.493	103.933	0.109
With log(population)	Null model	-1.301 (± 1.530)	0.887 (± 0.879)	–	0.550	106.522	–
	Stratification onset	-2.281 (± 1.633)	0.791 (± 0.837)	0.017 (± 0.013)	0.514	109.675	3.153
	Spring SST	1.625 (± 2.860)	1.752 (± 1.098)	-0.501 (± 0.420)	0.512	109.905	3.383
	Spring PEA	-4.868 (± 3.523)	0.699 (± 0.864)	1.067 (± 0.961)	0.524	110.042	3.521
	Winter SST	0.677 (± 2.131)	*1.820 (± 1.102)*	-0.485 (± 0.380)	0.513	109.689	3.167
	Winter PEA	-0.003 (± 1.581)	0.405 (± 0.845)	*-0.638 (± 0.363)*	0.485	108.421	1.899

Table S4.5. Parameter estimates, AICc and ΔAICc from models with single predictor variables for Isle of May. Interpretation of table as for Table S4.2.

	Predictor variable	Intercept	Population par. estimate	Parameter estimate	Year RE	AICc	ΔAICc
Excluding log(population)	Null model	**-1.408 (± 0.289)**	–	–	1.223	254.784	–
	Stratification onset	**-5.411 (± 1.316)**	–	**0.092 (± 0.030)**	0.988	249.929	**-4.855**
	Spring SST	2.810 (± 5.200)	–	-0.488 (± 0.601)	1.202	257.049	2.264
	Spring PEA	0.990 (± 8.263)	–	-0.689 (± 2.371)	1.219	257.614	2.830
	Winter SST	0.575 (± 3.756)	–	-0.283 (± 0.535)	1.214	257.420	2.636
	Winter PEA	1.367 (± 2.256)	–	-1.478 (± 1.192)	1.175	256.219	1.435
With log(population)	Null model	-4.804 (± 8.021)	0.909 (± 2.146)	–	1.217	257.520	–
	Stratification onset	0.770 (± 6.585)	-1.812 (± 1.894)	**0.106 (± 0.032)**	0.964	252.398	**-5.122**
	Spring SST	-1.110 (± 8.912)	1.144 (± 2.121)	-0.529 (± 0.601)	1.193	260.123	2.603
	Spring PEA	-2.425 (± 11.579)	0.898 (± 2.141)	-0.671 (± 2.361)	1.213	260.802	3.282
	Winter SST	-2.713 (± 8.949)	0.863 (± 2.135)	-0.274 (± 0.533)	1.209	260.619	3.100
	Winter PEA	3.116 (± 10.265)	-0.412 (± 2.356)	-1.590 (± 1.355)	1.174	259.551	2.031

Table S4.6. Parameter estimates, AICc and ΔAICc from models with single predictor variables for St Abb's Head. Interpretation of table as for Table S4.2.

	Predictor variable	Intercept	Population par. estimate	Parameter estimate	Year RE	AICc	ΔAICc
Excluding log(population)	Null model	**-0.754 (± 0.174)**	–	–	0.731	230.539	–
	Stratification onset	**-2.972 (± 0.881)**	–	**0.034 (± 0.013)**	0.625	227.875	**-2.665**
	Spring SST	-0.540 (± 3.211)	–	-0.024 (± 0.361)	0.731	233.449	2.910
	Spring PEA	3.391 (± 4.370)	–	-1.177 (± 1.241)	0.714	232.573	2.034
	Winter SST	0.133 (± 2.396)	–	-0.122 (± 0.328)	0.729	233.316	2.777
	Winter PEA	0.513 (± 0.733)	–	*-1.085 (± 0.613)*	0.674	230.568	0.029
With log(population)	Null model	**-10.782 (± 4.252)**	**2.457 (± 1.041)**	–	0.639	228.573	–
	Stratification onset	**-9.593 (± 3.907)**	*1.752 (± 1.010)*	**0.026 (± 0.013)**	0.578	228.445	-0.128
	Spring SST	**-12.915 (± 5.772)**	**2.599 (± 1.065)**	0.175 (± 0.323)	0.633	231.646	3.073
	Spring PEA	-7.629 (± 6.250)	**2.339 (± 1.043)**	-0.759 (± 1.115)	0.631	231.478	2.905
	Winter SST	**-13.021 (± 5.823)**	**2.698 (± 1.118)**	0.173 (± 0.310)	0.633	231.629	3.056
	Winter PEA	*-8.165 (± 4.952)*	*1.990 (± 1.125)*	-0.607 (± 0.629)	0.623	231.028	2.455

Table S4.7. Parameter estimates, AIC and ΔAIC from top-ranked all-sites models with multiple predictor variables. Fixed effects are reported as estimate (± standard error); random effects are reported as the standard deviation of the effect. ΔAIC was calculated relative to the best model in each set. Fixed effects highlighted in bold are those for which Wald Z tests indicated the parameter estimate was significantly different from 0; italics highlight parameter estimates approaching but not attaining significance (0.05 ≤ P < 0.1).

	Intercept	Pop. size	Spring PEA	Spring SST	Strat. onset	Winter PEA	Winter SST	Site RE	Region RE	Year RE	Site * year RE	Region * year RE	AIC	ΔAIC	weight
Excluding log(population)	0.056 (± 0.271)	–	–	–	–	**-0.749 (± 0.134)**	–	0.000	0.354	0.413	0.618	0.719	940.139	–	0.158
	-1.750 (± 0.849)	–	**0.617 (± 0.289)**	–	–	**-0.985 (± 0.177)**	–	0.000	0.000	0.339	0.682	0.670	940.336	0.197	0.143
	0.156 (± 1.913)	–	0.485 (± 0.306)	–	–	**-0.989 (± 0.173)**	-0.192 (± 0.173)	0.000	0.000	0.385	0.654	0.684	941.065	0.926	0.099
	1.881 (± 1.866)	–	–	–	–	**-0.798 (± 0.145)**	-0.232 (± 0.235)	0.000	0.214	0.451	0.610	0.732	941.251	1.112	0.091
	-1.188 (± 1.173)	–	*0.559 (± 0.297)*	–	-0.004 (± 0.005)	**-1.060 (± 0.206)**	–	0.000	0.000	0.372	0.674	0.662	941.862	1.723	0.067
	-0.483 (± 2.094)	–	*0.562 (± 0.299)*	-0.122 (± 0.184)	–	**-0.975 (± 0.177)**	–	0.000	0.000	0.325	0.666	0.698	941.891	1.752	0.066
	0.233 (± 0.960)	–	–	–	-0.002 (± 0.009)	**-0.790 (± 0.254)**	–	0.000	0.325	0.416	0.618	0.721	942.104	1.965	0.059
	0.365 (± 2.352)		–	-0.034 (± 0.260)	–	**-0.748 (± 0.134)**	–	0.000	0.338	0.409	0.617	0.725	942.122	1.983	0.059
Including log(population)	1.815 (± 2.145)	*-0.220 (± 0.131)*	0.441 (± 0.291)	–	–	**-0.970 (± 0.163)**	-0.302 (± 0.185)	0.000	0.001	0.497	0.639	0.620	940.422	–	0.152
	4.004 (± 1.711)	*-0.241 (± 0.141)*	–	–	–	**-0.828 (± 0.146)**	**-0.409 (± 0.192)**	0.068	0.000	0.573	0.604	0.670	940.697	0.276	0.132
	-1.391 (± 0.893)	-0.138 (± 0.126)	**0.635 (± 0.280)**	–	–	**-0.966 (± 0.172)**	–	0.000	0.000	0.398	0.677	0.632	941.165	0.744	0.105
	0.530 (± 0.647)	-0.149 (± 0.185)	–	–	–	**-0.768 (± 0.137)**	–	0.000	0.337	0.456	0.618	0.694	941.499	1.077	0.089
	1.199 (± 2.369)	-0.203 (± 0.137)	*0.539 (± 0.285)*	-0.233 (± 0.198)	–	**-0.947 (± 0.168)**	–	0.001	0.000	0.410	0.649	0.659	941.776	1.354	0.077
	1.880 (± 2.176)	*-0.228 (± 0.137)*	0.445 (± 0.292)	–	0.001 (± 0.006)	**-0.944 (± 0.205)**	-0.325 (± 0.217)	0.000	0.000	0.498	0.638	0.622	942.378	1.957	0.057
	1.610 (± 2.410)	-0.215 (± 0.133)	0.437 (± 0.292)	0.060 (± 0.316)	–	**-0.975 (± 0.165)**	-0.346 (± 0.294)	0.000	0.000	0.507	0.640	0.613	942.386	1.964	0.057

Supplement 5. Results from models testing for trends over time, and from models trialling different forms of input variables

Breeding success and oceanographic variables were tested for trends over time (Table S5.1); see main text for details on productivity model fitting details. Trends in oceanographic variables were modelled in the same framework, but with Gaussian error structure, and hence with observation-level random factors removed (i.e., 'site*year' and 'year' for all-sites and single-site models respectively); therefore, no random factors were required for local-scale models. Breeding success models showed convergence problems when fitted with raw 'year' input, so 'year' was scaled and centred. This reduced convergence problems, but means that parameters are not strictly comparable with those from oceanographic trend models.

Results of Spearman correlations to test for collinearity between predictor variables are presented in Table S5.2. Correlation coefficients were typically weak to moderate; see the main text for discussion of stronger correlations.

Models of productivity were fitted using both log-transformed and untransformed PEA (Table S5.3). For both spring and winter PEA, models with log-transformed PEA were associated with smaller AIC values than were models with untransformed PEA.

Productivity models were fitted with variables with a 1-year lag (Table S5.4; Fig. S5.1) for comparison with those without a lag (main text Table 2 and Fig. 2). Lagged spring SST showed support over the null model at Fair Isle, Isle of May and St Abb's Head; as with the unlagged form, higher productivity was associated with lower SSTs. The relationships at Isle of May and St Abb's Head were not found with the unlagged form, but the relationship at Fair Isle was weaker than the unlagged equivalent. The only other models that performed better than the null model were negative relationships with winter PEA at Bardsey Island and spring PEA at Fair Isle; both were less well supported than the unlagged equivalents. For models including data from all colonies, relationships were similar to those without lags, but ΔAIC was always greater for the unlagged form, indicating that unlagged variables performed better. Therefore, with the exception of spring SST at Isle of May and St Abb's Head, lagged variables performed worse than unlagged equivalents.

Table S5.1. Results from models of breeding success and oceanographic variables against time. Results presented indicate the parameter estimate of the predictor variable, along with its associated *P*-value; bold indicates that the parameter estimate is significantly different from 0; italics indicate the estimate approaches significance (i.e., 0.05 ≤ *P* < 0.1). Models of breeding success in Lambay and Puffin Island could not be fitted due to limited years of data. To aid model convergence, breeding success models were fitted using scaled and centred year; see text for further details of model fitting.

	Breeding success	Winter SST	Winter PEA	Spring SST	Spring PEA	Stratification onset
Across all sites	-0.235 (± 0.159), P = 0.141	0.038 (± 0.019), P = 0.054	0.020 (± 0.010), P = 0.046	0.044 (± 0.018), P = 0.026	0.006 (± 0.004), P = 0.173	-0.316 (± 0.180), P = 0.096
Bardsey Island	**0.724 (± 0.348), *P* = 0.038**	**0.052 (± 0.023), *P* = 0.035**	-0.011 (± 0.020), *P* = 0.588	**0.057 (± 0.020), *P* = 0.009**	-0.002 (± 0.007), *P* = 0.782	0.026 (± 0.769), *P* = 0.973
Boddam to Collieston	-0.179 (± 0.312), *P* = 0.567	*0.040 (± 0.021), P = 0.073*	*0.039 (± 0.022), P = 0.092*	*0.037 (± 0.018), P = 0.057*	0.005 (± 0.008), *P* = 0.589	**-1.285 (± 0.491), *P* = 0.018**
Coquet Island	0.336 (± 0.276), *P* = 0.224	**0.046 (± 0.021), *P* = 0.043**	0.003 (± 0.021), *P* = 0.904	*0.048 (± 0.024), P = 0.061*	0.007 (± 0.006), *P* = 0.264	-0.102 (± 0.522), *P* = 0.848
Fair Isle	-0.970 (± 0.706), *P* = 0.170	0.026 (± 0.017), *P* = 0.133	0.028 (± 0.022), *P* = 0.224	*0.039 (± 0.019), P = 0.052*	*0.009 (± 0.005), P = 0.076*	*-0.956 (± 0.475), P = 0.061*
Flamborough Head and Bempton Cliffs	**-0.560 (± 0.186), *P* = 0.003**	**0.047 (± 0.021), *P* = 0.037**	0.013 (± 0.018), *P* = 0.482	**0.069 (± 0.023), *P* = 0.008**	0.013 (± 0.008), *P* = 0.129	0.184 (± 0.322), *P* = 0.576
Fowlsheugh	**-0.361 (± 0.181), *P* = 0.047**	*0.040 (± 0.021), P = 0.070*	0.035 (± 0.020), *P* = 0.101	*0.038 (± 0.019), P = 0.067*	0.006 (± 0.007), *P* = 0.407	**-1.043 (± 0.381), *P* = 0.014**
Isle of Colonsay	-0.379 (± 0.432), *P* = 0.381	0.031 (± 0.023), *P* = 0.192	0.020 (± 0.017), *P* = 0.260	*0.043 (± 0.024), P = 0.086*	-0.002 (± 0.008), *P* = 0.801	-0.851 (± 0.529), *P* = 0.126
Isle of May	-0.190 (± 0.310), *P* = 0.541	0.035 (± 0.023), *P* = 0.138	**0.023 (± 0.009), *P* = 0.016**	0.032 (± 0.024), *P* = 0.194	0.002 (± 0.005), *P* = 0.670	**-0.767 (± 0.299), *P* = 0.020**
Lambay	–	**0.050 (± 0.021), *P* = 0.029**	-0.001 (± 0.024), *P* = 0.982	0.037 (± 0.025), *P* = 0.164	-0.002 (± 0.005), *P* = 0.659	0.458 (± 0.530), *P* = 0.400
Puffin Island	–	*0.045 (± 0.023), P = 0.064*	0.008 (± 0.012), *P* = 0.507	**0.056 (± 0.019), *P* = 0.008**	0.001 (± 0.008), *P* = 0.917	0.634 (± 0.515), *P* = 0.235
St. Abb's Head	**-0.380 (± 0.167), *P* = 0.023**	*0.042 (± 0.022), P = 0.069*	**0.022 (± 0.010), *P* = 0.048**	*0.041 (± 0.023), P = 0.092*	0.007 (± 0.006), *P* = 0.255	-0.513 (± 0.462), *P* = 0.282

Table S5.2. Spearman rank correlations between predictor variables, and associated *P*-values. Correlations were tested at the national scale (i.e. across all sites).

	Strat. onset	**Lagged strat. onset**	**Spring PEA**	**Lagged spring PEA**	**Spring SST**	**Lagged spring SST**	**Winter PEA**	**Lagged winter PEA**	**Winter SST**
Lagged strat. onset	ρ = 0.815 *P* < 0.001	–							
Spring PEA	ρ = -0.559 *P* < 0.001	ρ = -0.529 *P* < 0.001	–						
Lagged spring PEA	ρ = -0.537 *P* < 0.001	ρ = -0.558 *P* < 0.001	ρ = 0.950 *P* < 0.001	–					
Spring SST	ρ = -0.210 *P* < 0.001	ρ = -0.199 *P* = 0.001	ρ = 0.212 *P* < 0.001	ρ = 0.174 *P* = 0.005	–				
Lagged spring SST	ρ = -0.229 *P* < 0.001	ρ = -0.209 *P* < 0.001	ρ = 0.169 *P* = 0.006	ρ = 0.208 *P* = 0.001	ρ = 0.647 *P* < 0.001	–			
Winter PEA	ρ = -0.485 *P* < 0.001	ρ = -0.411 *P* < 0.001	ρ = 0.669 *P* < 0.001	ρ = 0.681 *P* < 0.001	ρ = 0.165 *P* = 0.007	ρ = 0.148 *P* = 0.016	–		
Lagged winter PEA	ρ = -0.428 *P* < 0.001	ρ = -0.465 *P* < 0.001	ρ = 0.681 *P* < 0.001	ρ = 0.681 *P* < 0.001	ρ = 0.112 *P* = 0.069	ρ = 0.166 *P* = 0.007	ρ = 0.825 *P* < 0.001	–	
Winter SST	ρ = 0.197 *P* = 0.001	ρ = 0.183 *P* = 0.003	ρ = 0.070 *P* = 0.257	ρ = 0.340 *P* = 0.059	ρ = 0.672 *P* < 0.001	ρ = 0.481 *P* < 0.001	ρ = 0.093 *P* = 0.131	ρ = 0.052 *P* = 0.395	–
Lagged winter SST	ρ = 0.162 *P* = 0.008	ρ = 0.212 *P* < 0.001	ρ = 0.072 *P* < 0.241	ρ = 0.061 *P* = 0.320	ρ = 0.488 *P* < 0.001	ρ = 0.655 *P* < 0.001	ρ = 0.051 *P* = 0.411	ρ = 0.097 *P* = 0.116	ρ = 0.673 *P* < 0.001

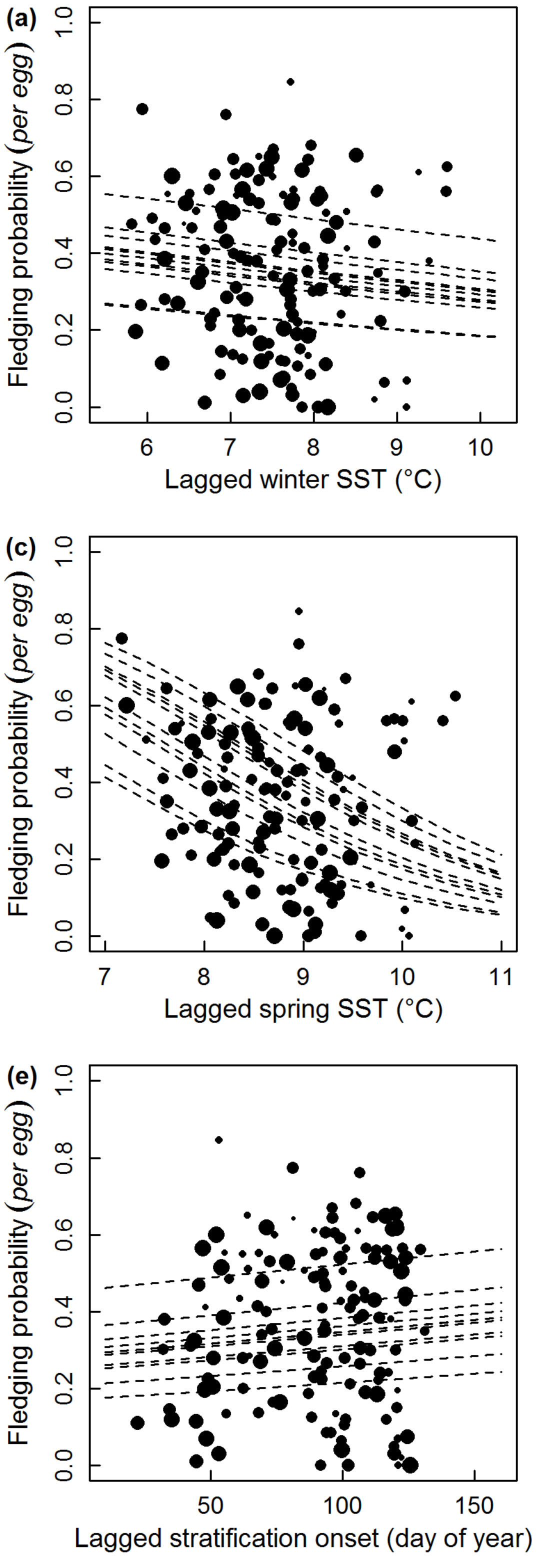
Table S5.3. Results from models of breeding success with log-transformed and untransformed PEA as predictors, fitted to data from all sites. Models were GLMMs with binomial error distribution, logit link function and ‘year’, ‘site’, ‘region’, ‘site*year’ and ‘region*year’ random effects. ΔAIC values are calculated relative to the null model, fitted with only intercept and random effects.

Variable	Parameter estimate (± SE)	*P* value	AIC	ΔAIC
Null model	–	–	1803.730	–
Spring PEA	-0.024 (± 0.014)	0.104	1803.181	-0.549
Log(spring PEA)	-0.602 (± 0.285)	0.035	1801.062	-2.669
Winter PEA	-0.217 (± 0.070)	0.002	1793.519	-10.211
Log(winter PEA)	-0.641 (± 0.201)	0.001	1792.228	-11.502

Table S5.4. Results from models relating breeding success to single oceanographic predictor variables with a 1-year lag. See main text for details of model fitting. Parameter estimates (± SE) are given, along with the ΔAIC (for all-sites models) or ΔAICc (for individual site models) value relative to a null model fitted with intercept and random effects only. Parameter estimates significantly different from 0 at *P* < 0.05, as indicated by Wald Z tests, are bold; results approaching but not attaining significance with 0.05 ≤ *P* < 0.1 are italic. Full model details are given in Appendix S6.

	Bardsey Island	Boddam to Collieston	Coquet Island	Fair Isle	Flamborough Head and Bempton Cliffs	Fowlsheugh	Isle of May	St Abb's Head	All sites
Null model	AICc = 187.621	AICc = 178.476	AICc = 103.824	AICc = 278.788	AICc = 225.489	AICc = 214.311	AICc = 254.784	AICc = 230.539	AIC = 1803.730
Lagged winter SST	0.037 (± 0.632), ΔAICc = 2.986	-0.496 (± 0.508), ΔAICc = 2.257	0.124 (± 0.326), ΔAICc = 3.522	-2.052 (± 1.732), ΔAICc = 1.473	-0.068 (± 0.433), ΔAICc = 2.889	-0.281 (± 0.378), ΔAICc = 2.445	-0.429 (± 0.523), ΔAICc = 2.254	-0.251 (± 0.324), ΔAICc = 2.323	-0.105 (± 0.248), ΔAIC = 1.827
Lagged winter PEA	**-2.133 (± 1.052), ΔAICc = -0.886**	-0.130 (± 0.536), ΔAICc = 3.123	0.244 (± 0.425), ΔAICc = 3.343	-1.880 (± 1.203), ΔAICc = 0.524	-0.110 (± 0.484), ΔAICc = 2.863	-0.376 (± 0.421), ΔAICc = 2.209	-0.510 (± 1.212), ΔAICc = 2.738	-0.862 (± 0.619), ΔAICc = 1.074	**-0.483 (± 0.175), ΔAIC = -7.091**
Lagged spring SST	-0.234 (± 0.689), ΔAICc = 2.874	0.017 (± 0.605), ΔAICc = 3.181	-0.043 (± 0.366), ΔAICc = 3.653	**-3.115 (± 1.399), ΔAICc = -2.046**	-0.221 (± 0.353), ΔAICc = 2.526	-0.425 (± 0.404), ΔAICc = 1.916	**-1.192 (± 0.425), ΔAICc = -3.636**	*-0.541 (± 0.280), ΔAICc = -0.502*	**-0.621 (± 0.250), ΔAIC = -4.247**
Lagged spring PEA	-3.720 (± 2.478), ΔAICc = 0.873	1.644 (± 1.225), ΔAICc = 1.478	1.013 (± 1.051), ΔAICc = 2.778	*-10.901 (± 6.243), ΔAICc = -0.191*	-1.140 (± 1.072), ΔAICc = 1.817	0.244 (± 1.274), ΔAICc = 2.952	-0.279 (± 2.398), ΔAICc = 2.901	-0.451 (± 1.311), ΔAICc = 2.796	*-0.528 (± 0.283), ΔAIC = -1.381*
Lagged stratification onset	-0.031 (± 0.032), ΔAICc = 2.047	-0.019 (± 0.019), ΔAICc = 2.258	0.002 (± 0.015), ΔAICc = 3.647	0.068 (± 0.059), ΔAICc = 1.572	0.004 (± 0.030), ΔAICc = 2.893	-0.008 (± 0.020), ΔAICc = 2.831	0.019 (± 0.036), ΔAICc = 2.632	0.007 (± 0.016), ΔAICc = 2.713	0.003 (± 0.005), ΔAIC = 1.756

Figure S5.1. Plots of breeding success against oceanographic predictor variables with a 1-year lag, along with fitted lines from binomial GLMMs including the 'site' and 'region' random effects. Each point represents one site-by-year observation; point sizes are scaled by log(nests surveyed) to reflect weightings of observations in models.



Supplement 6. Full model results from main analysis

Full details of models relating breeding success to single oceanographic predictor variables for single sites are given in Table S6.1. Only sites with ≥ 10 years of overlapping oceanographic and breeding success data were selected for this analysis. Models were generalised linear mixed models with binomial error structure and logit link. Only one predictor variable was entered into each model to avoid overfitting. The response variable was a matrix with number of fledged chicks as success and estimated number of failed chicks as failures. Only a 'year' random factor was fitted, which in these models represented an observation-level factor used to model overdispersion. The effect of each predictor variable was assessed by comparing each model's AICc to that from a null model, fitted with intercept and random effect only.

Full details of models relating breeding success to oceanographic predictor variables across all sites are given in Tables S6.2 (single predictor variable models) and S6.3 (multiple predictor variable models). Models were generalised linear mixed models with binomial error structure and logit link. For multiple predictor models, up to 5 predictor variables were fitted in each model, with no interaction terms considered. The response variable was a matrix with number of fledged chicks as successes and estimated number of failed chicks as failures. Random effects were 'site', 'region', 'year', 'site*year' and 'region*year', with the 'site*year' effect an observation-level factor used to model overdispersion. Single predictor variable models were assessed by comparing each model's AIC to that from a null model. Multiple predictor variable models were ranked by AIC, allowing all models to be compared to the best single model.

Table S6.1. Parameter estimates, AIC and ΔAIC from model fitting for single-site models with single predictor variables. Fixed effects are reported as estimate (± standard error); the 'year' random effect is reported as the standard deviation of the effect. ΔAIC was calculated relative to the null model for each site. Fixed effects highlighted in bold are those for which Wald Z tests indicated the parameter estimate was significantly different from 0; italics highlight estimates approaching significance (0.05 ≤ *P* < 0.1). See text for model fitting details.

Site	Predictor variable	Intercept	Parameter estimate	Year RE	AIC	ΔAIC	AICc	ΔAICc
Bardsey Island	Null model	**-0.888 (± 0.373)**	–	1.507	186.764	–	187.621	–
	Spring PEA	3.668 (± 6.012)	-1.719 (± 2.266)	1.483	188.195	1.431	190.042	2.420
	Lagged spring PEA	8.924 (± 6.534)	-3.720 (± 2.478)	1.401	186.648	-0.116	188.494	0.873
	Spring SST	-13.877 (± 8.707)	1.311 (± 0.877)	1.431	186.582	-0.182	188.428	0.807
	Lagged spring SST	1.411 (± 6.776)	-0.234 (± 0.689)	1.504	188.649	1.885	190.495	2.874
	Stratification onset	**-5.369 (± 2.133)**	**0.041 (± 0.019)**	1.351	184.420	-2.345	186.266	-1.356
	Lagged strat. onset	2.628 (± 3.609)	-0.031 (± 0.032)	1.470	187.822	1.058	189.668	2.047
	Winter PEA	-0.111 (± 0.449)	**-1.645 (± 0.693)**	1.295	183.685	-3.079	185.531	-2.090
	Lagged winter PEA	-0.086 (± 0.511)	**-2.133 (± 1.052)**	1.359	184.889	-1.875	186.735	-0.886
	Winter SST	*-8.998 (± 5.082)*	0.928 (± 0.579)	1.412	186.291	-0.473	188.137	0.516
	Lagged winter SST	-1.213 (± 5.513)	0.037 (± 0.632)	1.506	188.761	1.997	190.607	2.986
Boddam to Collieston	Null model	**-1.113 (± 0.259)**	–	0.995	177.476	–	178.476	–
	Spring PEA	-0.751 (± 4.170)	-0.123 (± 1.414)	0.994	179.468	1.992	181.650	3.174
	Lagged spring PEA	-5.996 (± 3.648)	1.644 (± 1.225)	0.940	177.772	0.296	179.953	1.478
	Spring SST	-1.606 (± 5.092)	0.057 (± 0.593)	0.995	179.466	1.991	181.648	3.172
	Lagged spring SST	-1.260 (± 5.207)	0.017 (± 0.605)	0.995	179.475	1.999	181.657	3.181
	Stratification onset	*-3.579 (± 1.902)*	0.024 (± 0.018)	0.942	177.855	0.380	180.037	1.561
	Lagged strat. onset	0.837 (± 2.014)	-0.019 (± 0.019)	0.964	178.552	1.076	180.733	2.258
	Winter PEA	**-1.115 (± 0.258)**	-0.141 (± 0.488)	0.992	179.393	1.917	181.574	3.099
	Lagged winter PEA	-1.111 (± 0.258)	-0.130 (± 0.536)	0.993	179.417	1.941	181.599	3.123
	Winter SST	-2.474 (± 3.875)	0.175 (± 0.498)	0.990	179.353	1.877	181.534	3.059
	Lagged winter SST	2.744 (± 3.960)	-0.496 (± 0.508)	0.965	178.551	1.075	180.732	2.257

Table S6.1 (cont.)

Site	Predictor variable	Intercept	Parameter estimate	Year RE	AIC	ΔAIC	AICc	ΔAICc
Coquet Island	Null model	0.233 (± 0.178)	–	0.579	102.490	–	103.824	–
	Spring PEA	-4.245 (± 3.532)	1.228 (± 0.968)	0.541	102.964	0.473	105.964	2.140
	Lagged spring PEA	-3.445 (± 3.819)	1.013 (± 1.051)	0.552	103.601	1.111	106.601	2.778
	Spring SST	0.775 (± 3.109)	-0.061 (± 0.352)	0.578	104.460	1.970	107.460	3.636
	Lagged spring SST	0.612 (± 3.224)	-0.043 (± 0.366)	0.578	104.477	1.986	107.477	3.653
	Stratification onset	-0.999 (± 0.940)	0.018 (± 0.014)	0.538	102.816	0.325	105.816	1.992
	Lagged strat. onset	0.088 (± 1.040)	0.002 (± 0.015)	0.578	104.470	1.980	107.470	3.647
	Winter PEA	**0.742 (± 0.297)**	**-0.697 (± 0.346)**	0.493	100.933	-1.558	103.933	0.109
	Lagged winter PEA	0.047 (± 0.369)	0.244 (± 0.425)	0.569	104.167	1.676	107.167	3.343
	Winter SST	0.791 (± 2.343)	-0.075 (± 0.315)	0.577	104.433	1.943	107.433	3.610
	Lagged winter SST	-0.679 (± 2.402)	0.124 (± 0.326)	0.575	104.346	1.856	107.346	3.522
Fair Isle	Null model	**-1.815 (± 0.695)**	–	2.985	278.038	–	278.788	–
	Spring PEA	**49.179 (± 20.227)**	**-13.414 (± 5.332)**	2.586	273.871	-4.166	275.471	-3.316
	Lagged spring PEA	*39.437 (± 23.595)*	*-10.901 (± 6.243)*	2.780	276.997	-1.041	278.597	-0.191
	Spring SST	**34.932 (± 10.162)**	**-4.280 (± 1.189)**	2.225	268.509	-9.529	270.109	-8.679
	Lagged spring SST	**24.732 (± 11.892)**	**-3.115 (± 1.399)**	2.671	275.142	-2.896	276.742	-2.046
	Stratification onset	-6.486 (± 6.587)	0.042 (± 0.058)	2.962	279.535	1.498	281.135	2.348
	Lagged strat. onset	-9.526 (± 6.744)	0.068 (± 0.059)	2.892	278.760	0.722	280.360	1.572
	Winter PEA	-0.513 (± 1.905)	-0.942 (± 1.295)	2.929	279.523	1.486	281.123	2.336
	Lagged winter PEA	0.823 (± 1.795)	-1.880 (± 1.203)	2.800	277.712	-0.326	279.312	0.524
	Winter SST	**26.625 (± 11.439)**	**-3.661 (± 1.474)**	2.535	274.626	-3.411	276.226	-2.561
	Lagged winter SST	14.057 (± 13.397)	-2.052 (± 1.732)	2.894	278.661	0.623	280.261	1.473

Table S6.1 (cont.)

Site	Predictor variable	Intercept	Parameter estimate	Year RE	AIC	ΔAIC	AICc	ΔAICc
Flamborough Head and Bempton Cliffs	Null model	-0.166 (± 0.222)	–	0.938	224.689	–	225.489	–
	Spring PEA	**5.717 (± 2.146)**	**-2.502 (± 0.909)**	0.785	220.357	-4.332	222.072	-3.417
	Lagged spring PEA	2.484 (± 2.502)	-1.140 (± 1.072)	0.910	225.591	0.902	227.306	1.817
	Spring SST	**5.594 (± 2.613)**	**-0.663 (± 0.300)**	0.831	222.359	-2.330	224.073	-1.416
	Lagged spring SST	1.730 (± 3.036)	-0.221 (± 0.353)	0.928	226.301	1.612	228.015	2.526
	Stratification onset	2.014 (± 2.816)	-0.023 (± 0.029)	0.922	226.096	1.407	227.810	2.321
	Lagged strat. onset	-0.589 (± 2.926)	0.004 (± 0.030)	0.937	226.668	1.979	228.382	2.893
	Winter PEA	0.072 (± 0.527)	0.253 (± 0.509)	0.931	226.443	1.754	228.157	2.668
	Lagged winter PEA	-0.275 (± 0.527)	-0.110 (± 0.484)	0.937	226.637	1.948	228.351	2.863
	Winter SST	2.735 (± 2.635)	-0.434 (± 0.393)	0.907	225.508	0.819	227.222	1.733
	Lagged winter SST	0.287 (± 2.883)	-0.068 (± 0.433)	0.937	226.664	1.975	228.378	2.889
Fowlsheugh	Null model	**-0.685 (± 0.202)**	–	0.827	213.453	–	214.311	–
	Spring PEA	2.986 (± 3.889)	-1.176 (± 1.244)	0.806	214.582	1.128	216.428	2.117
	Lagged spring PEA	-1.445 (± 3.975)	0.244 (± 1.274)	0.826	215.417	1.963	217.263	2.952
	Spring SST	1.368 (± 3.499)	-0.239 (± 0.407)	0.819	215.111	1.658	216.957	2.647
	Lagged spring SST	2.936 (± 3.446)	-0.425 (± 0.404)	0.801	214.380	0.927	216.226	1.916
	Stratification onset	-1.951 (± 1.935)	0.013 (± 0.020)	0.816	215.025	1.572	216.872	2.561
	Lagged strat. onset	0.069 (± 1.903)	-0.008 (± 0.020)	0.823	215.296	1.842	217.142	2.831
	Winter PEA	**-0.718 (± 0.201)**	-0.388 (± 0.451)	0.809	214.728	1.274	216.574	2.263
	Lagged winter PEA	**-0.725 (± 0.202)**	-0.376 (± 0.421)	0.808	214.674	1.220	216.520	2.209
	Winter SST	1.388 (± 2.818)	-0.270 (± 0.366)	0.814	214.917	1.464	216.763	2.453
	Lagged winter SST	1.462 (± 2.895)	-0.281 (± 0.378)	0.813	214.910	1.456	216.756	2.445

Table S6.1 (cont.)

Site	Predictor variable	Intercept	Parameter estimate	Year RE	AIC	ΔAIC	AICc	ΔAICc
Isle of May	Null model	**-1.408 (± 0.289)**	–	1.223	253.984	–	254.784	–
	Spring PEA	0.990 (± 8.263)	-0.689 (± 2.371)	1.219	255.900	1.916	257.614	2.830
	Lagged spring PEA	-0.439 (± 8.325)	-0.279 (± 2.398)	1.222	255.971	1.986	257.685	2.901
	Spring SST	2.810 (± 5.200)	-0.488 (± 0.601)	1.202	255.334	1.350	257.049	2.264
	Lagged spring SST	**8.777 (± 3.636)**	**-1.192 (± 0.425)**	1.017	249.434	-4.550	251.148	-3.636
	Stratification onset	**-5.411 (± 1.316)**	**0.092 (± 0.030)**	0.988	248.215	-5.769	249.929	-4.855
	Lagged strat. onset	-2.247 (± 1.599)	0.019 (± 0.036)	1.212	255.702	1.718	257.416	2.632
	Winter PEA	1.367 (± 2.256)	-1.478 (± 1.192)	1.175	254.505	0.520	256.219	1.435
	Lagged winter PEA	-0.452 (± 2.292)	-0.510 (± 1.212)	1.216	255.808	1.824	257.522	2.738
	Winter SST	0.575 (± 3.757)	-0.283 (± 0.535)	1.214	255.705	1.721	257.420	2.636
	Lagged winter SST	1.567 (± 3.635)	-0.429 (± 0.523)	1.199	255.323	1.339	257.038	2.254
St Abb's Head	Null model	**-0.754 (± 0.174)**	–	0.731	229.739	–	230.539	–
	Spring PEA	3.391 (± 4.370)	-1.177 (± 1.241)	0.714	230.859	1.120	232.573	2.034
	Lagged spring PEA	0.825 (± 4.595)	-0.451 (± 1.311)	0.729	231.621	1.882	233.335	2.796
	Spring SST	-0.540 (± 3.211)	-0.024 (± 0.361)	0.731	231.735	1.996	233.449	2.910
	Lagged spring SST	3.993 (± 2.457)	*-0.541 (± 0.280)*	0.665	228.323	-1.416	230.037	-0.502
	Stratification onset	**-2.972 (± 0.881)**	**0.034 (± 0.013)**	0.625	226.160	-3.579	227.875	-2.665
	Lagged strat. onset	-1.205 (± 1.018)	0.007 (± 0.016)	0.727	231.538	1.799	233.252	2.713
	Winter PEA	0.513 (± 0.733)	*-1.085 (± 0.613)*	0.674	228.853	-0.886	230.568	0.029
	Lagged winter PEA	0.248 (± 0.738)	-0.862 (± 0.619)	0.695	229.898	0.159	231.613	1.074
	Winter SST	0.133 (± 2.396)	-0.122 (± 0.328)	0.729	231.602	1.863	233.316	2.777
	Lagged winter SST	1.057 (± 2.342)	-0.251 (± 0.324)	0.719	231.148	1.409	232.862	2.323

Table S6.2. Parameter estimates, AIC and ΔAIC from all-sites models with single predictor variables. Fixed effects are reported as estimate (± standard error); random effects are reported as the standard deviation of the effect. ΔAIC was calculated relative to the null model for each site. Fixed effects highlighted in bold are those for which Wald Z tests indicated the parameter estimate was significantly different from 0; italics highlight parameter estimates approaching significance ($0.05 \leq P < 0.1$). See text for model fitting details.

Predictor variable	Intercept	Parameter estimate	Site RE	Region RE	Year RE	Site * year RE	Region * year RE	AIC	ΔAIC
Null model	-0.677 (± 0.268)	–	0.315	0.373	0.263	0.790	1.146	1803.730	–
Spring PEA	1.174 (± 0.895)	**-0.602 (± 0.285)**	0.461	0.000	0.183	0.754	1.189	1801.062	-2.669
Lagged spring PEA	0.945 (± 0.889)	*-0.528 (± 0.283)*	0.447	0.000	0.176	0.759	1.194	1802.349	-1.381
Spring SST	**5.554 (± 2.371)**	**-0.700 (± 0.264)**	0.323	0.545	0.000	0.756	1.154	1798.488	-5.242
Lagged spring SST	**4.792 (± 2.227)**	**-0.621 (± 0.250)**	0.326	0.509	0.000	0.766	1.150	1799.483	-4.247
Stratification onset	**-1.964 (± 0.709)**	*0.014 (± 0.007)*	0.432	0.448	0.221	0.736	1.186	1800.347	-3.383
Lagged strat. onset	-0.941 (± 0.592)	0.003 (± 0.005)	0.298	0.406	0.267	0.790	1.142	1805.486	1.756
Winter PEA	-0.322 (± 0.263)	**-0.641 (± 0.201)**	0.517	0.000	0.320	0.694	1.177	1792.228	-11.502
Lagged winter PEA	*-0.436 (± 0.235)*	**-0.483 (± 0.175)**	0.430	0.000	0.285	0.756	1.123	1796.639	-7.091
Winter SST	1.184 (± 1.801)	-0.240 (± 0.231)	0.388	0.276	0.093	0.781	1.170	1804.724	0.994
Lagged winter SST	0.134 (± 1.927)	-0.105 (± 0.248)	0.350	0.323	0.218	0.789	1.152	1805.557	1.827

Table S6.3. Parameter estimates, AIC, ΔAIC and Akaike weights from all-sites models with multiple predictor variables. Fixed effects are reported as estimate (± standard error); random effects are reported as the standard deviation of the effect. Fixed effects highlighted in bold are those for which Wald Z tests indicated the parameter estimate was significantly different from 0. See text for model fitting details.

Intercept	Spring PEA	Spring SST	Stratification onset	Winter PEA	Winter SST	Site RE	Region RE	Year RE	Site * year RE	Region * year RE	AIC	ΔAIC	Weight
4.429 (± 2.181)	–	**-0.539 (± 0.244)**	–	**-0.602 (± 0.190)**	–	0.526	0.000	0.000	0.687	1.185	1789.734	0	0.263
4.308 (± 2.185)	–	**-0.674 (± 0.336)**	–	**-0.609 (± 0.192)**	0.173 (± 0.295)	0.542	0.000	0.000	0.687	1.180	1791.383	1.649	0.115
4.206 (± 2.269)	–	**-0.544 (± 0.245)**	0.003 (± 0.008)	**-0.566 (± 0.214)**	–	0.551	0.000	0.000	0.685	1.185	1791.595	1.861	0.104
4.706 (± 2.408)	-0.090 (± 0.333)	**-0.541 (± 0.244)**	–	**-0.574 (± 0.217)**	–	0.533	0.000	0.000	0.687	1.185	1791.659	1.926	0.100
-0.322 (± 0.263)	–	–	–	**-0.641 (± 0.201)**	–	0.517	0.000	0.320	0.694	1.177	1792.228	2.495	0.076
4.521 (± 2.416)	-0.070 (± 0.335)	**-0.670 (± 0.336)**	–	**-0.586 (± 0.220)**	0.167 (± 0.296)	0.545	0.000	0.000	0.687	1.180	1793.340	3.606	0.043
1.283 (± 1.076)	–	–	–	**-0.622 (± 0.198)**	-0.212 (± 0.222)	0.502	0.000	0.249	0.694	1.186	1793.342	3.609	0.043
4.211 (± 2.264)	–	*-0.662 (± 0.344)*	0.001 (± 0.008)	**-0.591 (± -0.591)**	0.155 (± 0.316)	0.554	0.000	0.001	0.686	1.180	1793.354	3.621	0.043
4.441 (± 2.543)	-0.070 (± 0.341)	**-0.545 (± 0.245)**	0.003 (± 0.008)	**-0.548 (± 0.232)**	–	0.553	0.000	0.000	0.685	1.185	1793.553	3.819	0.039
-0.501 (± 0.806)	–	–	0.002 (± 0.008)	**-0.621 (± 0.219)**	–	0.537	0.000	0.312	0.690	1.182	1794.172	4.439	0.029
-0.156 (± 1.023)	-0.057 (± 0.342)	–	–	**-0.626 (± 0.222)**	–	0.525	0.000	0.315	0.693	1.178	1794.200	4.467	0.028
1.200 (± 1.725)	–	–	0.005 (± 0.008)	**-0.557 (± 0.226)**	-0.262 (± 0.237)	0.538	0.000	0.206	0.688	1.196	1794.994	5.260	0.019
1.611 (± 2.096)	-0.093 (± 0.344)	–	–	**-0.596 (± 0.221)**	-0.219 (± 0.224)	0.514	0.000	0.239	0.693	1.188	1795.268	5.534	0.017
4.414 (± 2.536)	-0.062 (± 0.341)	*-0.658 (± 0.344)*	0.001 (± 0.008)	**-0.573 (± 0.238)**	0.148 (± 0.316)	0.554	0.001	0.001	0.686	1.181	1795.322	5.588	0.016
3.962 (± 2.428)	–	**-0.650 (± 0.257)**	*0.012 (± 0.007)*	–	–	0.408	0.540	0.000	0.723	1.167	1795.925	6.191	0.012
-0.348 (± 1.360)	-0.048 (± 0.346)	–	0.002 (± 0.008)	**-0.609 (± 0.235)**	–	0.541	0.000	0.309	0.690	1.182	1796.153	6.419	0.011

Table S6.3 (cont.)

Intercept	Spring PEA	Spring SST	Stratification onset	Winter PEA	Winter SST	Site RE	Region RE	Year RE	Site * year RE	Region * year RE	AIC	ΔAIC	Weight
1.453 (± 2.112)	-0.072 (± 0.348)	–	0.005 (± 0.008)	**-0.539 (± 0.244)**	-0.265 (± 0.238)	0.544	0.000	0.199	0.687	1.197	1796.950	7.217	0.007
4.877 (± 2.565)	-0.396 (± 0.319)	**-0.592 (± 0.247)**	0.010 (± 0.007)	–	–	0.558	0.000	0.000	0.716	1.183	1797.241	7.507	0.006
6.310 (± 2.345)	**-0.589 (± 0.273)**	**-0.584 (± 0.244)**	–	–	–	0.471	0.000	0.000	0.736	1.182	1797.277	7.543	0.006
3.956 (± 2.425)	–	**-0.692 (± 0.353)**	*0.012 (± 0.007)*	–	0.054 (± 0.315)	0.401	0.556	0.000	0.723	1.165	1797.895	8.162	0.004
5.554 (± 2.372)	–	**-0.700 (± 0.264)**	–	–	–	0.323	0.545	0.000	0.756	1.154	1798.488	8.755	0.003
6.199 (± 2.355)	**-0.580 (± 0.275)**	**-0.666 (± 0.331)**	–	–	0.107 (± 0.285)	0.471	0.008	0.001	0.736	1.183	1799.137	9.403	0.002
4.877 (± 2.565)	-0.394 (± 0.319)	*-0.569 (± 0.346)*	0.010 (± 0.008)	–	-0.030 (± 0.311)	0.557	0.002	0.000	0.716	1.183	1799.232	9.498	0.002
0.925 (± 1.711)	–	–	**0.017 (± 0.007)**	–	*-0.408 (± 0.224)*	0.556	0.000	0.000	0.722	1.203	1799.428	9.694	0.002
5.139 (± 2.366)	–	**-0.901 (± 0.322)**	–	–	0.285 (± 0.272)	0.278	0.604	0.000	0.757	1.149	1799.440	9.707	0.002
2.331 (± 2.046)	-0.387 (± 0.321)	–	*0.013 (± 0.007)*	–	*-0.391 (± 0.224)*	0.546	0.000	0.000	0.720	1.202	1799.950	10.217	0.002
-1.964 (± 0.709)	–	–	*0.014 (± 0.007)*	–	–	0.432	0.448	0.221	0.736	1.186	1800.347	10.614	0.001
-0.325 (± 1.422)	-0.423 (± 0.324)	–	0.011 (± 0.008)	–	–	0.561	0.000	0.174	0.726	1.206	1800.959	11.226	0.001
1.174 (± 0.895)	**-0.602 (± 0.285)**	–	–	–	–	0.461	0.000	0.183	0.754	1.189	1801.062	11.328	0.001
3.430 (± 1.948)	**-0.627 (± 0.287)**	–	–	–	-0.285 (± 0.214)	0.472	0.000	0.000	0.750	1.190	1801.295	11.562	0.001
-0.677 (± 0.268)	–	–	–	–	–	0.315	0.373	0.263	0.790	1.146	1803.730	13.996	0
1.184 (± 1.801)	–	–	–	–	-0.240 (± 0.231)	0.388	0.276	0.093	0.781	1.170	1804.724	14.991	0

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