Supplementary information: Table of Contents

Appendix 1. Sample sizes for estimated reproduction and survival parameters.

Table S1. Annual sample size (N) for parameter *C*, *E*, *H, G*, *F*, ϕ_f and ϕ_{ad}. $\mathbf{N_C}$ is the total number of marked females observed on the nesting islands and $\mathbf{N_E}$ the number of females with a clutch. $\mathbf{N_H}$ is the number of females observed at Ny-Ålesund and $\mathbf{N_G}$ is the number of females with at least one gosling. $\mathbf{N_F}$ is the number of females observed with at least one fledgling. $\mathbf{N_{fledgling}}$ describes the number of marked fledglings observed at Ny-Ålesund to estimate ϕ_f and $\mathbf{N_{adult}}$ is the number of marked adults to estimate ϕ_{ad}.

Year	**Sample size**						
	$\mathbf{N_C}$	$\mathbf{N_E}$	$\mathbf{N_H}$	$\mathbf{N_G}$	$\mathbf{N_F}$	$\mathbf{N_{fledgling}}$	$\mathbf{N_{adult}}$
1990	54	16	54	33	33		101
1991			107	65	65	177	218
1992	210	55	186	70	70	107	389
1993	232	87	222	103	93	55	445
1994	267	9	257	12	7	1	516
1995	234	56	231	157	117	128	464
1996	279	82	273	168	155	228	561
1997			196	110	67	130	408
1998	331	67	257	43	18	89	655
1999	346	84	344	115	71	2	656
2000	426	97	381	86	74	5	891
2001	322	163	293	155	99	54	654
2002			209	58	47		482
2003	212	57	179	22	17	10	448
2004						15	309
2005	248	172	243	131	101	68	555
2006	227	109	219	114	63	6	491
2007	273	78	223	164	101	33	594
2008	193	120	174	59	25	6	395
2009	228	123	214	127	96	66	457
2010	252	110	218	164	87	54	492
2011	177	83	174	132	80	133	330
2012	222	112	184	128	95		413
2013	200	81	197	76	55	4	354
2014	214	93	188	87	55	1	392
2015	233	101	217	134	100	10	430
2016	262	96	248	164	106	177	458
2017	186	60	184	122	79		327

Appendix 2. Predictions of post-hoc linear regressions between environmental variables

The estimated correlation between (a) spring onset date and timing of snowmelt, (b) mid-June to mid-July temperature and onset of plant growth and (c) mid-July to mid-August precipitation and biomass of *P. arctica*. Timing of snow-melt at Ny-Ålesund was measured using satellite data (Maturilli, Herber & König-Langlo 2015). The measure of the onset of the plant growing season was defined as the mean (Julian) date when the pixel-specific Normalized Difference Vegetation Index (NDVI) values exceeded 70% of mid-summer NDVI. NDVI values were calculated from MODIS Terra data for a polygon of size 2.3 km close to Ny-Ålesund, which were available from Karlsen *et al.* (2014; 2018). The measure of average standing crop of *P. arctica* was taken from a long-term experiment at Ny-Ålesund. Measurements were taken during July to August from exclosures (to prevent grazing), the leaf length of four individual shoots was measured at five-day intervals, at ten exclosures, and standing crop was calculated as the average sum of leaf lengths per shoot (mm/shoot) over the growing season (Krikke 2014).

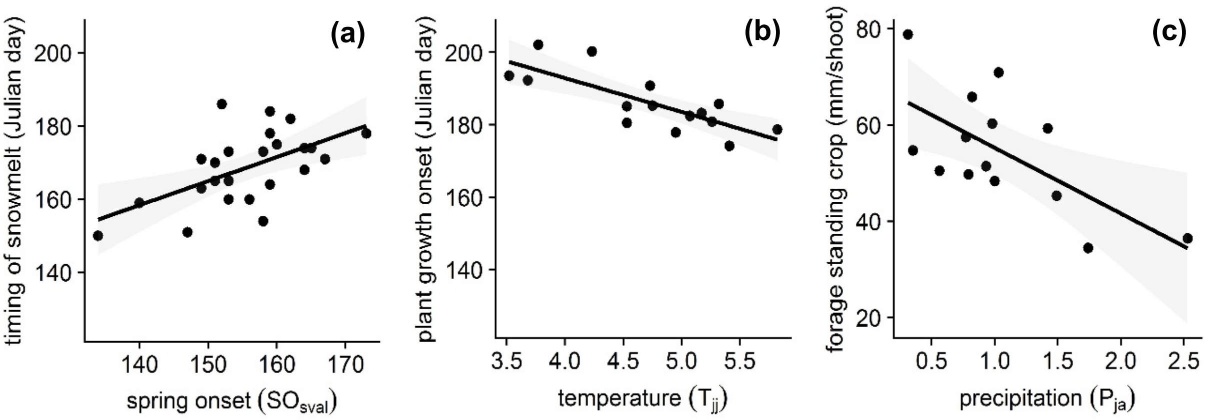

Figure S2. Predicted correlations between (a) timing of snow-melt and spring onset (b) onset of plant growth and temperature mid-June to mid-July, $T_{sval,jj}$, and (c) mid-July to mid-August precipitation, $P_{sval,ja}$, and biomass of *P. arctica* (i.e. average standing crop), shown as slopes with 95% confidence intervals estimated used the delta method (Powell 2007) with the data distribution.

References

Karlsen, S.R., Anderson, H.B., Van der Wal, R. & Hansen, B.B. (2018) A new NDVI measure that overcomes data sparsity in cloud-covered regions predicts annual variation in ground-based estimates of high arctic plant productivity. Environmental Research Letters, 13, 025011.

Karlsen, S.R., Elvebakk, A., Høgda, K.A. & Grydeland, T. (2014) Spatial and temporal variability in the onset of the growing season on Svalbard, Arctic Norway—measured by MODIS-NDVI satellite data. Remote Sensing, 6, 8088-8106.

Krikke, M. (2014) Are foraging conditions deteriorating on a goose grazed tundra on Spitsbergen? Masters Thesis, University of Groningen.

Maturilli, M., Herber, A. & König-Langlo, G. (2015) Surface radiation climatology for Ny-Ålesund, Svalbard (78.9° N), basic observations for trend detection. Theoretical and Applied Climatology, 120, 331-339.

Powell, L.A. (2007) Approximating variance of demographic parameters using the delta method: a reference for avian biologists. The Condor, 109, 949-954.

Appendix 3. D-separation tests and Fisher's C test for confirmatory path analysis

Confirmatory path analysis was used to identify the best model of reproduction, all proposed independence relationships among variables were tested using d-separation tests (Shipley 2009; Shipley 2016). Each d-separation gives the necessary conditions for two variables to be independent, conditional on a set of other variables. We determined a basis set of independence statements, containing all pairs of variables without a direct link (Shipley 2000; Shipley 2016). We tested the null probability of each conditional independence statement in the basis set and evaluated the fit of the path diagram with a Fisher's C test (Shipley 2000); $C = \sum \text{In } (p_i)$, where p_i is the null probability of each independence statement and C follows a Chi-squared distribution of $2k$ degrees of freedom. The Fisher's C test statistic for hypothesised path model of reproduction was 36.39 (df =34, p-value = 0.36), supporting the null hypothesis that all conditional independence claims were respected. Therefore, we could conclude that no links were missing from the model and that the path diagram fitted well.

Table S3. Tests of conditional independence for the basis set as specified by the a-priori hypothesised path model. X_||_Y {Z_i, Z_j.. indicates that X and Y are probabilistically independent conditional on Z covariates.

Basis set	Partial slopes (SE)	F value	Null probability
*G*_||_snow {SO, N_{ad}, *E*, T_{jj}, P_{jj}, fox}	0.01 (0.02)	0.63	0.53
*C*_||_ T_{jj} {SO, snow, N_{ad}}	0.15 (0.25)	0.61	0.54
E _||_ T_{jj} {SO, snow, N_{ad}}	0.16 (0.16)	0.96	0.35
*F*_||_T_{jj} {SO, snow, N_{ad} , *E*, fox, *G*, T_{ja}, P_{ja}}	-0.54 (0.32)	-1.69	0.09
*C*_||_P_{jj} {SO, snow, N_{ad}}	-0.03 (0.20)	-0.15	0.88
E _||_P_{jj} {SO, snow, N_{ad}}	0.08 (0.14)	0.61	0.55
*F*_||_P_{jj} {SO, snow, N_{ad}, *E*, fox, *G*, T_{ja}, P_{ja}}	-0.33 (0.25)	-1.33	0.18
*C*_||_fox {SO, snow, N_{ad}}	-0.33 (0.19)	-1.72	0.09
*E*_||_fox {SO, snow, N_{ad}}	-0.12 (0.13)	-0.93	0.37
*C*_||_ T_{ja} {SO, snow, N_{ad}}	0.16 (0.18)	0.88	0.38
*E*_||_T_{ja} {SO, snow, N_{ad}}	0.00 (0.12)	0.03	0.98
*H*_||_ T_{ja} {SO, snow, N_{ad}, *E*, T_{jj}, P_{jj}, fox}	0.32 (0.21)	1.51	0.13
G _||_ T_{ja} {SO, N_{ad}, *E*, T_{jj}, P_{jj}, fox}	0.00 (0.02)	0.04	0.97
*C*_||_P_{ja} {SO, snow, N_{ad}}	0.07 (0.22)	0.30	0.77
*E*_||_P_{ja} {SO, snow, N_{ad}}	-0.04 (0.15)	-0.28	0.78
*H*_||_P_{ja} {SO, snow, N_{ad}, *E*, T_{jj}, P_{jj}, fox}	-0.35 (0.24)	-1.46	0.14
*G*_||_P_{ja} {SO, N_{ad}, *E*, T_{jj}, P_{jj}, fox}	-0.03 (0.02)	-1.55	0.12

References

Shipley, B. (2000) A new inferential test for path models based on directed acyclic graphs. Structural Equation Modeling, 7, 206-218.

Shipley, B. (2009) Confirmatory path analysis in a generalized multilevel context. Ecology, 90, 363-368.

Shipley, B. (2016) Cause and correlation in biology: a user's guide to path analysis, structural equations and causal inference with R. Cambridge University Press.

Appendix 4. Hypothesised diagrams of the reproductive path model (included the 5 response variables; *C*, *E*, *H*, *G* and *F*) and survival (ϕ_f and ϕ_{ad}) models, including all potential covariates. Candidate model sets were constructed for each response variable, with all possible combinations of covariates, and an AIC-model selection approach was used to select the best-approximating model.

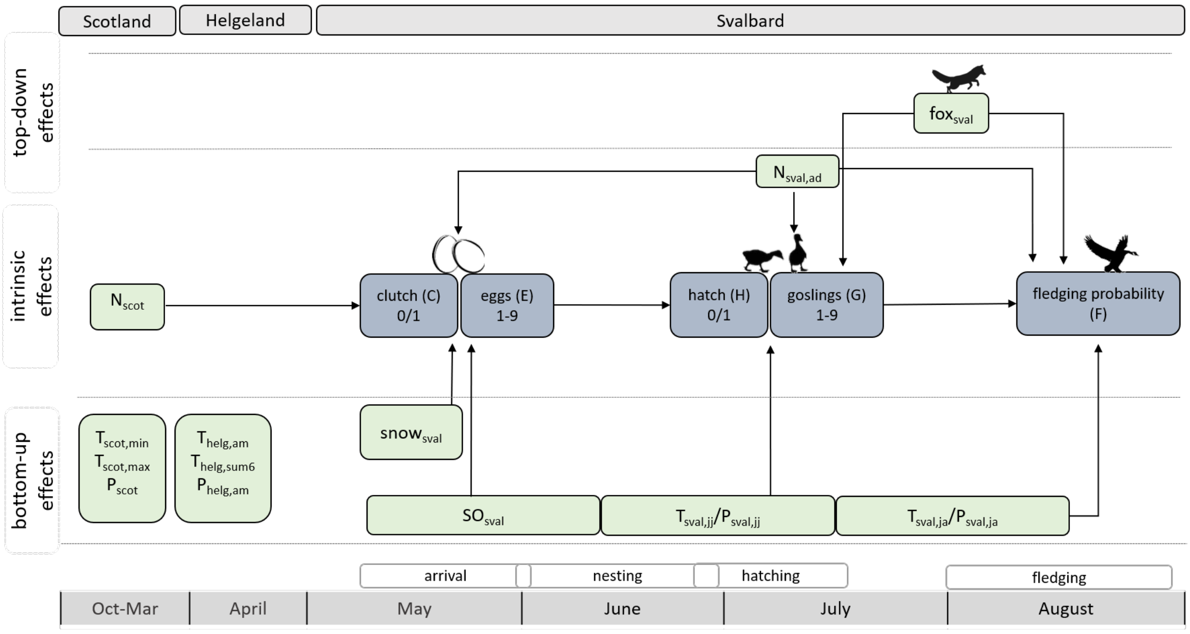

Figure S4.1. Hypothesised path model for reproduction with proposed links between covariates, from which a candidate model set was constructed (N.B. only one arrow is shown here for dependent parameters (i.e. *C* and *E*; *H* and *G*)).

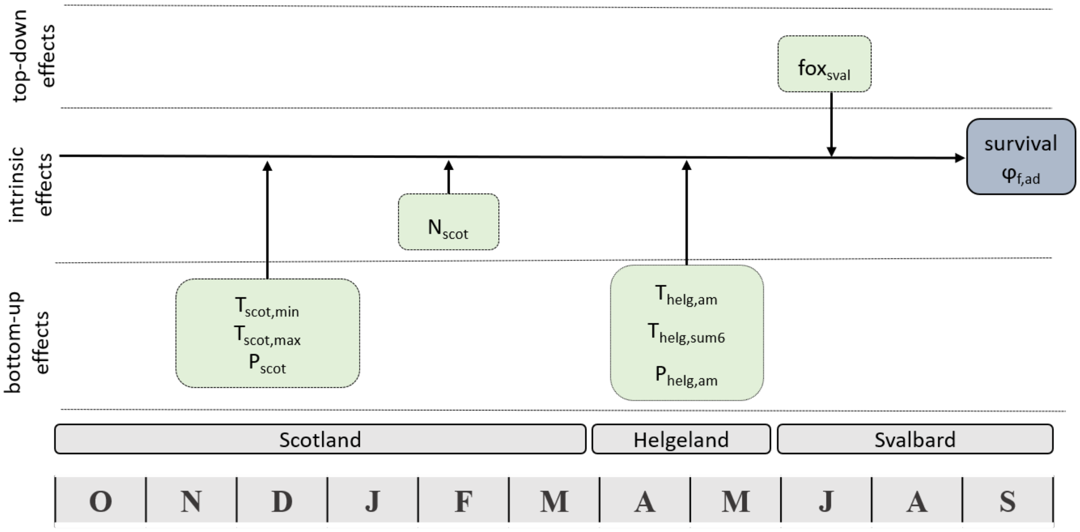

Figure S4.2. Illustration of hypothesised covariate effects on survival over the annual cycle (i.e. Scotland, Helgeland and Svalbard). All possible combinations of these covariates were included in the candidate model set and compared using AIC$_c$ and analysis of deviance.

Table S4.3. Models of vital rates including covariates used in population projection matrix analysis. Parameters describing the egg-laying phase (*C* and *E*) are not included, since this would inflate reproductive rates as both *E* and *H* are the expected number of offspring per female at different stages of the reproductive cycle.

Par	**Model with slope coefficients and 95% confidence intervals**
H	-0.15(-0.48,0.18) + -0.39(-0.79,-0.01)$\mathbf{SO}_{\mathbf{sval}}$ + 0.63(0.30,0.95)$\mathbf{P}_{\mathbf{helg,am}}$ + 0.22(-0.18,0.61)$\mathbf{T}_{\mathbf{sval,jj}}$
G	1.03(1.00,1.07) + -0.03(-0.07,-0.01)$\mathbf{fox}_{\mathrm{sval}}$ + -0.03(-0.07,-0.01)$\mathbf{N}_{\mathbf{sval,ad}}$
F	0.03(-0.52, 0.58) + -0.17(-0.25,-0.09)$\boldsymbol{G}$ + -1.23(-1.77,-0.69)$\mathbf{fox}_{\mathbf{sval}}$ + -0.54(-1.12, 0.04)$\mathbf{P}_{\mathbf{sval,ja}}$
$\phi_{\mathrm{f,ad}}$	0.46(0.32,0.60) + 1.56(1.41,1.71)$\mathbf{age}_{\mathbf{ad}}$ + 0.25(0.19,0.31)$\mathbf{T}_{\mathbf{scot,min}}$ + -0.058(-0.21, 0.09)$\mathbf{N}_{\mathbf{scot}}$

Appendix 5. Model selection tables

S5.1. Reproduction: AIC-based approach

Candidate model sets for each reproductive parameter, where all models included year and id as random effects. The tables below show the mean slope coefficient for each covariate effect in the model, degrees of freedom (df), AIC adjusted for small sample size (AIC_c), difference in AIC_c from a model and the lowest AIC_c model (ΔAIC_c) and the proportion of variance explained by the fixed effects (R^2).

Table S5.1.1. *C* (clutch success). Candidate model set (8 top-ranking models) and null model for the generalised linear model of clutch success, fitted with a binomial distribution.

SO_{sval}	$P_{helg,am}$	$T_{scot,max}$	$T_{helg,am}$	$T_{helg,sum6}$	$N_{sval,ad}$	N_{scot}	P_{scot}	$T_{scot,min}$	$snow_{sval}$	df	AIC_c	ΔAIC_c	R^2
-0.41	0.27	0.25								6	6230.41	0.00	0.04
-0.39	0.23									5	6230.76	0.35	0.03
-0.36										4	6230.76	0.35	0.02
-0.39	0.26	0.27		0.22						7	6231.27	0.87	0.04
-0.38		0.20								5	6231.36	0.95	0.03
-0.37									-0.17	5	6231.52	1.12	0.03
-0.37	0.26	0.27	0.20							7	6231.58	1.17	0.04
-0.43	0.25							0.17		6	6231.58	1.18	0.03
				Null model						3	6233.15	2.75	0

Table S5.1.2. *E* (clutch size). Candidate model set (8 top-ranking models) and null model for the linear model of clutch size.

SO_{sval}	$P_{helg,am}$	N_{scot}	$T_{helg,am}$	$T_{helg,sum6}$	$N_{sval,ad}$	P_{scot}	$T_{scot,max}$	$T_{scot,min}$	$snow_{sval}$	df	AIC_c	ΔAIC_c	R^2
-0.31	0.31	-0.63								7	5742.86	0.00	0.15
-0.31	0.31									6	5744.50	1.64	0.13
-0.33	0.32	-0.71						0.11		8	5746.19	3.34	0.16
-0.32	0.31	-0.75		-0.12						8	5746.25	3.39	0.16
-0.31	0.31	-0.67				0.10				8	5746.33	3.48	0.15
-0.34	0.32	-0.73	-0.11							8	5746.41	3.55	0.15
-0.32	0.33	-0.69					0.10			8	5746.42	3.57	0.16
-0.31	0.31	-0.68			0.02					8	5747.46	4.60	0.15
				Null model						4	5752.30	9.45	0

Table S5.1.3. *H* (hatching success). Candidate model set (10 top-ranking models) and null model for generalised linear model of hatching success, fitted with a binomial distribution.

Parameter					**df**	**AIC$_c$**	**ΔAIC$_c$**	**R^2**
E	**$T_{sval,jj}$**	**$N_{sval,ad}$**	**fox_{sval}**	**$P_{sval,jj}$**				
0.56	0.37				5	6216.50	0.00	0.10
0.56					4	6217.53	1.04	0.06
0.56	0.36	-0.10			6	6218.29	1.80	0.11
0.56	0.37		-0.05		6	6218.44	1.95	0.10
0.56	0.37			-0.00	6	6218.50	2.00	0.10
0.56		-0.13			5	6219.19	2.70	0.07
0.56				0.11	5	6219.26	2.77	0.06
0.56			-0.02		5	6219.53	3.04	0.06
0.56	0.37	-0.11		-0.04	7	6220.27	3.77	0.06
0.56	0.37	-0.09	-0.03		7	6220.28	3.79	0.11
Null model					3	6444.26	227.76	0

Table S5.1.4. *G* (number of goslings). Candidate model set (10 top-ranking models) and null model for generalised linear model of the number of goslings, fitted with a Poisson distribution.

Parameter					**df**	**AIC$_c$**	**ΔAIC$_c$**	**R^2**
E	**$N_{sval,ad}$**	**fox_{sval}**	**$P_{sval,jj}$**	**$T_{sval,jj}$**				
0.08	-0.03	-0.03			6	8928.01	0.00	0.04
0.08	-0.03	-0.03		0.02	7	8928.19	0.18	0.04
0.08		-0.04		0.03	6	8928.82	0.81	0.04
0.09	-0.04				5	8929.15	1.14	0.03
0.08		-0.04			5	8929.23	1.23	0.03
0.08	-0.04	-0.03	-0.01		7	8929.79	1.78	0.04
0.08	-0.04			0.02	6	8930.10	2.09	0.03
0.08		-0.04	-0.00	0.03	7	8930.78	2.77	0.04
0.09	-0.04		-0.01		6	8931.04	3.03	0.03
0.08		-0.04	0.01		6	8931.14	3.13	0.04
Null model					3	8990.28	62.27	0

Table S5.1.5. F (fledging probability)

Candidate model set (8 top-ranking models) and null model for generalised linear model of the proportion of goslings fledging, fitted with a binomial distribution.

Parameter					df	AIC$_c$	ΔAIC$_c$	R^2
G	**fox$_{sval}$**	**P$_{ja}$**	**N$_{sval,ad}$**	**T$_{sval,ja}$**				
-0.17	-1.23	-0.54			6	4345.26	0.00	0.27
-0.17	-1.26				5	4346.55	1.29	0.25
-0.17	-1.22	-0.55		-0.15	7	4346.99	1.74	0.27
-0.17	-1.24	-0.54	0.03		7	4347.26	2.00	0.27
-0.17	-1.25			-0.10	6	4348.44	3.19	0.25
-0.17	-1.26		-0.00		6	4348.56	3.30	0.25
-0.17	-1.25		0.00	-0.10	7	4350.46	5.20	0.25
-0.17		-0.62			5	4359.06	13.81	0.06
		Null model			3	4375.22	29.97	0

5.2. Reproduction: Analysis of deviance

Since several models had similar AIC$_c$ values, we used an analysis of deviance, conducted using the *afex* package in R (Singmann *et al.* 2015) to quantify the amount of variance explained by each covariate and whether the amount of explained variance was significant.

Table S5.2. Analysis of deviance for reproduction analyses**.** Results of the analysis of deviance are presented for each parameter, where an F statistic and P value were estimated for each covariate effect from the top-ranking model based on AIC$_c$.

Parameter	**Covariate**	**F**	**P**
C	SO_{sval}	6.25	0.01
	$P_{helg,am}$	2.95	0.09
	$T_{scot,max}$	2.35	0.13
E	SO_{sval}	14.71	<0.01
	$P_{helg,am}$	14.65	<0.01
	N_{scot}	4.90	0.03
H	*E*	227.79	<0.01
	$T_{sval,jj}$	3.04	0.08
G	*E*	60.14	<0.01
	$N_{sval,ad}$	3.23	0.07
	fox_{sval}	3.15	0.08
F	$P_{sval,ja}$	2.69	0.07
	G	15.63	<0.01
	fox_{sval}	15.82	<0.01

S5.3. Survival: AIC_c-based approach

Table S5.3. AIC_c-based model selection for survival. Candidate model set (8 top-ranking models) and null model of apparent survival rates (all models include age class). The number of parameters for the simplest model of survival (i.e. with only age class as a predictor/null model) was 2 (par: intercept =1, age = 1).

Parameter						**npar**	**AIC_c**	**$\Delta\text{AIC}_\text{c}$**	**R^2**
$T_{scot,min}$	**N_{scot}**	**$P_{helg,am}$**	**$T_{helg,sum6}$**	**fox_{sval}**	**P_{scot}**				
0.29	-0.28	-0.14	0.09	-0.16		7	34452.41	0.00	0.58
0.27	-0.25	-0.15		-0.15		6	34457.07	4.65	0.56
0.24	-0.27		0.10	-0.13	0.09	7	34463.19	10.78	0.55
0.26	-0.26		0.10	-0.08		6	34464.07	11.66	0.54
0.29	-0.25	-0.10	0.07		-0.08	7	34464.57	12.16	0.54
0.26	-0.25	-0.06	0.07			6	34465.59	13.18	0.53
0.28	-0.23	-0.11			-0.08	6	34467.01	14.60	0.53
0.26	-0.25		0.08			5	34467.35	14.94	0.52
0.25	-0.24	-0.07				5	34467.82	15.41	0.52
0.26	-0.25		0.08		-0.01	6	34469.24	16.83	0.52
0.23	-0.25			-0.11	0.08	6	34469.45	17.04	0.52
0.25	-0.24			-0.06		5	34469.92	17.51	0.51
0.24	-0.23					4	34471.15	18.74	0.50
Null model						2	34624.81	172.4	

S5.4. Survival: analysis of deviance

Since several models had similar AIC_c values we also performed an analysis of deviance, using the program MARK (ANODEV), to confirm that the covariates from the lowest AIC_c models explained significant variation.

Table S5.4. Analysis of deviance for survival analysis. Results are presented as an R^2 equivalent representing the variance explained by each term, calculated by $(\sigma^2_{\text{unconstrained time dependent}} - \sigma^2_{\text{covariate}})/\sigma^2_{\text{unconstrained time dependent}}$ (Grosbois *et al.* 2008), with the associated P-value (P).

Covariate	**R^2**	**P**
$T_{scot,min}$	0.32	<0.01
N_{scot}	0.31	<0.01
fox_{sval}	0.04	0.32
$T_{helg,sum6}$	0.04	0.38
$P_{helg,am}$	0.00	0.82

S5.5 Survival: post-hoc analysis of age-specific covariate effects on survival rates

The best additive model of survival (based on an AIC_c-model selection and analysis of deviance approach) included additive effects of $T_{scot,min}$ and N_{scot}. We tested whether the effect of $T_{scot,min}$ and N_{scot} differed between age classes (i.e. for fledglings or adults), using an AIC_c-based approach.

Table S5.5. Post-hoc AIC_c-based model selection for the best-fitting survival model with interactions between age classes and covariates. The number of parameters modelled (npar), AIC_c, ΔAIC_c from lowest-ranking model and the percentage of annual variation in apparent survival explained by the model terms (R^2) are shown.

Parameter				**npar**	**AIC_c**	**ΔAIC_c**	**R^2**
$T_{scot,min}$	**N_{scot}**	**age class: $T_{scot,min}$**	**age class:N_{scot}**				
0.25	-0.06		-0.21	5	34466.96	0.00	0.52
0.22	-0.08	0.04	-0.19	6	34468.71	1.75	0.52
0.15	-0.24	0.11		5	34470.74	3.78	0.51
0.27	-0.13			4	34471.15	4.18	0.50

References

Singmann, H., Bolker, B., Westfall, J., Højsgaard, S. & Fox, J. (2015) Package ‘afex’ for R: Analysis of Factorial Experiments.

Grosbois, V., Gimenez, O., Gaillard, J.M., Pradel, R., Barbraud, C., Clobert, J., Møller, A. & Weimerskirch, H. (2008) Assessing the impact of climate variation on survival in vertebrate populations. Biological Reviews, 83, 357-399.

Appendix 6. Time series of covariates from best models of reproduction and survival that do not show temporal trends (i.e. not shown in figure 5).

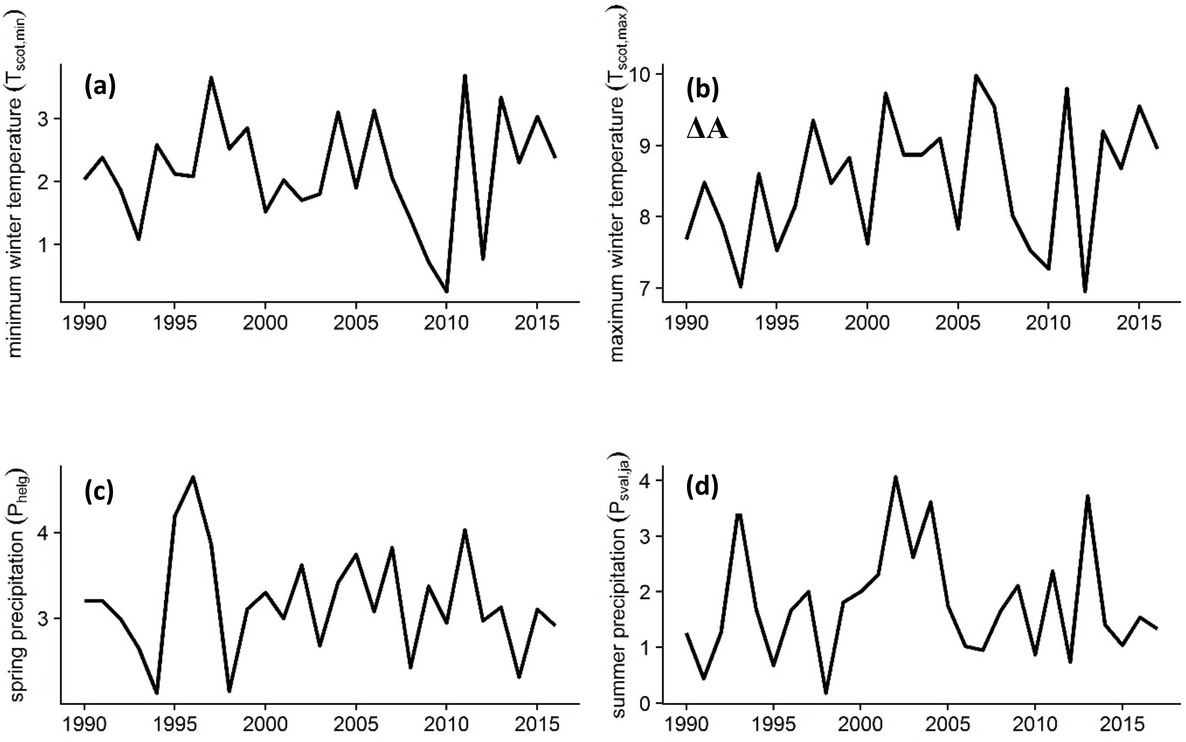

Figure S6. Annual mean (a) minimum ($T_{scot,min}$) and (b) maximum ($T_{scot,max}$) winter (October-March) temperature in Scotland, (c) April-May precipitation at Helgeland ($P_{helg,am}$) and mid-July to mid-August precipitation at Ny-Ålesund ($P_{sval,ja}$).

Appendix 7. Sensitivities of the asymptotic population growth rate

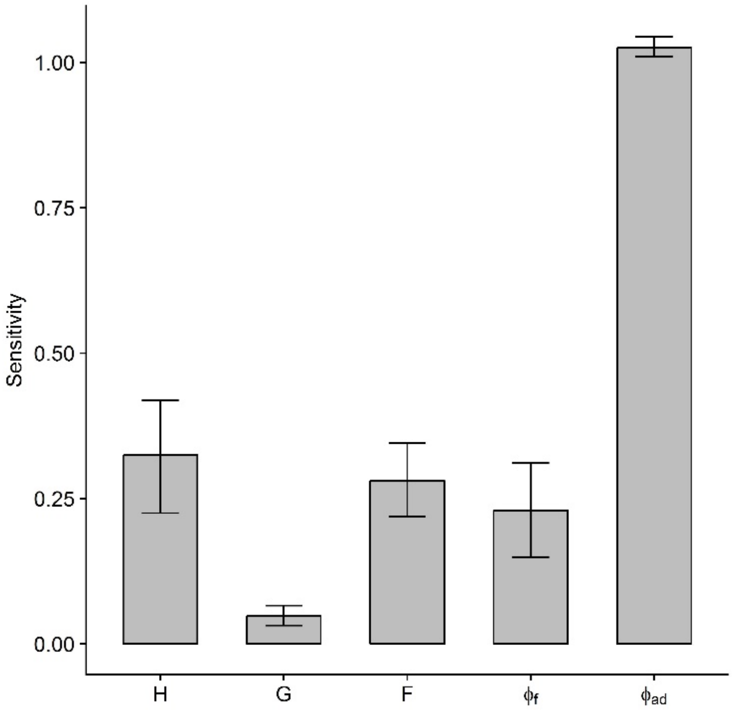

Figure S7. Sensitivities of the (asymptotic) population growth rate to lower-level parameters used in the retrospective perturbation analysis (LTRE). Here, all vital rates were estimated at mean covariate values. Error bars represent 95% confidence intervals, based on 10,000 simulations of vital rates.