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Persistent organic pollution in a high-Arctic top predator: sex-dependent thresholds in adult survival

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In long-lived species, any negative effect of pollution on adult survival may pose serious hazards to breeding populations. In this study, we measured concentrations of various organochlorines (OCs) (polychlorinated biphenyl and OC pesticides) in the blood of a large number of adult glaucous gulls (*Larus hyperboreus*) breeding on Bjørnøya (Bear Island) in the Norwegian Arctic, and modelled their local survival using capture–recapture analysis. Survival was negatively associated with concentrations of OCs in the blood. The effect of OCs was nonlinear and evident only among birds with the highest concentrations (the uppermost deciles of contamination). The threshold for depressed survival differed between the sexes, with females being more sensitive to contamination. For birds with lower OC concentration, survival was very high, i.e. at the upper range of survival rates reported from glaucous and other large gull species in other, presumably less contaminated populations. We propose two non-exclusive explanations. First, at some threshold of OC concentration, parents (especially males) may abandon reproduction to maximize their own survival. Second, high contamination of OC may eliminate the most sensitive individuals from the population (especially among females), inducing a strong selection towards high-quality and less sensitive phenotypes.

1. Introduction

Studying the impact of environmental and anthropogenic factors on animal populations is fundamental to conservation biology. For long-lived seabirds, our knowledge about the effect of climatic variability and fluctuations in food availability on important demographic traits has greatly improved during recent years [1–4]. The same applies to the effect of oil pollution [5,6]. However, the long-term quantitative effect of chronic environmental contamination by persistent organic pollutants (POPs) such as organochlorines (OCs) on adult survival is not known. Negative effects of pollution on adult survival may pose serious hazards to populations, especially in long-lived species.

The Norwegian Arctic is a sink for POPs transported by the atmosphere, ocean currents, transpolar ice packs and large Arctic rivers, and this has led to high levels of pollution in the food web [7]. As a result, top predators such as some seabirds and mammals are negatively affected by POPs and other contaminants [7,8].

The glaucous gull (*Larus hyperboreus*) at Bjørnøya (Bear Island) is one of the most comprehensively studied seabird populations with respect to the effects of POPs on breeding performance [8]. By measuring concentrations of OCs (polychlorinated biphenyl (PCB) and OC pesticides) non-invasively in large numbers of blood samples, it has been possible to quantify the effect of pollutants on important fitness components [9]. Studies on glaucous gulls during the last decade have documented a number of such effects on fitness-related traits. Birds with high levels of OCs have smaller eggs, lower egg viability, male-biased chick sex ratio at hatching, lower incubation constancy, smaller hatchlings, reduced chick growth and lower return rate of adults [9–12].

Although negative effects of OCs on the breeding performance of individual glaucous gulls are well known (reviewed in Verreault *et al.* [8]), there are no quantitative estimates of the effect of OCs on adult survival. In this study, we used capture–recapture methodology to estimate the apparent survival in male and female glaucous gulls in relation to their blood residues of OC. To our knowledge, this is the first study of any bird species to present quantitative survival estimates in relation to the level of pollution measured at the individual level.

2. Material and methods

(a) Study area and species

The study was carried out at Bjørnøya (Bear Island), a 178 km^2 island located in the Barents Sea (74°30′ N, 19°00′ E). The glaucous gull is one of the most common gull species in the Arctic and has a circumpolar distribution. The population size at Bjørnøya has been counted annually since 1987 (number of occupied nests in a study plot; figure 1).

The glaucous gull is a top predator of the Arctic ecosystem, and the diet mainly consists of marine invertebrates and other seabirds, including seabird eggs and chicks during the breeding season [13,14]. Seabirds deposit some of their OC burden in their eggs [15,16]. Therefore, glaucous gulls feeding on such eggs are potentially at risk of accumulating heavy loads of pollutants [14].

(b) Sampling and chemical analyses

In 1997, all adults (61 females and 50 males) included in this study were caught using nest traps during the same period of their seasonal cycle (late incubation period). Regarding other aspects such as age, the birds captured represented a random sample of the population. Glaucous gulls are size dimorphic and were sexed using the measurements of head and bill length [9]. Birds were weighed, and the residuals from the regression of body weight on head and bill length were used as a measure of body condition. Approximately 10 ml of blood was drawn from the brachial vein. Birds were equipped with alpha-coded PVC rings and numbered steel leg rings for identification.

OC analyses were performed at the Environmental Toxicology Laboratory at the Norwegian School of Veterinary Science. For details of the analyses, see Bustnes *et al.* [17]. We analysed for hexachlorobenzene (HCB), *p,p*′-dichlorodiphenyldichloroethylene (DDE), oxychlordane (OXY) and the PCB congeners 99, 118, 138, 153, 170 and 180 [18]. We used the blood concentration (nanograms per gram wet weight) as a measure of OCs. Other studies suggest a relatively high short- and long-term stability of the blood levels of OCs in incubating glaucous gulls under stable conditions such as at Bjørnøya, indicating that blood concentration is a reliable measurement of the relative OC burden of each individual [18,19].

OXY is presumably the most toxic compound and has been shown to provide a clear diagnostic criterion related to mortality in birds [20], and is also one of the compounds most often shown to have negative effects on reproductive performance in glaucous gulls in the present study population [11]. OXY levels ranged from 1.3 to 128.8 ng g^{-1} (median 13.2 ng g^{-1}) [18].

The distribution of both total levels of OCs and OXY was strongly skewed to the left (figure 2). For OXY, the skewness was 1.46 in males and 4.10 in females, which strongly deviated

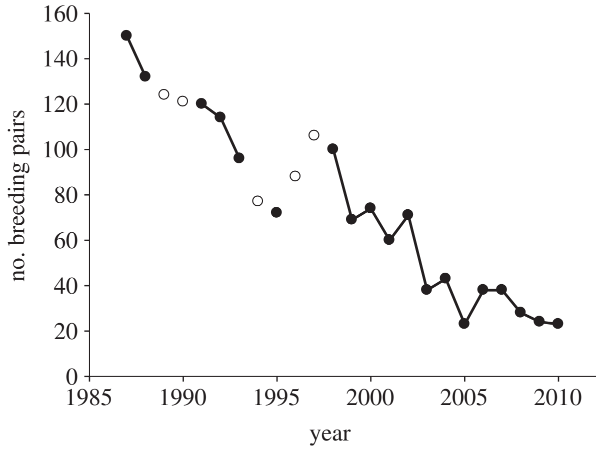

Figure 1. Number of nests occupied by glaucous gulls at Bjørnøya between 1987 and 2010 in a study plot. No monitoring was done in 1989, 1990, 1994, 1996 and 1997. Open symbols indicate extrapolations based on the PROC EXPAND procedure in SAS. In 1980 and 2006, total counts indicated population sizes of 2000 and 650 breeding pairs, respectively.

from normality (Kolmogorov–Smirnov tests: males, $D = 0.14$, $p < 0.01$; females, $D = 0.28$, $p < 0.01$). For the total concentration of OCs, the skewness was 1.48 in males ($D = 0.21$, $p < 0.01$) and 4.10 in females ($D = 0.25$, $p < 0.01$). However after log-transformation, the distribution of both OXY and total concentration of OC was very nearly normal for both males and females (all $D < 0.1$, $p > 0.15$). In general, males had a higher level of contamination than females (based on log-transformed data, equal variance, total contamination, $t_{107} = 5.05$, $p < 0.001$; OXY, $t_{107} = 4.69$, $p < 0.001$).

Log-transformed OXY levels were used in two ways: (i) by treating OXY levels as individual and time-independent covariates; and (ii) by grouping all individuals into 10 categories of equal size (deciles) according to their contamination.

The different OCs analysed were highly positively correlated with correlation coefficients ranging from 0.85 to 0.99 (table 1), which makes it difficult to separate the effect of single compounds in the analyses. We therefore examined the effect of the total contamination using the first principal component (PC1) from a principal component analysis including all compounds measured. PC1 had an eigenvalue of 8.30 and its correlation with all compounds was more than 90% (table 1). All loadings were within 0.32 and 0.34.

(c) Survival analyses

Apparent local survival (hereafter, survival) and re-sighting were estimated using capture–recapture methodology [21]. The effective sample size was $n = 408$, based on 7 years of re-sightings (1998–2004) [18]. Goodness of fit of the data was assessed using U-CARE [22,23]. The global test indicated a strong deviation from the assumption of independence of fates and identity of rates among individuals ($\chi^2_9 = 46.37$, $p < 10^{-6}$), which was due to the presence of trap-happiness ($D = -6.19$, $p < 10^{-9}$). Correcting for this capture heterogeneity using Pradel's [24] method resulted in a good fit and removed the overdispersion ($\chi^2_8 = 9.37$, $p = 0.31$, $\hat{c} = 1.17$). Subsequent analyses of survival and re-sighting were performed in MARK [25,26].

Survival models are compared using Akaike's information criterion, corrected for small sample sizes (AIC$_C$). Estimates and 95% confidence intervals (CI) are presented as 'mean [lower CI; upper CI]'.

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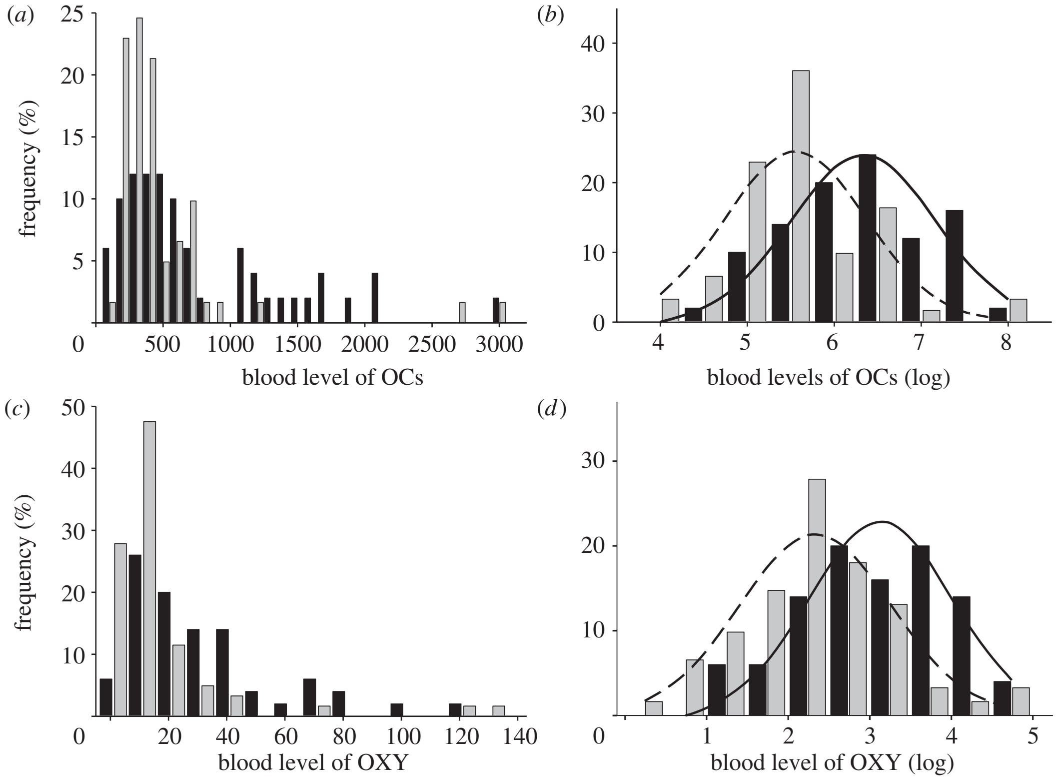

Figure 2. Frequency distribution of OC levels in the blood of male ($n = 50$) and female ($n = 61$) glaucous gulls, used as covariates to adult survival. (*a*) Frequency distribution of the total concentrations of all compounds (nanograms per gram wet weight; see text for compounds included). (*b*) The same data log-transformed. (*c*) Frequency distribution of OXY (nanograms per gram wet weight). (*d*) The same data log-transformed. Black bars and solid lines denote males, whereas grey bars and dashed lines denote females.

Table 1. Correlation matrix for nine different OC compounds measured in blood samples of 111 glaucous gulls from Bjørnøya in the high Arctic (OXY, HCB, DDE, and congeners of PCB [PCB99, PCB118, PCB138, PCB153, PCB170 and PCB180]) used as covariates to their annual survival. (Also shown is the correlation with the first principal component (PC1). All correlation coefficients are statistically significant ($p < 0.0001$).)

	OXY	HCB	DDE	PCB99	PCB118	PCB138	PCB153	PCB170	PCB180
PC1	0.97	0.93	0.91	0.98	0.99	0.99	0.99	0.96	0.93
OXY		0.88	0.88	0.94	0.94	0.93	0.95	0.92	0.90
HCB			0.85	0.91	0.92	0.92	0.89	0.86	0.82
DDE				0.87	0.90	0.87	0.87	0.84	0.81
PCB99					0.97	0.98	0.97	0.92	0.87
PCB118						0.99	0.98	0.94	0.90
PCB138							0.99	0.94	0.90
PCB153								0.95	0.92
PCB170									0.94

(d) Effect of adult survival on population decline

The population has experienced a steep linear decline ($r^2 = 0.92$; figure 1), which amounted to 8.2% per annum (p.a.) (s.e., 5.3%) between 1987 and 2010, resulting in a 50% probability of extinction within 19 years [18]. Based on the survival estimates obtained, it is possible to predict the population decline that is due to the effect of contamination on adult survival ϕ. This can be accomplished by quantifying the population decline in a population that would have growth rate λ_0 in the absence of any effect of contamination on survival; i.e. by letting recruitment compensate for normal mortality:

$$N_{t+1} = \lambda N_t = \underbrace{N_t^{\mathrm{lo}}\phi^{\mathrm{lo}} + N_t^{\mathrm{hi}}\phi^{\mathrm{hi}}}_{\text{survival}} + \underbrace{N_t(\lambda_0 - \phi^{\mathrm{lo}})}_{\text{recruitment}}. \tag{2.1}$$

If the fraction (q) of highly ('hi') and lowly ('lo') contaminated individuals in the population is assumed to be independent of time t, i.e.

$$\left.\begin{aligned} N_t^{\mathrm{hi}} &= q^{\mathrm{hi}} N_t \\ \text{and} \quad N_t^{\mathrm{lo}} &= (1 - q^{\mathrm{hi}}) N_t, \end{aligned}\right\}, \tag{2.2}$$

the annual multiplicative population growth rate can then be expressed as

$$\begin{aligned} \lambda = \frac{N_{t+1}}{N_t} &= (1 - q^{\mathrm{hi}})\phi^{\mathrm{lo}} + q^{\mathrm{hi}}\phi^{\mathrm{hi}} + (\lambda_0 - \phi^{\mathrm{lo}}) \\ &= \lambda_0 - q^{\mathrm{hi}}(\phi^{\mathrm{lo}} - \phi^{\mathrm{hi}}). \end{aligned} \tag{2.3}$$

Table 2. Models of survival and re-sighting of glaucous gulls on Bjørnøya. (Models include OXY levels as a continuous covariate or as group effects by deciles (D). Models are sorted by increasing ΔAIC_C (i.e. decreasing model fit). The best-supported models, having a comparable fit, are highlighted in bold. Significance (*P*) is based on likelihood ratio tests between each model and the null model (*R*, italics). Resighting was year-dependent and included a correction for capture heterogeneity in all models. Model A had a deviance of 712.26 and an AIC_C of 732.82.)

	model[a]	parameters	ΔAIC_C	AIC_C weight	*p*-value
A	**OXY/D9♀ + D8♂**	**10**	**0.00**	**0.224**	**0.0021**
B	**OXY/D9**	**10**	**0.94**	**0.140**	**0.0035**
C	OXY/D9♀ + D8♂ × sex	12	2.40	0.068	0.0103
D	OXY/D9♀	11	2.50	0.064	0.0107
E	OXY/D9 + sex	11	2.60	0.061	0.0113
F	OXY/continuous	10	2.75	0.057	0.0096
G	OXY/D9 (3 years)[b]	10	2.91	0.052	0.0105
H	OXY/D9 + body condition	11	2.96	0.051	0.014
I	OXY/D9 × sex	12	3.22	0.045	0.015
J	OXY/D9 (2 years)[b]	10	3.64	0.036	0.016
K	OXY/D9 + sex × condition	12	3.65	0.036	0.018
L	OXY/D9 × body condition	12	3.67	0.036	0.018
M	OXY/continuous + sex	11	4.12	0.029	0.024
N	OXY/D9♀ + D7♂	12	4.39	0.025	0.026
O	PC1/continuous	10	4.61	0.022	0.028
P	OXY/D8	10	5.50	0.014	0.047
Q	OXY/continuous × sex	12	5.75	0.013	0.047
R	*null model*	*9*	*7.36*	*0.006*	—
S	OXY/D9 × sex × condition	16	7.46	0.005	0.04
T	OXY/D7	10	7.53	0.005	0.17
U	re-sighting: OXY	10	7.85	0.004	0.21
V	OXY/D8♂	11	8.59	0.003	0.23
W	OXY/D5	10	8.70	0.003	0.39
X	OXY/D9 (1 year)[b]	10	9.03	0.002	0.51
Y	year	14	10.32	0.001	0.18

[a]Model notation: D*i*, first to *i*th decile *versus* ($i + 1$)th to 10th decile; PC1, first principal component of OCs; '+', additive effects; '×', multiplicative effects (additive plus interaction).
[b]Survival was assumed to be affected by contamination for *n* years after measurement, if a number in brackets is provided; otherwise for 7 years.

In other words, the effect of contamination is to reduce population growth by $q^{hi}(\phi^{lo} - \phi^{hi})$.

3. Results

The mean annual survival of glaucous gulls on Bjørnøya during the observation period was estimated to be time-invariant at 0.934 [0.828; 0.977]. Re-sighting rates of birds seen in the previous year varied between 0.41 and 0.89, with a mean of 0.78 [0.72; 0.83]. Neither survival nor re-sighting rates differed between the sexes (female survival, 0.945 [0.823; 0.985]; male survival, 0.915 [0.796; 0.967]).

Addition of OXY levels improved model fit considerably (table 2: model F) compared with the null model (R). Survival decreased with increasing OXY concentration (−1.80 [−4.49; +0.88]). Although the slope did not differ significantly between the sexes, it did not bound zero in females (model Q; females, −1.97 [−3.94; −0.01]; males, −0.78 [−2.77; +1.20]).

Findings were even more pronounced when considering OXY levels as a categorical covariate: while the first nine deciles had comparable survival, survival was significantly reduced in the decile with the highest levels of contamination (table 2: model B). Additive or multiplicative effects of sex did not lead to improvements over this model (models E, I), although there was a tendency that females responded more strongly to high levels of contamination (figure 3). The best-supported model overall (A) had sex-independent levels of survival but sex-dependent thresholds: according to this model, survival was 0.762 [0.588; 0.878] in the single most contaminated decile of females and the two most contaminated deciles of males, compared with 0.950 [0.846; 0.985] in birds with lower blood levels of OXY. The contamination threshold at which survival became depressed was estimated to be around 27 ng g^{-1} in females and 48 ng g^{-1} in males.

These findings could be reproduced when restricting the effect of OXY to the first 2 or 3 years after measurement (table 2: models G, J), but not when only considering the

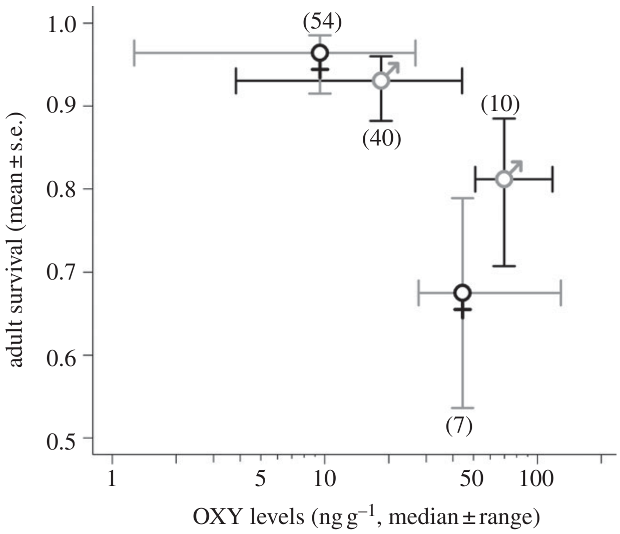

Figure 3. Apparent adult survival of male (♂) and female (♀) glaucous gulls breeding on Bjørnøya in the high Arctic in relation to their levels of OXY contamination in the blood. Horizontal bars indicate the range of OXY levels (in nanograms per gram wet weight; the thresholds differed significantly between the sexes); vertical bars indicate standard errors of survival estimates (survival rates did not differ significantly between the sexes). Survival is depressed for the most contaminated 10% of females (10th decile) and the most contaminated 20% of males (9th and 10th decile). The survival estimates are from the sex-specific model (C) in table 2. Sample sizes (number of birds) are given in parentheses.

first year (model X). Body condition did not affect survival (model H), nor did it interact with contamination or sex (models K, L, S). The PC1 of the contaminants measured had an effect similar to, but weaker than, OXY alone (model O, slope −0.26 [−0.64; +0.12]). Re-sighting rates were not significantly affected by OXY levels (model U, −0.17 [−0.43; +0.09]).

Based on equation (2.3) and the estimates derived from model A, we quantified the contribution of survival to the decline in population size (figure 1). The suppressed survival of highly contaminated birds could account for a population decline of 2.9% p.a. [$\lambda = \lambda_0 - 17/111(0.950 - 0.762)$]. The median time to quasi-extinction of the Bjørnøya population would increase from 19 to 50 years in the absence of this effect [18].

4. Discussion

The local survival of glaucous gulls at Bjørnøya was negatively affected by their OCs. The effect of OCs was highly nonlinear and only apparent among the individuals with the highest levels of contamination. The sexes differed significantly in the thresholds of this nonlinear response, but not in their survival estimates: survival was depressed at lower OC concentrations in females than in males (figure 3). The population currently declines at a rate of 8% p.a., which results in a median time to quasi-extinction of 19 years. Roughly, a third of the population decline was estimated to be due to the effect of contamination on adult survival. In the absence of this effect, median time to population quasi-extinction would have increased to 50 years.

We only measured the level of OC in 1 year, so an important assumption is that there are small changes in OC level over time in individual birds. Another study from the present population suggests that this is the case, as blood samples taken from the same individuals over 2 years show a repeatability of 70% [17]. Moreover, the estimated negative effect of OCs on survival was evident also 2 or 3 years after the OC level was measured, suggesting that changes in OC levels over time are of minor importance for the interpretation of the results in this study. Although different compounds of OCs are highly correlated and their effects difficult to separate, there is some evidence that OXY is the most toxic compound and provides a clear diagnostic criterion related to mortality in birds [20].

Since we analysed birds of unknown age, another possibly confounding factor could be that birds with high levels of OC had reached the age of senescence, and that mortality was really owing to old age rather than contamination. However, this seems unlikely. The general trend among birds is that the level of OCs, rather than simply increasing linearly with age, reaches a steady state early in life, where OC intake equals the elimination at a yearly basis [27]. For long-lived birds, it has been suggested that the steady-state equilibrium is reached around the age of reproduction [28], which is consistent with a previous analysis from the present study population documenting no increase in OCs with age among breeding birds [29].

Besides the individual-based evidence of depressed survival due to contaminants, there are two important findings from this study regarding the long-term population-level consequences of OC contaminations in adult breeding birds. One is the fact that the sexes respond differently to contamination levels, in that female survival is depressed at blood concentrations, where males are still unaffected. The other important finding is that adults with low levels of OC had unexpectedly high survival rates.

That females seem to be more sensitive to high levels of OC than males, could be related to sex-dependent differences in breeding effort. This is consistent with similar findings in the pied flycatcher *Ficedula hypoleuca* from two different study areas: Eeva *et al.* [30,31] showed that local survival in males in areas of heavy metal pollution (Cu) was higher than among females and even higher than survival of males in non-polluted areas. They suggested that pollution stress may produce different hormonal responses in males and females, triggering sex-dependent differences in breeding effort. If pollution stress increases corticosterone levels more in males than in females, males might redirect their behaviour towards their own survival by reducing their breeding investment [30,32]. It is well known that OCs are capable of acting as endocrine disrupters by mimicking steroids and binding to hormone receptors [33,34], and different hormonal responses related to breeding effort among male and female glaucous gulls seem possible. However, the role of hormonal mechanisms in bringing about this kind of pollution-related sex-specific local survival remains to be studied.

Regarding individuals with low OC burden, we estimated their survival rates at 95%. This figure is much higher than the estimate of only 84% adult survival in glaucous gulls from Coats Island (Nunavut, Canada [35]). A review of the adult survival in other large gulls from more temperate areas (based on mark–recapture analyses) shows a mean value of 89% (range 83–91% [35]), which is also lower than our estimate from Bjørnøya.

So why should breeding adults survive better on Bjørnøya, presumably the most OC contaminated area? Owing to lack of conclusive evidence, we suggest two possible causal pathways that might explain this finding. One main difference between the Bjørnøya population and the population from Coats Island is that the Bjørnøya population is strongly declining, whereas the Coats Island population is increasing owing to high breeding success and recruitment [35]. Although we have no quantitative estimates of breeding success for the time period from this study, there is good evidence that female levels of OCs have negative impacts on a number of parameters related to reproduction [9]. Furthermore, the population shows an annual decline of 8% and has a 50% probability of quasi-extinction within 19 years [18], while the low survival due to high OC levels alone could only account for a decline of 3.4%. This may suggest very low breeding success and recruitment of young. Although re-sighting rates were not affected by levels of contamination, it seems likely that parents (presumably mostly males) abandon reproduction and instead switch their investment in ensuring their own survival, when OC levels reach a certain threshold. Such strategies are typical of long-lived species that are adapted to variable environments [36]. However, under conditions of anthropogenic environmental change, this evolved life-history strategy to refrain from reproducing in stressful seasons may turn out to be maladaptive. This will be especially serious in the case of contamination, because the stressor becomes permanent, so that contaminated birds never experience stress-free breeding seasons.

Another possible, although not mutually exclusive, explanation is that contamination of OCs eliminates the most sensitive individuals (genotypes) from the population, as suggested by Fox [37]. This would entail a strong selection for high-quality and less sensitive individuals. The glaucous gull population on Bjørnøya has probably been exposed to high levels of OCs for more than four decades [38]. Although some of the variation in contamination among individuals may be related to their diet [14], high-quality individuals may have a better capacity (to pay the cost) to eliminate OCs, which, in general, have been suggested to reach a steady state where OC intake equals elimination [27,29]. The strong skew in OC towards low levels among females is consistent with such an explanation, as is the observation that the skewness towards low values was stronger among females than among males (figure 2).

In conclusion, the level of OCs in the blood of glaucous gulls from Bjørnøya has a strong impact on adult survival. However, the mechanisms behind and the consequences at the population level are poorly understood. A promising avenue for future research would be to measure OC and other pollutants in the blood of parents and chicks and then quantify the survival of adults and recruitment of young to the population over time. Such data would allow the estimation of the effect of pollution and other environmental factors on the population growth rate by means of matrix population models.

Permission to work at Bjørnøya was approved by the governor of Svalbard. Collection of Samples was conducted according to Norwegian ethics regulations and European Council guidelines for Laboratory Animal Science.

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Data accessibility. Individual input data and population viability analyses are available at Dryad (doi:10.5061/dryad.pm885).

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