Supplementary Material S1: Full model structure including tag-dependent observation process.

The model and motivation for estimating the parameters is explained in the main text of the paper. This supplementary provides all the steps contained in the code, and gives detail additional to that in the manuscript. Full code for implementing this model is given in S2.

The model includes one section, the process model, describing changes in the survival and mass of breeding female grey seals over time, including the effects of environmental drivers and pregnancy status. The second part of the model describes the observation processes, given the state of the system. These sub-models are intimately connected: for example, the breeding status of the animals (affected by mass gain and fertility) influences their observability.

Process model

Maternal expenditure occurs during lactation when each mother fasts while feeding her pup. The proportional mass loss during lactation was estimated using a general multiplier β acting on maternal postpartum mass. For female j pupping in year t , her observed mass at the start of the breeding season $M_{j,t}$ is a predictor of her mass at the end of breeding season $W_{j,t}$. The true mass of the female was assumed to be Normally distributed around the expected value, reflecting both the individual variation between females, and observation error in mass measurement.

$$W_{j,t} \sim N(\beta M_{j,t}, \sigma_W^2)$$

The mass of a female j at the end of breeding in year t influences mass at the beginning of breeding in year $t+1$ with an additional annual environmental effect ε_t common to all animals. A factor δ represents the possible effect of pregnancy on mass gain.

For a female pupping in year $t+1$

$$M_{j,t+1} \sim N(\delta \varepsilon_t W_{j,t}, \sigma_M^2)$$

For a female that does not pup in year $t+1$

$$M_{j,t+1} \sim N(\varepsilon_t W_{j,t}, \sigma_M^2)$$

For a female pupping in year $t+1$ the expected value of the end-of-season mass in year $t+1$ is then

$$E(W_{j,t+1}) = \varepsilon_t \ \delta \ \beta \ W_{j,t}$$

And for a non-pupping female

$$E(W_{j,t+1}) = \varepsilon_t \, W_{j,t}$$

So the product $\delta \, \beta$ can be interpreted as a general estimate of the ratio between the end-of-season mass for breeding and non-breeding females. Constants δ, β are estimable as separate parameters because we have values of both $W_{j,t}$ and $M_{j,t}$ in the data set. allowing direct estimation of β from data on breeding animals. As previously, maternal masses $W_{j,t}$ were assumed to be Normally distributed with constant variance.

All observations of mass are assumed to follow a Normal distribution, and the standard deviations for W and M are also estimated. For some animals, measurements of mass are not available for all years. These 'missing values' of mass can be estimated during the model fitting process.

Year-dependent proportional mass-gain ε_t is modelled as a function of environmental variables (NAO or sandeel abundance) represented here by x_t

$$\varepsilon_t = a + bx_t$$

The parameters a and b are to be estimated. If the 95% BCI (Bayesian Credible Interval) around the estimate for the parameter b does not include zero, this can be taken as evidence for an association between mass gain and the environmental variable.

Preliminary investigations did not find evidence for an effect of NAO at IM, so the covariate NAO was used at NR only. Sandeel data are not available for NR, so the sandeel abundance index data were used with IM data only.

Pupping is treated as a Bernouilli process. Pupping status $y_{i,t}$ for animal i in year t takes value 1 if the animal gives birth to a pup, and 0 if it does not. The underlying probability of pupping is $f_{j,t+1}$. This is associated with female mass at the end of the breeding season in the previous year $W_{j,t}$, scaled by the environmental year-effect. Pupping probability is treated as a logistic function of mass

$$f_{j,t+1} = \frac{\exp\left(a_p + b_p \, \varepsilon_t \, W_{j,t}\right)}{1+\exp\left(a_p + b_p \, \varepsilon_t \, W_{j,t}\right)}$$

Parameters a_p and b_p are to be estimated. If the 95% BCI around the estimate for the b_p does not include zero, this can be taken as evidence for an association between pupping probability $f_{j,t+1}$ and $W_{j,t}$. The sign of b_p indicates the type of association, positive or negative.

Preliminary investigations involved also fitting a similar relationship between survival probability and female mass

$$s_{j,t+1} = \frac{\exp\,(a_s \ + \ b_s\ \varepsilon_t\ W_{j,t})}{1 + \exp\,(a_s \ + \ b_s\ \varepsilon_t\ W_{j,t})}$$

However, we did not find evidence for a relationship between survival probability and mass. For IM the parameter b_s was estimated at -0.0102 (-0.03275, 0.0194) and for NR it was 0.00167 (-0.00691, 0.0120) i.e. the 95% Bayesian credible intervals spanned 0. Apparent survival is therefore modelled as a constant value at each colony. We estimate parameter a_s and then survival was calculated within the model as

$$s_{j,t+1} = \exp(a_s\ )\,/(1 + \exp(a_s\ ))$$

As we cannot distinguish between animals that die, and any that permanently emigrate from the study population, we estimate 'apparent survival' shortened to 'survival' in this paper.

The model includes the possibility that some females are available to be seen on only one occasion. For both NR and IM, we estimate the colony-specific probability that an animal seen for the first time is in this category, $p_{transient}$.

Probability of tag loss can also be estimated, because some animals carry multiple mark types e.g. tags and brands. Tag loss is assumed to be a Bernoulli process analogous to the survival of the animals themselves. The status of a tag (1=present, 0=absent) is written:

$$tag_{i,t+1} \sim Bernoulli((1 - tagloss)tag_{i,t})$$

Brands and pelage-ID are treated as permanent marks.

Observation model

Seals are marked with some combination of the following marks: brands, flipper tags, and pelage markings. Mark-dependent values of re-sighting probability p_{photo} and p_{tag} are estimated during the model-fitting process for each colony separately. The resulting probability of observing an animal depends on its survival, mark status, and pupping status.

We estimate distinct parameters p_{pup} representing the re-sighting probability of breeding females and $p_{no\ pup}$ for non-breeding females. These are probabilities for branded animals, which are assumed to be the most visible.

We assume that branded animals are re-sighted based on the brand, non-branded animals are re-sighted based on photo-ID (if the animal's pelage is known/photographed) and that tag-identification would be used if neither brand nor photo-ID were available[1].

For a branded animal i the probability of observation in year t is given by

$$Pobs_{i,t} = p_{pup}{}^{y_{i,t}} p_{no\ pup}{}^{1-y_{i,t}}$$

For an animal with no brand, but which has been photographed

$$Pobs_{i,t} = p_{pup}{}^{y_{i,t}} p_{no\ pup}{}^{1-y_{i,t}} P_{photo}$$

For an animal with no photo-ID record and no brand but which is tagged

$$Pobs_{i,t} = p_{pup}{}^{y_{i,t}} p_{no\ pup}{}^{1-y_{i,t}} P_{tag}$$

We assume that

$$0 < P_{photo} < 1$$

Parameter	Meaning	NR value	IM value	Prior
a_s	The survival probability parameter is calculated as $s = e^{a_s}$	2.09 (1.90, 2.20) corresponding survival probability 0.89 (0.87, 0.90)	2.75 (2.59, 2.94) corresponding survival probability 0.94 (0.93, 0.95)	$N(0{,}25)$
a_p	fecundity parameter, where *Pr(pupping)* is calculated as $p_{t+1} = e^{a_p + b_p \varepsilon_t W_t}$	-7.92 (9.41, -6.30)	-12.20 (-14.92, -9.78)	*N(0, 25)*
b_p	fecundity parameter, where *Pr(pupping)* is calculated as $p_{t+1} = e^{a_p + b_p \varepsilon_t W_t}$	0.08 (0.06, 0.09)	0.13 (0.11, 0.16)	*N(0, 25)*
β	Ratio of W (maternal mass at weaning) to M (maternal post partum mass)	0.65 (0.64, 0.66)	0.65 (0.65, 0.66)	*U(0.1,1)*
δ	Maternal mass gain (pregnancy) multiplier	1.34 (1.32,1.36)	1.40 (1.38,1.42)	$\Gamma(3{,}3)$

[1] Smout S, King R, Pomeroy P. Estimating demographic parameters for capture–recapture data in the presence of multiple mark types. Environ Ecol Stat. Springer US; 2011;18(2):331–47.

$P_{transient}$	Probability that a female recorded in the data set for the first time is a transient	0.21 (0.16, 0.27)	0.04 (0.01, 0.09)	*U(0.1,1)*
$P_{tagloss}$	Annual probability of tag loss	0.07(0.05, 0.09)	0.02 (0.01, 0.03)	*U(0.001,1)*
a	Intercept of relationship between proportional mass gain and environmental correlate $\varepsilon_t = a + bx_t$	1.12 (1.11, 1.14)	1.07(1.05, 1.09)	*N(0,4)*
b	Gradient of relationship between proportional mass gain and environmental correlate $\varepsilon_t = a + bx_t$	-1.50×10^{-2} (-3.14×10^{-2}, -3.96×10^{-4})	4.6×10^{-4} (3.50×10^{-6}, 8.60×10^{-4})	*N(0,4)*
P_{tag}	probability that a tagged animal will be seen, relative to probability that a branded animal is seen	0.68 (0.53,0.821)	0.25 (0.19, 0.32)	*U(0.01, 1)*
P_{photo}	probability that a pelage-ID animal will be seen, relative to probability that a branded animal is seen	0.94 (0.89, 0.993)	0.76 (0.69, 0.84)	*U(0.01, 1)*
p_{pup}	Probability that a female marked with a brand (i.e. highly visible) and pupping is present and will be seen at the colony	0.89 (0.85, 0.93)	0.83 (0.80, 0.86)	*U(0.5,1)*
$p_{no\ pup}$	Probability that an animal marked with a brand which is not pupping will be seen at the colony	0.08 (0.06, 0.11)	0.05 (0.03, 0.08)	*U(0,0.5)*

Table S1.1: Parameter estimates for the process and observation models. Mean values are calculated from 1000 samples from the Markov chain, and 95% Bayesian credible intervals are shown in brackets. Prior distributions used in Bayesian estimation are given in the right-hand column. For the Normal distribution $N(\mu, \sigma^2)$, parameters μ, σ^2 are the mean and variance respectively. For the Gamma distribution $\Gamma(s, r)$, the parameters s, r are the shape and rate respectively. Cells shaded grey correspond to parameters associated with the observation process.