

Effect of hunting and by-catches on the
observed rate of growth of the Baltic sea
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Introduction

According to the HELCOM grey seal abundance indicator (HELCOM (2018b)), the Baltic sea population fulfills the criteria of good environmental status (GES) if it, in the phase of exponential growth (prior to reaching carrying capacity), grows at a yearly rate of 7% or higher. Based on abundance monitoring data, the population has grown at a fairly steady yearly rate of 5.1% since 2003, and hence does not fulfill the criteria (HELCOM (2018b)). At the same time, the population has experienced an increased pressure from hunting and an unknown number of animals die from entrapment in fishing gear. The purpose of this work is evaluate the effect of hunting and by-catches on the observed rate of growth of the population: Are the criteria for GES likely to have been fulfilled in the absence of animal removals by hunting and by-catches? In order to answer this question, we will update the study of Harding et al. (2007) in light of new empirical evidence and in a more explicit way include the causes of mortality. While Harding et al. (2007) focus on projecting future scenario, we will look more closely in to the development of the population from the start of coordinated surveys in 2003 until 2021.

Materials and methods

As in Harding et al. (2007), we use an an age-structured model where $n_i(t)$ denotes the number of age-class i females in the population at census in year t . We assume the census is taken right after breeding to facilitate interpretation of parameters, such that n_1 denotes the number of new-born pups. Given an initial female population size of N_0 in year 2003, distributed across age-classes according to frequencies p_1, \dots, p_{46} , the population evolves according the recursion

$$\begin{aligned}n_i(2003) &= N_0 p_i, \\n_1(t) &= \sum_{i=1}^{46} n_i(t-1) f_i, \\n_i(t) &= n_{i-1}(t-1) s_i,\end{aligned}$$

for $i = 2, \dots, 46$ and $t = 2004, \dots, 2021$. Here f_i denotes the average number of female pups contributed by a female alive at her i :th birthday to the following year's breeding period, calculated as $f_i = b_i s_i$, where b_i represents the average number of female offspring conditionally on survival and s_i the probability that she survives to her following birthday.

We may now, in a similar way to Øigård et al. (2012), explicitly include hunting pressure in the recursion by modifying the last line to

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$$n_i(t) = n_{i-1}(t-1)\tilde{s}_i - n_i^{\text{hunt}}(t),$$

for $i = 2, \dots, 46, t = 2004, \dots, 2021$, where $n_i^{\text{hunt}}(t)$ denotes the number of age-class i female animals shot by hunters in the time-interval $(t-1, t)$ and \tilde{s}_i should be interpreted as the hypothetical survival rates in the absence of any hunting. These rates may further be factorised as $\tilde{s}_i = s_i^{\text{undist}} \times (1 - p_i^{\text{bycaught}})$, where p_i^{bycaught} denotes the probability that an individual in age-class i is by-caught and s_i^{undist} may be interpreted as the hypothetical survival rates in an undisturbed environment with no hunting and no animals being by-caught.

In order to get explicit measures of the loss of individuals due to hunting and by-catches, we introduce two separate populations of “ghosts” that are fed by killed animals from the recursion. The ghosts are further allowed to continue their lives and reproduce according to recursions

$$\begin{aligned} n_i^{\text{ghost-h}}(2003) &= N_0^{\text{ghost-h}} p_i^{\text{ghost-h}}, \\ n_1^{\text{ghost-h}}(t) &= \sum_{i=1}^{46} n_i^{\text{ghost-h}}(t-1) f_i, \\ n_i^{\text{ghost-h}}(t) &= n_{i-1}^{\text{ghost-h}}(t-1) s_i^{\text{undist}} + n_i^{\text{hunt}}(t), \end{aligned}$$

$i = 2, \dots, 46, t = 2004, \dots, 2021$, for the shot ghosts, and for the by-caught

$$\begin{aligned} n_i^{\text{ghost-bc}}(2003) &= 0, \\ n_1^{\text{ghost-bc}}(t) &= \sum_{i=1}^{46} n_i^{\text{ghost-bc}}(t-1) f_i, \\ n_i^{\text{ghost-bc}}(t) &= n_{i-1}^{\text{ghost-bc}}(t-1) s_i^{\text{undist}} + n_i(t-1) p_i^{\text{bycaught}}, \end{aligned}$$

$i = 2, \dots, 46, t = 2004, \dots, 2021$. Finally, we may define an “undisturbed” population size as

$$N^{\text{undist}}(t) = \sum_{i=1}^{46} n_i(t) + n_i^{\text{ghost-h}}(t) + n_i^{\text{ghost-bc}}(t),$$

$t = 2003, \dots, 2021$, which we interpret as the hypothetical size in the absence of hunting and by-catches.

Parametrising the model

In order to parametrise the model, we will take advantage of data reported within the various HELCOM indicator programmes (HELCOM (2018b), HELCOM (2018c), HELCOM (2018a)), as well as hunting statistics reported to the Swedish and Finnish authorities.

Reproduction

Due to environmental contaminants, like PCBs, the reproduction of grey seals was severely disturbed in the Baltics during the 1970-80:ies. Harding et al. (2007) assume an adult pregnancy rate of 75% based on Bergman (1999) and personal communication with Bergman, but notes that this is low in comparison to studies from other regions. Figure 1, based on the reproductive status of 917 female seals collected since 2002 (HELCOM (2018c)), suggests that pregnancy rate has increased and is now closer to 87% for adult females. Since pregnancy is measured postpartum and only the female proportion of the population is modelled, the reproductive proportion in age-class i in Figure 1 hence corresponds to the contribution $2b_{i-1}$ of the previous age-class.

We will use the fitted values for age classes > 3 to parametrise b_4, \dots, b_{46} and set $b_1 = b_2 = b_3 = 0$ since fitted values for low ages are likely to be inflated by smoothing and potential errors in the determination of ages.

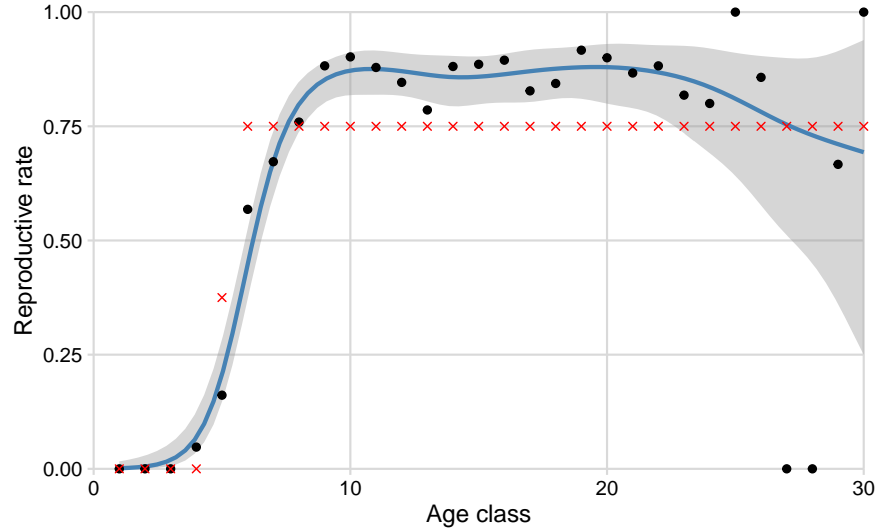


Figure 1: Proportion of hunted females showing signs of reproduction as a function of age class. Black dots show observed proportions for each ageclass, the blue line a fitted logistic additive model and red crosses the corresponding values used by Harding et al. (2007)

Survival and age-distributions

An often cited estimate of adult yearly survival is 0.935 obtained by Harwood and Prime (1978), based on females 7 years or older shot at Farna Islands in 1972 ($n = 554$) and 1975 ($n = 482$). This uses the Chapman-Robson estimator (Chapman and Robson (1960)) corrected for a rate of population increase of 7% (Eberhardt (1988)). They actually obtain estimates 0.944 for 1972 and 0.936 for 1975 but argue that “A constant survival of 0.94 implies that some animals will survive to be infinitely old ... To compensate for this an annual survival of 0.935 has been used”.

At age 8, female grey seals have almost reached their maximum size (body length). Hence, hunted animals at this age or higher are likely to accurately reflect the age-distribution of the population in the segment. The average age among hunted seals in this group is $\bar{T} = 13.8$ years ($n = 397$) and the Chapman-Robson estimate of yearly survival equals $(\bar{T} - 8)(1 + (\bar{T} - 8) - n^{-1})^{-1} = 0.85$ (0.84, 0.86). Correcting for the observed yearly population increase of 5.1% gives our estimate of survival $0.85 \times 1.05 = 0.9$ (0.88, 0.91). This is lower than the value 0.95 used by Harding et al. (2007), but that was set high to compensate for a low reproduction (75% fertility rate).

In order to obtain a value for juvenile survival, we set $s_i = 0.9$ for $i > 1$ and adjust s_1 until we obtain the observed rate of increase. This gives $s_1 = 0.73$. While these values are interesting on their own, they merely provide us with lower bounds for s_i^{undist} . Hence, we will try a range of values $s_i^{\text{undist}} \in \{0.9, 0.91, 0.92, 0.93, 0.94, 0.95\}$ for $i > 1$ and adjust s_1^{undist} to obtain the observed rate of increase.

The initial analysis, without explicit hunting, with adult survival 0.9 and juvenile 0.73 will also be used to derive a stable age-distribution c_i^{stable} , $i = 1, \dots, 46$ as the first eigen-vector of the corresponding Leslie matrix.

Abundance monitoring data

Grey seals have been counted (max-counts of repeated visits) at haul-out sites during moulting in the entire Baltic sea since 2003 as part of the HELCOM indicator for population trends and abundance of seal (HELCOM (2018b)). While longer time-series exists for some regions, notably Swedish waters, they will not be used in this study due to the migratory nature of the grey seal and some methodological differences

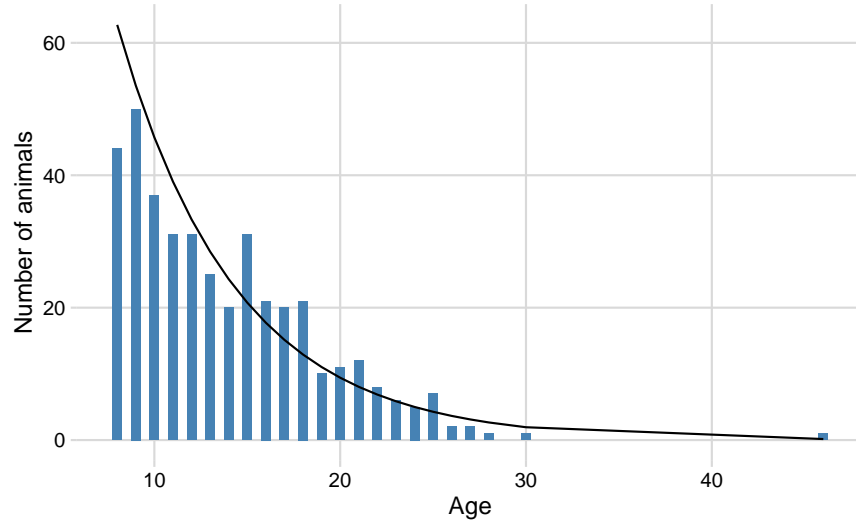


Figure 2: Age distribution among age 8+ year hunted female seals together with fitted exponential curve.

in survey protocol. Figure 3 show counts together with a log-linear fit corresponding to a yearly population increase of 5.1% (4.5%, 5.7%). Since only hauled-out seals are counted, this is estimated to correspond to 60-80% of the total population (Hiby et al. (2007)).

While the observed rate of increase is not an explicit parameter in the model, other parameters will be tuned in order to obtain this rate. To set a value for initial population size, we will use the count from 2003 of 16133 animals to generate three potential values $N_0 \in \{16133/(2 \times 0.8), 16133/(2 \times 0.7), 16133/(2 \times 0.6)\} = \{10083, 11524, 13444\}$. This corresponds to 80%, 70% and 60% of the population being counted out of which half are female.

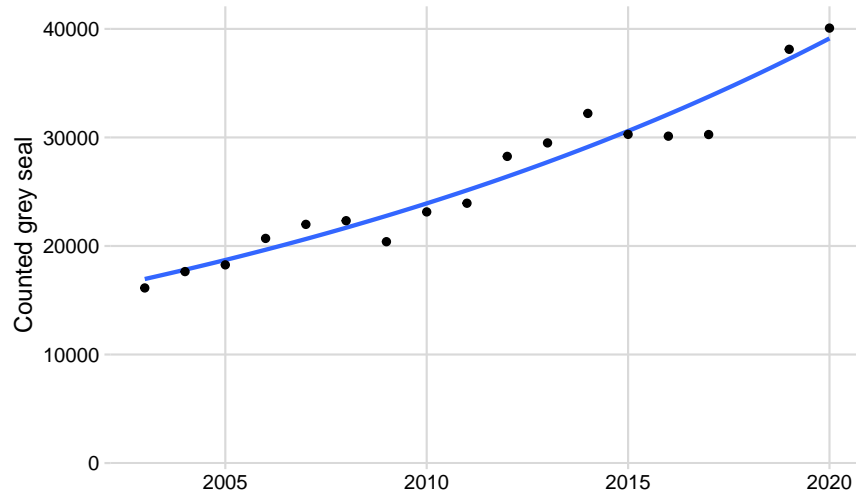


Figure 3: Grey seal counted in the annual moulting survey together with a log-linear fit.

Hunting

Hunting of grey seal in Swedish and Finnish waters has increased during the study period. Figure 4 shows the yearly number of shot grey seals reported to Swedish and Finnish authorities. Grey seals are also hunted in Estonian waters, but numbers are small in comparison.

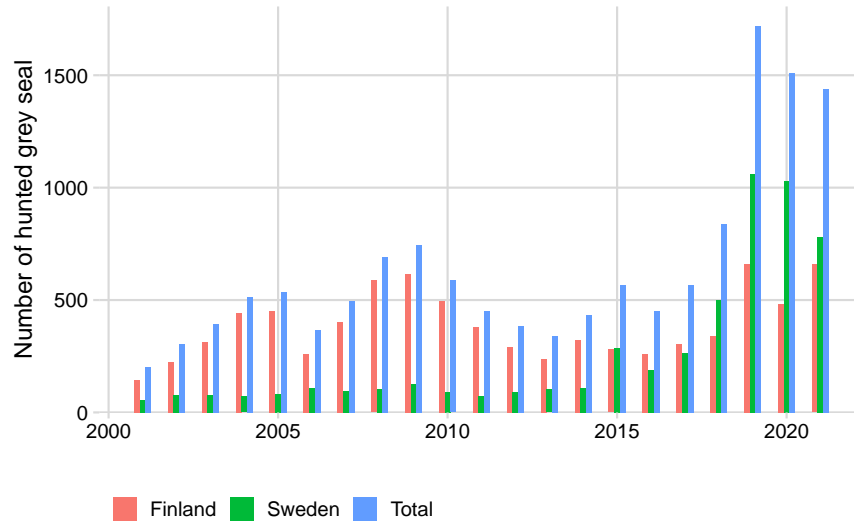


Figure 4: Yearly number of hunted grey seal reported to Swedish and Finnish authorities (year 2021 incomplete).

While hunters report sex and age-class (juvenile/adult) of shot animals when possible, we will use the more detailed data available for animals that are part of the indicator for nutritional status of seals (HELCOM (2018a)). In Figure 5 we show the age-structure of seals shot by Swedish and Finnish hunters, clearly a much higher proportion of pups are shot in Finland.

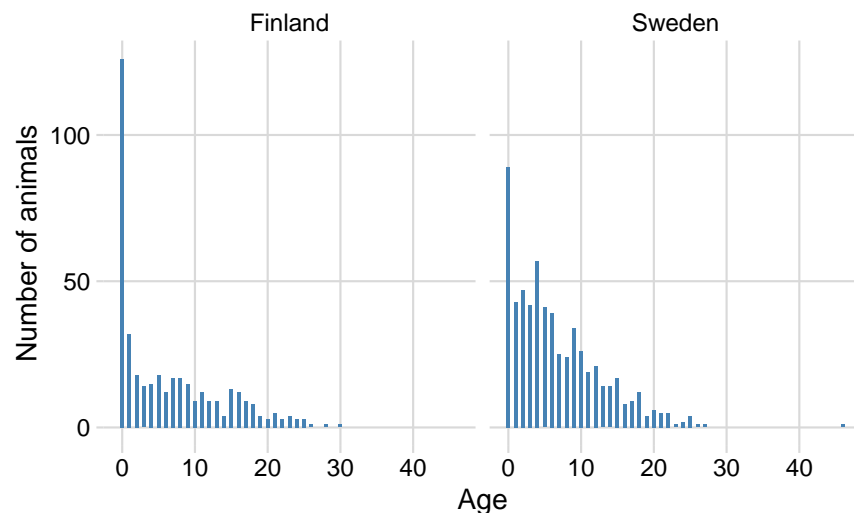


Figure 5: Number of female grey seals of different ages among hunted animals

To account for this, we will use country-wise age-structures and set $n_i^{\text{hunt}}(t) = c_{i,\text{fi}}^{\text{hunt}} n_{\text{fi}}^{\text{hunt}}(t) + c_{i,\text{se}}^{\text{hunt}} n_{\text{se}}^{\text{hunt}}(t)$, where $n_{\text{fi}}^{\text{hunt}}(t)$ and $n_{\text{se}}^{\text{hunt}}(t)$ denotes half the number of shot animals in the time-interval $(t - 1, t)$ in Finland

and Sweden respectively, and $c_{i,fi}^{\text{hunt}}$, $c_{i,se}^{\text{hunt}}$ the proportion of animals in age-class i derived from frequencies reported in Figure 5.

By-catches

Estimating annual numbers of by-catches, animals dying due to entrapment in fishing gear, is difficult. Lunneryd et al. (2005) estimate the number of grey seals by-caught in Swedish waters during 2001 to be 462, which could be as high as 10% of the population. Vanhatalo et al. (2014) estimate by-catches in the Baltic sea during 2012 to be about 2000 animals, which is closer to 5%. However, given the observed annual rate of increase of the population, such high proportions seem unlikely.

One explanation of the estimated high rates is that mainly unproductive sub-adult animals are by-caught. Indeed, among by-caught animals collected for analysis 54% are in the first ageclass (Figure 6).

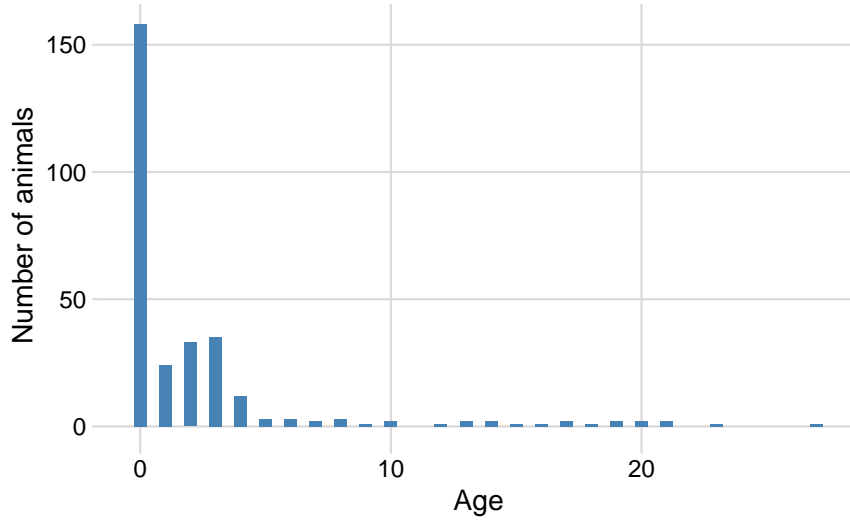


Figure 6: Number of female grey seals of different ages among by-caught animals

In order to obtain an estimate of bycatch rates, we note that $p_i^{\text{bycaught}} = p^{\text{bycaught}} \times c_i^{\text{bycaught}} / c_i^{\text{stable}}$, where p^{bycaught} denotes the proportion of by-caught animals in the population, c_i^{bycaught} denotes the proportion of age-class i individuals among bycaught animals (corresponding to frequencies in Figure 6) and c_i^{stable} the stable age-distribution of the population. Since the ratio $c_i^{\text{bycaught}} / c_i^{\text{stable}}$ is somewhat unstable given the limited number of by-caught animals in older age-classes, we divide it into three age-classes such that

$$c_i^{\text{bycaught}} / c_i^{\text{stable}} = \begin{cases} c_J^{\text{bycaught}} / c_J^{\text{stable}} & \text{if } i = 1, \\ c_{SA}^{\text{bycaught}} / c_{SA}^{\text{stable}} & \text{if } 1 < i < 6, \\ c_A^{\text{bycaught}} / c_A^{\text{stable}} & \text{if } i \geq 6, \end{cases}$$

where e.g. $c_{SA}^{\text{bycaught}} = c_2^{\text{bycaught}} + c_3^{\text{bycaught}} + c_4^{\text{bycaught}} + c_5^{\text{bycaught}}$, see Figure 7.

Summary of parameters

- Reproduction b_i , $i = 1, \dots, 46$. Based on fitting a logistic additive model to data from HELCOM (2018c) (Figure 1) and dividing by 2. Further, reproduction was set to zero for the first three age classes.

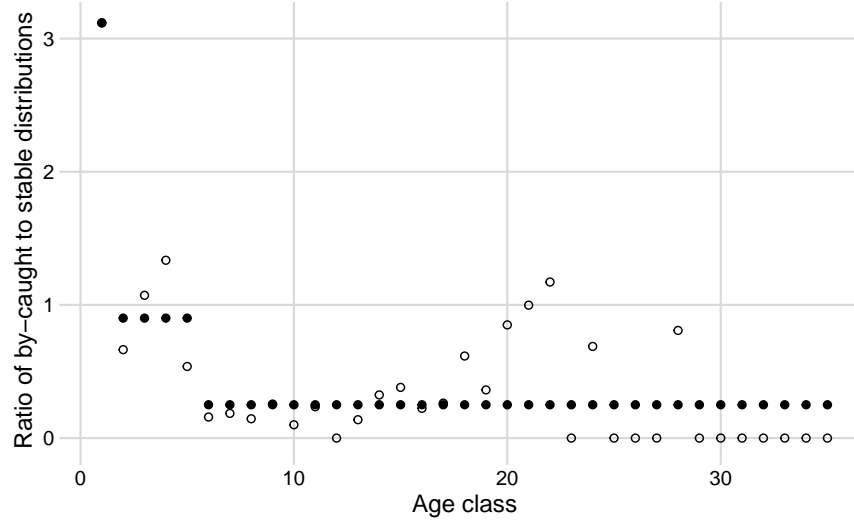


Figure 7: Fitted ratio $c_i^{\text{bycaught}}/c_i^{\text{stable}}$ as a piece-wise constant (filled circles) and individual values (circles). The probability of being by-caught is obtained by multiplication with p^{bycaught} .

- Adult survival was set constant for age-classes >1 . A range of values $s_2^{\text{undist}} = s_3^{\text{undist}} = \dots = s_{45}^{\text{undist}} \in [0.9, 0.95]$, $i > 1$, was tried and for each value juvenile survival s_1^{undist} was adjusted in order to obtain the observed rate of increase.
- Starting population N_0 was set based on half of the counts in 2003 adjusted by three potential values of proportion counted (80%, 70%, 60%) as $N_0 \in \{10083, 11524, 13444\}$. Starting age-distribution was set as the stable age-distribution in a model without explicit hunting, juvenile survival 0.73 and adult survival 0.85.
- By-catch probabilities p_i^{bycaught} were set as the product of population by-catch proportion p^{bycaught} and class-wise ratio of by-catch age frequencies and stable distributions as in Figure 7. Here, by-catch proportion was set to a range of values $p^{\text{bycaught}} \in \{0, 0.01, 0.02, 0.04, 0.05\}$.

Results and discussion

The model was fitted for a range of adult survival rates, proportion of counted individuals in the population survey and by-catch rates. For each set of parameters, juvenile survival was adjusted to fit the observed rate of increase 5.1%.

In Figure 8 (A) we show the population rates of increase of a hypothetical undisturbed population for the various scenarios examined, and in Figure 8 (B) the corresponding juvenile survival rates. Empty circles correspond to unrealistic combinations of adult and juvenile survival. Here values with juvenile survival greater than adult or juvenile survival lower than 0.73 obtained in the model where hunting and by-catches were included in the survival rate, are considered unrealistic.

In Figure 9, population trajectories are shown for a particular choice of fix parameters. Due to an increased hunting pressure since 2019 (Figure 4), the local rate of increase of the projected observed population has decreased λ (corresponding to approximately 4% and stable across scenarios).

We have fit an age-structured model of the abundance of the Baltic sea grey seal population during 2003-2021 in order to investigate effects of hunting and by-catches on the observed rate of increase of the population. In parametrising the model, we have utilized a range of data-sources, in particular reported ages of animals collected as part of Swedish and Finnish monitoring programmes. Hence, our results depend to some extent

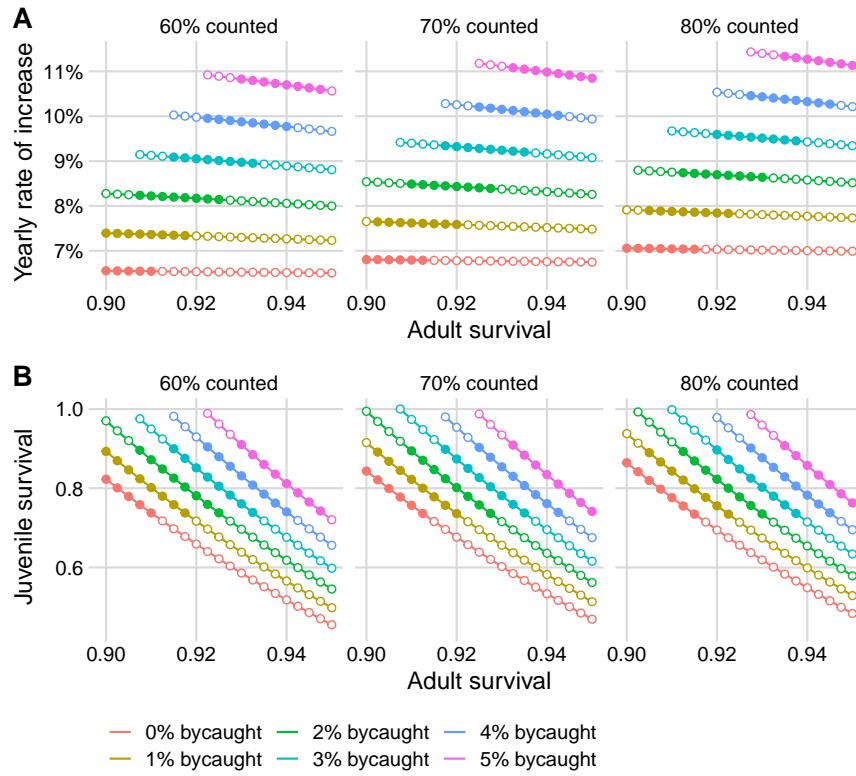


Figure 8: (A) Yearly rates of increase of the hypothetical undisturbed population $N^{\text{undist}}(t)$ under various scenarios and as a function of adult survival. (B) Fitted juvenile survival as a function of adult survival under various scenarios. In all frames, empty circles correspond to unrealistic combinations of adult and juvenile survival.

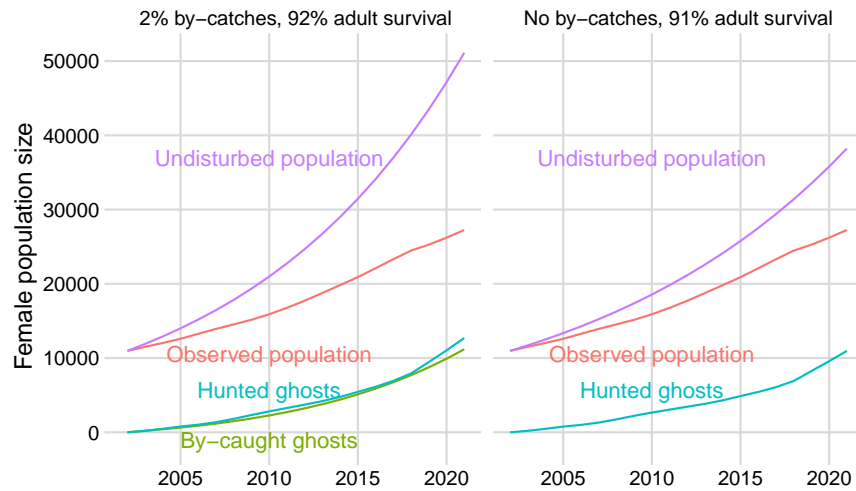


Figure 9: Population trajectories for two scenarios when 70% of animals are counted; 91% adult survival, and 2% by-catches, 92% adult survival no by-catches.

on how representative these are to the population. Further, we have not taken the geographical distribution of animals nor hunting pressure into account. While the grey seal is highly migratory and the Baltic sea population considered a single population, spatially uneven pressure may have influence on observed rates.

Due to lack of reliable data on by-caught animals, this was set as a fixed proportion of the population each year. In reality, the proportion may have decreased over the study period due to improvement in fishing gear. We note however that by-catch proportions of 5% or higher are unlikely, since they lead to rates of increase greater than 10% which is the expected rate of a healthy and undisturbed population (Harding et al. (2007)).

In all parameter combinations involving by-catches, the estimated yearly rate of increase is higher than the 7% required for GES as defined by HELCOM (2018b). This suggests that failure to reach GES can largely be attributed to anthropogenic removals in the form of hunting and by-catches.

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