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Possible impacts on the British grey seal population of deliberate killing related to salmon farming

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Summary

We develop a stochastic population dynamics model of the British grey seal population in which the population naturally grows at an exponential rate, but there is additional mortality associated with the protection of salmon farms cause an additive reduction in seal survival. We use two indices of salmon farming intensity to estimate this additional mortality and fit the resulting models to the observed 1984-2002 pup production data at a regional level.

The best fitting model relates seal mortality to salmon production in tonnes. Estimated anthropogenic mortality rates in recent years are highest in the Outer Hebrides (~6%, 95% CI ~2-11%), lower in the Inner Hebrides (~3%, 95%CI ~1-4%) and very low in the Orkneys (<1%, 95% CI 0-1%). These fits require that up to 4000 seals were shot each year in the Outer Hebrides, up to 570 in the Inner Hebrides, and up to 660 in Orkney. Re-running the model with known mortalitites in the Moray Firth included made little difference to the results.

We conclude that salmon farming activity alone can explain the observed pattern of pup production. However, the levels of unreported mortality required in the Outer Hebrides appear unfeasibly high.

Introduction

The aim of this paper is to determine whether the observed pattern of grey seal pup production at a regional level could be explained by deliberate killing of seals to protect salmon farms, and to estimate how many seals would have been killed if this was the case. We used a modified version of the stochastic population dynamics model used to estimate grey seal population size (Thomas and Harwood 2004) in which we assume that seal survival and fecundity are density independent. Survival rates of both pups and adults are reduced in proportion to two alternative indices of farming activity: annual salmon production in tonnes and total staff numbers. In addition, we consider a model in which the effect of a unit change in farming activity is assumed to be the same in all regions, and one in which the effect is different for each region. Finally, there are two different ways in which data on salmon farming can be related spatially to grey seal populations. In total, therefore, there are eight different combinations of data and model. We fitted these to regional pup production data for 1984-2002 using the particle filtering algorithm described in Thomas and Harwood (2004). Model fits were compared using mean posterior Akaike Information Criterion (MPAIC; see Thomas and Harwood 2003). Using the best model, we translate the mortality estimate into an estimate of the number of seals killed.

Data on salmon farming activity in the North Sea was not available separately from that on the west coast, so it was not possible to incorporate this in the model. However, data on actual estimates of the actual number of seals shot in the Moray Firth were available and we investigated the effects of incorporating this information in the model.

Material and Methods

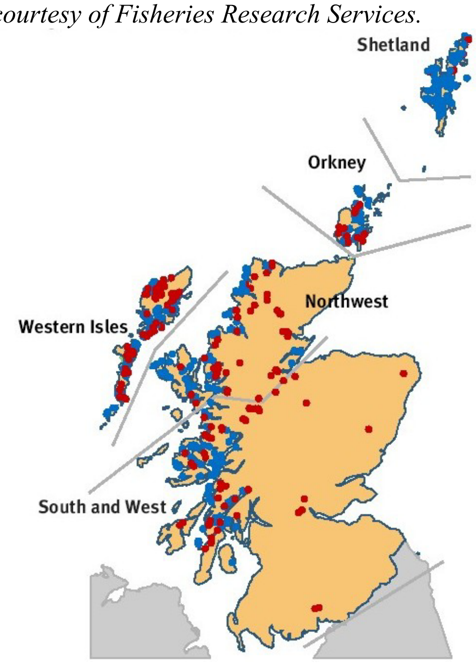
Data

We used pup production estimates for 1984-2002 (Duck 2003), aggregated at a regional level (North Sea, Inner Hebrides, Outer Hebrides and Orkney).

Salmon farming data by region are given in Stagg and Smith (2003) for 1994-2002 and Stagg and Gauld (1998) 1992-1994. Data for 1984-1992 are not available by region, but were provided at the national level by R.M. Smith (Fisheries Reserch Services Marine Lab, Aberdeen, pers. comm.). To estimate regional numbers, we calculated the proportion of the annual national salmon production and staff numbers in each region for 1992-1994, and pro-rated the 1984-1992 totals according to these proportions.

The regions used to summarise salmon production (Figure 1) do not coincide exactly with those used to designate grey seal colonies. The Orkney and Western Isles salmon regions are equivalent to the Orkney and Outer Hebrides seal regions, and the South and West salmon region is essentially equivalent to the Inner Hebrides seal region. However, seals from the Outer Hebrides are known to frequent the north west coast of the mainland, so we fitted one set of models in which Outer Hebrides seals were only affected by activity in the Western Isles salmon region, and another set in which they were affected by the Western Isles and the Northwest salmon regions combined.

Figure 1. Salmon production regions and locations of active smolt sites (in red, not used in analysis) and salmon sites (in blue). Figure courtesy of Fisheries Research Services.



The Northwest salmon region contains a majority of farms on the west coast, but it also contains three in the Moray Firth. The latter area is part of the North Sea seal region. Farming activity data for these three farms are not available separately, and we initially assumed that no North Sea seals were shot by salmon farmers. However, Butler (2004) has estimated the numbers of grey, common and unknown species of seal killed in the Moray Firth area for the period 1994-2002. We assumed that the proportion of the unknown seals that were grey seals was equal to the proportion of known seals that were grey seals. This produced the data in Table 1. These data were not used in the initial model runs, but the best-fitting model was re-run with these numbers as a form of sensitivity analysis.

Table 1. Estimated number of seals killed in Moray Firth 1994-2002.

Year	1994	1995	1996	1997	1998
Grey seals	136	132	132	128	137
Year	1999	2000	2001	2002	
Grey seals	192	181	234	110	

Models

We used a set of state-space models similar to the density independent model described by Thomas and Harwood (2004, model M_2). This assumes constant natural adult survival ϕ_a, pup survival ϕ_p and fecundity α. Without density dependence, there is no movement of recruiting females among regions. Additionally, we assumed that the anthropogenic rate of mortality is additive to natural mortality, that it is linearly related to salmon farming activity, and that it is the same for adults and pups. The number of adult seals surviving in a given year, *t*, is a binomial random variable with probabiltiy $\phi_a - \delta_r s_{r,t}$ where $s_{r,t}$ is the level of salmon farming activity (production or staff) in region *r* at time *t*, and δ_r is a model parameter equivalent to the level of additional seal mortality per unit of farming activity. Similarly, pup survival is a binomial random variable with probability $\phi_p - \delta_r s_{r,t}$.

We ran two different models. In the full model, we allowed the effect of a unit change in farming activity, δ_r, to vary by region. This model has 6 parameters: $\phi_a, \phi_p, \alpha, \delta_2, \delta_3$ and δ_4. Note that δ_1 cannot be estimated because we assume no farming activity in the North Sea region. We also ran a reduced model in which we assumed that effect of a unit change in farming activity was the same for all regions, i.e., $\delta_r = \delta$. This model has 4 parameters: ϕ_a, ϕ_p, α and δ.

Fitting method and priors
We used the algorithm described by Thomas and Harwood (2004), with measurement error CV fixed at 25%. We used 100 runs with 100,000 particles starting each run. This produced an effective sample size greater than 1000 in all cases.

Priors for the biological model parameters were the same as those used by Thomas and Harwood (2004). Prior distributions on the additional mortality parameters, $\underline{\delta}$, were specified as follows: (1) since the parameters are bounded $(0,+\infty)$ a gamma distribution was used; (2) the priors should be quite uninformative, so the standard deviations were set equal to the mean; (3) the upper 95th percentile of the prior distribution was set so that the decrease in mortality at the maximum value of farming activity (production or staff numbers) was 0.1.

Table 2. Prior parameter distributions

Parameter	Prior	Expected value
ϕ_a	Beta(22.05,1.15)	0.95
ϕ_p	Beta(14.53,6.23)	0.7
α	Beta(22.05,1.15)	0.95
δ [1]	Gamma(1,4x10^{-7}) Gamma(1,3.5x10^{-5})	4x10^{-7} 3.5x10^{-5}

[1] First row is for salmon production, second is for staff numbers

Comparison of models
To compare the models, we calculated the mean posterior Akaike Information Criterion (MPAIC) using the same method as Thomas and Harwood (2003). We also calculated Akaike weights (Burnham and Anderson 1998 p124), which can be thought of in this context as the posterior probability of each model being the best approximating model.

Results

Models where the salmon activity data for the Outer Hebrides seal region was made up of both Western Isles and Northwest salmon regions had consistently lower MPAIC values than those where just the Western Isles data was used (Table 3). The reduced model was preferred over the full model. Salmon production was preferred as a covariate over staff numbers when Western Isles and Northwest regions were combined. The best model, therefore, had one δ parameter, salmon production as the index of farming activity and combined the production data from the Western Isles and the Northwest.

Posterior parameter estimates for this model are shown in Figure 6, and estimated true pup production in Figure 7. The fit of the model to the data looks reasonable, except for Inner Hebrides where it has not fit the rapid increase and subsequent stabilization in pup production. The estimated mean adult survival rate (0.92) is rather lower than the prior (0.95), and the δ parameter is an order of magnitude higher.

Table 3. Mean posterior log-likelihood, AIC and Akaike weights. The model with lowest mean posterior AIC is highlighted.

Model	LnL	AIC	Akaike weight
Outer Hebrides = Western Isles			
Production, 1δ	-625.0	1258.0	0.02
Production, 3δs	-624.1	1260.2	0.01
Staff, 1δ	-624.5	1257.1	0.03
Staff, 3δs	-623.8	1259.5	0.01
Outer Hebrides = Western Isles + Northwest			
Production, 1δ	**-621.5**	**1250.9**	**0.67**
Production, 3δs	-621.9	1255.9	0.06
Staff, 1δ	-622.9	1253.8	0.16
Staff, 3δs	-622.9	1257.9	0.02

The estimated total population sizes, mortality rates (δ x salmon production) and anthropogenic mortality are shown in Figures 8-10. Highest mortality rates occur in the Outer Hebrides (6.7% in 2000, 95%CI 2.3-10.9%), and these also correspond with the highest absolute mortality (4100 seals in 2000, 95% CI 1,100-8,200). Estimated mortality rates are much lower in the Inner Hebrides and Orkney, peaking at 3.4% in 2001 (95% CI 0.5-4.4%) and 0.7% in 2002 (95% CI 0.2-1.2%) respectively. Estimated numbers shot peak at 570 (95% CI 160-1100) in the Inner Hebrides and 660 (95% CI 180-1300) in the Orkney..

Re-fitting this model including the known kills in the Moray Firth produced very similar results. Estimated mean posterior adult survival was slightly higher (0.93) as was δ (1.19 x 10^{-6}). The estimated population sizes in the Hebrides and Orkney regions in 2002 were 3-7% lower, but estimated mortality rates were 16% higher. As a result, the estimated absolute mortality in these regions was 7-13% higher. Estimates of population size were also lower in the North Sea region. The resulting estimates of mortality rates are shown in Table 4. The highest estimated mortality rate was 1.31, in 2001.

Table 4. Estimated additional mortality rate of seals in North Sea region, from the model with lowest mean posterior AIC, refit with known mortality of seals in the Moray Firth included. Figures in brackets are 95% confidence intervals.

Year	1994	1995	1996	1997	1998
Grey seals	1.06 (0.88-1.33)	0.98 (0.81-1.24)	0.94 (0.77-1.18)	0.86 (0.70-1.10)	0.87 (0.71-1.12)
Year	1999	2000	2001	2002	
Grey seals	1.17 (0.95-1.53)	1.05 (0.84-1.38)	1.31 (1.04-1.73)	0.58 (0.46 0.78)	

Discussion

Increases in salmon production coincided with a stabilization in the pup production estimates, particularly in the Outer Hebrides. However, our analysis shows that, in the absence of any density dependence, a very large number of seals would have to be shot to achieve this. It seems unlikely that the shooting of 4000 seals per year in the Outer Hebrides could have gone undetected.

In order to perform these analyses we had to fix the CV of the pup production estimates at 25%, following Thomas and Harwood (2004). This weakened our ability to discriminate among the models and widened the confidence limits on our estimates of population size, mortality rates and absolute mortality. Use of other model selection criteria such as Bayes Factors (Carlin and Louis 2000) or the Deviance Information Criterion (Spiegelhalter et al. 2002), may result in a different model being selected as preferable. Multi-model inference could also be used (Burnham and Anderson 1998).

We assumed that the seal mortality **rate** was affected by salmon farming activity, implying that for a given level of activity larger seal populations result in a higher absolute level of mortality. However, an alternative model would have been to assume that salmon farming activity affected the actual number of seals killed..

References

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Figure 2. Annual production of salmon (tonnes) in the four grey seal regions. "Outer Hebrides" is based only on data from the Western Isles salmon production region.

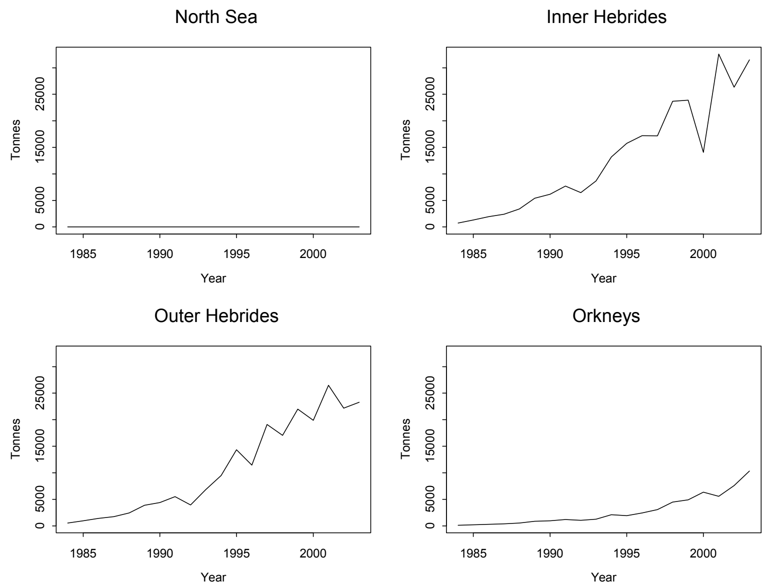

Figure 3. Annual production of salmon (tonnes) in the four grey seal regions. "Outer Hebrides" values are based on data from the Northwest and Western Isles salmon production region.

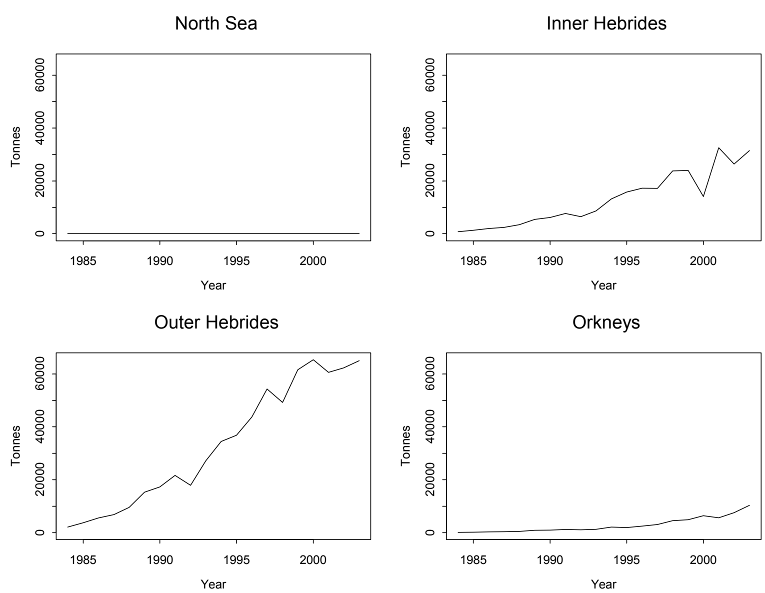

Figure 4. Annual staff numbers (full time + part time) in the four grey seal regions. OuterHebrides figures are based only on data from the Western Isles salmon production region.

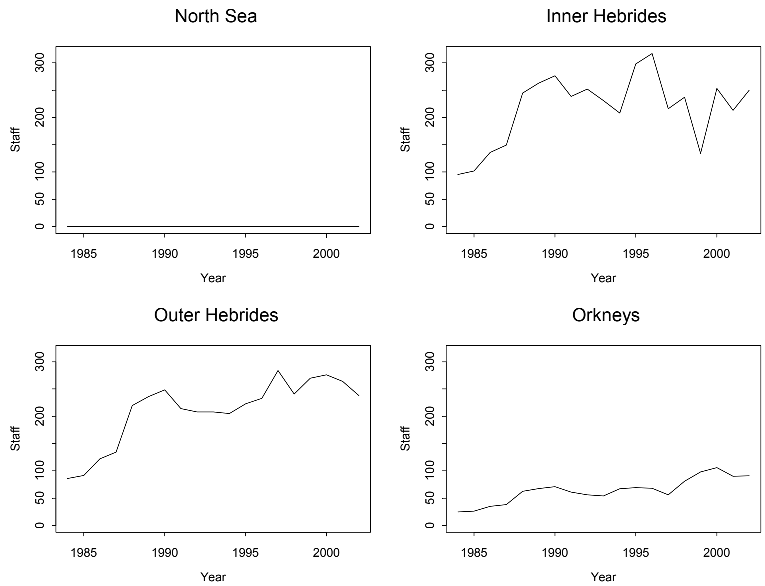

Figure 5. Annual staff numbers (full time + part time) in the four grey seal regions. "Outer Hebrides" figures are based on data from the Northwest and Western Isles salmon production region.

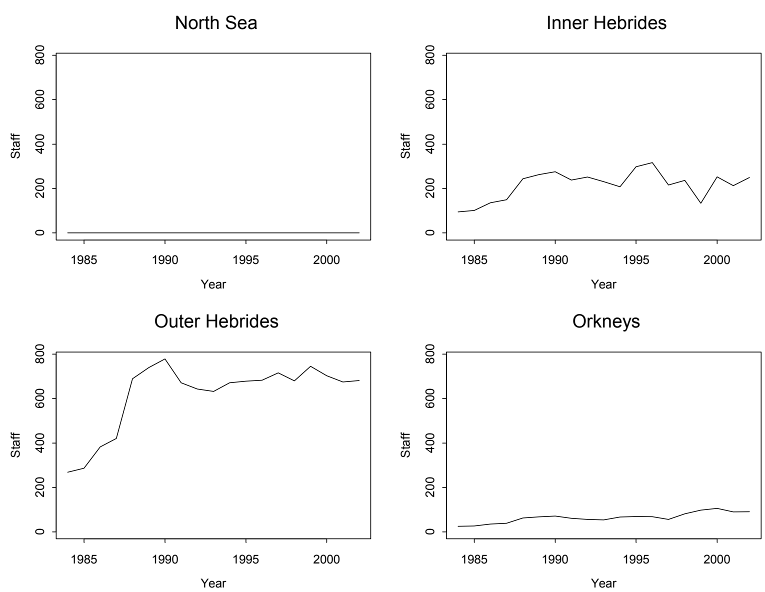

Figure 6. Posterior parameter estimates (histograms) and priors (solid lines) from the model with lowest mean posterior AIC: that with one δ parameter, salmon productivity as the index of farming activity and combined the productivity data from western isles and northwest. The vertical line shows the posterior mean, and its value is given in the title of each plot after the parameter name.

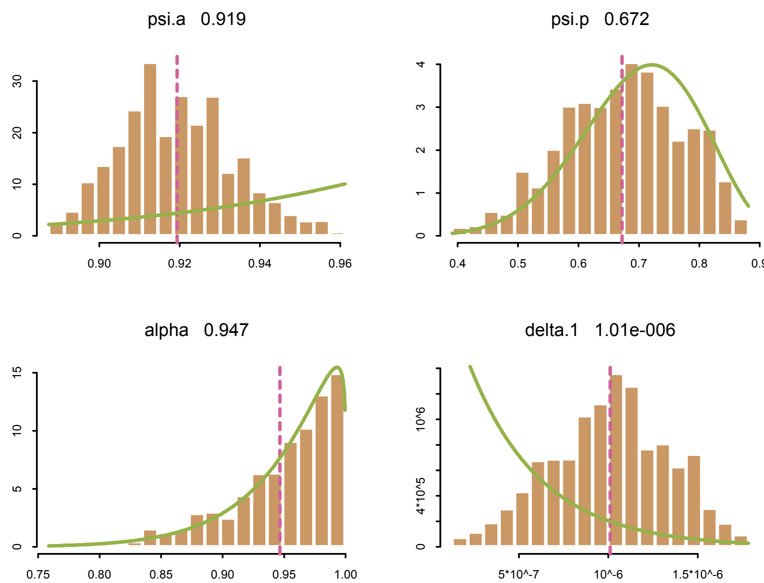

Figure 7. Estimates of pup production from the model with lowest mean posterior AIC. Input data are shown as circles, while the lines show the weighted mean of the particle values, bracketed by 2.5th and 97.5th percentiles.

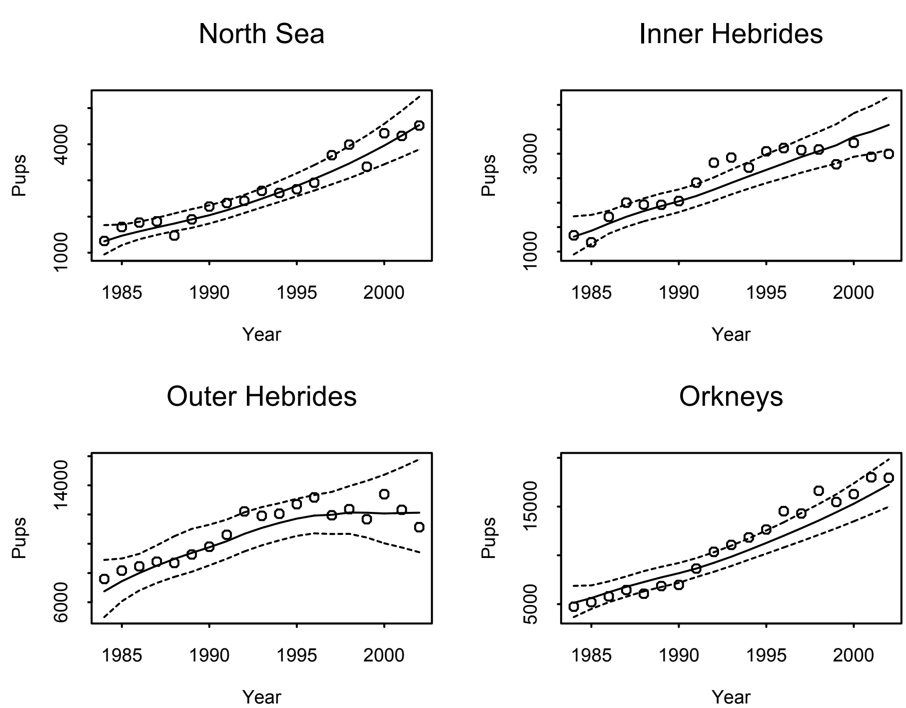

Figure 8. Estimated total population size (adults and pups) after the breeding season from the model with the lowest mean posterior AIC.

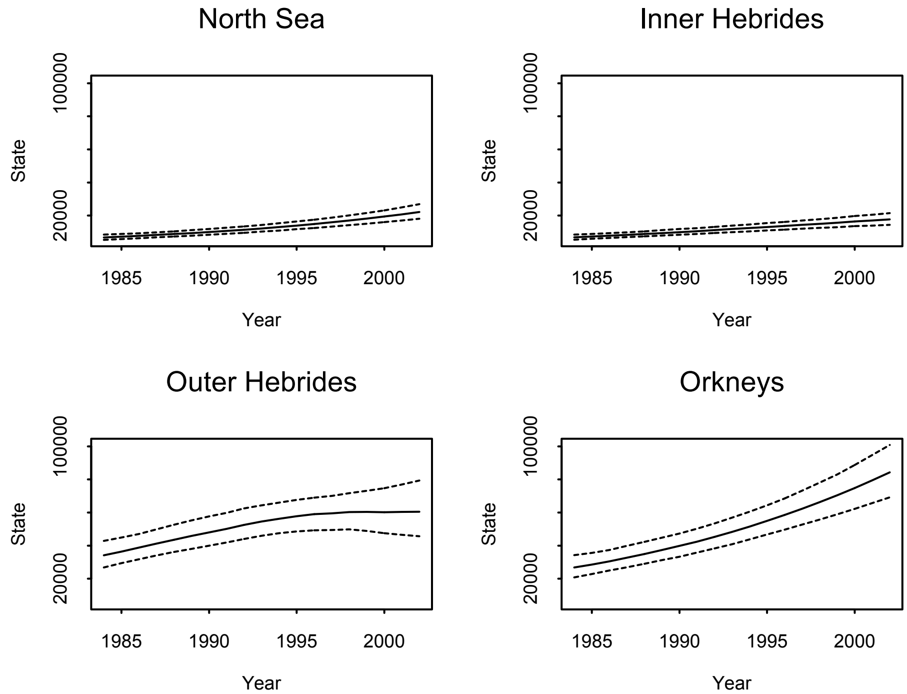

Figure 9. Estimated mortality rate from the model with the lowest mean posterior AIC.

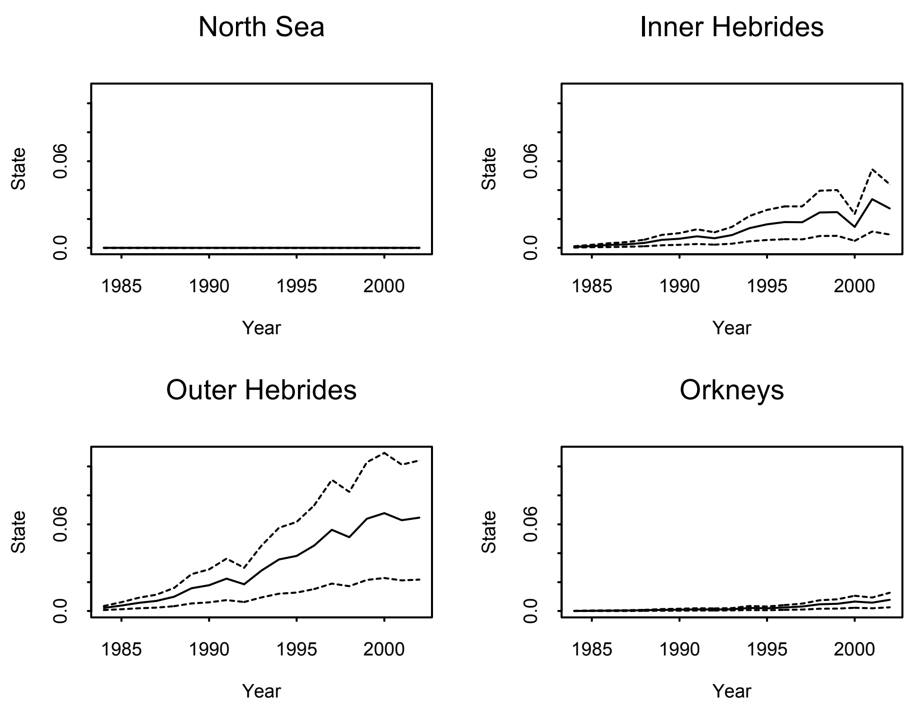

Figure 10. Estimated anthropogenic mortality(adults and pups) from the model with lowest mean posterior AIC.

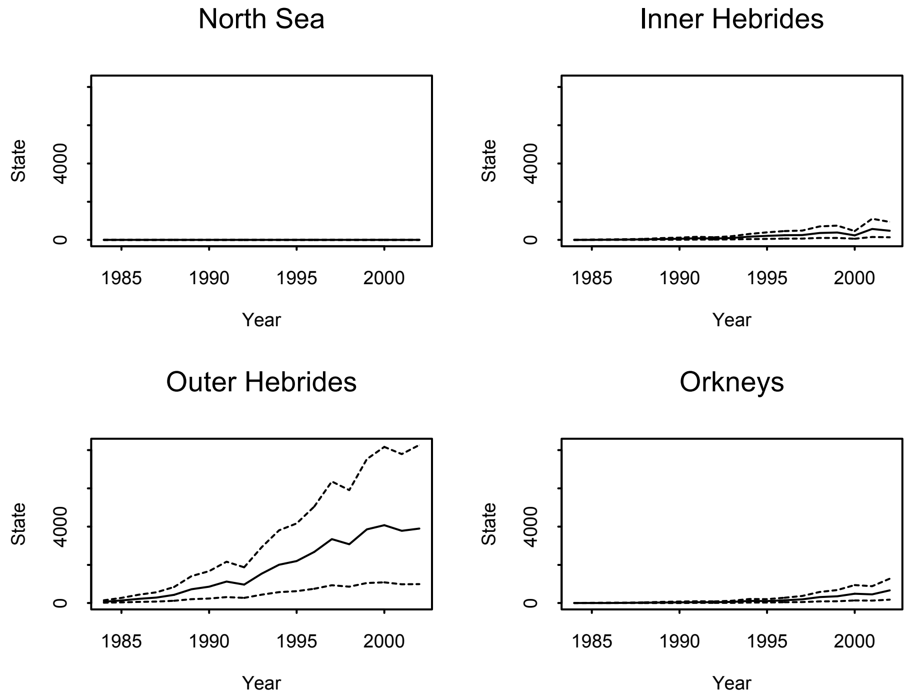

Figure 11. Estimates of pup production from the model with lowest mean posterior AIC, refit with known mortality of seals in the Moray Firth included. Input data are shown as circles, while the lines show the weighted mean of the particle values, bracketed by 2.5th and 97.5th percentiles.