Marine Mammal Scientific Support Research Programme MMSS/002/15

Harbour Seal Decline HSD2

Annual Report

Harbour seal decline – vital rates and drivers

Sea Mammal Research Unit
Report to
Marine Scotland, Scottish Government

April 2019

V1.1

Arso Civil, M[1]., Langley, I.[1], Law, A.[1], Hague, E.[1], Jacobson, E.[2], Thomas, L.[2], Smout, S.C.[1], Hewitt, R.[3], Duck, C.[1], Morris, C.[1] , Brownlow, A.[4], Davison, N.[4], Doeschate, M.[4], McConnell, B.[1], and Hall, A.J.[1]

[1]Sea Mammal Research Unit, Scottish Oceans Institute, University of St Andrews, St Andrews, Fife, KY16 8LB.

[2] Centre for Research into Ecological and Environmental Modelling (CREEM), University of St Andrews, St Andrews KY169LZ.

[3] Institute of Biological and Environmental Science, University of Aberdeen, Lighthouse Field Station, Cromarty IV11 8YL.

[4] Scottish Marine Animal Stranding Scheme, SAC Veterinary Services Drummondhill, Stratherrick Road, Inverness, IV2 4JZ.

Editorial Trail			
Main Author	**Comments**	**Version**	**Date**
M. Arso Civil	Author	V1	10/04/2019
A. Hall	Author	V1	18/04/2019
B. McConnell	Author	V1	23/04/2019
A. Hall	Reviewer	V1.1	29/04/2019

Dedication

This report is dedicated to the memory of naturalist Andy Law, who meticulously collected all the photo-ID data from the Isle of Skye. He will be sorely missed.

Citation of report

Arso Civil, M., Langley, I., Law, A., Hague, E., Jacobson, E., Thomas, L., Smout, S.C., Hewitt, R., Duck, C., Morris, C., Brownlow, A., Davison, N., Doeschate, M., McConnell, B., and Hall, A.J. 2019. *Harbour Seal Decline – vital rates and drivers. Report to Scottish Government HSD2*. Sea Mammal Research Unit, University of St Andrews, pp. 46.

Executive Summary

Numbers of harbour seals (*Phoca vitulina*) have dramatically declined in several regions of the north and east of Scotland, while numbers have remained stable or increased in regions on the west coast. For any management and mitigation plans to address this situation, the relative contribution of various factors in the decline of harbour seals in Scotland need to be identified, understood and assessed. Potential drivers of the decline include changes in prey quality and/or availability, increasing grey seal population size which may be influencing harbour seal populations through direct predation or competition for prey resources, and the occurrence and exposure of seals to toxins from harmful algae (domoic acid and saxitoxins).

Integrated population model

In Year 4, efforts towards developing an integrated harbour seal population model included review and expert elicitation of plausible ranges for harbour seal vital rates, simulation of population trends with different sets of vital rates, and analysis of population sensitivity to changes in individual vital rates. Through the expert elicitation process, participants decided on consensus distributions that reflected the availability and uncertainty of published estimates of vital rates for harbour seals. The simulation exercise demonstrated that the population is sensitive to changes in adult survival, and that a decrease in adult survival is required to explain a decline of the magnitude observed at sites like Scapa Flow, Orkney. The next step will be to incorporate photographic mark-recapture data and environmental covariates into the integrated population model framework.

Photo-identification mark-recapture to estimate fecundity and survival

Photo-identification data were collected at selected harbour seal haulout sites in Orkney, Kintyre and Loch Dunvegan (Isle of Skye) during the pupping seasons of 2016, 2017 and 2018, primarily during the months of June and July. To build individual sighting and reproductive histories, which will be then used to estimate fecundity and survival rates, all photographs are first graded for photographic quality, and then individual seals are identified from the unique patterns on their pelage. Photo-identification data collected in 2018 are currently being processed. For 2016 and 2017, a summary of all catalogued seals by area with details of estimated age class and reproductive history is provided. The total number of seals identified in each area and year ranged between 155 and 550 seals, with Isle of Skye having the largest numbers, both for adults and pups. There was a consistency in the proportion of females seen with a pup and/or pregnant between years in each area. However, these proportions should not be interpreted as fecundity rates. The re-sighting rates of adult females that had pupped in 2016 were high in all three areas (range 77.8 % to 88.5%), and 59.0% to 61.1% of these females were seen again with a new pup in 2017.

Live capture-release studies

Pregnancy rates: Further analysis of the proportion of live captured females that were pregnant in each region was carried out. A proportion of the sampled females (n=23) were subsequently observed during the photo-ID fieldwork in Orkney and the Moray Firth. This provided a training dataset of animals observed pregnant or with a pup. Combining these observations with the pregnancy hormone, progesterone, concentrations in the blood and blubber for these animals resulted in a probability estimate of the proportion of pregnant females in each region. There was no difference in the percentage of animals that, according to their hormone levels, had a >60% probability of pupping among the different regions, despite a lower percentage in Orkney compared to elsewhere (Moray Firth 83%, Pentland Firth 88%, Skye 83%, Orkney 69%). This was largely due to the small sample sizes and the degree of regional variability. However, comparing these results with the regional fecundity estimates may indicate if reproduction is indeed lower in the regions of decline.

Nutritional stress indicators: Serum and plasma samples were analysed for selected clinical chemistry parameters to determine nutritional condition. A principal component analysis (PCA) was used to investigate whether there were any differences between the samples collected from the animals on Isle of Skye compared to Orkney. The variability in the data was much greater for Orkney than for Isle of Skye but the values were all within what would be considered clinically normal for this species. Thus, from these data there was no evidence that the captured seals are experiencing nutritional stress or were malnourished.

Toxins in prey and live captured seals

Toxins from harmful algal blooms continue to be found in the urine of harbour seals. Low levels of domoic acid were measured in live captured animals. However, these levels probably underestimate the peak levels

that individuals would have been potentially exposed to during feeding bouts, due to the short half-life of domoic acid and the time elapsed between feeding and sampling. Work is currently underway to estimate peak exposure.

The role of toxins in harbour seal health may also be inferred by measuring their levels in prey items. Samples of fish prey of various species found in the diet of harbour seals in two of the study areas, Scapa Flow in Orkney and Loch Dunvegan on Isle of Skye, were obtained. Concentrations of domoic acid were low in all species although all fish were sampled outside a toxic bloom event period. To better understand how the toxin levels in prey relate to the domoic acid levels found in urine and faeces, estimated domoic acid ingestion rates were compared to toxic thresholds. Results showed that up to 6% of adults and 31% of juveniles could be consuming levels high enough to affect kidney and reproductive function. However, all were below any lethal thresholds. If possible, further samples will be collected during bloom events in these regions.

During the fish-sampling fieldwork at sea, opportunity was taken to evaluate different methods to characterise prey presence at a selection of the putative seal feeding areas, inferred from telemetry movement data. The methods included sonar logs and baited camera traps. In addition, the species of fish caught at each sampling location also served as a (biased) proxy of species presence. This evaluation is on-going.

Counts of harbour seals during the moult

Aerial surveys of harbour seal numbers hauled out during the moult were conducted in the study sites of Kintyre, Scapa Flow (Orkney) and Loch Dunvegan (Isle of Skye) in August 2015, 2016 and 2017, respectively, as part of the annual surveys conducted by SMRU (funded by Scottish Natural Heritage (SNH) and Natural Environment Research Council (NERC)). Results on the number of harbour (and grey) seals counted within the defined study areas are presented and the population trends have not changed (stable in Kintyre and Skye, declining in Orkney). The Kintyre area was also surveyed in 2018; photographs taken and resulting counts are currently being processed.

Stranded seals

A summary of all seal carcasses reported to Scottish Marine Animal Stranding Scheme (SMASS) within and nearby the study sites between March 2018 and March 2019 is provided, with details on species, age class and proximate cause of death when available. A total of 162 seal carcasses were reported in this period, mostly reported in Orkney (n=133). These included 123 grey seals, 19 harbour seals, and 20 seals for which species could not be determined. Post-mortem examination could only be conducted for one carcass, as the others were not in good condition or could not be recovered. Proximal cause of death was determined for 26 seals from observations, 25 of which were possible cases of grey seal attack, including three harbour seals, 21 grey seals (mostly weaned pups) and 1 seal of unknown species.

Contents

Introduction

The UK has around 30% of Europe's harbour seals (*Phoca vitulina*), with Scotland having approximately 79% of the UK harbour seal population. The majority are distributed around the west coast and throughout the Inner and Outer Hebrides and Northern Isles. On the east coast, their distribution is more restricted with the main concentration now being in the Moray Firth (SCOS, 2017).

Harbour seals are listed under Annex II of the EU Habitats Directive, requiring specific areas to be designated as Special Areas of Conservation (SACs) for their protection. In Scotland, eight SACs have been designated specifically for harbour seals, with one additional site where harbour seals are a 'feature of qualifying interest'. In addition, it is an offence to intentionally or recklessly harass seals at any of the 194 haul-out sites that have been designated around the Scottish coast, of which 62 are used mainly by harbour seals and 67 shared by harbour and grey seals.

The Sea Mammal Research Unit (SMRU) has been conducting surveys to monitor the populations of harbour seals on an approximately five-year cycle since the late 1980s. These surveys detected a decline in Scottish harbour seals in the early 2000s (Lonergan et al., 2007; Thompson et al., In Press), which has continued in some of the surveyed regions. The decline is more apparent for the east and north coasts of Scotland and in the Northern Isles, with declines of around 52% along the east coast of Scotland, 85% in Orkney and 30% in Shetland (although the latter has increased by 10% between 2009 and 2015), compared to counts in 2000. In contrast, populations on the west coast and in the Western Isles are either stable or increasing (SCOS, 2017). More importantly, the decline in seal counts represents real reductions in the numbers present in those regions rather than being a consequence of changes in seal behaviour (e.g. changes in the proportion of time seals spend onshore during the moult) (Lonergan et al., 2013).

To determine the management and mitigation options to address this situation, the relative contribution of various factors potentially involved in the dramatic decline needs to be identified, understood and assessed. Potential drivers include changes in prey quality and/or availability, increasing grey seal population size which may be influencing harbour seal populations through direct predation or competition for resources, and the occurrence and exposure of seals to toxins from harmful algae. Irrespective of the factor or factors driving the decline, changes observed at the population level must originate from changes in vital rates (i.e. survival and fecundity rates). Consequently, it is fundamental to obtain information on such life history parameters from long-term studies (e.g. Bowen et al., 2003) in regions with contrasting seal population trajectories (declining compared to stable or increasing populations). At present, life history information for harbour seals in Scotland is available only from Loch Fleet and the Moray Firth (Cordes and Thompson, 2014; Mackey et al., 2008), but is completely lacking for other regions in Scotland. Survival and fecundity rates can be estimated from photographic capture histories of harbour seals, individually identified from their distinct and unique pelage patterns. Recognising differences in such population parameters and their drivers between regions of contrasting population trajectories will allow the determination of how and where the potentially important factors are acting.

In complex ecosystems, populations may experience pressure from multiple causes (e.g. food shortage, predation, toxin exposure and anthropogenic mortality). However, it is often difficult to estimate the likely impacts of stressors even where these are known to be at work in a population (e.g. observations of biotoxin exposure in individual animals, observations of carcasses showing signs of trauma). Causes of mortality or poor condition may impact different parts of the population in different ways (e.g. young or pregnant animals might be especially vulnerable to nutritional stress). Also, for long-lived animals such as harbour seals, considerable time lags may also be seen between cause and consequence in terms of population numbers. Consequently, the outcomes of combined effects at the level of population abundance may be difficult to predict intuitively. However, a structured population model allows for the explicit modelling of such impacts, integrating the effects of stressors that may be acting in combination, and allowing for the prediction of longer-term, population-level outcomes.

Matthiopoulos et al. (2014) developed and fitted an age-structured population model to data from the well-studied sub-population of harbour seals in Loch Fleet (Moray Firth) to evaluate the contributions of different proximate causes to the observed decline. Further work by Caillat et al. (In Press) and Caillat and Smout (2015) saw improvements to this baseline model, including an improved treatment of seasonal haul out probabilities, to produce a more realistic and robust version. This will be the baseline model for the current task HSD2 under the Marine Mammal Scientific Support Research Programme MMSS/02/15.

Harbour Seal Decline HSD2

A summary of the work carried out by the SMRU under the Marine Mammal Scientific Support Research Programme MMSS/02/15 during the year April 2018 to March 2019 for the task HSD 2 *Harbour seal decline – vital rates and drivers* under the theme Harbour Seal Decline is presented here.

This task has five main objectives:

- an improved understanding of the population dynamics of harbour seals;
- new estimates of harbour seal vital rates;
- an improved understanding of spatial overlap between grey and harbour seals;
- an improved understanding of the main (potential) extrinsic factors driving survival and reproduction and therefore population change;
- an improved understanding of the effects of predation by grey seals.

It comprises six 'approaches' entitled:

1. integrated population model;
2. investigate harbour seal vital rates and movements using capture-mark-recapture and telemetry;
3. live capture-release at the photo-ID study sites;
4. counts of harbour and grey seals at and adjacent to the study sites from air surveys;
5. improving understanding of potential drivers of population change;
6. carcass collection.

The deliverables for Year 4 under each approach are detailed in Appendix 1.

Approach 1. Integrated population model

2.1 Methods

2.1.1 Vital rates review

Informative priors on population demographic parameters (e.g. survival and fecundity rates) can be used to restrict parameter ranges and to suggest to a population dynamics model the values considered to be most likely. Because informative priors can impact model results, it is important that they are used carefully. We expect the photographic capture-recapture data collected as part of Approach 2 to inform site-specific estimates of current (2016-2019) adult male survival, adult female survival, and fecundity within the integrated population model (IPM). However, these studies cannot provide information on pup survival, juvenile survival, or on historical (pre-2016) adult survival or fecundity. One advantage of using a Bayesian modelling framework is that results from previous studies can be included as informative priors in the model.

In order to review and agree the form of priors to use for vital rates, an expert elicitation was conducted using a modified version of the Sheffield Elicitation Framework (SHELF; Gosling, 2018) to construct defensible informative priors for vital rates of harbour seals. First, a Google Scholar search for published estimates of harbour seal survival and fecundity was done using search terms including “Phoca vitulina”, “vital rates”, “survival”, “fecundity”, “demography”, etc. and colleagues were asked if they knew of any reports or other grey literature on the topic. For each study, the location, study type, time period, population trend, and any other information that might be relevant to interpreting the results were noted. Estimates of survival and fecundity were compiled into annotated tables and figures and circulated as a briefing paper to a panel of 11 scientists with expertise in harbour seal biology and population modelling.

In preparation for the exercise, participants were asked to complete an online training in expert elicitation (SMRU Consulting, 2018). They were then asked to use a combination of information contained in the briefing paper and their own expertise to provide their best judgement of the lower limit, upper limit, median, and 25th and 75th quantiles of the true values of pup survival, juvenile survival, adult male survival, adult female survival, and fecundity that would be applicable to populations in Scotland that were stable or slightly increasing (+0-5% per year). To assist in this process, experts were given a distribution visualization tool (Oakley, 2018) and R code to simulate and visualize harbour seal population trajectories with different vital rates.

Experts provided independent judgements of quantities of interest for each vital rate. Their judgements were translated to beta distributions using the R package SHELF (Oakley, 2018). A linear average of expert judgements was calculated; then, a composite beta distribution was fitted to this linear average. This composite distribution was superimposed on the individual experts’ distributions and quantities of interest (lower limit, upper limit, median, and 25th and 75th quantiles) were calculated. A meeting was convened to review the elicitation results. In the meeting, experts discussed the individual and composite distributions in the context of the literature and justified their choices. In some cases, experts were unsatisfied with the resulting composite distribution; in these cases the distributions were altered slightly to better represent consensus opinion. After the meeting, composite distributions were finalized for use as informative priors in the Bayesian population model.

2.1.2 Simulation study

The ultimate cause or causes of the observed decline in harbour seals at Scapa Flow (Orkney) and in other areas of Scotland are not known. The population modelling approach cannot provide direct evidence for any hypothesized cause of decline. However, simulation exercises can identify which vital rates are likely driving the observed decline and support further investigations of hypotheses that align with the supported changes in vital rates. This process may help to exclude certain hypotheses.

First, possible causes of decline in harbour seals in Scotland were reviewed to identify the expected demographic signature of each cause. A workshop previously identified possible causes of the observed declines in harbour seal populations (Hall and Kershaw, 2012). The four possible causes of observed declines that were scored as high priority for further research were 1) lack of available prey; 2) environmental variability; 3) competition with grey seals; and 4) corkscrew trauma. Several other possible causes, including biotoxins and deliberate killing, were listed as being of medium research priority. These possible causes are not necessarily independent; for example, environmental variation may be driving a lack of available prey. For each possible mechanism, experts listed vital rates that would be impacted by that mechanism. To motivate simulation exercises, the possible mechanisms were grouped into three categories (Table 1):

- **Reduced quality or quantity of prey due to environmental variation or indirect competition with grey seals.** This would be expected to decrease survival across age classes, but possibly particularly pups and juveniles who have not established successful foraging strategies. At the extreme, fecundity may decrease if nutritional stress causes adult females to abort foetuses.
- **Biotoxins or exposure to contaminants**. Even at non-lethal doses, exposure could decrease survival through e.g. immunosuppression. This would be expected to affect all age classes. Depending on the type and amount of toxin, fecundity may also be reduced.
- **Predation and trauma.** In this scenario, individuals in the population would be expected to be healthy. If killer whales were the predators, pup survival may be most impacted because they might target pupping beaches. Predation would not impact fecundity.

Table 1. Hypothesized drivers of harbour seal decline (rows) and their expected effects on vital rates (columns). Numbers indicate the order in which vital rates are expected to be affected for each hypothesis, from first (1) to last (4).

Hypothesis	**Vital Rates Affected**			
	Fecundity	Pup Survival	Juvenile Survival	Adult Survival
Prey Quality/Quantity	3	1	2	4
Biotoxins/Contaminants	2	1	1	1
Predation/Trauma	NA	1	2	2

To investigate the effects of changes (reductions) in vital rates on the population trajectory, different scenarios were simulated using a population model. The model is based around an age- and sex-segregated Leslie matrix model (Caswell, 2001; Leslie, 1945; Leslie, 1948), with five life stages: pup age 0, juveniles age 1, 2, 3, and adults age 4+. Only adult survival rates are sex-specific. The median vital rates from the expert elicitation process (Table 2) were used as defaults in this model. The simulation model also included an observational component, where, following Matthiopoulos et al. (2014) and Caillat et al. (In Press), the proportion of animals hauled out during the moult is assumed to be 0.1 for pups, 0.5 for juveniles and adult females, and 0.6 for adult males. The simulated population is designed to be like that of Scapa Flow (Orkney), with a starting population size of 4500 animals, and a timespan of 35 years.

The sensitivity of the simulated population to changes in different vital rates was investigated. First, the simulation was run with default vital rates and compared the expected number of animals hauled out to the observed counts at Scapa Flow. Then, for each vital rate, reductions in that vital rate were simulated beginning at year 15 of the simulation run (coinciding with the time when the decline in harbour seal numbers was first detected (SCOS, 2017)), with all other vital rates remaining constant. The expected number of hauled out individuals were then compared to the observed number of hauled out individuals during aerial survey moult counts. The goal of this exercise was to identify, for each vital rate, the magnitude of reduction required to produce the observed decline in counts of hauled out animals. These results were then considered in the context of Table 1.

2.1.3 Implementation

All data manipulation, statistical analyses, and figure generation were conducted in R (v.3.5.2; R Core Team, 2018). Packages *dplyr* (Wickham et al., 2017), *lubridate* (Grolemund and Wickham, 2011), *magrittr* (Bache and Wickham, 2014), *readxl* (Wickham and Bryan, 2019), *tibble* (Müller and Wickham, 2019) and *tidyr* (Wickham and Henry, 2019) were used for data manipulation. Plots were generated with *ggplot2* (Wickham, 2016).

2.2 Results

2.2.1 Vital rates review

Through the elicitation process, the experts were able to consider different published estimates in context and decide on the most plausible limits and distributions for the true values (Table 2). The consensus distributions reflected the availability of published estimates and uncertainty associated with those estimates, as well as the expertise of the panel members. Because the experts decided that the limits for the vital rates should be other than 0 and 1, beta distributions were used, scaled within lower and upper limits to represent the consensus distributions.

Table 2. Description of composite distributions resulting from the expert elicitation process. Quantities of interest (LL: lower limit, Q25: 25th quantile, Q50: median, Q75: 75th quantile, UL: upper limit) and shape parameters for beta distributions scaled within lower and upper limits to be used as informative priors for pup survival, juvenile survival, adult male survival, adult female survival, and fecundity.

	Quantities of Interest					Beta Parameters	
	LL	Q25	Q50	Q75	UL	Shape 1	Shape 2
Pup Survival	0.08	0.25	0.35	0.5	0.75	1.47	1.91
Juvenile Survival	0.65	0.75	0.8	0.85	0.95	2.16	2.16
Adult Male Survival	0.75	0.85	0.89	0.92	0.98	2.91	2.04
Adult Female Survival	0.85	0.92	0.94	0.96	1	3.76	2.58
Fecundity	0.5	0.84	0.88	0.92	0.98	7.13	2.05

2.2.2 Simulation study

A population of harbour seals was first simulated over a 35-yr period with constant vital rates equal to the median values from the expert elicitation (Figure 1). The expected number of hauled out animals was close to the observed for the first ~15 years of the study, but the low counts between years 20-30 were not consistent with the simulated population trajectory.

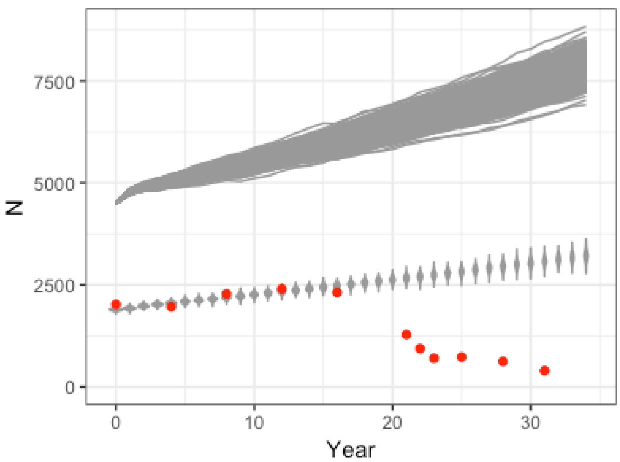

Figure 1. Population trajectories and expected counts for 1000 simulations with baseline vital rates (medians from the expert elicitation process shown in Table 2). The grey lines indicate the simulated population size. The grey violin plots show the expected number of hauled out individuals in the population and the red dots show the observed number of hauled out individuals during the aerial survey count.

Then reductions in vital rates were simulated, beginning in year 15, approximately when the observed population counts began to decrease rather than increase. The simulation was not sensitive to reductions in pup survival, juvenile survival, or fecundity (Figure 2 A-C). Decreasing pup survival, juvenile survival, or fecundity from year 15 onwards caused the simulated population to decline, but the magnitude of the decline was not consistent with the low observed counts between years 20 and 30. Even a 100% reduction in these parameters beginning at year 15 would be insufficient to explain the observed decrease in the population. However, the simulation was very sensitive to decreases in adult (male and female) survival (Figure 2 D). A 10-11% reduction in adult survival from year 15 onwards would be sufficient to explain the observed decline. In summary, this simulation exercise demonstrates that while the possibility of decreases in pup survival, juvenile survival, or fecundity cannot be excluded from causing a population decline of the magnitude observed at Scapa Flow, there must have been a decrease in adult survival.

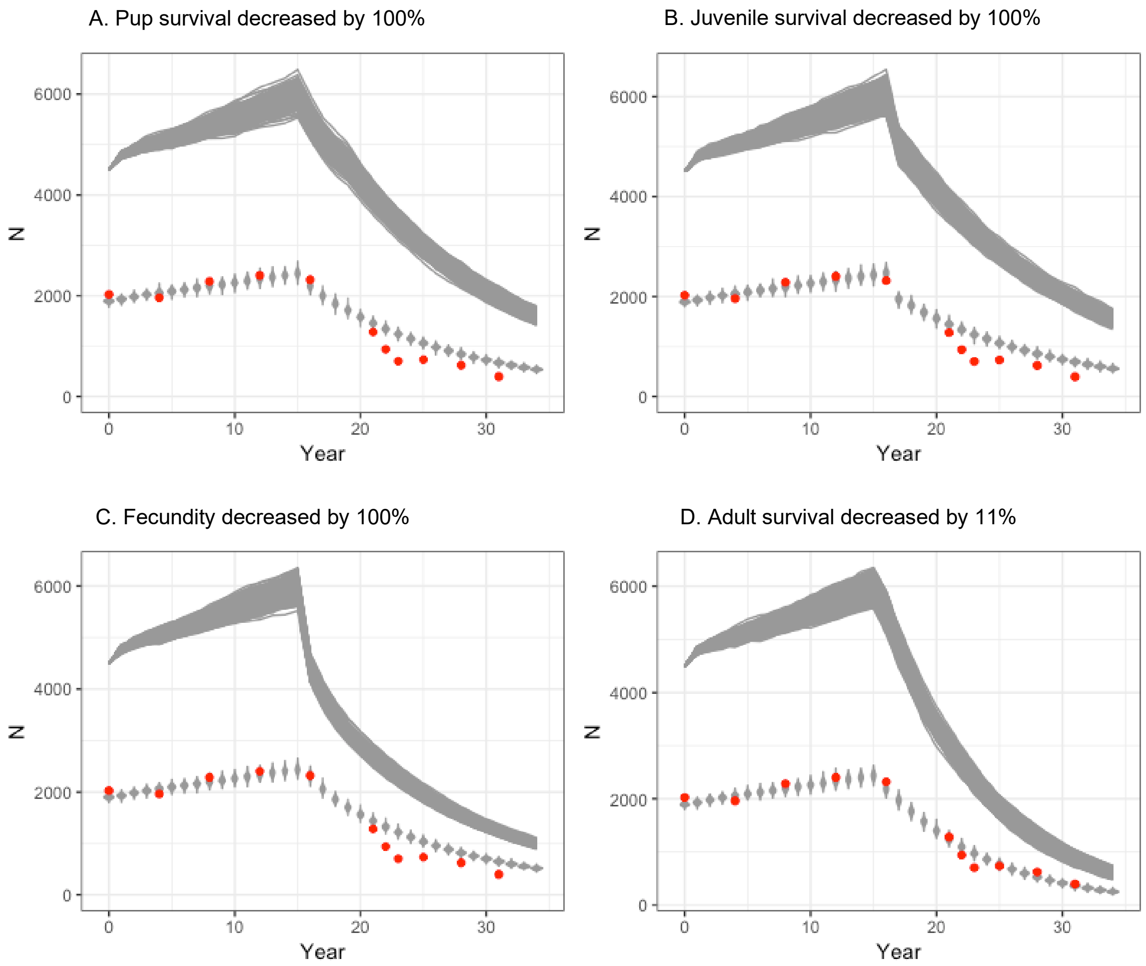

Figure 2. Results of simulated population trajectories with changes to vital rates. In each subplot, the grey lines indicate the simulated population size. The grey violin plots show the expected number of hauled out individuals in the population and the red dots show the observed number of hauled out individuals during the aerial survey count.

2.3 Future work

In Year 5 of the project, the photographic mark-recapture data collected as part of Approach 2 will be incorporated into an integrated population model. The integrated model will allow more precise estimation of survival and fecundity. Other work will involve refining the observational component of the population model, particularly regarding haul out probabilities and the probability of observation and investigating the incorporation of covariates into the model (e.g. fish abundance, harmful algae bloom occurrence and grey seal population size). Depending on results, there might be scope to consider expanding the model to include data from additional sites in Scotland in the future, possibly in a spatially explicit modelling framework (Chandler and Clark, 2014).

Approach 2. Investigate harbour seal vital rates and movement using capture mark-recapture and telemetry

The calculation of vital rates will not start until year five, following the collection of field data for four consecutive pupping seasons (2016 to 2019). Until then, progress on the processing of photo-identification data collected at the different study sites is reported. Here we report on results deriving from the processing of photo-identification data collected in 2017; the 2018 data is currently being processed and will be reported in the annual report for Year five.

3.1 Photo-identification data collected in 2017

3.1.1 Photo-ID data collection

Photo-identification data were collected at selected haulout sites in Orkney, Kintyre and Isle of Skye during the pupping season in 2017, primarily in June and July. In Orkney and Kintyre, selected sites were visited on a daily basis when weather conditions and time allowed. Sites were visited around low tide, as that is when the highest number of seals are likely to be hauled out. Photographs were taken from a distance (50 to 150 m away) of as many seals as possible, ideally from both right and left sides, using a digital camera attached to a scope, mounted on a tripod. During field observations, relevant information was recorded with a time-stamp in order to link photographs to each observation. Such information included observation of pregnancy, presence of a pup associated with a female, presence of umbilical cord in pups, evidence of suckling, injuries and particular behaviours.

In Orkney, photo-identification study sites were located in South Burray (two sites, in Wha Taing and Langa Taing) and in Widewall Bay (three sites, by Oyce of Herston East and West, and by Kirkhouse) (Figure 3). In total 85 trips were conducted to collect photo-identification data at the main monitored sites, with 5,749 photographs collected. A haulout site located in North Burray was only visited twice as access was too challenging (Figure 3).

In Kintyre, four main haulout sites were visited to obtain photo-identification data (Seal Rock, Yellow Rock Island Muller North and South), with a fifth being visited occasionally (Southend) (Figure 4). In total, 88 trips were conducted which allowed the collection of 2,726 photographs.

In Isle of Skye, photo-identification data were collected from boat platforms using a digital camera with a x 400 zoom lens, two to four times per week between the end of May and the end of July 2017. The boats departed from Dunvegan Castle grounds for seal-watching trips around the nearby skerries in Loch Dunvegan (Figure 5), offering an opportunity to take close-up photographs of the seals. A total of 26 trips were conducted, and 9,217 photographs collected.

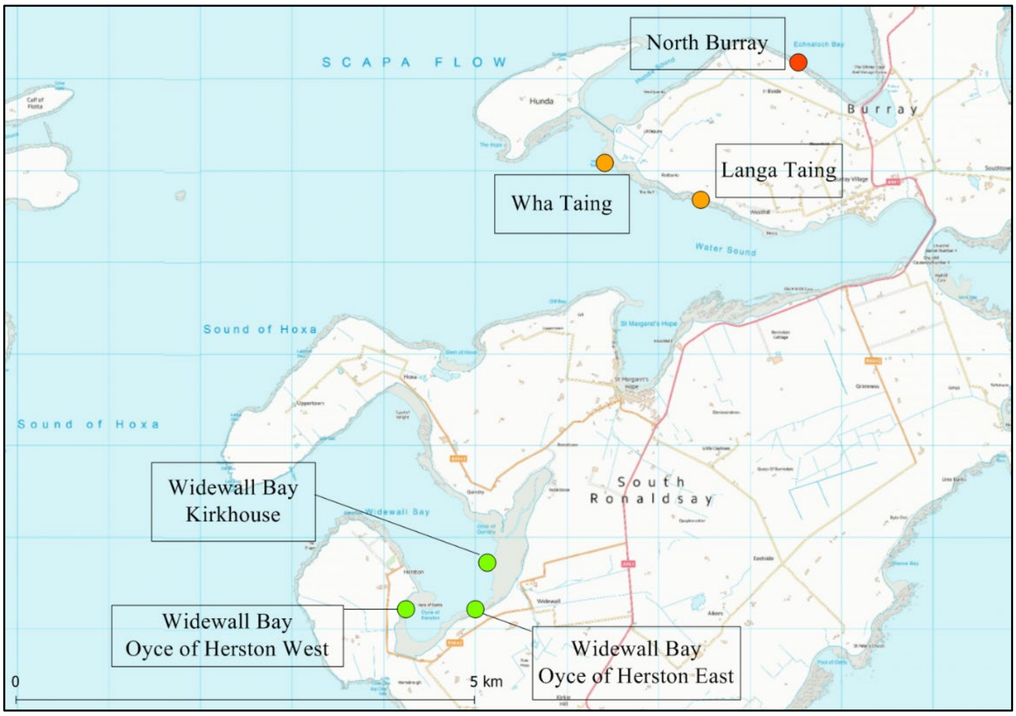

Figure 3. Locations of the haulout sites in Orkney where photo-identification data were collected in 2017

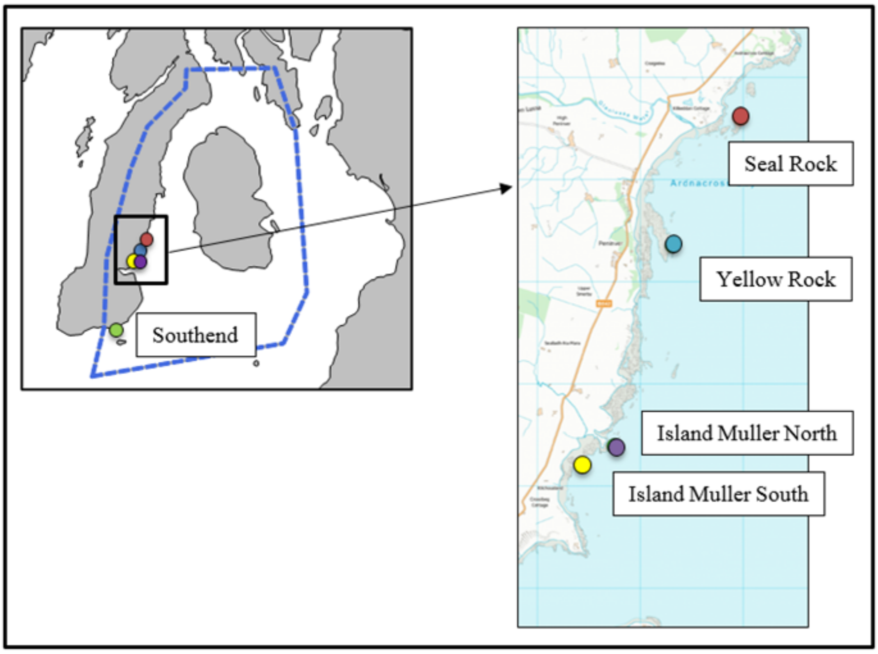

Figure 4. Locations of the haulout sites in Kintyre where photo-identification data were collected in 2017.

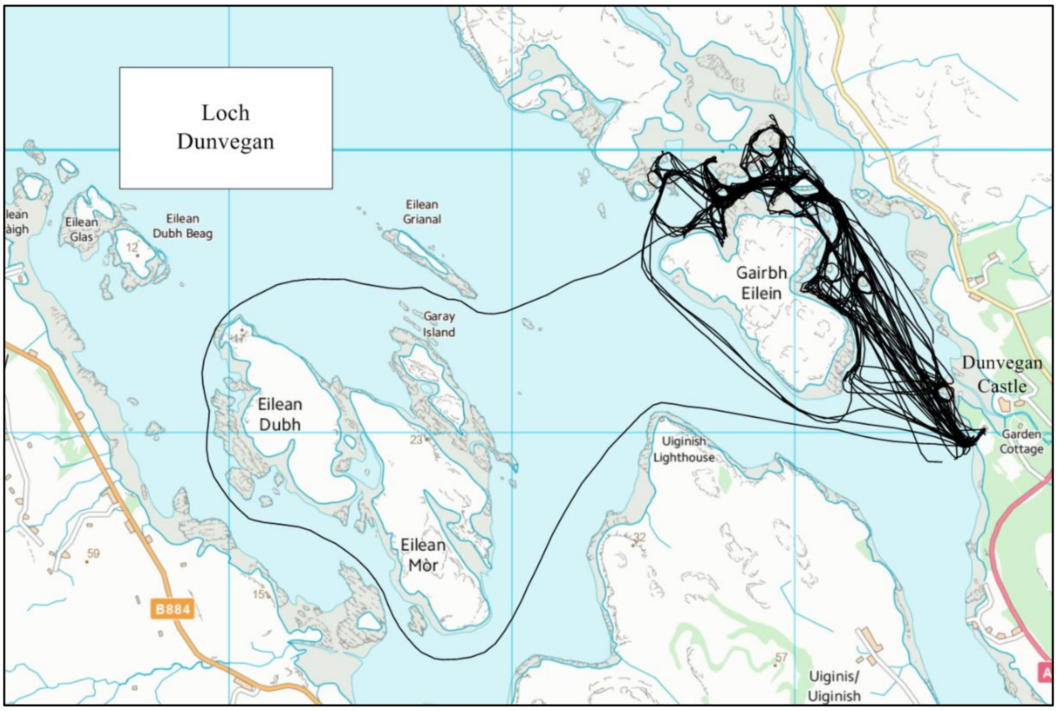

Figure 5. Map showing the boat tracks of the photo-identification trips conducted in 2017 in Loch Dunvegan.

3.1.2 Photo-ID data processing

All photographs were graded for their quality, following a protocol adapted from Cunningham (2009) to take account of photographic quality (focus, resolution of the image), the angle of the seal and the visibility of the pelage patterns (e.g. wet versus dry pelage) (Figure 6). Seals were individually identified from their unique pelage pattern markings, mainly using the head and neck areas, as those were the easiest to photograph in hauled-out seals (i.e. other parts such as the back or a full lateral body length view are more difficult to obtain consistently for all observed seals). All newly identified seals were given an ID number and the best left-side (L), right-side (R) and front-side (F) photographs added to a catalogue of uniquely identified seals from each study site. Three age classes were defined based on the size of the seal: pup, juvenile and adult. Sex was determined from photographs of the genitalia. To help identify mum-pup pairs through the season, as well as pups left on their own, efforts were made to identify pups from the unique pattern in their pelage when possible.

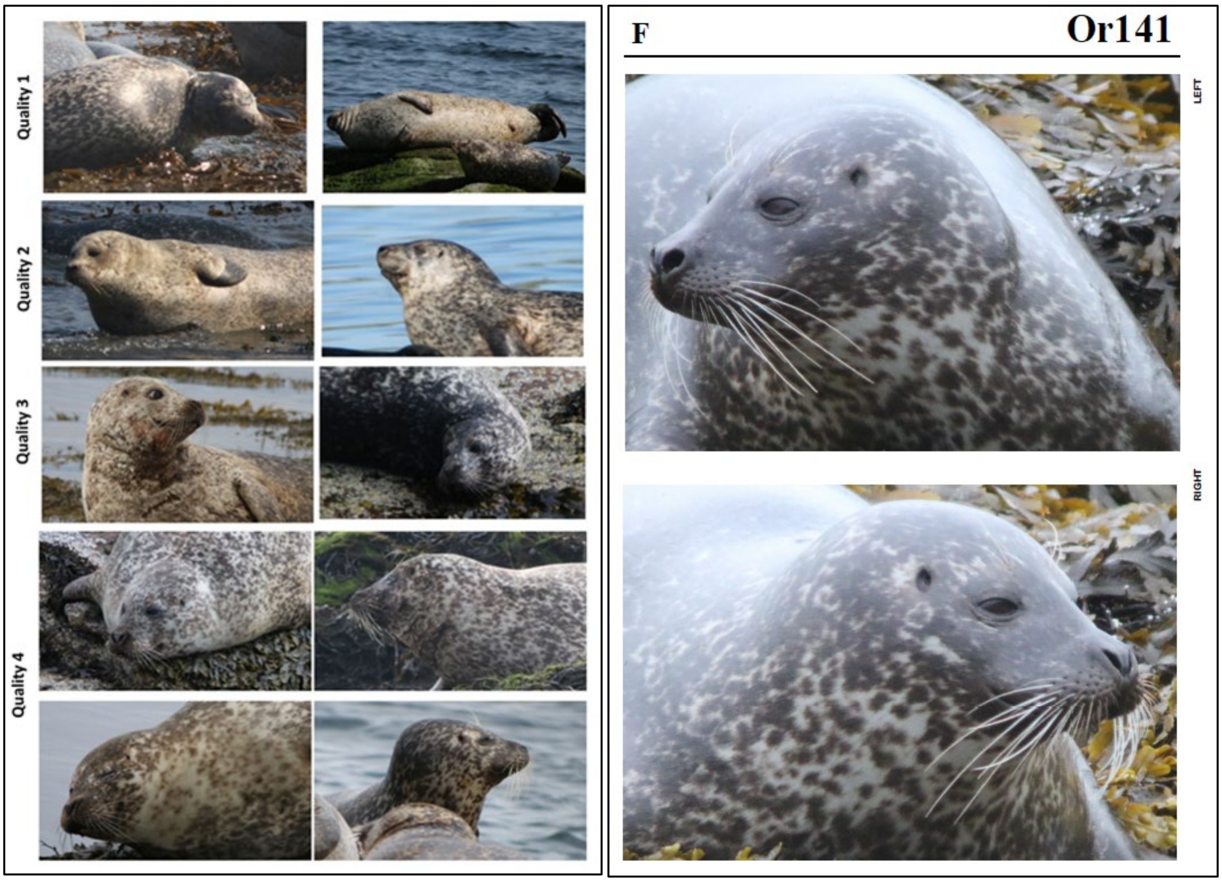

Figure 6. Criteria to grade photographs based on their photographic quality (left) and example of left- and right-sides for catalogued seal Or141 from Orkney (right).

Table 3 below shows a summary of the total number of photographs taken in each study area, as well as the proportion of those that were graded as quality 3 or 4 (best qualities). Note that the methods used in Isle of Skye to take photographs (i.e. from a boat and very close distance of the seals) differ from those used for Orkney and Kintyre (i.e. camera attached to a scope, at a distance of 50 to 150 meters from the seals), which explains the highest proportion of quality 3 and 4 photographs in Isle of Skye.

Table 3. Total number of photographs taken at each of the study areas in 2017, with details on the number (and proportion) of photographs that were graded as quality 3 or 4 (best quality photographs).

Area	Total number of photos	Quality 3 – 4 photos
Orkney	5,749	3,804 (66%)
Kintyre	2,726	1,700 (62%)
Isle of Skye	9,217	7,802 (85%)

3.1.3 Identified seals

Table 4 shows a summary of the number of seals identified from photographs taken in 2016 and 2017 at the monitored sites in the different study areas. For each of the study areas, a summary of the number of seals identified in each estimated age class (based on size) and sex is given. The proportion of adult females that had a pup is also provided for each study area and year, as a percentage of the total number of adult females identified (see Table 5). At the end of the project, in Year 5, the sighting and reproductive histories of these females will be used to estimate fecundity (and survival) rates at each of the study areas, fitting appropriate capture-mark-recapture models (e.g. Cordes and Thompson, 2014). **Consequently, the proportions shown here should not be interpreted as fecundity rates**. Also note that the proportion of females seen with a pup for 2016 might differ from those reported in Year 3 annual report (see results for Approach 2 in Arso Civil et al., 2018). These proportions are based on the total number of seals that have been classified as adults (based on size) and as females (based on photographs of the genitalia as well as association with a pup). Hence, because additional adults of unknown sex seen in 2016 were then sexed as females in 2017, the proportions of adult females for 2016 might differ.

Table 4. Number of seals identified in Orkney, Kintyre and Isle of Skye in 2016 and 2017, by sex and age class. The summary data refers only to the main monitored sites. Other secondary sites where photographs were taken in 2016 and/or 2017 have been excluded.

Year	Area	Total IDs	Total Female	Total Male	Total Unknown	Total Adult	Total Juvenile	Total Pup
2016	Orkney	183	79	31	73	114	18	51
2017	Orkney	155	72	28	55	94	20	41
2016	Kintyre	251	55	71	125	172	43	36
2017	Kintyre	174	55	40	79	120	34	20
2016	Isle of Skye	371	96	65	210	270	18	83
2017	Isle of Skye	550	110	63	377	329	109	112

Table 5. Number of adult (estimated based on size) females that were seen in each area and year, and proportion of adult females that were seen with a pup and/or seen pregnant; note that females might be seen pregnant at the start of the season but then not seen again or seen at the end of the season without a pup.

Year	Area	Adult females	% with pup	% with pup or pregnant
2016	Orkney	69	65.2%	73.9%
2017	Orkney	61	67.2%	73.8%
2016	Kintyre	49	49.0%	71.2%
2017	Kintyre	50	44.0%	72.0%
2016	Isle of Skye	95	64.2%	69.5%
2017	Isle of Skye	109	78.0%	88.1%

The total number of seals identified in each area and year ranged between 155 and 550, with Isle of Skye having the largest number of identified seals, both for adults and pups (Table 4). Differences in the number of seals identified in the juvenile age class in different years should not be interpreted as a reflection of the haulout sites age class structure or as an indication of change in age class structure between years. Given that the main objectives of the individual histories resulting from the photo-ID data are to estimate adult survival and fecundity rates (i.e. based on the adult reproductive part of the population), identifying juvenile seals is not a priority for the project at this point. For example, the number of juvenile seals identified in Isle of Skye in 2016 was only 18, while this number increased to 109 in 2017, primarily because of a difference in the effort to identify juvenile seals between years. Photographs of juvenile seals that have not been identified or incorporated into the catalogue are currently labelled as "juvenile" in the database, meaning effort can be done in the future to identify them if needed.

There was a consistency in the proportion of females seen with a pup and/or pregnant in Orkney in 2016 (65.2% and 73.9%, respectively) and 2017 (67.2% and 73.8%, respectively) (Table 5). Proportions for Kintyre and Isle of Skye differed slightly more between years but were still quite consistent. In 2017, Isle of Skye had the highest proportion of 'adult females with pup' out of the three study areas (78.0%). The proportions of adult females with pup were the lowest in Kintyre, for both years (49.0% and 44.0%). However, as reported for 2016 (Arso Civil et al., 2018), in this region, a proportionately large number of females that were photographed pregnant at the start of the season in June were then either not seen again or seen at the end of the pupping season without a pup. It is reasonable to think that those females pupped in another site away from the monitored sites. When adding those females to those seen with a pup, the proportions changed to 71.2% in 2016 and 72.0% in 2017, similar to those reported for Orkney for those years (Table 5).

The proportion of non-pup seals (i.e. adults and juveniles) identified in 2016 that were re-sighted in 2017 was larger in Isle of Skye (78.1%) than in Orkney or Kintyre (66.0% and 43.7%, respectively; Table 6). A high proportion of the adult females seen in 2016 were also seen in 2017 at the three study sites (70.7% to 90.5%). Between 77.8% and 88.5% of the females that pupped in 2016 (i.e. known reproductive females) were re-sighted in 2017 at the study areas. Between 59.0% and 61.1% of the females that pupped in 2016 were observed with a new pup in 2017 (Table 6).

Table 6. Proportion of seals identified in 2016 that were re-sighted in 2017 in Orkney, Kintyre, and Isle of Skye, classified by group of interest (i.e. all non-pup seals, adult females and pupping females).

Group	**Orkney**	**Kintyre**	**Isle of Skye**
Non-pup seals re-sighted in 2017	66.0%	43.7%	78.1%
Adult females re-sighted in 2017	76.8%	70.7%	90.5%
Pupping females in 2016 re-sighted in 2017	84.4%	77.8%	88.5%
Pupping females in 2016 also pupping in 2017	60.0%	61.1%	59.0%

3.2 Summary of photo-identification effort conducted in 2018 across the study sites

In 2018, photo-identification data were collected in Orkney, Kintyre and Isle of Skye. Efforts focused on the main monitoring sites to facilitate daily collection of photographs. The North Burray site and the Widewall Bay site by Oyce of Herston West in Orkney were not visited due to accessibility problems (Figure 3). Photo-identification data were collected during 57, 51 and 27 days in Orkney, Kintyre and Isle of Skye, respectively. The processing of the 2018 photographs is currently ongoing, and results will be reported in the annual report for Year five.

Approach 3. Live capture-release at the photo-ID study sites

The objectives for the live captures were to ensure that the sites chosen for the mark-recapture studies were representative of the seals in the study regions and to obtain data on individual covariates for the model (Arso Civil et al., 2018). Capturing females in the Orkney study region, with such a small remaining population, was very difficult in 2017. In addition, the sites in Isle of Skye were male dominated at the time of the captures in April as the females seem to move there just before pupping. Furthermore, the data already obtained from the live captures, particularly the telemetry dive behaviour and movement data, had not been analysed. Therefore, the resources for this task were reassigned to provide support for the thorough analyses of the datasets and to provide additional support for the other outstanding tasks (assisting with developing and running the integrated model, see Approach 1, and analysis of the individual covariate data).

4.1 Pregnancy rates

The proportion of live captured females that were pregnant, as determined from high levels of the pregnancy hormone progesterone in their blood and blubber samples, were reported in Year 3 (see Arso Civil et al., 2018). However, the threshold for determining pregnancy for the specific ELISA assay used in this study (DRG International, Marburg, Germany) and particularly for progesterone concentrations in the blubber of seals (as has been recently published for humpback whales (Pallin et al., 2018)) has not been established. Consequently, further work was carried out during Year 4 to refine the pregnancy estimates by combining data on progesterone concentrations in samples with observations during the breeding season.

To evaluate the relationship between the hormone levels and the probability of pregnancy, a training dataset is required. This was made available through the additional sighting information for female harbour seals that had been captured in Orkney in 2016 and 2017 and at Loch Fleet in 2015 and 2017. There were 51 females for which either a blood or blubber sample was available (preferably both) and information about their pregnancy status was obtained from follow up observations during the breeding season when photo-identification data were collected. Data for Isle of Skye could not be used as none of the captured animals were observed at the breeding study site during photo-identification data collection.

Once the relationship between hormone levels and probability of pregnancy was determined from the training dataset (by fitting logistic regression models, see below), blood and blubber samples from the Isle of Skye animals and from the additional harbour seals captured in the Pentland Firth for a related study, as well as the remaining Loch Fleet and Orkney animals were used to determine overall pregnancy proportions using the established relationship and threshold.

A total of 29 females were included in the training dataset, of which 23 were seen with a pup and 22 were seen pregnant (with obvious movement of the foetus in the uterus or the obvious change of shape). Those in which a clear status could not be determined (for example those that were only seen once or were not in an orientation where the shape of the animal or movement of the foetus could be determined) were excluded. Concentrations of progesterone in the plasma or blubber of the three groups (pupped, seen pregnant or either pupped or seen pregnant) are shown in Figure 7 (where 0 = no, 1 = yes).

The difference between the mean progesterone concentrations are given in Table 7. In all cases the concentrations were significantly higher in the observed pregnant or pupped group, between 4 and 5 times in the plasma and 3 to 7 times in the blubber. However, the coefficient of variation for the plasma was 91% for the training dataset and 159% for the blubber. This is apparent in Figure 7, where more outliers with very high blubber progesterone concentrations compared to the plasma concentrations were observed.

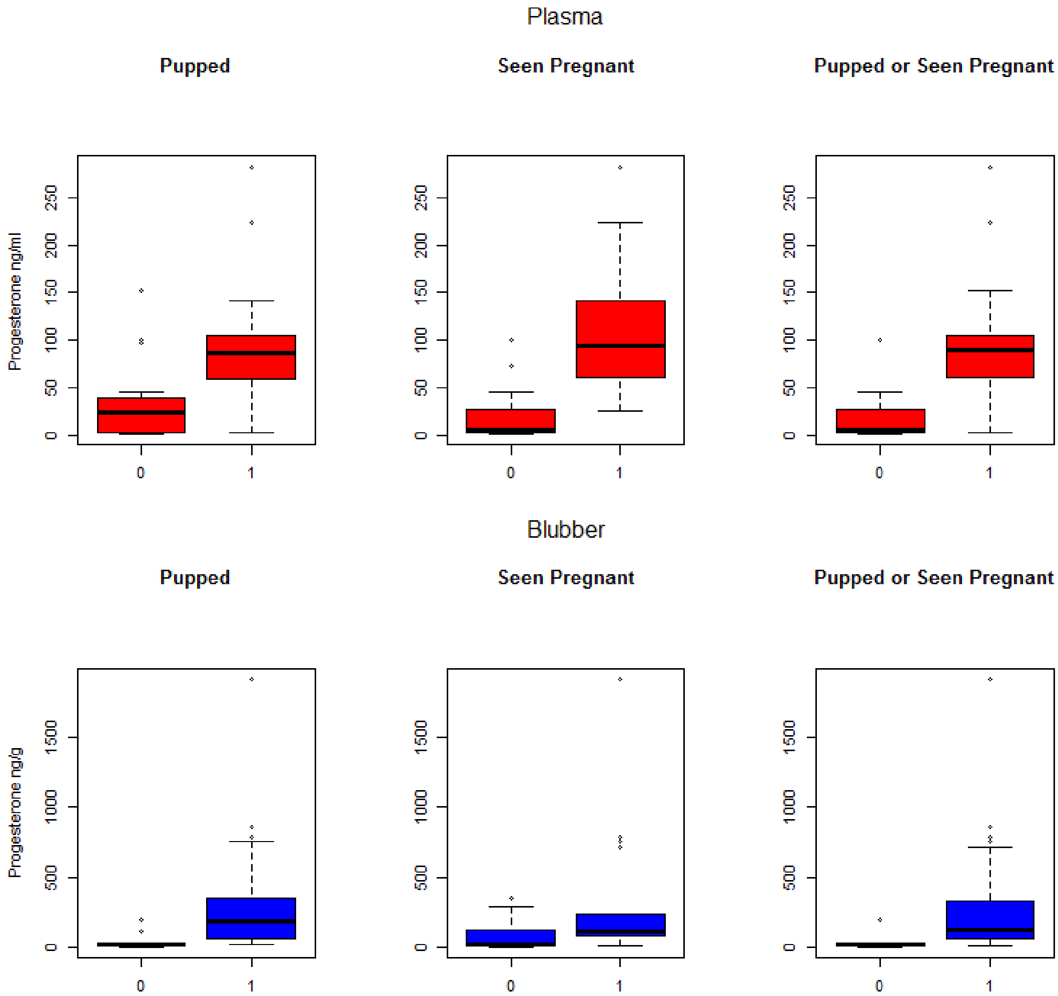

Figure 7. Concentrations of progesterone in the plasma and blubber of female harbour seals that were subsequently observed during the breeding season.

Table 7. Mean progesterone concentrations in the plasma (ng ml^{-1}) and blubber (ng g^{-1}) of harbour seals in the training dataset, classified by observation (seen pregnant, pupped, seen pregnant or with pup).

	Seen Pregnant		**p**	**Pupped**		**p**	**Seen pregnant or with pup**		**p**
	Yes	No		Yes	No		Yes	No	
Mean (±SD) Plasma progesterone ng ml^{-1}	108.6 (62.9)	22.1 (22.77)	p=0.0008	94.5 (62.2)	33.3 (43.5)	p<0.00001	97.0 (60.7)	21.1 (26.4)	p<0.00001
Mean (±SD) Blubber progesterone ng g^{-1}	332.6 (478.9)	89.6 (121.5)	p=0.05	339.9 (438.37)	44.9 (58.6)	p=0.005	317.1 (426.3)	40.3 (59.1)	p<0.005

4.2 Predicting pupping or pregnancy

Using the training dataset (n=29 animals with blubber and plasma progesterone and observations during the breeding season), the best logistic regression model (generalised linear model with a binomial link function) for estimating (i.e. predicting) “pupping” included only blubber progesterone as a predictor (p=0.035). However, only 14% of the deviance was explained by this model. For those animals that were ‘seen pregnant’ the best model included only plasma progesterone (p=0.0002). In this case 40% of the deviance was explained by the model. In the model where animals were seen pregnant or with a pup the model retained both blubber and plasma progesterone (without an interaction term) which explained 48% of the model deviance. This model was then used to estimate the probability of pregnancy for the 49 females for which both plasma and blubber progesterone concentrations had been determined but which had not been observed again after release. Figure 8 shows the probability of pregnancy or pupping estimated from the model for the unknown females against the plasma progesterone concentrations. The size of the symbols is proportional to the concentration of progesterone in the blubber (plotted on a log scale). The horizontal line shows the 80% probability limit.

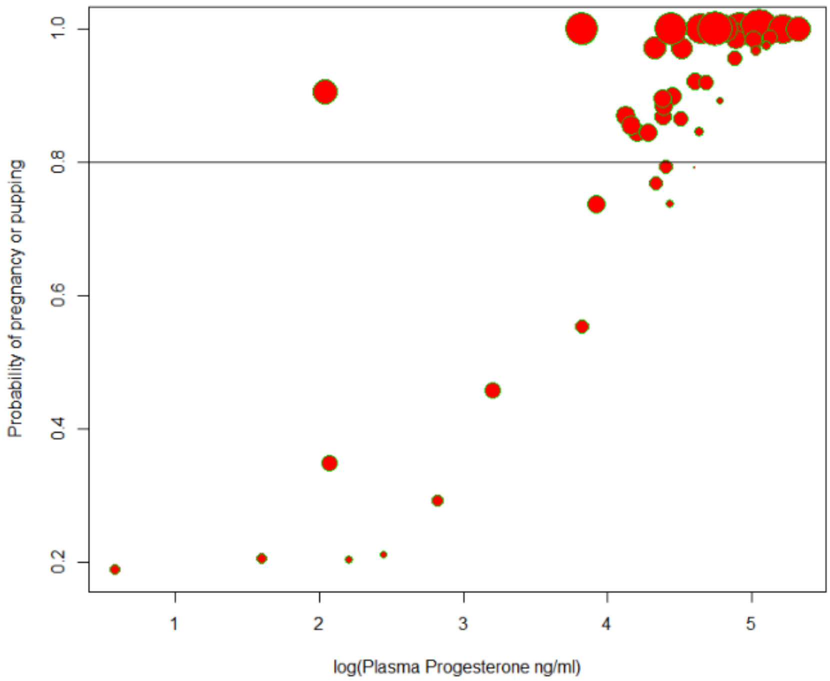

Figure 8. Probability of pregnancy or pupping by plasma progesterone with symbol size proportional to blubber progesterone for the females that were not observed after release.

The number of animals in each region with estimated pregnancy or pupping probabilities from the model are shown in Table 8. There was no difference in the percent of animals with a probability of pupping of >60% among the different regions, despite a lower percentage in Orkney compared to elsewhere. However, the differences in concentrations in relation to time of year need to be investigated as progesterone increases during gestation so the closer to pupping the samples are collected, the more accurate the estimate of pregnancy or pupping probability is likely to be due to higher levels of reproductive hormones.

Table 8. Number of released animals by estimated probability of pregnancy or pupping as estimated from the plasma and blubber progesterone model by region. The probabilities >60% are given in bold.

Probability of pregnancy or pupping	0.0-0.2	0.21-0.4	0.41-0.6	**0.61-0.8**	**0.81-1.0**	Total	Percentage > 60% probability
Region							
Moray Firth	0	1	1	**3**	**7**	12	**83%**
Orkney	1	1	2	**2**	**7**	13	**69%**
Pentland Firth	0	1	1	**1**	**13**	16	**88%**
Isle of Skye	0	2	0	**1**	**9**	12	**83%**
Total	1	5	4	**7**	**36**	53	

4.3 Nutritional stress indicators

Serum and plasma samples were analysed for selected clinical chemistry parameters to determine nutritional condition of the captured seals. These included calcium, alanine transaminase, lactate, urea, total protein, cholesterol and glucose. Assays were carried out using standard wet-chemistry techniques and kits supplied by Randox Ltd (Crumlin, UK) with appropriate quality controls included in each run. All assays were carried out in duplicate using UV-VIS spectroscopy methods. A principal component analysis (PCA) was used to investigate whether there were any differences between the samples collected from the animals on Isle of Skye compared to those from Orkney, and between sexes or age group.

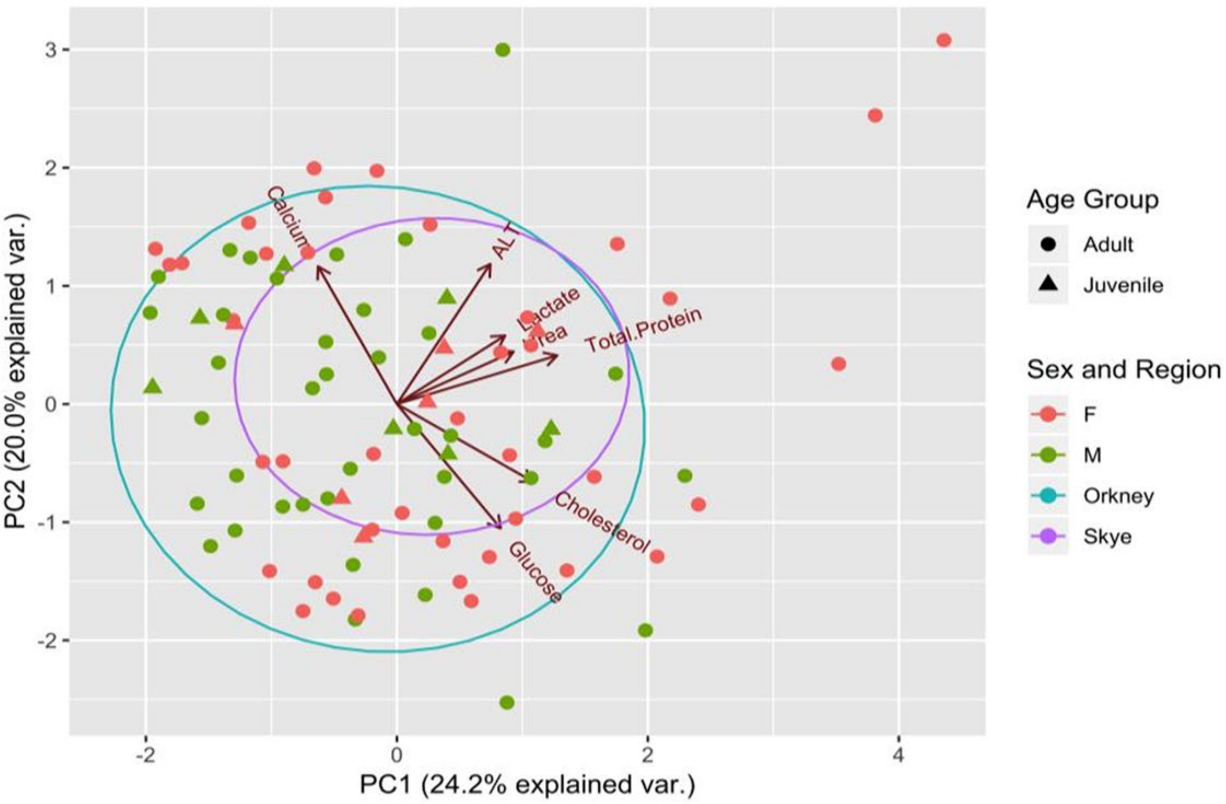

Figure 9. Principal component analysis of seven clinical chemistry parameters in blood samples of captured seals, showing no clustering by region or sex.

The results of the PCA are shown in Figure 9. The first two components explained 42% of the variation in the data and no difference was seen between regions or sexes. The variability in the data was much greater for Orkney than for Isle of Skye but the values were all within what would be considered clinically normal for this species. Thus, from these data we find no evidence that the captured seals are experiencing nutritional stress or are malnourished.

4.4 Relational database

A relational Access Database was developed to store all the data relevant to the live capture approach. A layout of the tables in the HSD2 database and links to external data sets is shown in Figure 10. The database is populated with data collected during the HSD2 project as well as historical data collected by SMRU which provides additional comparative or control data. This has increased the sample sizes for some parameters, particularly the biochemical health measures and the diet data. Thus, for some measurements the database contains information on ~500 individuals captured and sampled since 2000. The database has been stored on the University of St Andrews Central File Server which is regularly backed up by the University's IT services team. It will form the basis for the deposition of the data collected during the project as required by Marine Scotland.

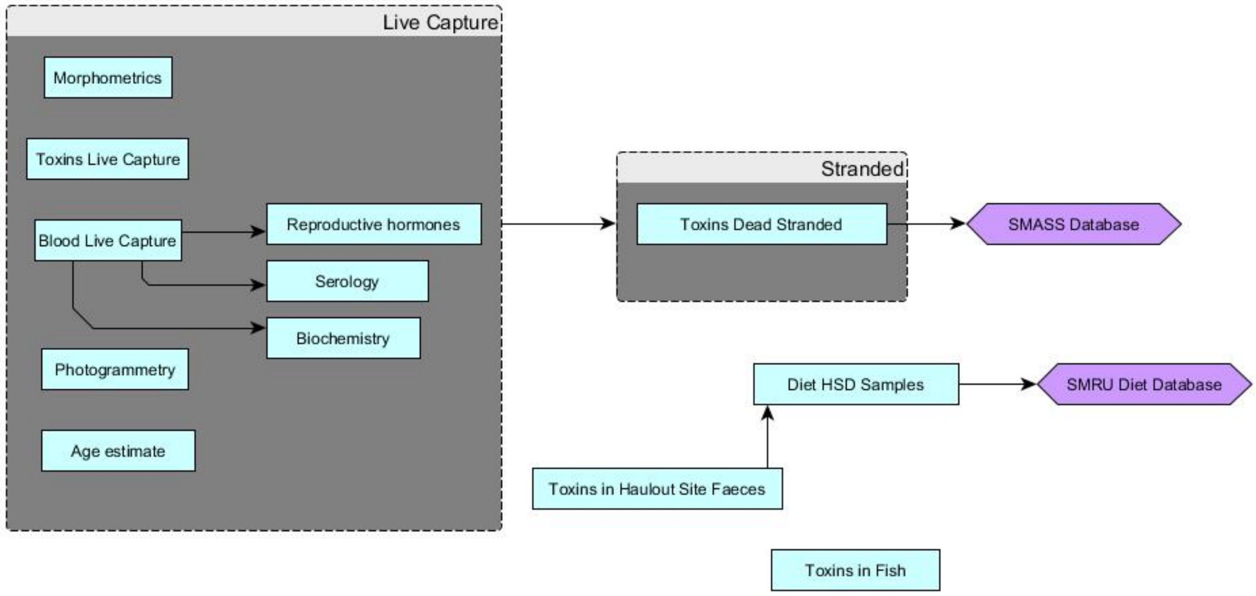

Figure 10. Links between the tables in the HSD2 Access Database and the external data sources.

Approach 4. Counts of harbour and grey seals at and adjacent to the study sites from air surveys

5.1 Moult air surveys

SMRU carries out annual moult surveys in August to count the number of harbour and grey seals along the Scottish coastline (SCOS, 2017). Seals are well camouflaged when hauled out on rocky or seaweed covered shores and are difficult to detect. Surveys are carried out from a helicopter using a thermal-imaging camera, enabling the detection of groups of seals at a distance of up to three km, and groups of seals are photographed using a digital camera equipped with an image-stabilised zoom lens. Further details on how the surveys are conducted can be found in SCOS (2017).

Existing counts of harbour and grey seals conducted between 1985 and 2014 during the August moult were reported in the first year annual report (see Arso Civil et al., 2016). The study sites of Kintyre, Scapa Flow (Orkney), and Loch Dunvegan (Isle of Skye) were surveyed in August 2015, 2016 and 2017, respectively, as part of the SMRU annual moult counts. The Kintyre area was also surveyed in 2018; photographs taken and resulting counts are currently being processed. These will be reported in the annual report for Year five.

Counts of harbour seals and grey seals for Kintyre (2015) and Orkney (2016) were reported in the Year 3 Annual report (see Arso Civil et al., 2018) (Figure 11). A total of 548 harbour seals and 19 grey seals were counted in Loch Dunvegan area (Isle of Skye) during the August moult counts in 2017 (Figure 12). The last count in that same area was conducted in 2014, when 344 harbour seals and 6 grey seals were counted (see Arso Civil *et al*., 2016 for a summary of counts in the different study areas).

Figure 13 shows how the abundance and distribution of grey and harbour seals has changed over the 20-year period, 1997 compared to 2017. Whilst grey seals hauled out on land during the summer (also counted during the harbour seal August moult surveys) have increased on the east coast, harbour seals have increased on the west coast, particularly in the Inner Hebrides. This difference has led to the hypothesis that competition between the species may be a factor in the decline and research into this is continuing.

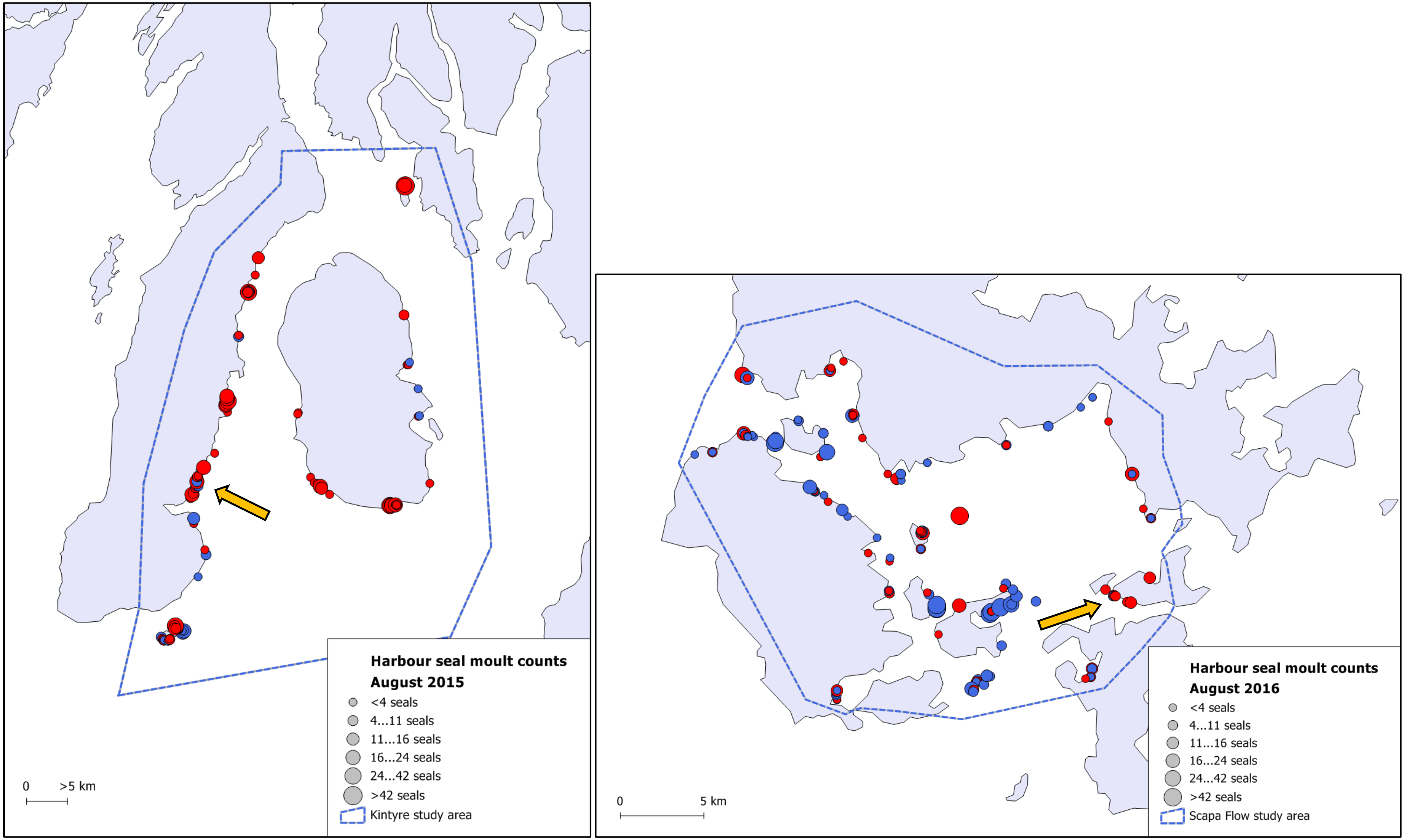

Figure 11. August moult harbour (red) and grey (blue) seals in the Kintyre (left) and Scapa Flow (Orkney) (right) study areas conducted in 2015 and 2016, respectively. The yellow arrows point to the location of the main photo-identification study sites in each region. Note: the scaling is different between the maps to accommodate the difference between the size of the study areas.

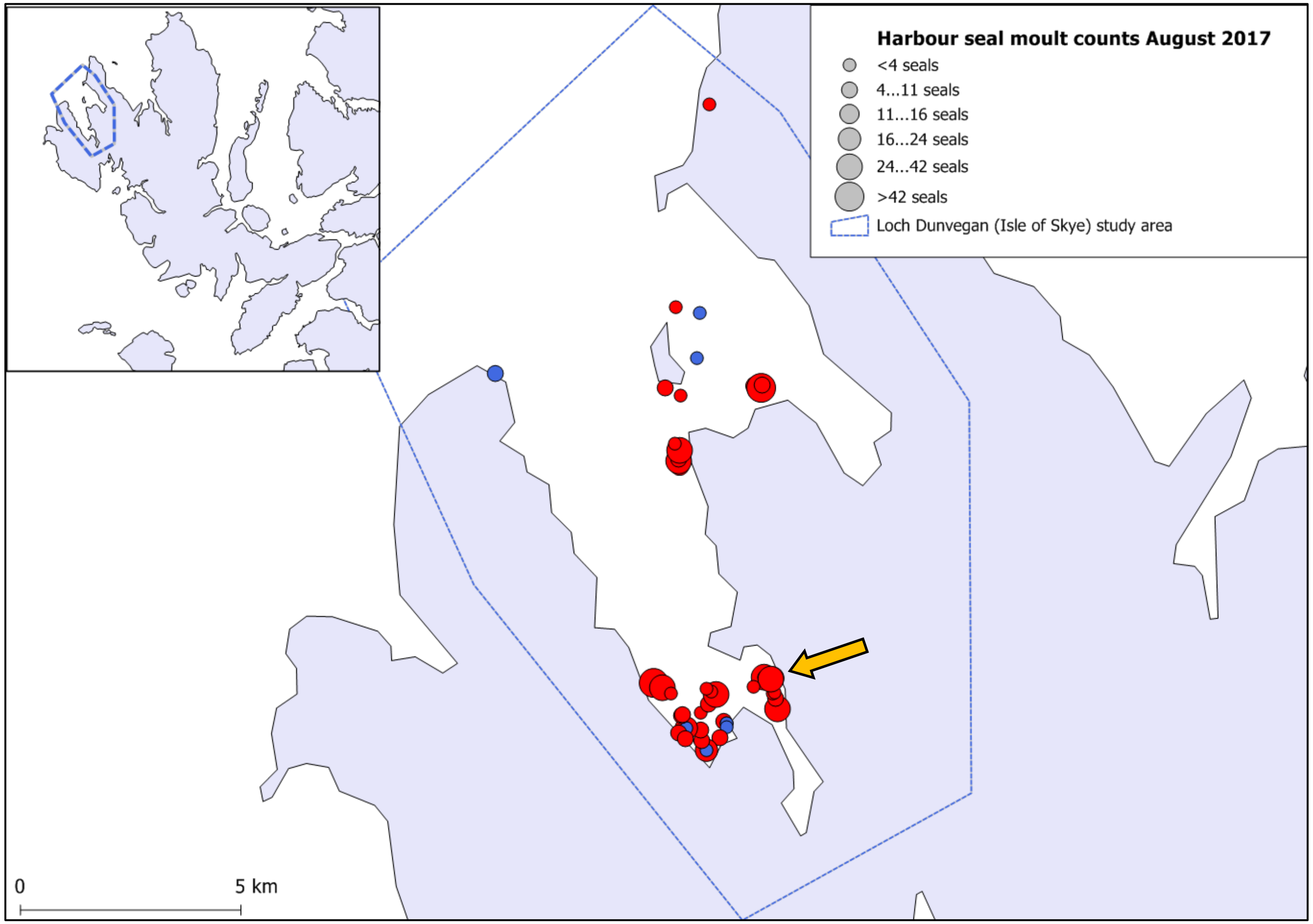

Figure 12. August moult harbour (red) and grey (blue) seals in the Loch Dunvegan area (Isle of Skye) conducted in 2017. The yellow arrow points to the location of the main photo-identification study sites in that region. Note: the scaling is different this map and those in Figure 11 to accommodate the difference between the size of the study areas.

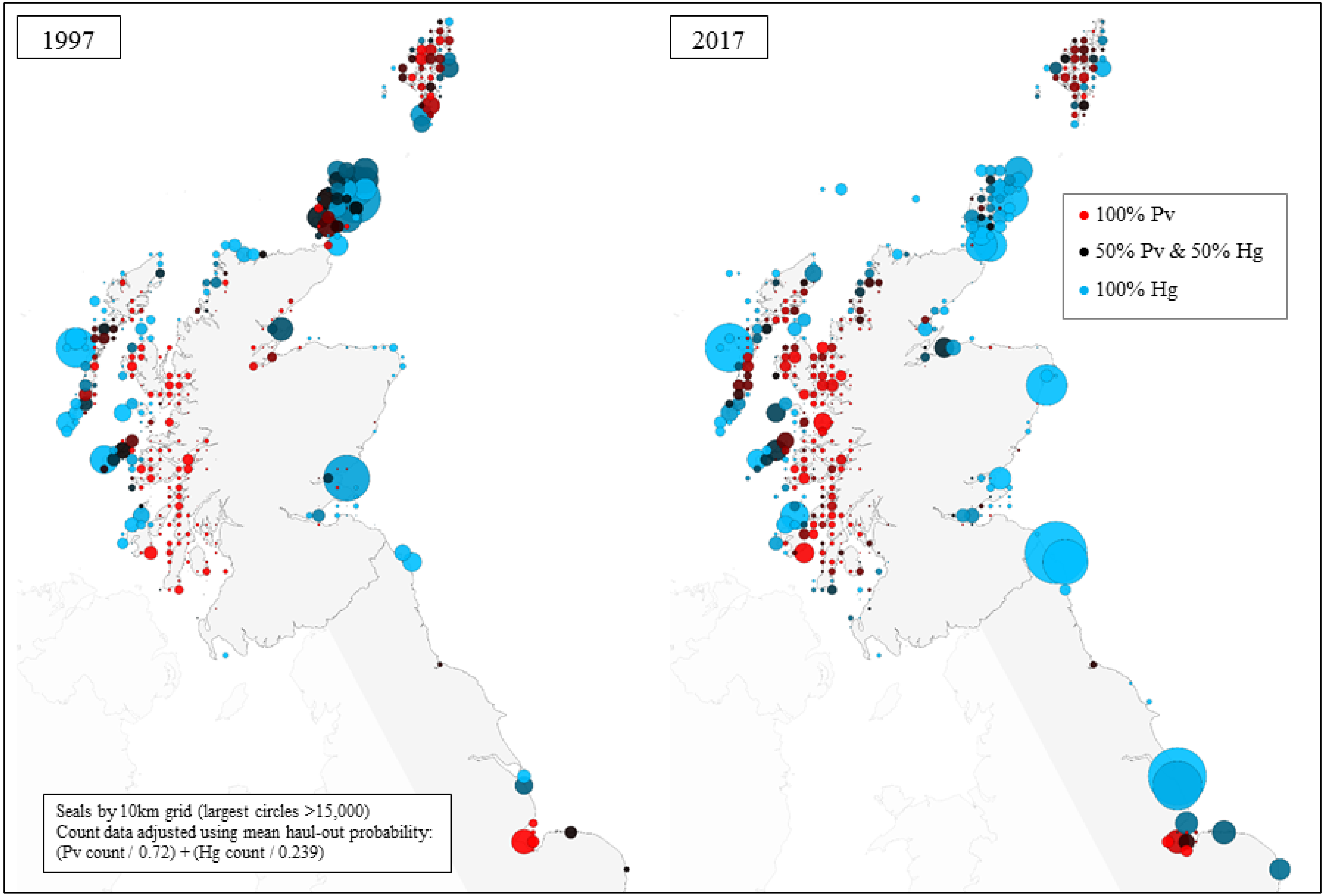

Figure 13. Comparison between the abundance and distribution of harbour and grey seals counted during the summer, 1997 compared with 2017.

Approach 5. Improving understanding of potential drivers of population change

6.1 Toxin uptake

The objective under this approach was to estimate the exposure of harbour seals to toxins from harmful algae, particularly domoic acid (Arso Civil et al., 2018) as a potential drive of the decline (Hall and Frame, 2010; Jensen et al., 2015).

Concentrations of domoic acid in the urine of the live captured seals from the Moray Firth, Orkney, Pentland Firth and Isle of Skye between 2015 to 2018 have now been analysed (n=190). All samples were collected between February and May and results are shown in Figure 14. The concentrations found in the seals captured in the Pentland Firth in 2017 and 2018 were significantly higher than at other sites. However, the highest levels measured represent relatively low concentrations from a toxicological perspective.

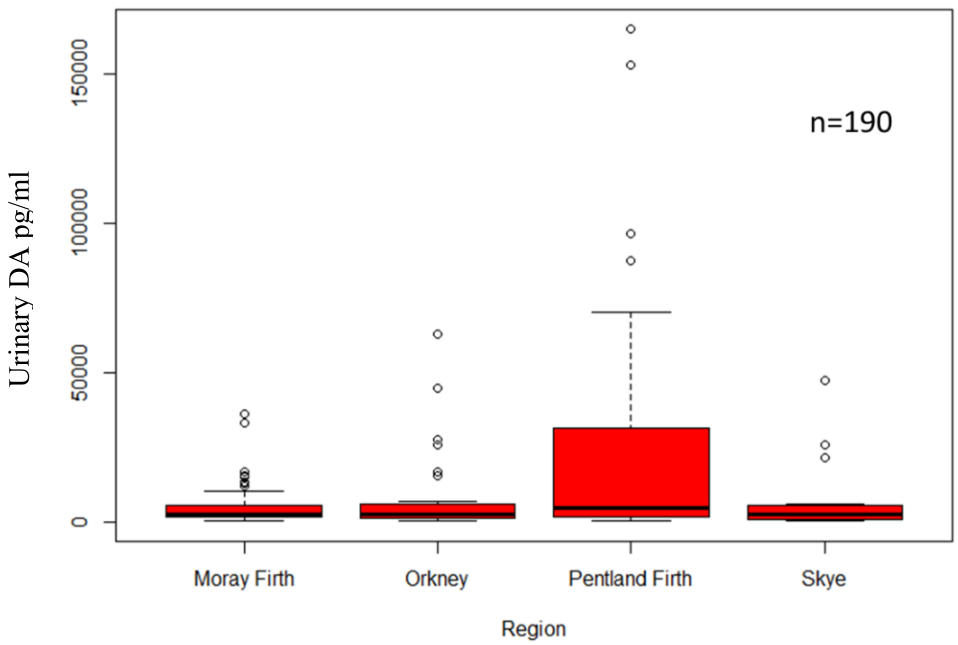

Figure 14. Urinary domoic acid concentrations in harbour seals captured between 2015 and 2018 by region.

The domoic acid levels found probably underestimate of the peak levels that individuals would have been exposed to during feeding bouts. This is due to the short half-life of domoic acid and the time elapsed between feeding and sampling. Work is currently underway to estimate peak exposure. This involves two stages: first, the probable half-life of domoic acid is estimated from captive studies; second, telemetry movement data are used to identify foraging trips and to estimate the distribution of likely intervals between a feeding bout and sampling during the subsequent haulout. Since digestion may be deferred until the animals haulout (Sparling et al., 2007), two model scenarios will be considered: digestion initiated immediately post-feeding and digestion initiated at the start of the subsequent haulout. This work is on-going, but provisional information is summarised below to outline the method. However, the information is purely illustrative at this point.

The fate of ingested domoic acid on the levels found in the urine are summarised in Figure 15. These data were obtained from captive experiments where three seals, hauled out on land, were fed with fish dosed with known amounts of iohexol as a non-toxic surrogate for domoic acid, the fate of which is regarded as a pharmaco-kinetically equivalent to domoic acid. Blood domoic acid concentrations were monitored and urine domoic acid concentration was estimated by multiplying blood concentration values by a factor of 1.3 (Jones, 2006).

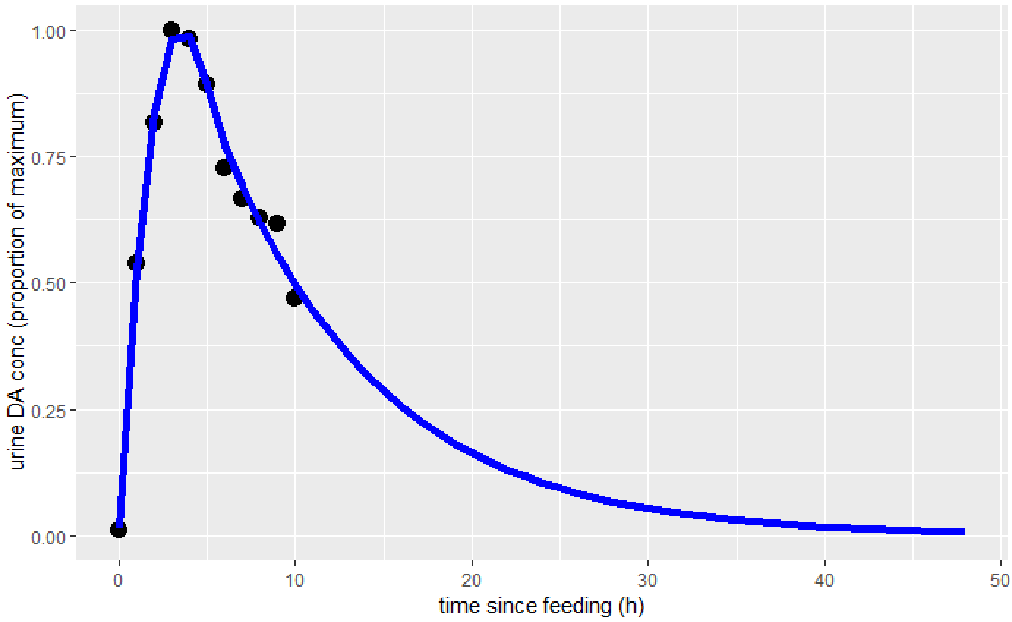

Figure 15. The estimated urine concentration of domoic acid following oral administration, expressed as a proportion of maximum level. This graph is illustrative, and model uncertainty is not shown.

The movements of ten seals tagged at Orkney in 2017 were discretised to 30 minutes intervals; movement data from Isle of Skye will be analysed separately. The durations of haulout periods were recorded, and these periods were then excluded from the analysis. The resulting tracks were divided into separate foraging bouts. Periods where travel rate was less than 0.3 m/s were, simplistically, treated as foraging periods (although this will also include periods resting at sea). Two random sampling processes will then be undertaken. The first is to pick a random time within a randomly sampled haulout bout: this reflects the random time when a seal was captured and sampled during a haulout bout. The second process is to randomly sample from the observed distribution of end-of-feeding to start-of-haulout intervals. The sum of these two intervals will reflect the likely delay between feeding and sampling. This process will be repeated 1,000 times to assess uncertainty in the maximum levels.

Since digestion may be deferred until the start of a haulout an alternative model will also be run where digestion is delayed until then (the equivalent of zero *time since feeding* in Figure 15).

6.2 Toxins in prey items

In order to better understand the role of domoic acid exposure in the harbour seal decline, fish prey surveys were carried out at the two study sites, Orkney and Isle of Skye in May and June 2018, with two main objectives: (1) to obtain fish samples for domoic acid content analysis and (2) to evaluate fish prey survey methods with the aim of estimating prey presence and at selected foraging hot spots identified from the telemetry data (see section 5.3). Fish prey surveys were also conducted in Orkney in 2017, and results are reported in Year 3 annual report (Arso Civil et al., 2018).

The distribution of fishing effort is shown in Figure 16. Fishing effort was limited to those sites that were accessible using an 8m survey boat from either Dunvegan (Isle of Skye) or Stromness (Orkney). A total of 64 individual fish samples were collected in Isle of Skye (n=6) and Orkney (n=58). These included additional samples provided by local fishermen on Isle of Skye, and by sea anglers in Orkney who had been fishing on the same days and at the same locations and who were kindly able to provide additional fish viscera for analysis. The number of sampled prey fish in Isle of Skye remains low (n=6) and more samples are required from that area. Also, all the fish were collected during a period when no large harmful algal blooms had been reported in the areas. Thus, efforts will be made to obtain prey samples during bloom events in these regions in 2019.

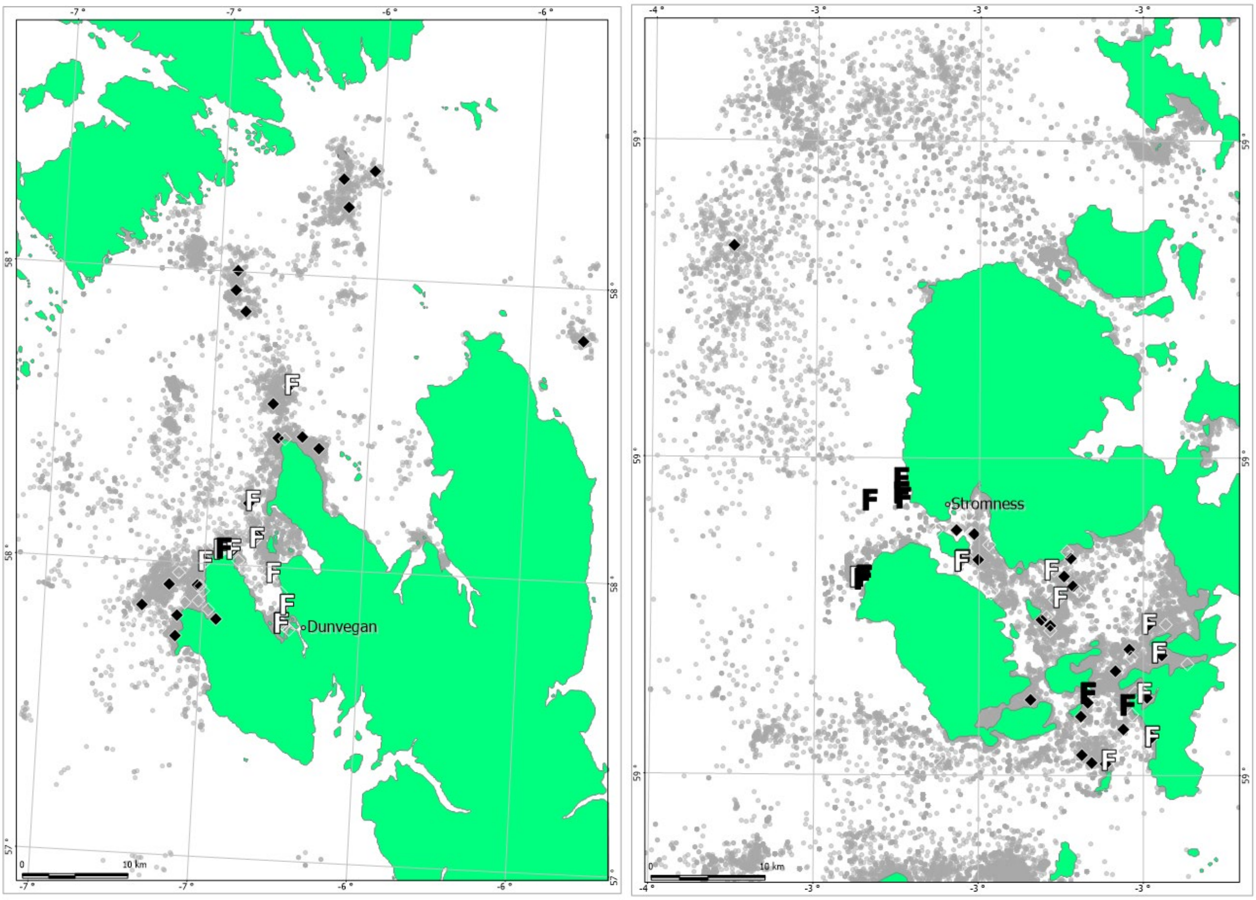

Figure 16. Maps showing the location of survey fishing effort (F) in Isle of Skye (left) and Orkney (right). The solid characters indicate where fish were caught. The survey targets are shown as diamonds. The grey dots indicate harbour seal foraging locations from historic telemetry data.

Figure 17 shows the concentration of domoic acid in prey sampled from all regions and years. The estimated ingestion of domoic acid did not exceed the lethal dose threshold in any of the samples. However, as stated above, all fish were sampled outside a toxic bloom event period.

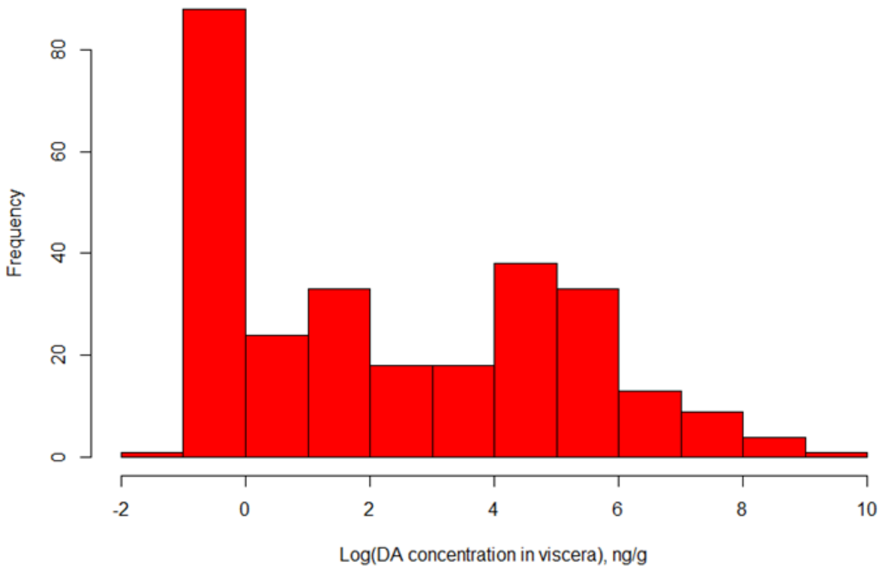

Figure 17. Domoic acid in the viscera of fish prey collected from all regions between 2010 and 2018.

Scat samples collected in 2015, 2016 and 2017 during scat collection trips or during the live captures were processed to separate all hard parts for prey identification. These data are indicative of prey species that are consumed by seals at the study regions. To better understand how the toxin levels in prey relate to the domoic acid levels found in urine and faeces, data on toxins in fish prey guts were combined with a simple bioenergetics model and information on the spring and summer diet of harbour seals in Orkney. Fish were randomly sampled from the known diet (by species and weight, and by season (spring and summer)), based on the prey identification from the scat samples, and up to an estimated seal daily calorific requirement. Individual prey items were randomly assigned a concentration of domoic acid drawn from observed values in the caught and analysed fish guts (Figure 17). Results showed that the estimated ingestion of domoic acid outside the periods of large blooms (i.e. all fish were sampled outside a toxic bloom event) did not exceed the lethal dose threshold (Figure 18). However, it was estimated that 6% of the adults and 31% of the juveniles were likely to be ingesting concentrations of domoic acid that exceed a level that has been shown to cause kidney dysfunction and to affect the production of progesterone in cattle (Pizzo et al., 2015).

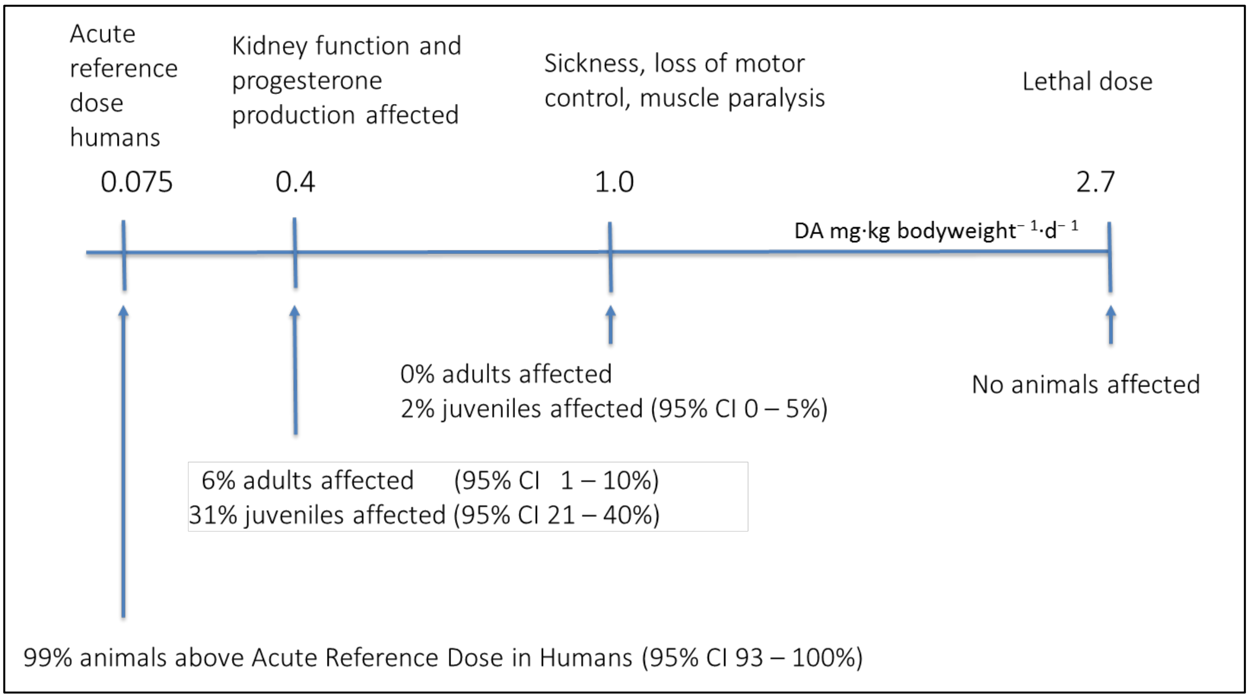

Figure 18. Estimated percentage of Orkney harbour seals affected by domoic acid ingestion compared to thresholds for effects in laboratory animals and humans.

6.3 Prey survey technique evaluation

During the fish-sampling fieldwork at sea, opportunity was taken to evaluate different methods to characterise prey presence at a selection of the putative seal feeding areas. The methods included sonar logs and baited camera traps. In addition, the species of fish caught at each sampling location also served as a (biased) proxy of species presence. This evaluation is on-going. However provisional information is summarised below to outline the method. Note that this information is currently illustrative only.

1300 minutes of baited camera effort were viewed and tabulated. The results are shown in Table 9 and Figure 19 and Figure 20. Further analysis on this technique, as well as an assessment of opportunistic sonar surveys, are yet to be completed.

Table 9. Species observed in each of nine baited camera surveys. The locations of each are shown in Figure 19. The duration of camera effort (minutes) and the time (minutes) to the first sighting of each species are shown.

Date	Code	Region	Place	Camera effort	Edible crab	Octopus	Small fry species	Dab	Haddock	Common dogfish
22/05/2018	S2	Skye	Dunvegan Head	218	20	40	-	-	-	-
22/05/2018	S3	Skye	Dunvegan Head	120	-	-	-	-	-	-
28/05/2018	O2	Orkney	Graemsay	329	144	-	-	-	-	-
30/05/2018	O3	Orkney	Barrell of Butter	44	-	-	6	-	-	-
30/05/2018	O4	Orkney	Flotta	90	-	-	-	-	-	-
30/05/2018	O5	Orkney	Widewall	180	-	-	-	-	-	-
30/05/2018	O6	Orkney	Widewall	181	-	-	-	-	-	-
02/06/2018	O9	Orkney	Billa Croo East	71	-	-	1	-	-	17
02/06/2018	O10	Orkney	Billa Croo East	97	-	-	-	5	44	-

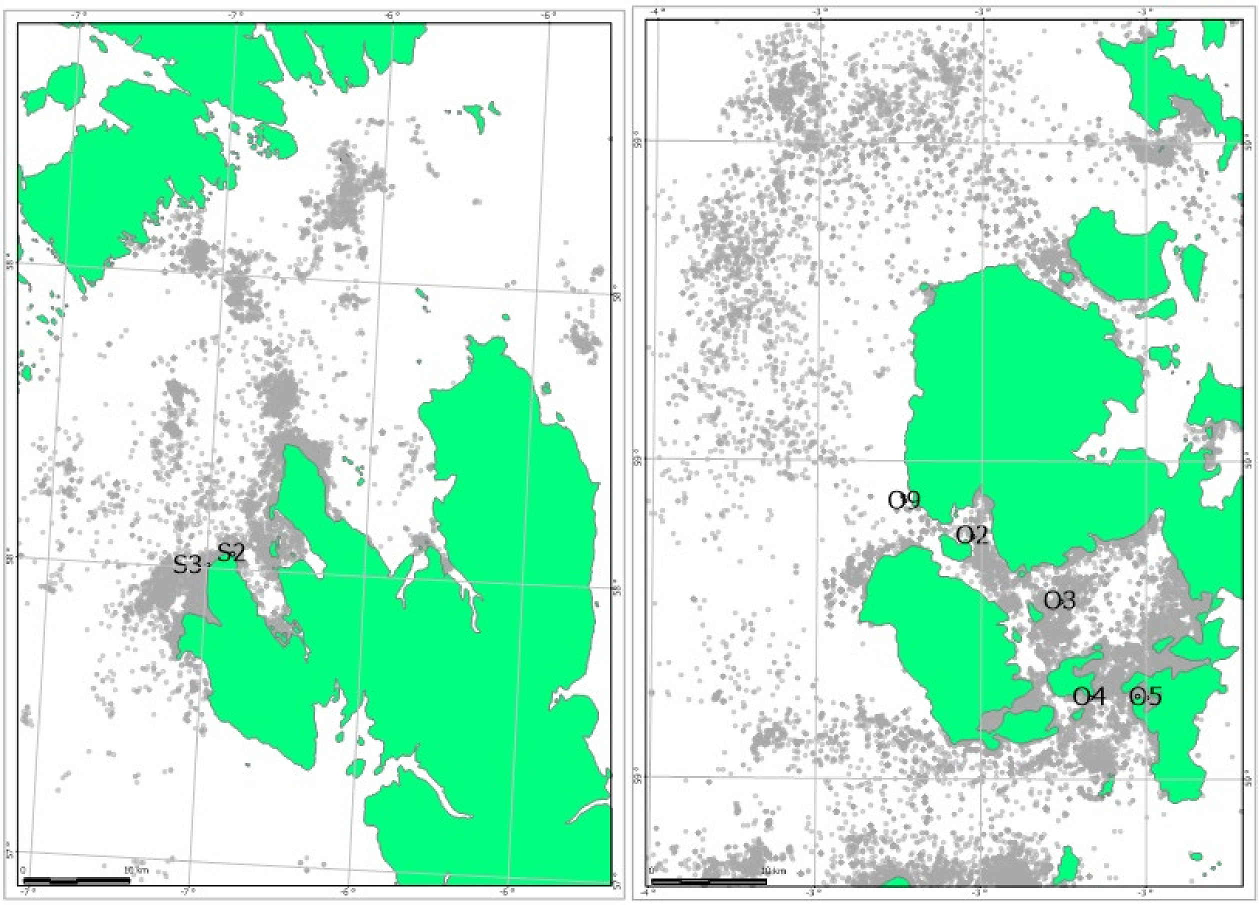

Figure 19. Locations of baited camera sites shown in Table 1 for Isle of Skye (left) and Orkney (right). Station O6 (not shown) is 600m west of O5, and station O10 (not shown) is 300 m north of O9.

Figure 20. Screen-shot from a baited camera survey at site Q9 showing a common dogfish

Approach 6. Carcass collection

A total of 162 seal carcasses were reported to the Scottish Marine Animal Stranding Scheme (SMASS) between 1st of March 2018 and 24th of March 2019 in the three study areas (Orkney, Isle of Skye and Kintyre and the Clyde). Figure 21 shows the locations of all reported carcasses during the time period in the vicinity of all study areas, and Figure 22 shows a detail of the locations for each of the study areas. Tables 2.A, 2.B, and 2.C in Appendix 2 summarize details on species, age class and proximate cause of death, when available.

Most of the reported seal carcasses were found in Orkney (n=133) with less seals reported in Strathclyde (where Kintyre and the Clyde are included) (n=12) or Isle of Skye (n=17). In Orkney, 117 grey seals (18 adults, 46 juveniles, 31 pups and 21 of unknown age), two harbour seals (both pups) and 14 carcasses that could not be identified to the species level were reported (Table 2.A). None of the carcasses could be sent for post-mortem examination. Proximate cause of death was established for 20 grey seals (4 pups, 9 juveniles and 7 of unknown age) and one carcass of unknown species as a case of possible grey seal predation. For the remaining carcasses, proximate cause of death could not be determined due to advance autolysis and damage to the carcasses. Tissue samples were taken from one harbour seal pup and 10 grey seals.

In the Kintyre and Clyde area, the reported 12 seal carcasses included six grey seals (two adults, two juveniles, one pup and one seal of unknown age), 4 harbour seals (one juvenile and three seals of unknown age) and 2 carcasses that could not be identified to the species level (Table 2.B in Appendix 2). None of the carcasses could be sent for post-mortem examination. Proximate cause of death could only be determined for one grey seal of unknown age as a case of possible grey seal predation. The remaining carcasses could not be examined due to advance autolysis and damage. Samples were taken for one adult grey seal carcass.

A total of 17 seal carcasses were reported in Isle of Skye (Table 2.C in Appendix 2). These included 13 harbour seals (one neonate, three pups, one juvenile, one adult and 7 seals of unknown age) and 4 seals of undetermined species. Of these, a post-mortem was conducted on the neonate harbour seal, with proximal cause of death stablished as starvation/maternal separation. For the remaining carcasses, proximal cause of death was determined for one juvenile harbour seal and two other harbour seals of unknown age as possible grey seal predation.

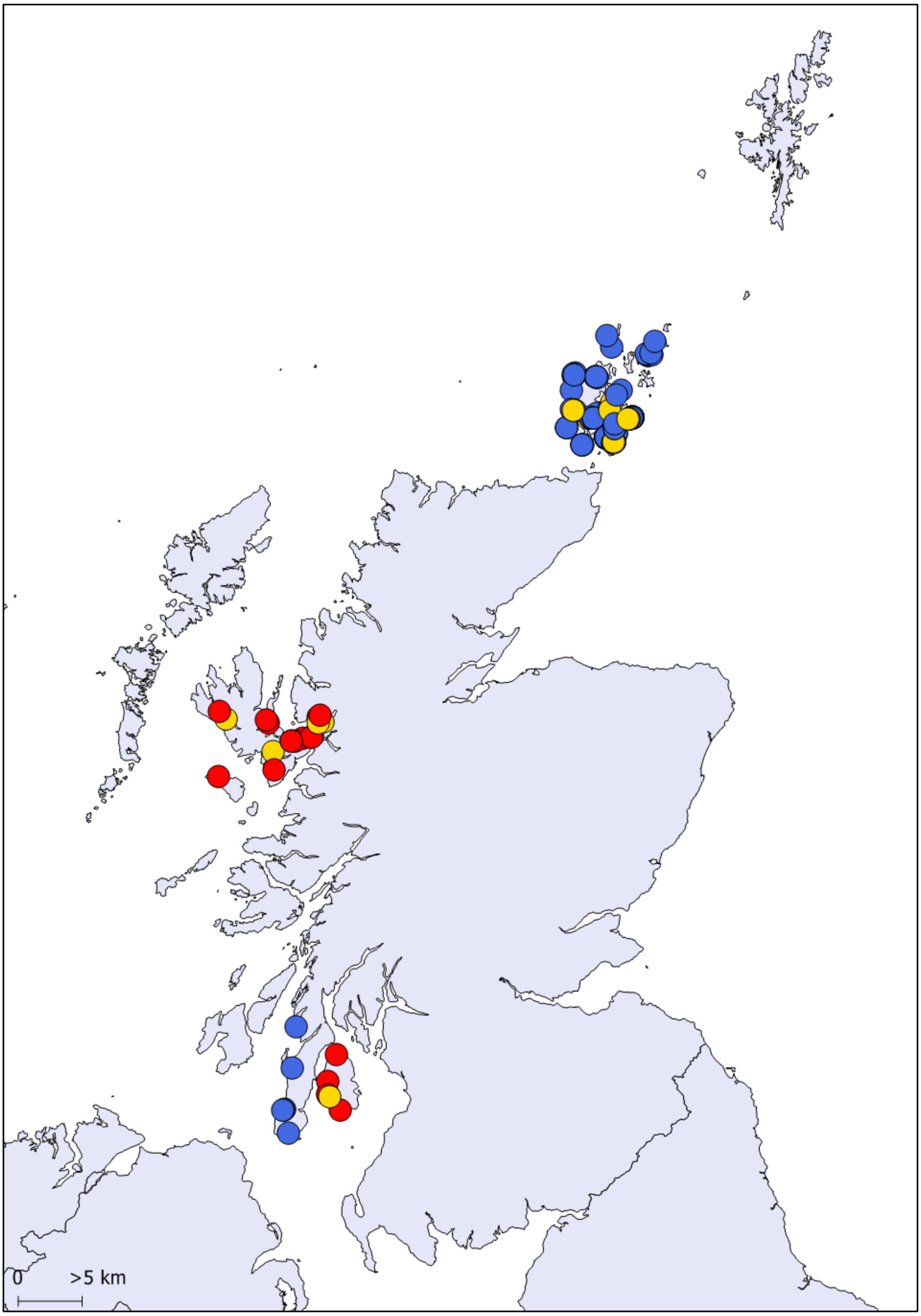

Figure 21. Location of all seal carcasses reported to SMASS between March 2018 and March 2019 within the vicinity of the study areas. Red = harbour seal, blue = grey seal, yellow = pinniped, species unknown.

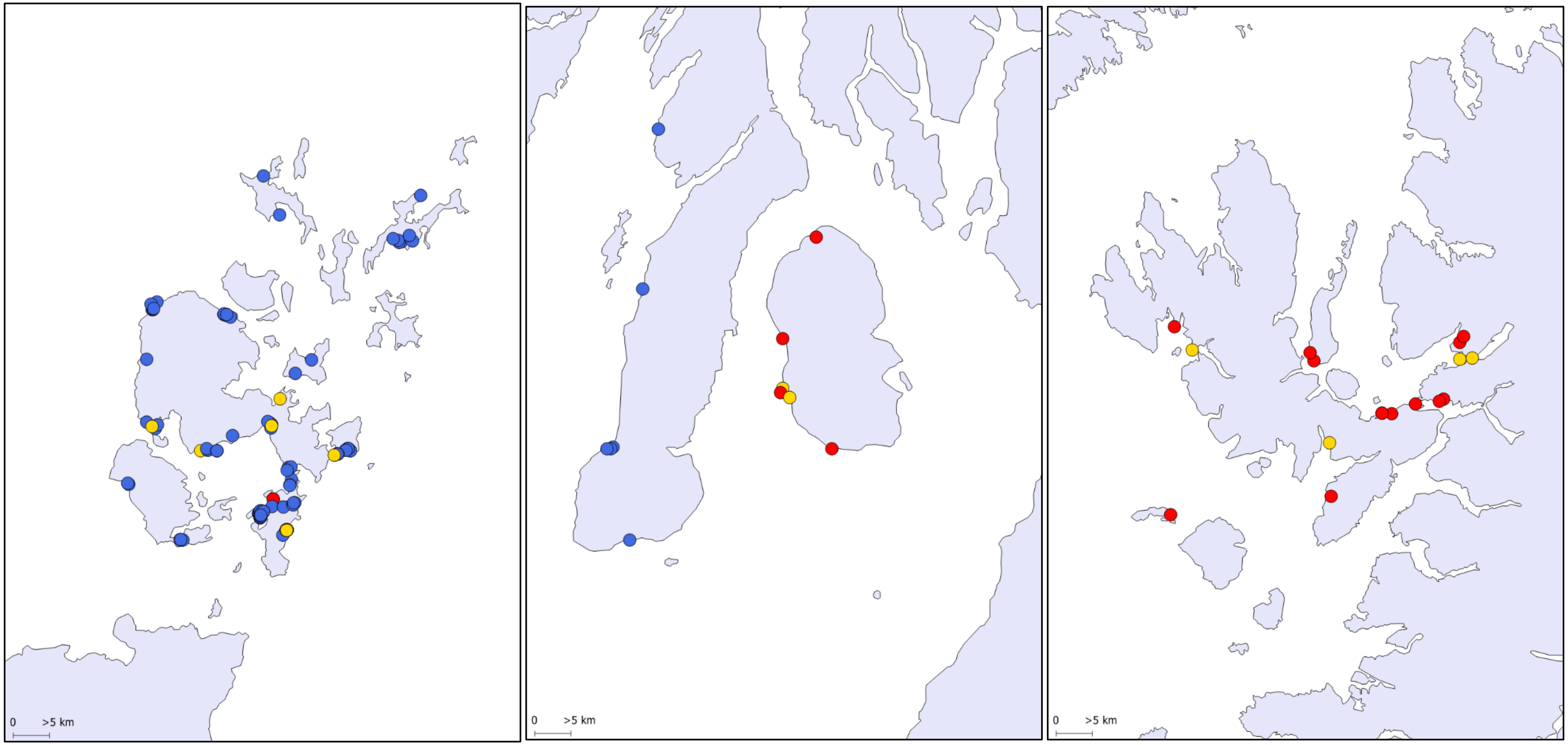

Figure 22. Location of all seal carcasses reported to SMASS between March 2018 and March 2019 within the vicinity of Orkney (left), Kintyre and the Clyde area (centre) and Isle of Skye (right). Red = harbour seal, blue = grey seal, yellow = pinniped, species unknown.

Appendices

8.1 Appendix 1: Deliverables for Year 4 (HSD 2)

Approach 1. Integrated population model.

Model outputs for various plausible scenarios, including the impact of grey seal predation (using data from the Scottish Marine Animal Stranding Scheme to estimate potential levels of harbour seal mortality) and the impact of toxin-related health effects, will be delivered. This will allow exploration of various combinations of mortality and reproductive rates that may account for the observed rates of population change at different study sites. This will enable a quantitative approach to suggesting the sensitivity of local populations to potential future risks e.g. increased grey seal predation, including estimation of uncertainty in any predictions. It will also be possible to investigate the impact of different types of temporal variation in population stressors including steady time trends or unpredictable, sporadic variation such as intermittent 'bad years' for algal blooms.

Approach 2. Investigate harbour seal vital rates and movement using capture-mark-recapture and telemetry.

The calculation of vital rates will not start until year five, following the collection of field data for four consecutive pupping seasons (2016 to 2019). Until then, progress on the processing of photo-identification data collected at the different study sites is reported regarding:

1. Catalogue of individual seals identified from photographs in 2017, with information, when available, on approximate age class, sex, pregnancy (from visual observation), and presence of associated pup.

2. Summary of photo-identification data collected in 2018 across the study sites.

Approach 3. Live Captures.

The objectives for the live captures were to ensure that the sites chosen for the mark-recapture studies were representative of the seals in the study regions and to obtain data on individual covariates for the model (Arso Civil et al., 2018). Capturing females in the Orkney study region, with such a small remaining population, was very difficult in 2017. In addition, the sites in Isle of Skye were male dominated at the time of the captures in April as the females seem to move there just before pupping. Furthermore, the data already obtained from the live captures, particularly the telemetry dive behaviour and movement data, had not been analysed. Therefore, the resources for this task were reassigned to provide support for the thorough analyses of the datasets and to provide additional support for the other outstanding tasks (assisting with developing and running the integrated model and analysis of the individual covariate data).

This report therefore focusses on the continuing analysis of the data collected from the 2016 and 2017 live captures in Orkney and Isle of Skye, including additional data available from comparative harbour seal studies in the Pentland Firth and the Moray Firth (Loch Fleet, in collaboration with the University of Aberdeen).

Deliverable 1: Data on the movements of harbour seals between haulout sites within the time period of the photo ID study to be used to inform the photo ID field effort and data analysis.

1. Estimates of pregnancy and natality for a subset of harbour seals using the study sites.

2. Comparisons between the age, condition, pregnancy, toxin exposure and health status among individuals captured at study sites in regions with different abundance trajectories.

Approach 4. Counts of harbour and grey seals at and adjacent to the study sites from air surveys.

1. Moult season counts of harbour seals for parameterisation of the integrated population model.

2. Abundance of grey seals using the study sites and adjacent haulout sites to provide covariates for assessing the spatial overlap between grey seals and harbour seals.

Approach 5. Improving understanding of potential drivers of population change

1. Comparisons between the toxin up-take of harbour seals in regions with different population abundance trajectories.

2. Comparisons between the prey available to harbour and grey seals in the vicinity of the haulout sites and the levels of toxins in the prey species at sites with different population abundance trajectories.

Approach 6. Carcass collection

1. Full necropsy reports on any dead seals found and collected within the regions of the study sites (in collaboration with Scottish Marine Animal Stranding Scheme)

2. Comparison between the causes of death in regions of decline compared to those of stability or increase

8.2 Appendix 2. Summary of all seal carcasses reported to SMASS

Table 2.A. Summary of seal carcasses reported to SMASS between March 2017 and February 2018 in Orkney. Pv = Harbour seal, Hg = Grey seal, Unk = unknown seal species (continues in the next four pages).

Species	Date	Location	Area	Latitude	Longitude	Sex	Post-mortem	Age Group	Findings
Unk	15/05/2018	Myre bay near Myre farm	Orkney	58.91806	-3.17384	U	No	unknown	Not Examined: Insufficient Data
Unk	09/12/2018	Scapa beach	Orkney	58.96192	-2.97535	U	No	unknown	Not Examined: Advanced Autolysis
Unk	20/12/2018	Eastside beach South Ronaldsay	Orkney	58.80064	-2.92238	U	No	unknown	Not Examined: Insufficient Data
Unk	20/12/2018	Eastside beach South Ronaldsay	Orkney	58.80065	-2.92064	U	No	unknown	Not Examined: Insufficient Data
Unk	20/12/2018	Eastside beach South Ronaldsay	Orkney	58.80154	-2.92239	U	No	unknown	Not Examined: Insufficient Data
Unk	20/12/2018	Eastside beach South Ronaldsay	Orkney	58.80156	-2.92066	U	No	unknown	Not Examined: Advanced Autolysis
Unk	20/12/2018	Eastside beach South Ronaldsay	Orkney	58.80156	-2.92066	U	No	unknown	Not Examined: Insufficient Data
Unk	20/12/2018	Eastside beach South Ronaldsay	Orkney	58.80142	-2.92206	U	No	unknown	Not Examined: Insufficient Data
Unk	06/01/2019	Kirkwall	Orkney	58.99722	-2.94583	U	No	unknown	Not Examined: Insufficient Data
Unk	15/01/2019	East end of Noost beach Orkney	Orkney	58.95306	-3.31500	U	No	juvenile	Not Examined: Advanced Autolysis
Unk	15/01/2019	Tankerness	Orkney	58.91583	-2.77667	M	No	adult	Not Examined: Advanced Autolysis
Unk	01/01/2019	Churchill Barrier 3 Burray	Orkney	58.86889	-2.91389	U	No	unknown	Physical Trauma: Possible Grey Seal Attack
Unk	20/01/2019	Scapa beach next to slipway.	Orkney	58.95667	-2.97000	U	No	unknown	Not Examined: Carcase Not Found
Unk	09/03/2019	Dingieshpwe beach	Orkney	58.91472	-2.78639	U	No	unknown	Not Examined: Advanced Autolysis
Pv	26/07/2018	Wha Taing Burray.	Orkney	58.84795	-2.96175	F	No	pup	Not Examined: Samples Taken
Pv	26/07/2018	Wha Taing Burray.	Orkney	58.84795	-2.96175	U	No	pup	Not Examined: Advanced Autolysis
Hg	07/04/2018	Newark bay South Ronaldsay	Orkney	58.80156	-2.92066	U	No	unknown	Not Examined: Advanced Autolysis
Hg	22/08/2018	Palace Birsay	Orkney	59.12769	-3.32252	U	No	adult	Not Examined: Advanced Autolysis
Hg	30/08/2018	Point of Snusan Orkney	Orkney	59.12773	-3.31903	U	No	unknown	Not Examined: Advanced Autolysis
Hg	31/08/2018	Birsay Beach	Orkney	59.12862	-3.31906	U	No	unknown	Not Examined: Advanced Autolysis
Hg	31/08/2018	Scapa beach	Orkney	58.95386	-2.97165	U	No	unknown	Not Examined: Advanced Autolysis
Hg	11/09/2018	Scapa Beach	Orkney	58.95927	-2.97008	U	No	unknown	Not Examined: Advanced Autolysis
Hg	16/10/2018	Newark bay	Orkney	58.92302	-2.74849	U	No	juvenile	Not Examined: Samples Taken
Hg	17/10/2018	Newark bay	Orkney	58.92302	-2.74849	U	No	juvenile	Not Examined: Samples Taken
Hg	20/10/2018	Kettletoft Sanday	Orkney	59.23363	-2.59930	M	No	juvenile	Not Examined: Samples Taken
Hg	02/11/2018	Kettletoft Sanday	Orkney	59.23270	-2.60454	F	No	adult	Not Examined: Samples Taken

Hg	03/11/2018	Skail	Orkney	59.05301	-3.33534	U	No	unknown	Not Examined: Advanced Autolysis
Hg	08/11/2018	Backaskail Sanday	Orkney	59.23628	-2.60812	F	No	adult	Not Examined: Samples Taken
Hg	11/11/2018	Newark bay Deerness	Orkney	58.92391	-2.74850	U	No	pup	Not Examined: Not Priority
Hg	12/11/2018	Newark bay Deerness	Orkney	58.92302	-2.74849	M	No	adult	Not Examined: Samples Taken
Hg	13/11/2018	Stywick Sanday	Orkney	59.23557	-2.56604	M	No	adult	Not Examined: Samples Taken
Hg	04/12/2018	Lairo Water Shapinsay	Orkney	59.05617	-2.85598	U	No	juvenile	Physical Trauma: Possible Grey Seal Attack
Hg	19/11/2018	St. Marys	Orkney	58.89497	-2.91968	U	No	pup	Not Examined: Not Priority
Hg	20/11/2018	Newark Bay Deerness	Orkney	58.92305	-2.74327	U	No	pup	Not Examined: Not Priority
Hg	20/11/2018	Newark Bay Deerness	Orkney	58.92303	-2.74501	U	No	pup	Not Examined: Not Priority
Hg	30/11/2018	Scapa beach	Orkney	58.96192	-2.97535	U	No	pup	Not Examined: Removed by Tide
Hg	01/12/2018	Rackwick Hoy	Orkney	58.86663	-3.38018	U	No	pup	Not Examined: Not Priority
Hg	01/12/2018	Newark Deerness	Orkney	58.92208	-2.75368	U	No	adult	Not Examined: Delay in Reporting
Hg	01/12/2018	Newark Deerness	Orkney	58.92305	-2.74327	U	No	pup	Not Examined: Not Priority
Hg	16/12/2018	Birsay	Orkney	59.13861	-3.30896	U	No	juvenile	Physical Trauma: Possible Grey Seal Attack
Hg	16/12/2018	Sanday	Orkney	59.24361	-2.57493	U	No	juvenile	Physical Trauma: Possible Grey Seal Attack
Hg	26/12/2018	Newark bay Deerness	Orkney	58.92393	-2.74676	U	No	juvenile	Physical Trauma: Possible Grey Seal Attack
Hg	01/12/2018	Newark Deerness	Orkney	58.92208	-2.75368	U	No	pup	Not Examined: Not Priority
Hg	01/12/2018	Newark Deerness	Orkney	58.92127	-2.73977	U	No	pup	Not Examined: Not Priority
Hg	02/12/2018	Sand of Wright South Ronaldsay	Orkney	58.82521	-3.00096	U	No	pup	Not Examined: Not Priority
Hg	02/12/2018	Sand of Wright South Ronaldsay	Orkney	58.82520	-3.00269	U	No	pup	Not Examined: Not Priority
Hg	02/12/2018	Sand of Wright South Ronaldsay	Orkney	58.82610	-3.00099	U	No	adult	Not Examined: Advanced Autolysis
Hg	02/12/2018	Sand of Wright South Ronaldsay	Orkney	58.82431	-3.00094	U	No	pup	Not Examined: Not Priority
Hg	27/12/2018	South Walls Hoy	Orkney	58.78452	-3.22814	U	No	juvenile	Physical Trauma: Possible Grey Seal Attack
Hg	09/12/2018	Rackwick Hoy	Orkney	58.86574	-3.37840	U	No	pup	Not Examined: Insufficient Data
Hg	09/12/2018	Scapa beach	Orkney	58.96191	-2.97710	U	No	unknown	Not Examined: Advanced Autolysis
Hg	10/12/2018	Ness Point Stromness	Orkney	58.95002	-3.30528	U	No	pup	Not Examined: Advanced Autolysis

Hg	27/12/2018	South Walls Hoy	Orkney	58.78464	-3.22641	U	No	juvenile	Physical Trauma: Possible Grey Seal Attack
Hg	10/12/2018	Evie	Orkney	59.12247	-3.11268	U	No	juvenile	Not Examined: Advanced Autolysis
Hg	16/12/2018	Sands of Wright	Orkney	58.82254	-2.99742	M	No	juvenile	Not Examined: Advanced Autolysis
Hg	16/12/2018	St Margaret's Hope	Orkney	58.83625	-2.96489	U	No	juvenile	Not Examined: Advanced Autolysis
Hg	16/12/2018	Hoxa	Orkney	58.82800	-2.98891	U	No	pup	Not Examined: Advanced Autolysis
Hg	16/12/2018	Sands of Wright	Orkney	58.82343	-2.99917	U	No	juvenile	Not Examined: Advanced Autolysis
Hg	16/12/2018	Sands of Wright	Orkney	58.81894	-2.99905	U	No	juvenile	Not Examined: Advanced Autolysis
Hg	16/12/2018	Burray barrier east side	Orkney	58.83939	-2.90434	U	No	juvenile	Not Examined: Advanced Autolysis
Hg	16/12/2018	East side South Ronaldsay	Orkney	58.80156	-2.92066	U	No	juvenile	Not Examined: Advanced Autolysis
Hg	16/12/2018	Sands of Wright	Orkney	58.81894	-2.99905	U	No	juvenile	Not Examined: Advanced Autolysis
Hg	16/12/2018	Sands of Wright	Orkney	58.82163	-2.99912	U	No	juvenile	Not Examined: Advanced Autolysis
Hg	16/12/2018	Sands of Wright	Orkney	58.82164	-2.99740	U	No	juvenile	Not Examined: Not Priority
Hg	16/12/2018	Sands of Wright	Orkney	58.82254	-2.99742	U	No	juvenile	Not Examined: Advanced Autolysis
Hg	16/12/2018	Hoxa	Orkney	58.82883	-2.99587	U	No	juvenile	Not Examined: Advanced Autolysis
Hg	16/12/2018	Hoxa	Orkney	58.82889	-2.98895	U	No	pup	Not Examined: Not Priority
Hg	16/12/2018	St Margaret's Hope	Orkney	58.83560	-2.93197	U	No	juvenile	Not Examined: Advanced Autolysis
Hg	16/12/2018	Hoxa	Orkney	58.82972	-2.99763	U	No	juvenile	Not Examined: Advanced Autolysis
Hg	16/12/2018	Sands of Wright	Orkney	58.82164	-2.99740	U	No	juvenile	Not Examined: Advanced Autolysis
Hg	16/12/2018	Churchill Barrier	Orkney	58.84029	-2.90437	U	No	adult	Not Examined: Advanced Autolysis
Hg	16/12/2018	Hoxa	Orkney	58.82798	-2.99065	U	No	adult	Not Examined: Advanced Autolysis
Hg	16/12/2018	Hoxa	Orkney	58.82972	-2.99936	U	No	juvenile	Not Examined: Advanced Autolysis
Hg	16/12/2018	Sands of Wright	Orkney	58.81985	-2.99735	U	No	juvenile	Not Examined: Advanced Autolysis
Hg	16/12/2018	East side South Ronaldsay	Orkney	58.80156	-2.92066	U	No	pup	Not Examined: Advanced Autolysis
Hg	16/12/2018	Churchill Barrier	Orkney	58.84211	-2.89921	U	No	juvenile	Not Examined: Advanced Autolysis
Hg	16/12/2018	Sands of Wright	Orkney	58.82164	-2.99740	U	No	juvenile	Not Examined: Advanced Autolysis
Hg	16/12/2018	Sands of Wright	Orkney	58.82343	-2.99917	U	No	juvenile	Not Examined: Advanced Autolysis
Hg	16/12/2018	Hoxa	Orkney	58.82795	-2.99410	U	No	juvenile	Not Examined: Advanced Autolysis
Hg	16/12/2018	Burray barrier	Orkney	58.84029	-2.90437	U	No	unknown	Not Examined: Advanced Autolysis
Hg	16/12/2018	East side South Ronaldsay	Orkney	58.80154	-2.92239	U	No	pup	Not Examined: Advanced Autolysis
Hg	16/12/2018	Hoxa	Orkney	58.82889	-2.98895	U	No	pup	Not Examined: Advanced Autolysis
Hg	16/12/2018	Sands of Wright	Orkney	58.82344	-2.99745	U	No	juvenile	Not Examined: Advanced Autolysis

Hg	16/12/2018	Churchill Barrier	Orkney	58.83939	-2.90434	U	No	adult	Not Examined: Advanced Autolysis
Hg	16/12/2018	Churchill Barrier	Orkney	58.84209	-2.90268	U	No	adult	Not Examined: Advanced Autolysis
Hg	30/12/2018	St Magnus Orphir	Orkney	58.91914	-3.15303	U	No	juvenile	Physical Trauma: Possible Grey Seal Attack
Hg	16/12/2018	Sands of Evie	Orkney	59.12074	-3.10564	U	No	adult	Not Examined: Advanced Autolysis
Hg	16/12/2018	St Mary's	Orkney	58.89593	-2.91102	U	No	pup	Not Examined: Advanced Autolysis
Hg	16/12/2018	Sands of Evie	Orkney	59.11815	-3.09333	U	No	pup	Not Examined: Advanced Autolysis
Hg	06/01/2019	Swanbister	Orkney	58.91833	-3.12694	U	No	juvenile	Physical Trauma: Possible Grey Seal Attack
Hg	16/12/2018	Sands of Evie	Orkney	59.12337	-3.11271	U	No	adult	Not Examined: Advanced Autolysis
Hg	17/02/2019	St Mary's	Orkney	58.89111	-2.92306	U	No	juvenile	Physical Trauma: Possible Grey Seal Attack
Hg	17/12/2018	Eastside beach South Ronaldsay	Orkney	58.79339	-2.93257	U	No	pup	Not Examined: Advanced Autolysis
Hg	17/12/2018	Whale sand Westray	Orkney	59.27192	-2.95439	U	No	pup	Not Examined: Advanced Autolysis
Hg	17/12/2018	Kirbister bay	Orkney	58.94130	-3.08251	U	No	juvenile	Not Examined: Advanced Autolysis
Hg	19/12/2018	Scapa beach	Orkney	58.96277	-2.98060	F	No	juvenile	Not Examined: Samples Taken
Hg	18/11/2018	Backaskail beach Sanday	Orkney	59.23891	-2.62219	U	No	pup	Physical Trauma: Possible Grey Seal Attack
Hg	20/12/2018	Dingieshowe	Orkney	58.91565	-2.77957	U	No	adult	Not Examined: Advanced Autolysis
Hg	20/12/2018	Dingieshowe	Orkney	58.91565	-2.77957	U	No	pup	Not Examined: Advanced Autolysis
Hg	20/12/2018	Dingieshowe	Orkney	58.91565	-2.77957	U	No	unknown	Not Examined: Advanced Autolysis
Hg	01/12/2018	Newark Deerness	Orkney	58.92210	-2.75194	U	No	pup	Physical Trauma: Possible Grey Seal Attack
Hg	21/12/2018	Newark bay Deerness	Orkney	58.92300	-2.75195	U	No	juvenile	Not Examined: Advanced Autolysis
Hg	21/12/2018	Newark bay Deerness.	Orkney	58.92300	-2.75195	U	No	juvenile	Not Examined: Advanced Autolysis
Hg	21/12/2018	Ness road Stromness	Orkney	58.95547	-3.30028	U	No	pup	Not Examined: Advanced Autolysis
Hg	23/12/2018	Glims Holm	Orkney	58.87708	-2.90879	U	No	unknown	Not Examined: Weather/travel difficulties
Hg	26/12/2018	Newark bay Deerness	Orkney	58.92391	-2.74850	U	No	adult	Not Examined: Advanced Autolysis
Hg	26/12/2018	Newark bay Deerness	Orkney	58.92391	-2.74850	U	No	juvenile	Not Examined: Advanced Autolysis
Hg	26/12/2018	Newark bay Deerness	Orkney	58.92393	-2.74676	U	No	adult	Not Examined: Advanced Autolysis
Hg	20/12/2018	Dingieshowe	Orkney	58.91565	-2.77957	U	No	pup	Physical Trauma: Possible Grey Seal Attack
Hg	26/12/2018	Newark bay Deerness	Orkney	58.92393	-2.74676	U	No	adult	Not Examined: Advanced Autolysis

Hg	27/12/2018	South Walls Hoy	Orkney	58.78364	-3.22638	U	No	juvenile	Not Examined: Carcase Incomplete/Scavenger Damage
Hg	08/02/2019	Balfour Shapinsay	Orkney	59.03556	-2.90306	U	No	pup	Physical Trauma: Possible Grey Seal Attack
Hg	27/12/2018	South Walls Hoy	Orkney	58.78422	-3.21982	U	No	pup	Not Examined: Advanced Autolysis
Hg	01/12/2018	Newark Deerness	Orkney	58.92300	-2.75195	U	No	unknown	Physical Trauma: Possible Grey Seal Attack
Hg	27/12/2018	Tankerness	Orkney	58.91472	-2.78476	U	No	pup	Not Examined: Advanced Autolysis
Hg	30/12/2018	St Magnus Orphir	Orkney	58.91914	-3.15303	F	No	juvenile	Not Examined: Samples Taken
Hg	01/12/2018	Newark Deerness	Orkney	58.92127	-2.73977	U	No	unknown	Physical Trauma: Possible Grey Seal Attack
Hg	31/12/2018	Ophir	Orkney	58.92091	-3.15655	U	No	unknown	Not Examined: Advanced Autolysis
Hg	10/12/2018	Evie	Orkney	59.12247	-3.11268	U	No	unknown	Physical Trauma: Possible Grey Seal Attack
Hg	16/12/2018	Sands of Evie	Orkney	59.12076	-3.10214	U	No	unknown	Physical Trauma: Possible Grey Seal Attack
Hg	20/12/2018	Dingieshowe	Orkney	58.91565	-2.77957	U	No	unknown	Physical Trauma: Possible Grey Seal Attack
Hg	06/01/2019	Swanbister	Orkney	58.91806	-3.12694	M	No	juvenile	Not Examined: Advanced Autolysis
Hg	06/01/2019	Swanbister	Orkney	58.91861	-3.12611	U	No	juvenile	Not Examined: Advanced Autolysis
Hg	07/01/2019	Warbeth beach Orkney	Orkney	58.95889	-3.33167	M	No	juvenile	Not Examined: Morphometrics taken
Hg	09/01/2019	Churchill Barrier 3 Glims Holm Burray.	Orkney	58.86861	-2.91389	U	No	juvenile	Not Examined: Carcase Unrecoverable
Hg	12/01/2019	Geo slipway Deerness	Orkney	58.92167	-2.75278	U	No	unknown	Not Examined: Advanced Autolysis
Hg	13/01/2019	Evie beach	Orkney	59.12194	-3.10472	U	No	juvenile	Not Examined: Morphometrics taken
Hg	18/01/2019	Grobost Westray	Orkney	59.33000	-3.00444	U	No	unknown	Not Examined: Advanced Autolysis
Hg	05/01/2019	Rackwick Hoy.	Orkney	58.86750	-3.38194	U	No	unknown	Physical Trauma: Possible Grey Seal Attack
Hg	15/01/2019	Tankerness Orkney	Orkney	58.91611	-2.77806	U	No	unknown	Physical Trauma: Possible Grey Seal Attack
Hg	18/02/2019	Brough of Birsay	Orkney	59.13556	-3.32528	U	No	unknown	Not Examined: Advanced Autolysis
Hg	06/03/2019	The Riv Sanday	Orkney	59.30389	-2.54250	U	No	adult	Not Examined: Samples Taken
Hg	24/03/2019	St. Magnus Kirk Birsay	Orkney	59.12944	-3.31722	U	No	juvenile	Not Examined: Advanced Autolysis

Table 2.B. Summary of seal carcasses reported to SMASS between March 2018 and February 2019 in Kintyre and Clyde area. Pv = Harbour seal, Hg = Grey seal, Unk = unknown seal species.

Species	Date	Location	Area	Latitude	Longitude	Sex	Post-mortem	Age Group	Findings
Unk	03/03/2019	Blackwatersfoot Arran	North Ayrshire	55.50083	-5.33417	U	No	pup	Not Examined: Advanced Autolysis
Unk	01/04/2018	Near the Doon Fort Blackwaterfoot Arran.	North Ayrshire	55.51247	-5.35134	U	No	unknown	Not Examined: Insufficient Data
Pv	28/07/2018	Kilmory beach Isle of Arran	North Ayrshire	55.4374	-5.23426	U	No	unknown	Not Examined: Advanced Autolysis
Pv	04/10/2018	Dougarie Arran	North Ayrshire	55.57616	-5.35677	U	No	juvenile	Not Examined: Advanced Autolysis
Pv	28/10/2018	Drumadoon Point Arran	North Ayrshire	55.50696	-5.35562	U	No	unknown	Not Examined: Weather/travel difficulties
Pv	17/12/2018	Lochranza Arran	North Ayrshire	55.70829	-5.29166	U	No	unknown	Not Examined: Weather/travel difficulties
Hg	04/11/2018	Machrihanish	Argyll and Bute	55.42607	-5.72664	M	No	adult	Not Examined: Samples Taken
Hg	23/11/2018	Machrihanish Beach	Argyll and Bute	55.42324	-5.73111	U	No	adult	Not Examined: Advanced Autolysis
Hg	19/09/2018	Carskay beach Southend	Argyll and Bute	55.30796	-5.6777	U	No	juvenile	Not Examined: Samples Taken
Hg	23/03/2019	Cretshengan	Argyll and Bute	55.83667	-5.66222	U	No	juvenile	Not Examined: Advanced Autolysis
Hg	31/12/2018	Machrihanish	Argyll and Bute	55.42295	-5.74057	U	No	pup	Not Examined: Advanced Autolysis
Hg	09/12/2018	Muasdale Kintyre	Argyll and Bute	55.63073	-5.6793	U	No	unknown	Physical Trauma: Possible Grey Seal Attack

Table 2.C. Summary of seal carcasses reported to SMASS between March 2018 and February 2019 in Isle of Skye. Pv = Harbour seal, Hg = Grey seal, Unk = unknown seal species

Species	Date	Location	Area	Latitude	Longitude	Sex	Post-mortem	Age Group	Findings
Unk	08/08/2018	Smugglers bay Strome.	Skye	57.35849	-5.56789	U	No	pup	Not Examined: Insufficient Data
Unk	28/05/2018	Kilbride beach Skye	Skye	57.19972	-6.00313	U	No	unknown	Not Examined: Advanced Autolysis
Unk	31/10/2018	Ullinish Skye	Skye	57.34363	-6.45626	U	No	unknown	Not Examined: Advanced Autolysis
Unk	10/08/2018	Ardaneaskan	Skye	57.35561	-5.60588	U	No	unknown	Not Examined: Insufficient Data
Pv	12/03/2018	Balmacara	Skye	57.28600	-5.65053	U	No	adult	Not Examined: Carcase Incomplete/Scavenger Damage
Pv	18/02/2019	Camus Ban Harlosh Skye.	Skye	57.38167	-6.51778	U	No	juvenile	Physical Trauma: Possible Grey Seal Attack
Pv	17/07/2018	near Ashaig Skye.	Skye	57.25598	-5.81345	F	Yes	neonate	Maternal Separation/Starvation
Pv	28/07/2018	Ashaig Skye	Skye	57.25597	-5.84332	U	No	pup	Not Examined: Advanced Autolysis
Pv	28/07/2018	Ashaig Skye.	Skye	57.25597	-5.84332	U	No	pup	Not Examined: Advanced Autolysis
Pv	18/06/2018	Achintraid Loch Kishorn	Skye	57.38430	-5.60869	U	No	pup	Not Examined: Insufficient Data
Pv	04/07/2018	Kyleakin Skye	Skye	57.27440	-5.73901	U	No	unknown	Not Examined: Advanced Autolysis
Pv	26/07/2018	Between Kyle of Lochalsh and Balmacara	Skye	57.28108	-5.66498	U	No	unknown	Not Examined: Advanced Autolysis
Pv	16/08/2018	Near Coroghan Castle Canna	Skye	57.05910	-6.48974	U	No	unknown	Not Examined: Advanced Autolysis
Pv	12/09/2018	Ardarroch	Skye	57.39449	-5.59805	U	No	unknown	Not Examined: Advanced Autolysis
Pv	05/10/2018	Achnacloich Skye.	Skye	57.10847	-5.98830	U	No	unknown	Not Examined: Advanced Autolysis
Pv	14/03/2019	West Suisnish Raasay.	Skye	57.33833	-6.06833	U	No	unknown	Physical Trauma: Possible Grey Seal Attack
Pv	17/03/2019	Clachan Raasay	Skye	57.35194	-6.08222	U	No	unknown	Physical Trauma: Possible Grey Seal Attack
Unk	08/08/2018	Smugglers bay Strome.	Skye	57.35849	-5.56789	U	No	pup	Not Examined: Insufficient Data

References

Arso Civil, M., Smout, S., Duck, C., Morris, C., Cummings, C., Langley, I., Law, A., Morton, C., Brownlow, A., Davison, N., Doeschate, M., Lacaze, J.-P., McConnell, B., Hall, A., 2018. *Harbour Seal Decline - vital rates and drivers. Report to Scottish Government HSD2*. Sea Mammal Research Unit, University of St Andrews, pp 63.

Arso Civil, M., Smout, S., Onoufriou, J., Thompson, D., Brownlow, A., Davison, N., Duck, C., Morris, C., Cummings, C., Pomeroy, P.P., McConnell, B., Hall, A., 2016. *Harbour Seal Decline - vital rates and drivers, Report to Scottish Government HSD2*. Sea Mammal Research Unit, University of St Andrews, pp 64.

Bache, S.M., Wickham, H., 2014. magrittr: A forward-pipe operator for R. Retrieved from https://CRAN.R-project.org/package=magrittr.

Bowen, W.D., Ellis, S.L., Iverson, S.J., Boness, D.J., 2003. Maternal and newborn life-history traits during periods of contrasting population trends: implications for explaining the decline of harbour seals (*Phoca vitulina*), on Sable Island. *Journal of Zoology,* **261**, 155-163.

Caillat, M., Cordes, L., Thompson, P.M., Matthiopoulos, J., Smout, S., 2019. Use of state-space modelling to identify ecological covariates associated with trends in pinniped demography. *Aquatic Conservation: Marine and Freshwater Ecosystems,* **29**(S1), 101-118.

Caillat, M., Smout, S., 2015. *Harbour seal decline: Population modelling*. Sea Mammal Research Unit, University of St Andrews, Report to Scottish Government no. CSD 4, pp, 29.

Caswell, H., 2001. *Matrix population models - construction, analysis, and interpretation*, 2nd Edition ed. Sinauer Assoc., Inc., Publishers, Sunderland, MA.

Chandler, R.B., Clark, J.D., 2014. Spatially explicit integrated population models. *Methods in Ecology and Evolution* **5**, 1351-1360.

Cordes, L.S., Thompson, P.M., 2014. Mark-recapture modeling accounting for state uncertainty provides concurrent estimates of survival and fecundity in a protected harbor seal population. *Marine Mammal Science*, **30**, 691-705.

Cunningham, L., 2009. Using computer-assisted photo-identification and capture-recapture techniques to monitor the conservation status of harbour seals (*Phoca vitulina*). *Aquatic Mammals,* **35**, 319-329.

Gosling, J.P., 2018. *SHELF: The Sheffield Elicitation Framework*, in: L.C. Dias, A. Morton, J. Quigley (Eds.), Elicitation: The Science and Art of Structuring Judgement. Springer International Publishing, Cham, 61-93.

Grolemund, G., Wickham, H., 2011. Dates and times made easy with lubridate. *Journal of Statistical Software* **40**, 1-25.

Hall, A., Kershaw, J., 2012. *Review of the status, trends and potential causes for the decline in abundance of harbour seals around the coast of Scotland*. Sea Mammal Research Unit. Marine Mammal Scientific Support Research Programme MMSS/001/11.

Hall, A.J., Frame, E., 2010. Evidence of domoic acid exposure in harbour seals from Scotland: a potential factor in the decline in abundance? *Harmful Algae,* **9**, 489-493.

Jensen, S.K., Lacaze, J.P., Hermann, G., Kershaw, J., Brownlow, A., Turner, A., Hall, A., 2015. Detection and effects of harmful algal toxins in Scottish harbour seals and potential links to population decline. *Toxicon* **97**, 1-14.

Jones, A.W., 2006. Urine as a biological specimen for forensic analysis of alcohol and variability in the urine-to-blood relationship. *Toxicological reviews,* **25**, 15-35.

Leslie, P.H., 1945. On the use of matrices in certain population mathematics. *Biometrika*, **33**, 183-212.

Leslie, P.H., 1948. Some Further Notes on the Use of Matrices in Population Mathematics. *Biometrika*, **35**, 213-245.

Lonergan, M., Duck, C., Moss, S., Morris, C., Thompson, D., 2013. Rescaling of aerial survey data with information from small numbers of telemetry tags to estimate the size of a declining harbour seal population. *Aquatic Conservation: Marine and Freshwater Ecosystems* **23**, 135-144.

Lonergan, M., Duck, C., Thompson, D., Mackey, B., Cunningham, L., Boyd, I., 2007. Using sparse survey data to investigate the declining abundance of British harbour seals. *Journal of Zoology,* **271**, 261-269.

Mackey, B.L., Durban, J.W., Middlemas, S.J., Thompson, P.M., 2008. A Bayesian estimate of harbour seal survival using sparse photo-identification data. *Journal of Zoology*, **274**, 18-27.

Matthiopoulos, J., Cordes, L., Mackey, B., Thompson, D., Duck, C., Smout, S., Caillat, M., Thompson, P., 2014. State-space modelling reveals proximate causes of harbour seal population declines. *Oecologia,* **174**, 151-162.

Müller, K., Wickham, H., 2019. tibble: Simple Data Frames. Retrieved from https://CRAN.R-project.org/package=tibble.

Oakley, J., 2018. SHELF: Tools to support the Sheffield Elicitaion Framework. Retrieved from https://github.com/OakleyJ/SHELF.

Pallin, L., Robbins, J., Kellar, N., Bérubé, M., Friedlaender, A., 2018. Validation of a blubber-based endocrine pregnancy test for humpback whales. *Conservation Physiology*, **6**(1), COY31.

Pizzo, F., Caloni, F., Schreiber, N.B., Schutz, L.F., Totty, M.L., Albonico, M., Spicer, L.J., 2015. Direct effects of the algal toxin, domoic acid, on ovarian function: Bovine granulosa and theca cells as an in vitro model. *Ecotoxicology & Environmental Safety,* **113**, 314-320.

R Core Team, 2018. R: A language and environment for statistical computing. R Foundation for Statistical Computing. R Foundation for Statistical Computing, Vienna, Austria. URL https://www.R-project.org/.

SCOS. *Scientific advice on matters related to the management of seal populations*: 2017. Natural Environmental Research Council, Sea Mammal Research Unit. University of St Andrews, St Andrews.

SMRU Consulting, 2018. Probabilistic Judgements for Expert Elicitation. Retrieved from http://www.smruconsulting.com/online-elicitation-training/.

Sparling, C.E., Fedak, M.A., Thompson, D., 2007. Eat now, pay later? Evidence of deferred food-processing costs in diving seals. *Biology Letters,* 3, 94-98.

Thompson, D., Duck, C., Morris, C., Russell, D.J.F., 2019. The status of harbour seals (*Phoca vitulina*) in the United Kingdom. *Aquatic Conservation: Marine and Freshwater Ecosystems*, 29(S1), 40-60.

Wickham, H., 2016. *ggplot2: Elegant Graphics for Data Analysis*. Springer-Verlag New York.

Wickham, H., Bryan, J., 2019. readxl:Read Excel Files. Retrieved from https://CRAN.R-project.org/package=readxl.

Wickham, H., Francois, R., Henry, L., Müller, K., 2017. dplyr: A Grammar of Data Manipulation. R package version 0.8.0.1. Retrieved from https://CRAN.R-project.org/package=dplyr.

Wickham, H., Henry, L., 2019. tidyr: Easily Tidy Data with “spread()” and “gather()” Functions. Retrieved from https://CRAN.R-project.org/package=tidyr.