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Harbour Seal Decline HSD2

Annual Report

Harbour seal decline – vital rates and drivers

Sea Mammal Research Unit
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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 have 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 needs 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.

Previous work by Matthiopoulos *et al.* (2014) and Caillat and Smout (2015) developed and fitted an age-structured population model to data from the well-studied subpopulation of harbour seals in Loch Fleet (Moray Firth), to evaluate the contributions of different potential proximate causes to the observed decline. After reviewing the existing software, this model has been re-coded directly into R, a framework that will allow for future development and maintenance, and has been designed to be adapted to different model structures and future data sets. Preliminary results are consistent with those obtained from the original OpenBUGS modelling. Future work will have as its key objective the identification of the important drivers of population change in harbour seals, from those being studied as listed above. Temporal and spatial variation in these drivers will be incorporated into the population model.

Harbour seal haulout sites located in different regions of Scotland were visited in the spring and the summer of 2015 to collect information on their suitability for long-term monitoring of harbour seal populations, including their suitability for live captures, scat sampling, aerial and ground survey counts during pupping and moulting and photo-identification. This will allow empirical data to be collected and vital rates (fecundity and survival) to be estimated, for inclusion in the population model.

A haulout site located in West Burray (Orkney) has been selected to represent a region of decline, and a haulout site by Peninver (East Kintyre) has been selected to represent a region of stability or increase. In addition, photo-identification data will also be collected in Dunvegan Loch (Isle of Skye). The regional scope of local populations at each study site (Orkney, Kintyre and Isle of Skye) has been defined to direct future collation of any relevant environmental and biological data. Existing aerial survey counts of harbour and grey seals at each of the defined areas have been collated for use in the age-structured population model.

As part of the live captures programme, female harbour seals will be fitted in 2016 with low-cost electronic location tags, developed to allow a larger number of captured seals to be tagged and designed to regularly relay GPS locations from terrestrial locations. Data from these tags and from ten SMRU GPS/GSM phone tags will inform and direct the extent of the photo-identification re-sighting effort at haulout sites in 2016.

Domoic acid (DA) concentrations have been measured in urine and faecal samples collected from harbour seals in 2015, as a continuation of the work carried out by Jensen *et al.* (2015). DA is still being found in harbour seals around the Scottish coast and whilst concentrations vary between the different matrices (blood, faeces and urine) and samples, due to variation in exposure and time from uptake to excretion, some individuals appear to be consuming relatively high levels of toxin. Data from the monitoring of biotoxins in shellfish by the Centre for Fisheries and Aquaculture Science (Cefas) and Harmful Algal Blooms (HABs) by the Scottish Association for Marine Science (SAMS) were available for all of 2015 and January 2016. These datasets provide some indication of the occurrence of HABs and toxin-producing blooms in the regions of interest.

To further improve understanding of potential drivers of population change, initial contacts have been made to investigate the availability of prey samples relevant to seals foraging from the study sites, as well as the availability of prey abundance data from long-term fish surveys in the different regions of interest.

An update is provided on the current state of knowledge of the causes of spiral lacerations in seals based on necropsy results of stranded individuals since November 2014. Occurrences around Scotland are summarised along with objective assessments of the cause of the wound patterns, based on a weighted scoring system.

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1 Introduction

The UK is home to around 30% of Europe's harbour (or common) seals (*Phoca vitulina*), with Scotland holding 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, 2014).

In Scotland, the Marine (Scotland) Act (2010) prohibits the taking of seals except under licence granted by the Scottish Government for the explicit protection of fisheries or aquaculture activities, or for scientific and welfare reasons. Harbour seals are also 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 at any of the 194 seal 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), which has continued in some of the surveyed regions. The decline is more apparent for the east and north coast of Scotland and in the Northern Isles, with declines by around 95% in the Tay estuary (east coast), 75% in Orkney and 30% in Shetland, compared to counts in 2000. In contrast, populations on the west coast and in the Western Isles are either stable or increasing (SCOS, 2014). Most importantly, the decline in seal counts are likely to represent real reductions in the numbers present in those regions rather than 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).

In order to determine the management and mitigation options to address this situation, the relative contribution of various factors potentially involved in the dramatic decline in the abundance of harbour seals in Scotland 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). Thus, 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). At present, life history information for harbour seals in Scotland is available only from Loch Fleet and the Moray Firth (Mackey *et al.*, 2008, Cordes and Thompson, 2013a), but is completely lacking from other regions in Scotland. Survival and fecundity rates were 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 natural and or anthropogenic 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. Thus 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 subpopulation of harbour seals in Loch Fleet (Moray Firth), to evaluate the contributions of different proximate causes to the observed decline. Further work by Caillat and Smout (2015) saw improvements to this baseline model, including an improved treatment of seasonal haulout 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.

A summary of the work carried out by the Sea Mammal Research Unit under the Marine Mammal Scientific Support Research Programme MMSS/02/15 during the year April 2015 to March 2016 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.

And 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 1 under each approach are detailed in Appendix 1.

This report includes progress on each of the approaches within the Task for Year 1, except for approach three, which will not start until Year 2 of the project.

2 Approach 1. Integrated population model

In a previous study (Matthiopoulos *et al.*, 2014), an age-structured population model was created and fitted to data from one well-studied system in the Moray Firth area. The model assumed a closed population, included sex-and-age-dependent fecundity and survival rates, and also allowed for the effects of time and population size on those rates (i.e. the model allowed for density-dependent effects in this population). The effect of shooting on the local population was also included. A Bayesian hidden-process methodology was used to fit the model, allowing for uncertainties in observations (such as variations in haulout probability) and in the demographic birth/death processes themselves (Newman *et al.*, 2006). Further work by Caillat and Smout (2015) saw the improvements to this baseline model, including an improved treatment of seasonal haulout probabilities.

Original model development (Matthiopoulos *et al.*, 2014; Caillat and Smout, 2015) was carried out using the freely-available software OpenBUGS (Lunn *et al.*, 2009). This framework is well suited to the treatment of hidden-process models, and has the great advantage that models can be developed and shared by different users using a common language and the now-considerable supporting literature of textbooks and papers. However, the complex Moray Firth model with its large and diverse data sets was challenging to implement and modify in OpenBUGS. Problems occurred at three levels (i) coding errors not detected by the OpenBUGS compiler might cause models to fail, and given the complexity of the model, these errors were sometimes difficult to detect, (ii) when running the model, numerical errors generated by internal routines often occurred and had to be addressed by trial-and-error methods e.g. stepwise resetting of initial values – a very time-consuming process for the developer, (iii) some models ran, but would not converge within a reasonable time period. In order to address these difficulties, it was decided to re-code the model into a framework that will allow the best possibilities for future development and maintenance so that the modelling can be adjusted to suit the needs of the harbour seal decline project over the coming years. Ultimately it is hoped that this work will allow for the better exploration of biological questions but initially the focus has been methodological, aiming to provide efficient and adaptable software for the project.

2.1 Methods

2.1.1 Review of existing software

The freely-available JAGS software (Plummer, 2003) has a similar syntax to OpenBUGS and is similarly well suited to implement hidden process models. However, it is also a ‘black box’ package that seems likely to present similar problems to OpenBUGS when difficulties are encountered in de-bugging code or data. Some R packages now exist for running Bayesian models. There are specialist examples for time series data (e.g. msm) and some more general packages using MCMC (e.g. mcmc, MCMCpack) which will work very effectively for parameter estimation in simpler models, but these are not well adapted for implementing a hidden process model where the hidden states must be estimated and updated along with the parameters. It was therefore decided to code the model directly into R, with customised MCMC code written for this example but designed to be adapted to different model structures and future data sets.

2.1.2 R-coding

The model was coded in R, using a Metropolis Hastings sampler to explore the posterior distribution of parameters and states. The underlying population model equations and structure are closely based on the existing implementation (Matthiopoulos *et al.*, 2014) but for clarity, a full account of the model equations describing population dynamics and observation processes is given here in Appendix 2. Prior distributions are given in Appendix 3 and the survey data set is included in Appendix 4. Help files and R code for implementing the baseline model are in Appendices 5 and 6.

2.2 Results

The model converged after approximately 100,000 iterations (10 hrs on an I7 computer), though mixing of the time-series of hidden states was not very satisfactory with low acceptance rates (Figure 1).

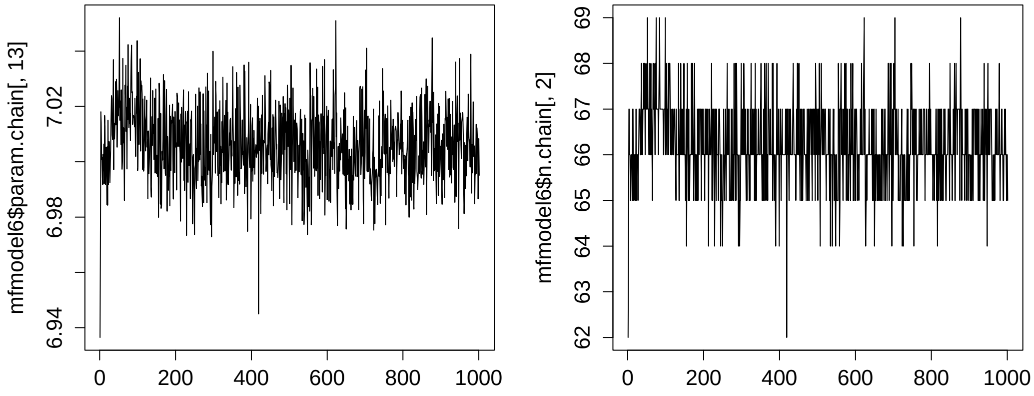


Figure 1. Examples of Markov chain showing satisfactory mixing of general parameters (left panel) but poor mixing of the hidden states (right panel).

Results presented here therefore are preliminary. Figure 2 shows population size, and time-series survival rates.

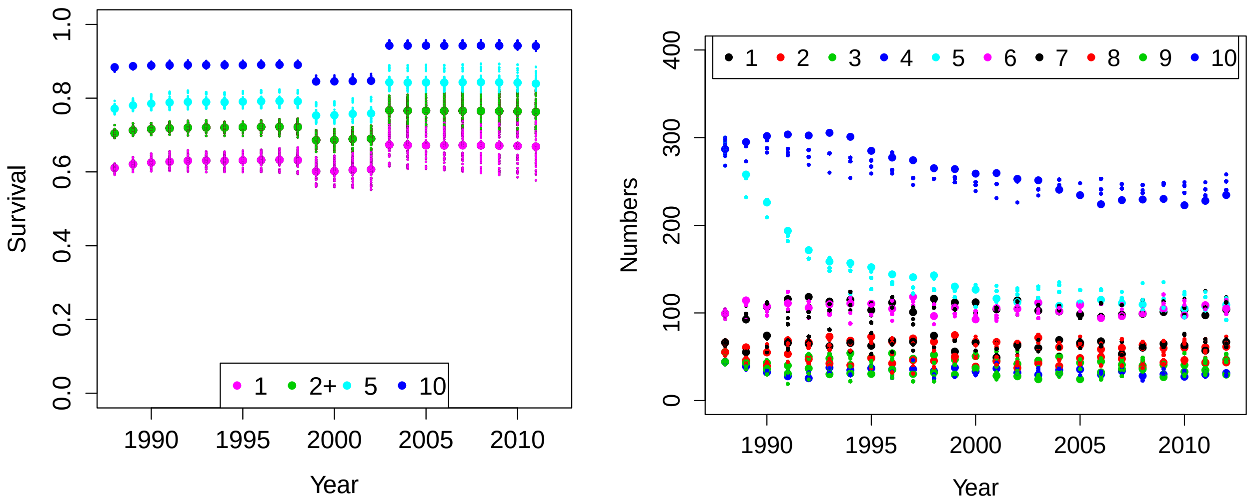


Figure 2. Time-dependent survival rates (left panel) by age category, where category 1 are pups, 2+ are juveniles, 5 are adult males and 10 are adult females. The right hand panel shows estimated numbers-at-age with the same age categories.

These trends are consistent with those obtained from the original OpenBUGS modelling, e.g. it is clear that shooting had an important impact on the population, resulting in substantially increased mortality in all age classes. There is also a general trend that fecundity appears to have increased with time, the reasons for which are not known. The initial apparent decline in numbers of adult males in the population might be a result of incorrect assumptions about the initial population structure, and this will be further investigated.

2.3 Future model development

Future work will have as its key objective the identification of important drivers of population change in harbour seals. Temporal and spatial variation in these drivers will be incorporated into the population model.

- Methodological improvements are still needed to improve the mixing of the chain of hidden states; alternative methods, especially changes to the proposal distributions, will be explored.

- Within the Moray Firth site, previous work using OpenBUGS suggests that temporal variation in grey seal abundance and sandeel abundance impacts harbour seal populations, and these conclusions will be tested also using the R framework.
- The likely utility of the hidden state model framework for data-sparse sites will be explored using existing data sets, to investigate how far useful conclusions might be drawn from limited data at such sites in order that the best possible use is made of new data collected within the project as a whole.
- Part of the model comprises a simulation function that predicts population size and structure, given starting values and population parameters. This can be used to test hypotheses for other local harbour seal populations where information about vital rates is limited, but plausible ranges of these rates can be suggested from data or expert opinion.

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

3.1 Trial sites visited in 2015

Fieldwork was conducted during the spring and the summer of 2015 to identify suitable study sites for long-term studies in HSD2. Visited sites were selected based on data from the August moult aerial surveys collected by SMRU on an annual basis (i.e. aerial photographs of haulout sites and counts of seals) (e.g. Duck *et al.*, 2014), to meet the following criteria:

- Tens of seals are present at the haulout at most low tides;
- Haulout is representative of surrounding region with regard to population trends;
- No other significant haulout sites are present within a few km;
- Seals are generally visible from the side;
- Seals are visible from one (or two close) observation points;
- The position of the seals is not dependent on wind direction (e.g. never hidden on the other side of a skerry);
- Seals are located at a distance which allows the collection of photographs for individual identification (ideally within 200 m);
- Observation point(s) are within manageable walking distance of nearest road;
- Haulout used for pupping and moulting;
- Haulout site suitable for live captures.

Based on the criteria described above, an initial list of 177 trial sites were selected at locations along the Scottish shoreline. Fieldwork was conducted between 30th May and 23rd July 2015 by four different teams of observers in seven different study sites (Shetland, Orkney, North Mainland, NW Mainland, Isle of Skye, West Mainland and the East Coast). Each team was provided with (1) detailed OS maps; (2) daily log-book; (3) binoculars and camera equipment; (4) count data forms; and (5) haulout description data forms.

A total of 112 trial sites were visited in 2015 (see Table 1 and Figure 3), of which 12 were not accessible by foot and thus no data were collected from these sites. Sites that were not visited at all were those that would have proved logistically difficult to access (e.g. on the Outer Hebrides, smaller islands or sites that could not be reached by foot based on the OS maps) or could not be visited due to weather and time constraints.

Table 1. Summary of the number of trial sites visited in 2015.

Study Area	No. visited sites
East Coast	4
North Mainland	7
NW Mainland	9
Orkney Islands	36
Shetland Islands	25
Isle of Skye	12
West Coast Mainland	19
Total	**112**

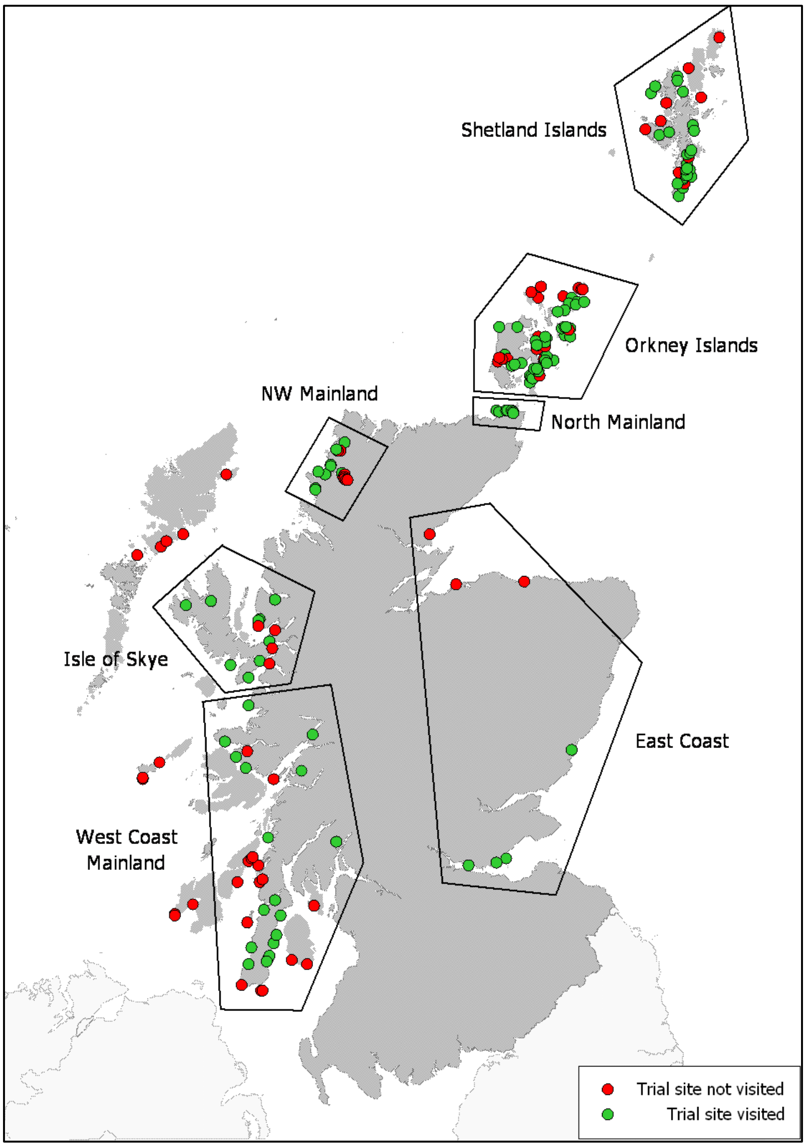


Figure 3. Map showing the sites that were visited (green) or not visited (red) at the different study areas.

After collating all the information recorded at each of the visited sites, all potential study sites were ranked using the following criteria below, in order to select those suitable for long-term intensive studies under the project HSD2:

- harbour seals moult and breed at the same site;
- site is logistically accessible;
- there are sufficient animals to allow for robust estimation of population parameters;
- the site is suitable for photography using digi-scoping and/or Unmanned Aerial Vehicle (UAV);
- the site is accessible for scat collection;
- adjacent grey seal populations, if there are any, are countable;
- live captures of harbour seals can be carried out at the site;
- harbour seals can be observed without undue disturbance;
- the site can be monitored so that any carcasses can be collected for necropsy;
- there is good visibility of females during breeding, for estimation of fecundity.

The visited sites differed by which and how many of the above listed criteria they met. For example, some sites might be easy to access from land, but may not be a breeding site or not enough seals are present to allow for robust estimation of population parameters.

To choose a study site representing a region of population decline, sites located in Orkney, Shetland and North Mainland were considered (Figure 3) (see SCOS 2014 for details on population trajectories in different regions). After internal discussions, it was decided that the selected site representing a region of decline would be the haulout located on West Burray, (Langa Taing) Orkney (58°50'57"N 2°57'46"W) (Table 2). This site was chosen over others in Orkney for its easy access, being a breeding site with high enough numbers of animals observed (the highest compared to any other visited Orkney site), and its suitability for conducting live captures, scat sampling and photo-identification data collection. Its location in Scapa Flow also offers advantages when defining the regional scope of the local population (see section 5.1). Some of the visited sites in Shetland had similar characteristics, however, it was decided to select a site in Orkney because the population declining trend for this region is more apparent than for Shetland, and because there is a longer-term dataset on aerial survey counts of harbour and grey seals for Orkney than for Shetland, which will be beneficial for fitting the population dynamics model from Approach 1.

Visited sites from regions of stability or increase were located in NW mainland, Isle of Skye and the West Coast mainland (Figure 3). In general, these sites were more difficult to access from land than sites in Orkney and Shetland, and many sites were located on skerries too far from land to obtain individual photographs of seals using digi-scoping, e.g. sites in NW end of Isle of Skye or at Applecross. Also, in many cases, haulout sites would be composed of a series of rocks or small skerries distributed in such way that only a small proportion of the hauled out seals would be visible to the observer accessing the site from land (e.g. sites in Arisaig and Mallaig). Again, after consideration, it was decided that the selected site representing a region of stability or increase would be Yellow Rock in East Kintyre in the West Coast (55°27'41"N 5°32'30"W). This site is extremely easy to access, is suitable for scat sampling and photo-identification data collection, has a reasonable number of seals during the moult and breeding seasons and seems suitable for live captures.

Ground counts, photo-identification data and scat samples will be collected at each of these two main sites. Live captures will only be conducted at the Orkney site for 2016 and will be on hold for East Kintyre until the presence of pups is confirmed in 2016. Additionally, photo-identification data will also be collected at Dunvegan, Isle of Skye (57°27'0.53"N 6°35'56.79"W) using the well-established seal tour boats operated from Dunvegan Castle. Scat collection will also continue at Kinghorn, Kirkcaldy, East Coast (56° 4'57.58"N 3° 9'31.74"W), where additional photo-identification may be collected depending on availability of photographic equipment and personnel.

Table 2. Trial sites selected to conduct fieldwork in 2016 with details on the type of data collection planned at each site.

Study area	**Study sites**	**Photos**	**Scat**	**Live captures**
West Coast - Kintyre	4 – Yellow Rock	yes	yes	To decide in 2017
Orkney Islands – Scapa Flow	88 – West Burray	yes	yes	yes – 2016
East Coast – Firth of Forth	155 – Kinghorn, Kirkcaldy	maybe	yes	No
West Coast – Isle of Skye	168 - Dunvegan	yes	no	No

3.2 Data collection in 2015

Data collected at the visited trial sites in 2015 included ground counts, presence of pups and pregnant females, photographs for identification of individual seals, and scat samples for toxicology and diet analysis.

3.2.1 Ground counts

In total, 238 ground counts were made at 100 different trial sites, in all seven study areas. On 21 occasions (9%) no seals were found when visiting a haulout (onshore or in the water). On another 15 occasions (6%) only grey seals were observed, on 117 occasions (50%) only harbour seals were observed, and on 85 occasions (35%) both species were observed. The number of adult (i.e. non pup) harbour seals observed ranged between 1 and 79 seals (mean = 10 seals) with the largest numbers observed in Isle of Skye (see Figure 4).

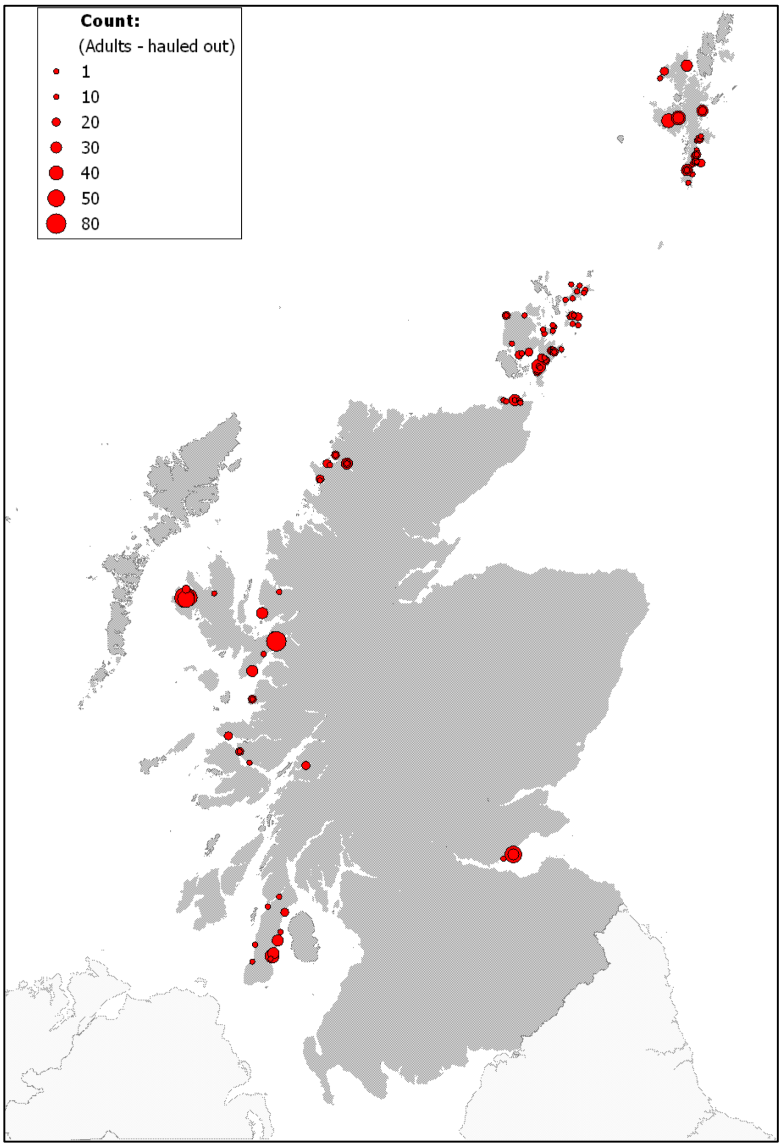


Figure 4. Number of adult harbour seals counted at the visited haulout sites in 2015.

3.2.2 Presence of pups and pregnant females

The presence of pups and pregnant females was recorded at each of the visited sites in order to provide information about the haulout usage for breeding by harbour seals. Out of the 100 trial sites visited, pups were observed in 48 sites (43%). At another 45 sites (40%) no pups were observed, but pregnant females were present at 11 of those sites (Figure 5). For the remaining 19 sites (17%), either no seals were observed at all or no observations were made due to the impossibility of accessing the site.

Out of the 238 ground counts recorded, pups were present on 125 occasions. Pregnant females were recorded on 34 occasions, in which pups were also present on 12 occasions. The number of pups observed in any one haulout ranged between 1 and 14 pups.

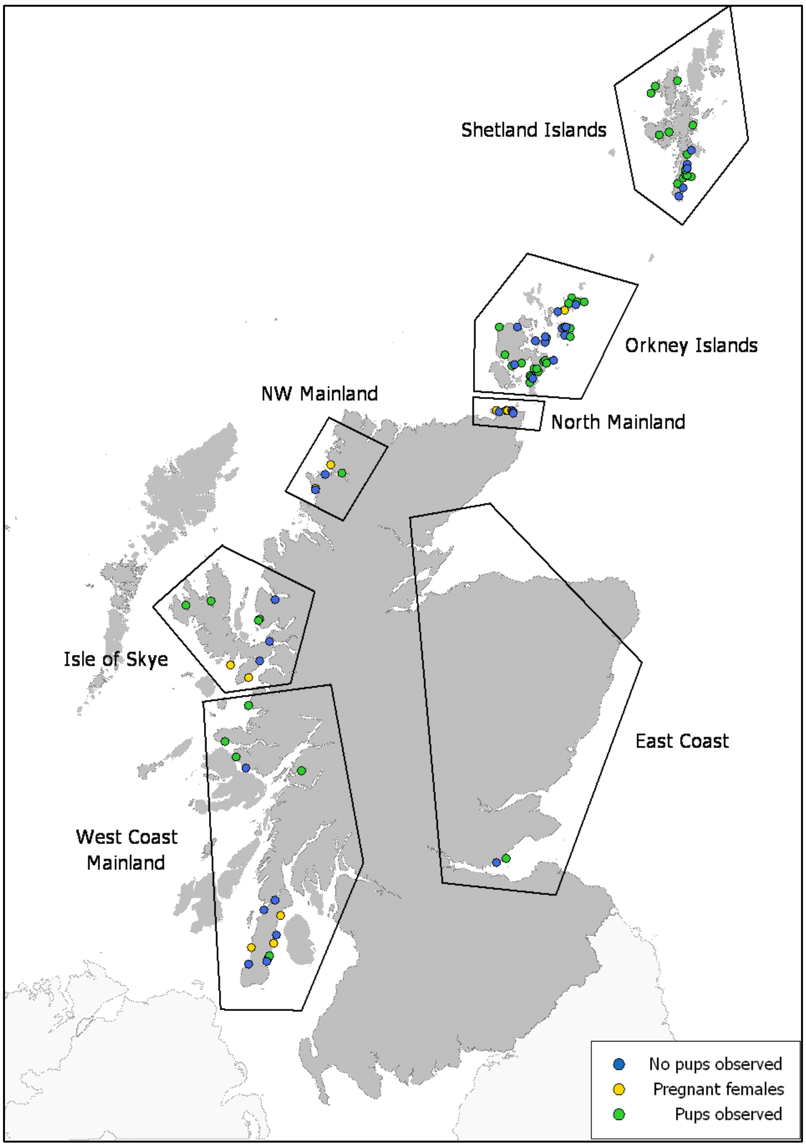


Figure 5. Trial sites visited in 2015 in which pups were observed (green), only pregnant females but no pups were observed (yellow), and no pups neither pregnant females were observed (blue).

3.2.3 Photographs

Photographs of each trial site were taken for descriptive purposes and, when possible, seals were photographed for individual identification based on their pelage pattern. Over 6000 photographs were taken in 2015 at all seven study areas. Photo-identification data were collected by the team that covered Shetland, NW mainland, East coast and Orkney (only mainland, visited during the return trip from Shetland). This team was equipped with a digiscope system, comprising a tripod with a gimbal head, a digital camera (Canon 70D), and a telescope (20-60 x 80 mm Swarowski HD-ATS 80). The equipment was chosen on the basis of recommendation and experience by researchers from the University of Aberdeen Lighthouse Field Station who have been collecting photo-identification on harbour seals in the Moray Firth since 2006 (see Cordes and Thompson, 2013a, b, 2015). All other teams were equipped with DSLR cameras with either 300 or 400 mm lenses, making photo-identification only possible if seals were located within 10s of metres away.

Photo-identification data were processed for those sites that proved to be most suitable for such data collection and that were visited on repeated occasions. The goals of this data processing were to provide preliminary data on the minimum number of individuals present at the selected haulout sites, sexing the individuals where possible, start building catalogues of individually identified seals at different study sites, and more generally to test the performance of the photographic equipment and set up protocols for photo-identification data collection and processing for the long-term study.

Photo-identification data were processed for six different haulout sites located on the East coast, Orkney and Shetland (see Table 3). All photographs were first graded for their quality, following a protocol adapted from Cunningham (2009) to take account of photographic quality (i.e. focus, resolution of the image), the angle of the seal and the visibility of the pelage pattern. When possible, the sex of the individuals was determined from pictures of their genitalia, as well as the presence of a pup suckling for females.

Table 3. Summary of processed photo-identification data with information on the number of photo-ID trips, the number of individual seals identified from the R and/or L side, and the number of females, males and individuals of unknown sex identified at each site.

Site	# trips	R-side	L-side	Both sides	Females	Males	Unknown sex
155 – Kinghorn (East Coast)	5	23	31	15	3	6	31
88 – West Burray (Orkney)	4	15	19	9	9	1	15
134 – Voe of Sound (Shetland)	7	35	37	27	24	2	19
135 – Scudills Wick (Shetland)	2	7	7	5	5	0	4
151 – Rerwick Sands (Shetland)	1	9	6	4	6	0	5
149 – Bixter Voe (Shetland)	3	9	6	5	7	0	3

Adult 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). Pups and yearlings (born the previous year) were not included in the identification trials because their pelage pattern is obscured by the darker pelage in pups or an early moult in yearlings. All identified individual seals were given an ID number and their best L and R photographs added to a catalogue (see Figure 6).

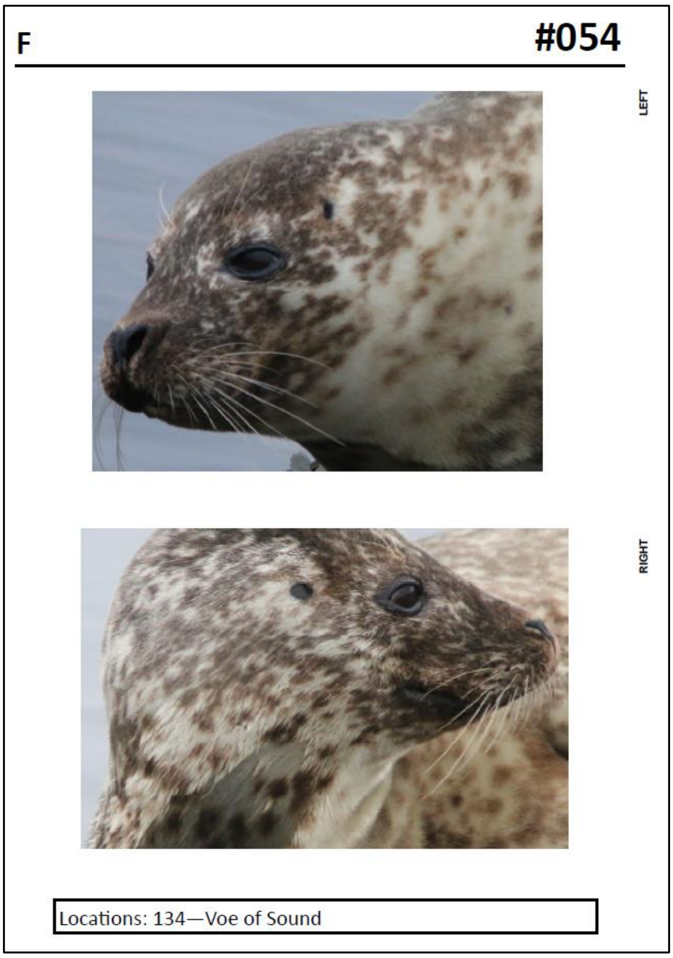


Figure 6. Example of female harbour seal #054 identified from its unique pelage pattern in Voe of Sound, Shetland.

Any injuries and lesions observed on individual seals during the photo-identification processing were noted for future reference. Flipper-tagged seals were photographed at Kinghorn, Kirkcaldy (East coast) on two occasions and at West Burray (Orkney) on one occasion. In the latter, the seal also showed evidence of a recently shed satellite tag on the back of its neck. On another occasion a satellite tagged seal was observed on the Sebay Skerries (Orkney). The information was shared within SMRU and with the University of Aberdeen to identify the tagged seals.

3.2.4 Scat samples

Scat sampling was conducted at the haulout at Kinghorn, Kirkcaldy (N56.0819 W3.5398, east coast) on eight different occasions during low spring tides, obtaining a total of 5 samples during three different trips (see Table 4). Trips were conducted in all months between September 2015 and March 2016, except during December. The main limitations to conducting the trips were weather, tide and daylight conditions during the winter. The number of seals at the haulout decreased substantially during those months, with no seals observed during the last trip in January 2016.

Table 4. Summary of scat sampling trips to Kirkcaldy Seafield tower. Pv = Harbour seals present at haulout site; Hg = Grey seals present at haulout site.

Date	Location	Time	Pv	Hg	Scat samples
15/09/2015	Kinghorn, Kirkcaldy	09:53	34	11	3
01/10/2015	Kinghorn, Kirkcaldy	10:00	37	8	0
13/10/2015	Kinghorn, Kirkcaldy	08:50	6	1	1
30/10/2015	Kinghorn, Kirkcaldy	09:40	4	2	0
26/11/2015	Kinghorn, Kirkcaldy	08:17	6	3	0
14/01/2016	Kinghorn, Kirkcaldy	11:05	0	0	0
25/02/2016	Kinghorn, Kirkcaldy	09:38	16	3	0
10/03/2016	Kinghorn, Kirkcaldy	09:17	6	1	1

3.2.5 Domoic acid in harbour seal samples from 2015

Following on from the work by Jensen *et al.* (2015), domoic acid (DA) concentrations in samples collected from harbour seals (scats from haulout sites, and faeces and urine from live captured animals) have been measured in 2015 (and also in 2014, not previously reported elsewhere). Apart from two samples, these are not from the two regions now chosen for the study starting in year 2. However, the results give a general indication of the uptake of toxins by seals in more recent years and add to the 2008-2013 dataset previously published (Jensen *et al*., 2015).

Urine samples from harbour seals captured and released in the Moray Firth (n=23), one faecal sample collected from the haulout site at Kinghorn, Kirkcaldy (east coast), and two additional urine samples from harbour seals live captured in Orkney in 2014 were analysed for domoic acid. The Biosense competitive ELISA (Biosense Laboratories AS, Bergen, Norway) as validated for harbour seal samples by Jensen *et al.* (2015) was used to detect DA. Samples were analysed following the protocol of Lefebvre *et al.* (1999) with urine samples diluted 1:100 and faecal extractions 1:400.

3.2.5.1 Urine samples

As an indication of the level of exposure to domoic acid in harbour seals during 2014 and 2015, urine and faecal samples from the live captures that were carried out in the Moray Firth (Ardersier, Dornoch Firth and Loch Fleet) were analysed for the presence and concentration of toxin. Figure 7 shows the concentrations of DA in the urine samples analysed to date and the annual fluctuations in the concentrations seen. It was not possible to control for time of year in the sampling regime. Clearly, due to the highly seasonal nature of the blooms and the consequent production of toxin, seasonal differences will have a confounding effect, although there is evidence that DA persists in the food chain and sediments outwith the peak of the HAB bloom (Burns and Ferry, 2007). In general, concentrations in Moray Firth seals were comparable across the years, despite samples being collected in different seasons (either spring or early autumn), and were low (note: the concentrations are reported in pg/ml). These absolute levels are difficult to interpret as it is not known when the animals ingested the toxin. Therefore the observed low concentration levels could reflect recent low exposure or, since the half-life of DA is very short (<6h), past higher exposure.

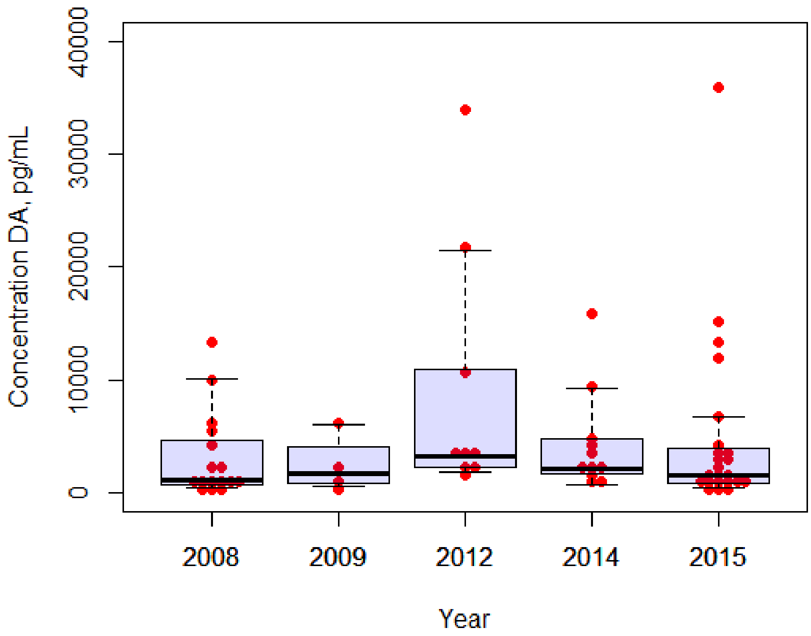


Figure 7. Concentration of domoic acid in urine samples from live captured harbour seals in Moray Firth.

Figure 8 shows the concentration of DA in urine samples from seals live captured in Orkney. The samples collected in 2014 are from harbour seals captured at the chosen study site at West Burray. In general the concentrations measured in the seals from Orkney were lower than those in the Moray Firth although one individual had very high urinary levels, twice those seen elsewhere. Since these animals were not from the same areas and islands within Orkney and again were sampled at different times of the year, the main conclusion here is that DA is present in the region and potentially sometimes at relatively high concentrations.

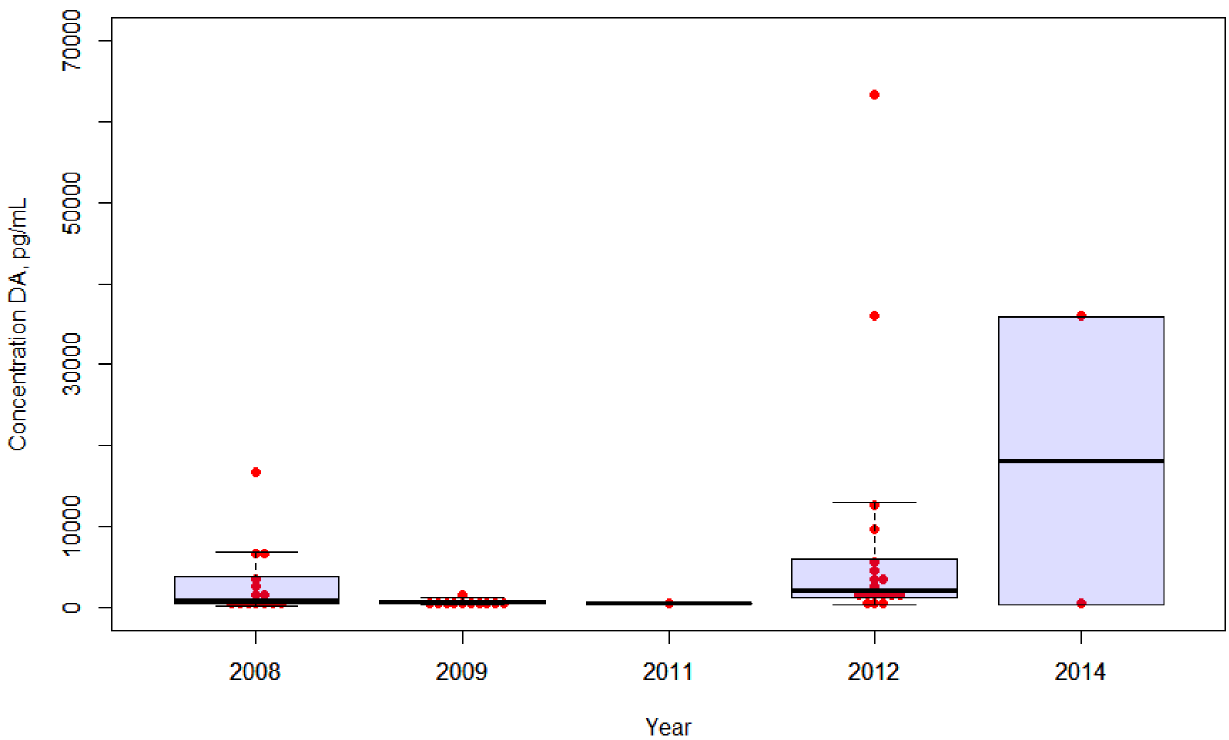


Figure 8. Concentration of domoic acid in urine samples from live captured harbour seals in Orkney.

For comparison, Figure 9 shows the concentration of DA in all urine samples analysed to date from live captured harbour seals, colour coded by region. The highest concentrations were found in 2012 and 2013 from the east coast of Scotland (East Scotland and the Moray Firth). Unfortunately, samples from the West Coast were not available for comparison in recent years. However, two individuals sampled in Orkney in 2014 and the Moray Firth in 2015 had relatively high concentrations of DA in their urine.

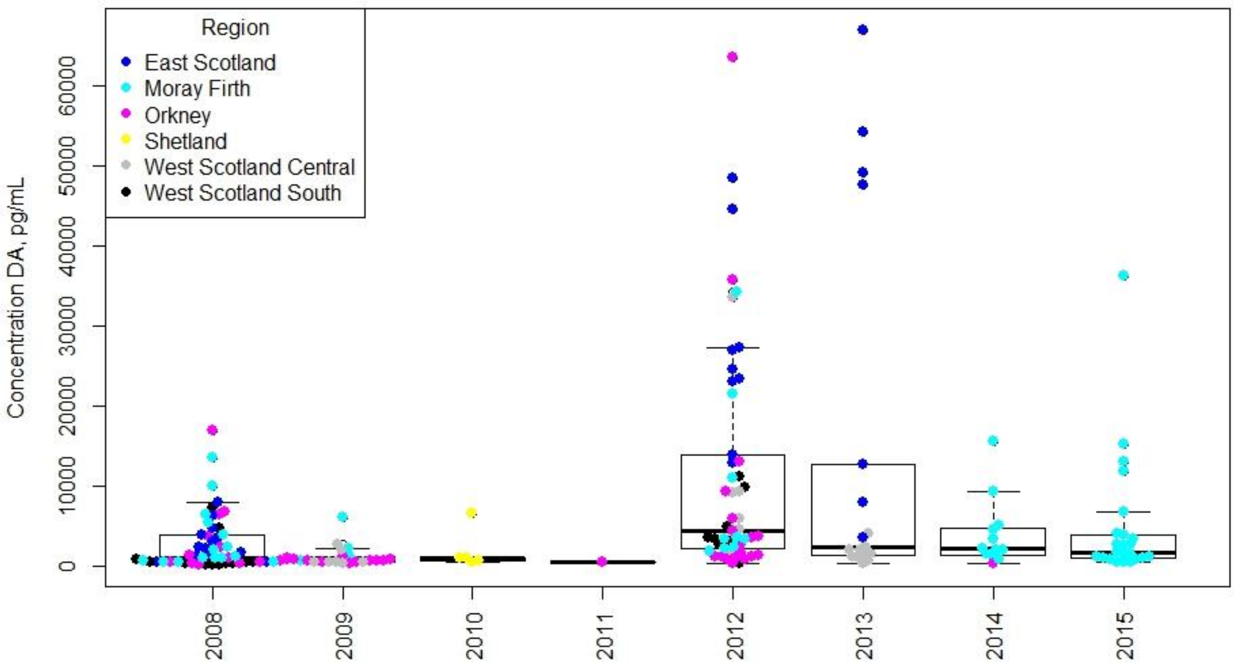


Figure 9. Concentration of domoic acid in urine samples from live captured harbour seals colour coded by region.

3.2.5.2 Faecal samples

Faecal samples from live captured animals

Where possible faecal samples were also collected from the live captured harbour seals. The concentrations of DA measured are shown in Figure 10. Fewer samples were available for this analysis. Concentrations are again plotted by year, and colour coded by region (note: concentrations in faecal samples are given in ng/ml, as concentrations are much higher than in urine samples). Here, levels were higher in 2012-2014 than in earlier years and one sample from the east Scotland region in 2012 had exceptionally high levels (~100 ng/ml). Two samples from the Moray Firth in 2014 had levels >20ng/ml. No samples were available from 2015.

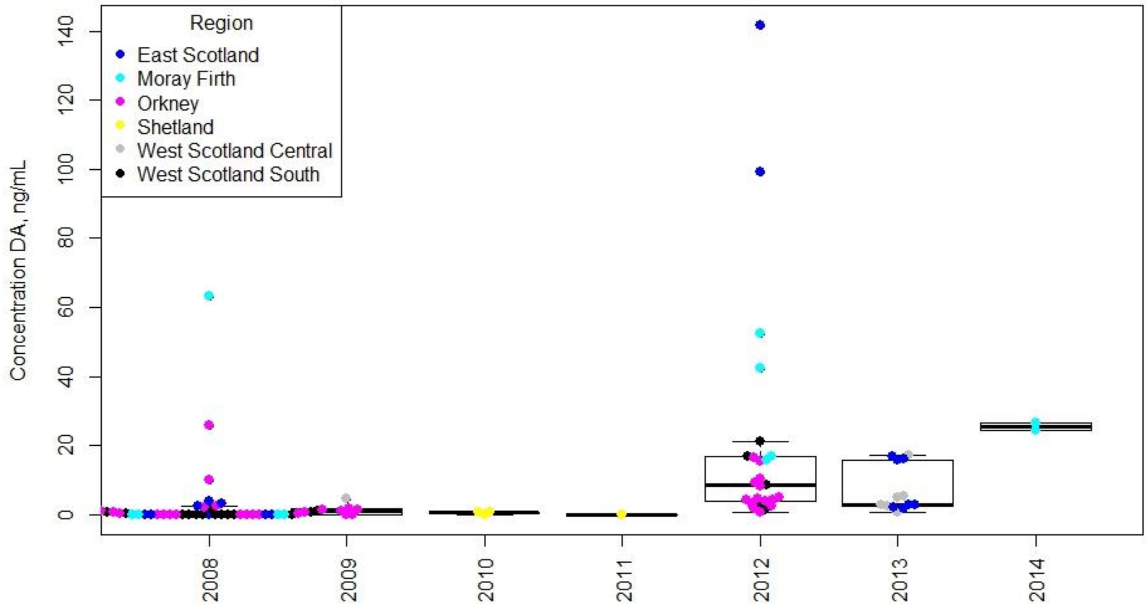


Figure 10. Concentration of domoic acid in faecal samples from live captured harbour seals colour coded by region.

<u>Faecal samples from harbour seal haulout sites</u>

Anonymous faecal samples were also obtained from harbour seals haulout sites, particularly during the harbour seal diet study and a subsample was analysed for DA. Figure 11 shows the concentrations found. Again these are reported as ng/ml and a few were very high, above ~250ng/ml, from East Scotland in 2013. However, recent samples showed much lower levels, although sample sizes were small.

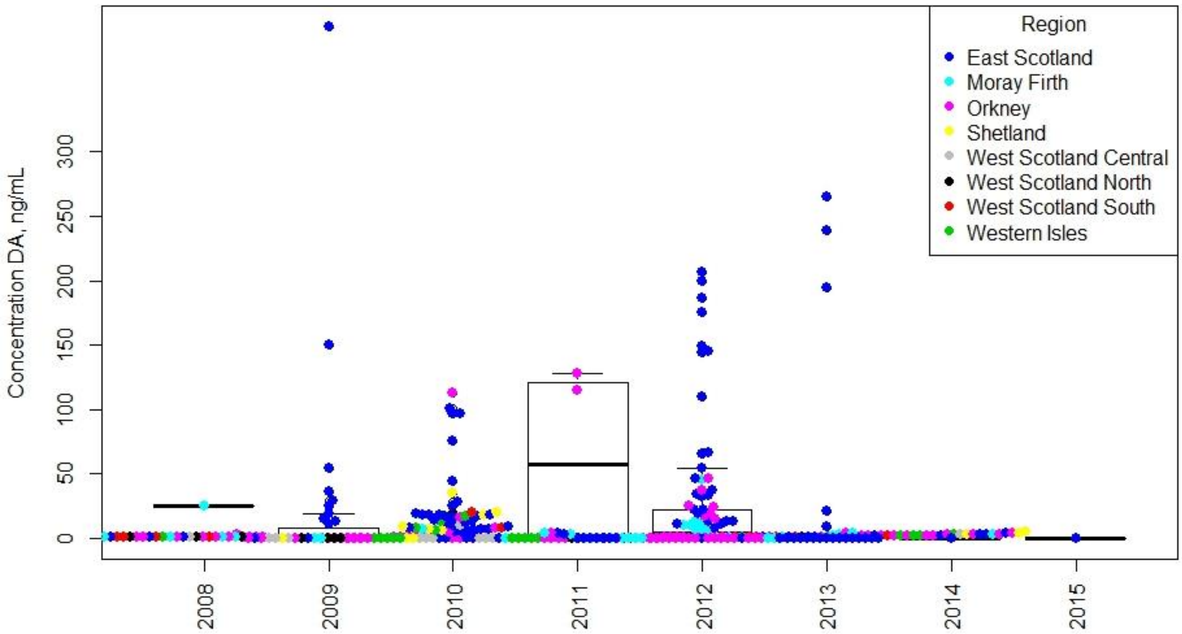


Figure 11. Concentration of domoic acid in faecal samples from harbour seal haulout sites colour coded by region.

The single sample collected from the haulout site on the east coast at Kinghorn (Kirkcaldy) in 2015 was negative for domoic acid (<LOD). Unfortunately, although three samples were collected only one was of sufficient quantity for DA analysis.

In conclusion, DA is still being found in harbour seals around the Scottish coast and whilst concentrations vary between the different samples, due to variation in exposure and time from uptake to excretion, some individuals appear to be consuming relatively high levels of toxin. Although these are still below the concentrations reported in acutely affected California sea lions (Scholin *et al.*, 2000), lower level exposure could be causing more chronic effects and recent studies have found effects on ovarian function *in vitro* suggesting a potential endocrine disrupting effect (Pizzo *et al.*, 2015).

3.2.6 Necropsy reports

Two seal carcasses were recovered by the Scottish Marine Animal Stranding Scheme (SMASS) within regions of the trial sites in 2015 (Scapa Flow in Orkney and west coast between Isle of Skye and the south end of Kintyre). Approach 6 provides full details on necropsy reports since November 2014.

3.2.7 UAV flight trials

Low level local aerial survey by Unmanned Aerial Vehicle (UAV) under SMRU Civil Aviation Authority permit 0239 was trialled at Kinghorn haulout, Kirkcaldy (east coast).

A preliminary site survey was carried out on 10 June 2015 to assess site topography, accessibility and flying risk assessments. Much of the haulout site proved to be clearly visible with dead ground to seaward, from a suitable but publicly accessible beach site and within manageable flying range. Around 30+ harbour and 20+ grey seals were hauled out within the area. Ideally a team of 3 would be required for surveys: (1) pilot, (2) co-pilot, (3) site supervisor for the public.

The first aerial survey trial was carried out using S900 hexacopter on 22 July 2015 in overcast, showery conditions. The aims were to (a) acquire experience of flying this site, (b) assess harbour seal reactions to UAV survey, and (c) obtain photo-id images. Three flights were carried out, for durations of 13, 7 and 4 minutes. No significant flying hazards were encountered, although members of the public were on site and questioning staff. A mixed haulout of harbour seals, some with pups, and grey seals were present on the closest site. On the first flight, approaches were at approximately 20m altitude. On site, altitude was reduced slowly. Grey seals were disturbed by the UAV at 10m altitude in hover, these went into the water, followed by some of the adjacent harbour seals. During the next flight, two hours later, seals were mostly unresponsive (some heads up, alert), including newly hauled out animals. Temporary problems with the power supply to the UAV imaging systems, traced to low voltage in failing batteries, produced excessive vibration on the camera mount, preventing good quality UAV image collection. A shorter flight over the haulout using a GoPro III instead of the main video camera obtained images of low resolution.

Successful imaging for photo-id can be obtained from 30m height (Pomeroy *et al.*, 2015). The reactions of the seals to the UAV survey at this site are consistent with surveys carried out elsewhere and suggest an ideal survey height of between 30-20m. Repeat surveys are therefore planned for 2016.

3.3 Development of telemetry tags

As part of the live capture programme, it is planned to fit all adult female harbour seals with electronic location tags. Data from these tags will inform the extent of the photo ID re-sighting effort. The minimum requirement of the tags is to relay the locations where the tagged seals haulout up to the breeding period in July. Thus it was decided to develop a low-cost tag that would allow a larger number of captured seals to be tagged.

Extra funding (£30k) for this project has recently been obtained from Vodafone UK. This will provide for 10 SMRU GPS/GSM phone tags. In addition to satisfying the primary requirement of recording inter-haulout movement they will also provide valuable information of at-sea usage. However, since more than 10 adult females may be caught in the April 2016 live capture field trip, there is still a need to develop a low cost location tag.

A low-cost cheap commercial GSM/GPS tracker was sourced – the Itrack Mini GPS Basic tracker. This is designed to regularly relay GPS locations from terrestrial locations. It is modified as follows:

1. Provision of a larger battery.

2. Operation to be controlled by a dedicated external micro-controller. This will cold-start the device at regular intervals (say every 4 h) to minimise energy drain from the battery. It is not expected that any locations will be obtained when a seal is at sea. However, since the objective is to guide recapture effort only at haulout sites, the tags are fit for purpose.

3. Construction of a waterproof (pressure resistant to 100m) outer shell.

All these modifications are well underway. Prototype tags will be available for testing by the end of March 2016.

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

This approach starts in year 2.

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

5.1 Regional scope of local populations

Before collating existing counts of harbour and grey seals at and adjacent to the study sites from air surveys, the regional scope of the local populations at each study site was defined. The geographical limits of each local population were delimited based on the location of the main study haulout sites in relation to adjacent ones (from aerial surveys count data), as well as available information on the individual movements of seals from telemetry tags, and the feasibility of conducting aerial and ground surveys in each area.

5.1.1 Orkney

In Orkney, the regional scope of the local population will include the whole of Scapa Flow (see Figure 12). The main study site is located at West Burray (58°50'57"N 2°57'46"W). The defined study area is suitable for conventional air surveys during the breeding and moult seasons. Ground counts can be carried out at haulout sites located around Scapa Flow on the mainland, Burray, Hunda and South Ronaldsay, but not at the slands (Graemsay, Hoy, Fara, Flotta, Cava and Switha) unless a boat is used. Information on the accessibility to haulout sites is available from the 2015 fieldwork, and should be used to plan the ground counts during 2016 in that area. Nine haulout sites were visited around Scapa Flow in 2015, of which 8 were described as having easy access by foot and one medium difficulty to access it.

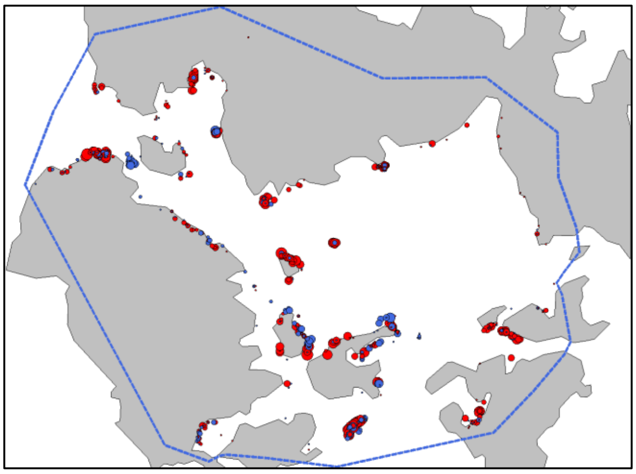


Figure 12. Regional scope for Orkney study sites for HSD2 (delimited by blue line) with aerial survey harbour seal (red circles) and grey seal (blue circles) counts for 1985-2014. The red arrow points towards the location of the main study site on West Burray.

5.1.2 West coast - Kintyre

On the west coast, the main study site will be Yellow Rock, located by Peninver in East Kintyre. The regional scope for that area has been defined to include the east coast of Kintyre from Tarbert to Southend, Sanda Island, Isle of Arran, the south half of Bute, and the Firth of Clyde waters (see Figure 13). Apart from the main study site at Peninver, there are another 5 haulout sites along the east coast of Kintyre described as easy access (3 sites) or medium difficulty access (2 sites) based on 2015 notes which will be visited regularly during 2016 to carry out ground counts.

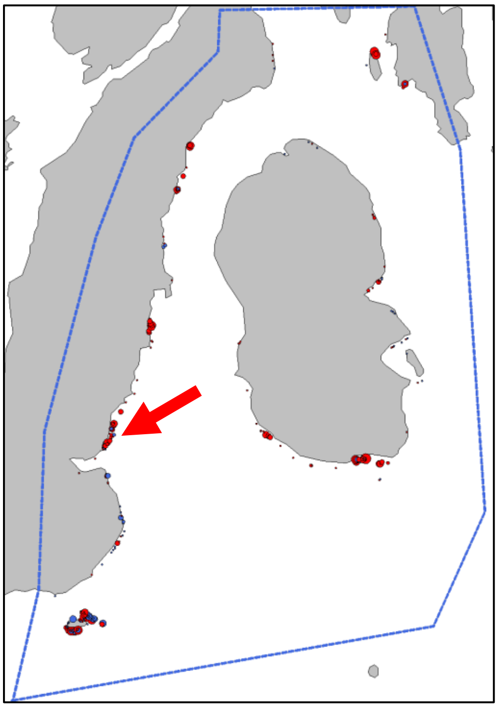


Figure 13. Regional scope for Kintyre study sites for HSD2 (delimited by blue line) with aerial survey harbour seal (red circles) and grey seal (blue circles) counts for 1985-2014. The red arrow points to the location of the main study site at West Kintyre.

5.1.3 Isle of Skye

At the Isle of Skye, the main study site for photo-identification will be the skerries in Dunvegan Loch where daily bout tours departing from Dunvegan Castle operate to see the harbour seals (Figure 14).

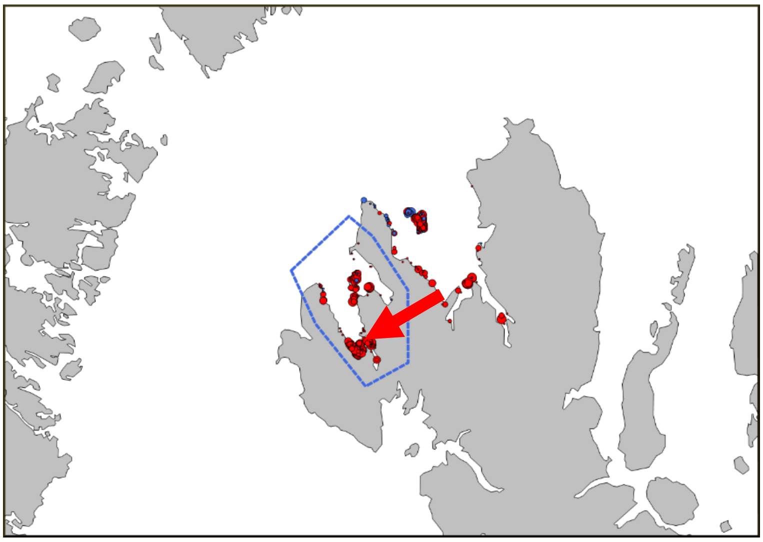


Figure 14. Regional scope for Isle of Skye study site for HSD2 (delimited by blue line) with aerial survey harbour seal (red circles) and grey seal (blue circles) counts for 1985-2014. The red arrow points to the location of the main study site in Isle of Skye.

The regional scope for that study site includes the Special Area of Conservation (SAC) of Ascrib, Isay and Loch Dunvegan. Ground counts will be conducted at the main study site from the tour boat, and at close haulout sites SW of the main site, by Skinidin and Colbost. The other haulout sites in the area are not accessible by foot and thus no ground counts will be conducted. The study area of Isle of Skye will be covered by aerial surveys during the moult at least once during the HSD2 project as part of the August aerial surveys conducted by SMRU.

5.2 Existing counts from aerial surveys

Counts of harbour and grey seals are available for the three study sites from 1985 to 2014 (Table 5). In 1985 and 1989 no thermal imaging was used in the aerial surveys in Scapa Flow. The counts for that area in those two years may be excluded from some parts of the analysis in Approach 1 for methodology consistency with the rest of the historical dataset, which used thermal imaging.

Table 5. Counts of harbour and grey seals from aerial surveys conducted between 1985 and 2014 for the three study sites. Numbers of seals are total number of seals counted within each of the above defined areas. *Blank cells* = no aerial survey.

Harbour seals				**Grey seals**			
	Scapa Flow (Orkney)	Dunvegan (Isle of Skye)	Kintyre (west coast)		Scapa Flow (Orkney)	Dunvegan (Isle of Skye)	Kintyre (west coast)
1985	2025			**1985**	89		
1986				**1986**			
1987				**1987**			
1988		455		**1988**		0	
1989	1961	391	210	**1989**	128	3	62
1990		316		**1990**		1	
1991		276		**1991**		0	
1992		228		**1992**		0	
1993	2285	443		**1993**	150	0	
1994				**1994**			
1995				**1995**			
1996		438	651	**1996**		1	0
1997	2403			**1997**	560		
1998				**1998**			
1999				**1999**			
2000		628		**2000**		1	
2001	2319			**2001**	180		
2002				**2002**			
2003				**2003**			
2004		407		**2004**		2	
2005		381	460	**2005**		3	86
2006	1280			**2006**	639		
2007	940	440	650	**2007**	374	32	208
2008	703			**2008**	275		
2009				**2009**			
2010	734			**2010**	269		
2011				**2011**			
2012				**2012**			
2013	624			**2013**	858		
2014		344		**2014**		6	

6 Approach 5. Improving understanding of potential drivers of population change

6.1 Feasibility of scat collection across trial sites

Information on the feasibility of scat sampling across trial sites was collected during 2015 for 104 sites in all study areas. Sites were classified according to their accessibility and type of terrain for scat collection into the following categories: (1) **Feasible** (n=47): rocky shores generally covered by seaweed, easy access at low tide by foot; (2) **Not feasible** (n=4): access to the site is not possible; (3) **Potentially feasible** (n=17): no clear or easy access to the site or site only accessible at spring low tides; (4) **Boat** (n=34): site located on an island or skerries that can only be accessed by boat; (5) **Grey seals** (n=2): site is feasible for scat collection but only or mainly grey seals were observed when visited. No information on feasibility for scat collection was recorded in another 3 sites (**No information**) (Figure 15).

6.2 Investigation of the availability of prey samples relevant to seals foraging from trial sites

Following internal discussions within SMRU it was concluded that investigation of the availability of prey samples relevant to seals foraging from the study sites would be best completed once fieldwork starts in the spring and summer of 2016, and contacts can be made with local fishermen and sports fishermen in the study regions (Orkney and East Kintyre). However, initial contacts with the Orkney Fisheries Association (OFA) were made through Marine Scotland Science and will be followed up for further information on how best to obtain prey samples from Orkney.

6.3 Collate prey abundance data

Contacts were made within Marine Scotland Science with the Sea Fisheries programme manager and with the Inshore Fisheries Group to discuss the availability of long-term fish survey data at and around the trial sites. The standard datasets on ground fish offshore surveys used for stock assessment purposes, available from the International Council for the Exploration of the Sea (ICES) website, have a much larger spatial resolution (and consequently sparse sample points) than the regional scope of the local study populations (see section 7.1). However, these datasets are still of interest for Approach 1 as they may be informative of long-term changes in fish availability in different areas around Scotland on the larger scale, and these could then be potentially linked to contrasts between study sites (e.g. declining *vs*. stable/increasing sites). Prey species of interest are those included in harbour seal diet, e.g. cod, haddock and whiting, as well as mackerel, sandeels and clupeid species such as herring and sprat. On the other hand, fine-scale survey data from inshore fisheries would also be very useful. Discussions will continue during 2016 to liaise with Marine Scotland Science for further advice on available fish survey datasets.

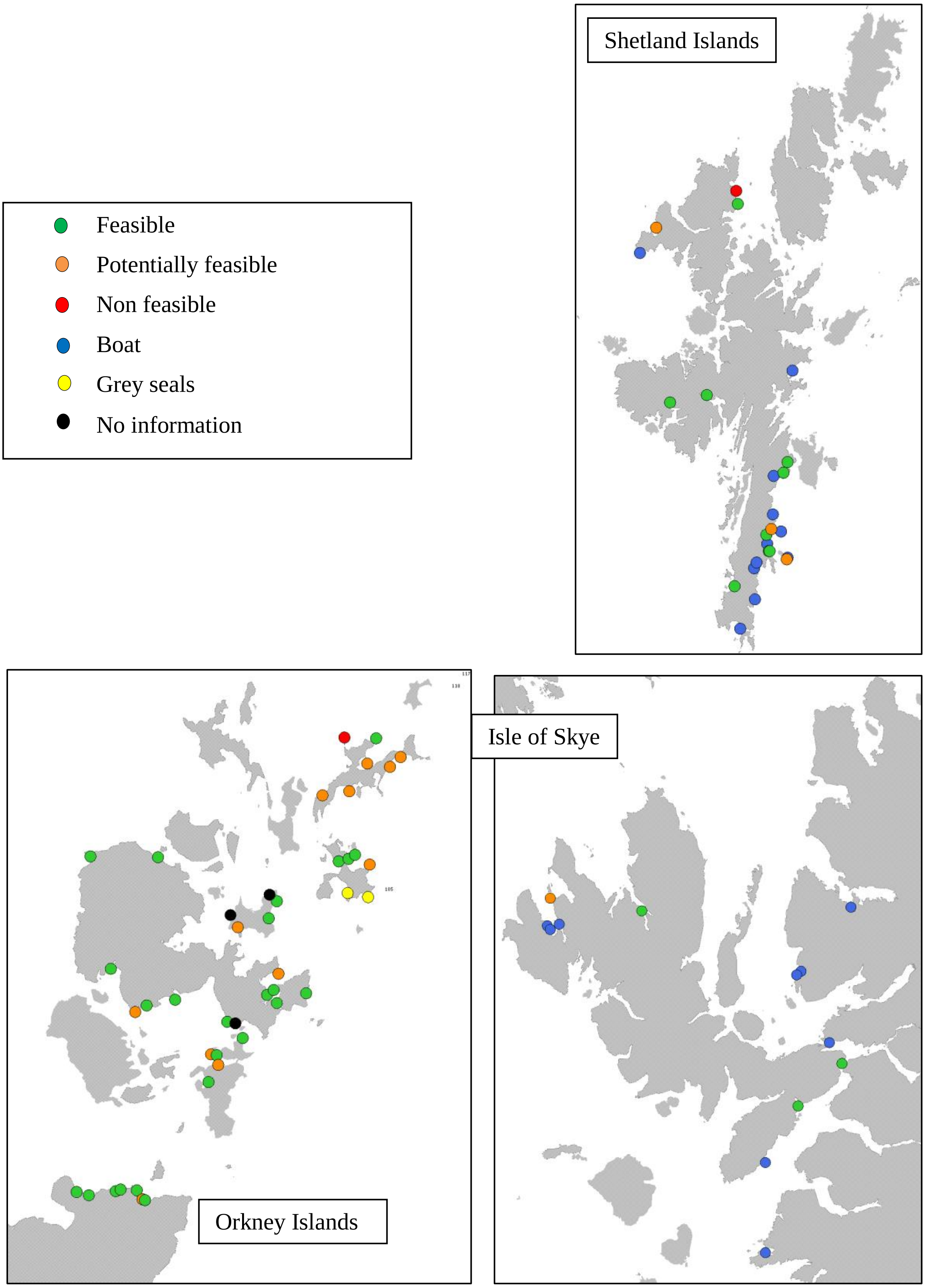
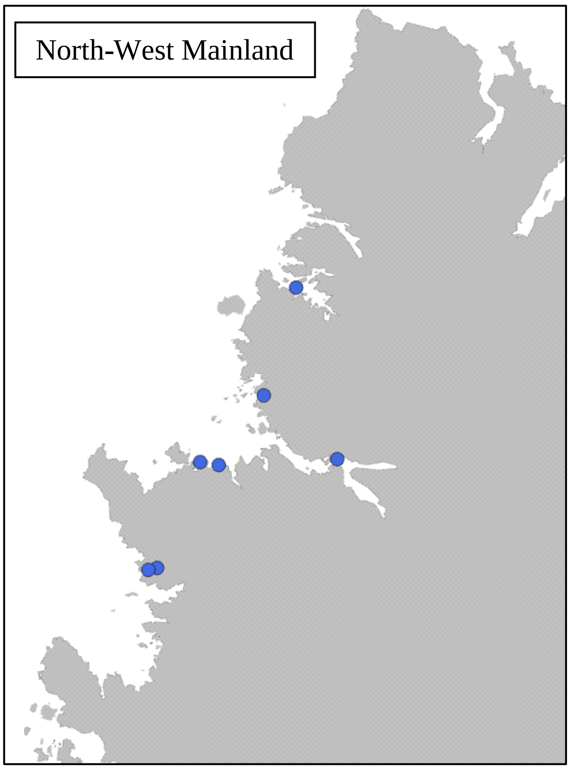


Figure 15. Feasibility of scat collection across the trial sites in Shetland, Orkney, Isle of Skye, west coast and NW mainland. Sites are classified as Feasible (green), Non feasible (Red), Potentially feasible (orange), Boat (blue), Grey Seals (yellow) or No information (black).



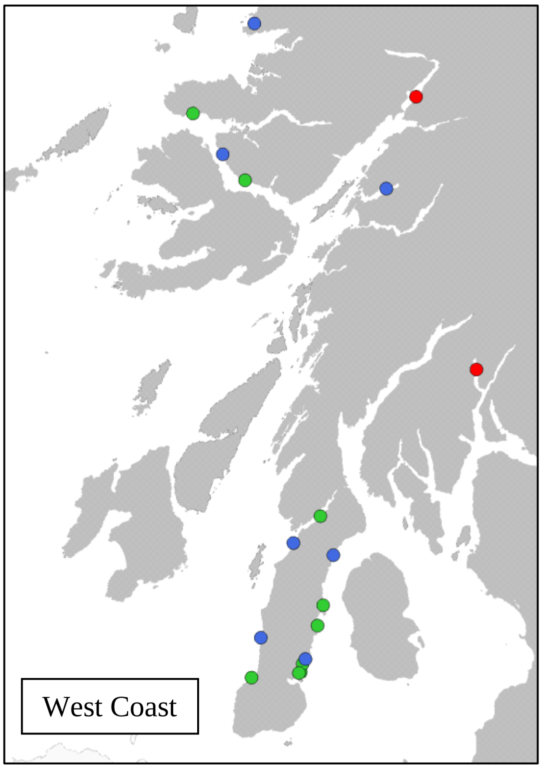


Figure 15 (continued). Feasibility of scat collection across the trial sites in Shetland, Orkney, Isle of Skye, West Coast and NW Mainland. Sites are classified as Feasible (green), Non feasible (Red), Potentially feasible (orange), Boat (blue), Grey Seals (yellow) or No information (black).

6.4 Collate data from the monitoring of Harmful Algal Blooms

Data from the monitoring of biotoxins in shellfish by the Centre for Fisheries and Aquaculture Science (CEFAS) and HABs by the Scottish Association for Marine Science (SAMS) are available for 2015 and January 2016. These include:

- Biotoxins:
    - Paralytic Shellfish Poisoning toxins (PSP, e.g. saxitoxin and its derivatives)
    - Amnesic Shellfish Poisoning toxins (ASP, i.e. domoic acid)
    - Diarrhoetic Shellfish Poisoning toxins (DSP, e.g. okadaic acid)
    - Azasparacids (AZA)
    - Yessotoxins (YTX)

Weekly screening of shellfish samples, including common mussels and Pacific oysters from commercial shellfish producers and samples submitted by local authorities, are carried out by CEFAS in Weymouth and results are available via the Food Standards Agency (FSA) website. Where biotoxins are detected the quantity of toxin is reported in the sample, either as an absolute concentration or as a scoring above or below a threshold for toxicity (absolute concentrations are reported as 'µg or mg toxin equivalents' as many derivatives of the toxin groups can be found within a sample). Temporal variation in these results is seen due to the very large variability in occurrence of toxin-producing algae between seasons and years (see sections 8.4.1 and 8.4.2 below for examples). The location of the producers and councils submitting shellfish for analysis are shown in Figure 16.

- Harmful Phytoplankton:
    - *Pseudo-nitzschia spp.* (produces ASP toxins)
    - *Alexandrium spp.* (produces PSP toxins)
    - *Dinophysis spp.* (produces DSP toxins)
    - *Prorocentrum lima* (produces DSP toxins)
    - *Prorocentrum cordatum* (produces DSP toxins)
    - *Prorocentrum reticulatum* (produces DSP toxins)
    - *Lingulodinium polyedrum* (produces Yessotoxins)

Weekly water samples are collected from stations at the same sites and the phytoplankton preserved, identified and quantified at SAMS. These results are also available from the FSA Scotland website. Certain 'trigger' levels (cells / L) have been set by the regulators which if exceeded result in the closure of the shellfish fisheries in the region. This is different for each phytoplankton genus and species but the most stringent is the level for the *Alexandrium spp*. which is set at 40 cells/l due to the serious health effects of the PSP toxin if ingested.

These datasets provide some indication of the occurrence of HABs and toxin-producing blooms in the regions of interest. However, the analysis of the geographic spread of the blooms is limited to specific monitoring sites ***inshore*** which may not be representative of the uptake of toxins by the seals that may be foraging further offshore. These data will therefore be supplemented by data on the concentration of toxins in harbour seal excreta and in their fish prey, collected at the same time.

6.4.1 Biotoxin data

Figure 16 shows the monitoring sites for the shellfish data (figure from Cefas and SAMS, 2014). For the toxins there are six sites in the south-west region where the year two photo-id study will be carried out. However, there is only one site in Orkney and this is not in the region where the photo-id and captures will be carried out.

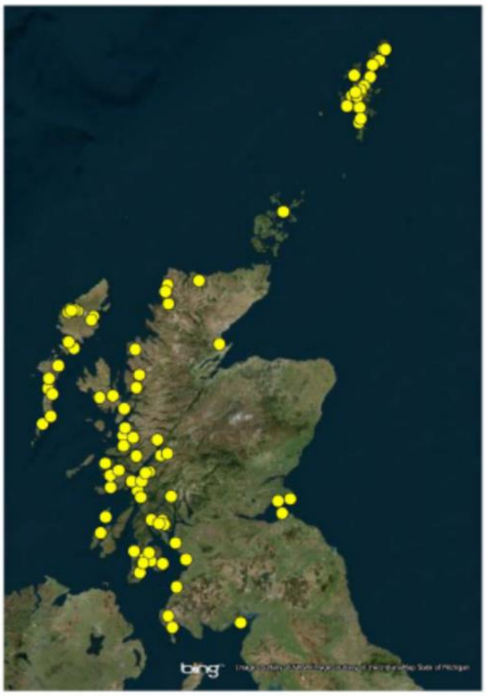


Figure 16. Biotoxins in shellfish monitoring sites around Scotland

An example of the toxin data for the south-west region (Argyll and Bute) is shown in Figure 17. The figure shows the concentration of PSP toxin that was detected and quantified in common mussels and Pacific oysters, by date. The horizontal line shows the toxic level of 400 μg STX equivalent/mg shellfish flesh (samples were coded as zero where no toxin was detected). A cluster of contaminated shellfish was reported in late April / early May, 2015. Figure 18 shows the data for the ASP toxins in the shellfish with some high levels in shellfish collected in early summer and late autumn, 2015. The limit for shellfish that is fit for human consumption of shellfish flesh is also shown as a horizontal line (20 mg/kg).

6.4.2 Harmful Algal Bloom data

Water samples are also collected from many of the shellfish monitoring stations shown in Figure 16 and are screened for harmful algae by SAMS each week. For example, Figures 19 and 20 show the occurrence of *Pseudo-nitzschia* in water samples collected from the study regions during 2015. The 'trigger' level of 50,000 cells/L is shown as a horizontal line. Peaks were seen in June and September. These correspond to some extent with the ASP positive shellfish samples from Argyll and Bute seen in Figure 18, with some lag time between the bloom and the uptake by the shellfish. Unfortunately, no shellfish were sent for testing from Orkney during 2015.

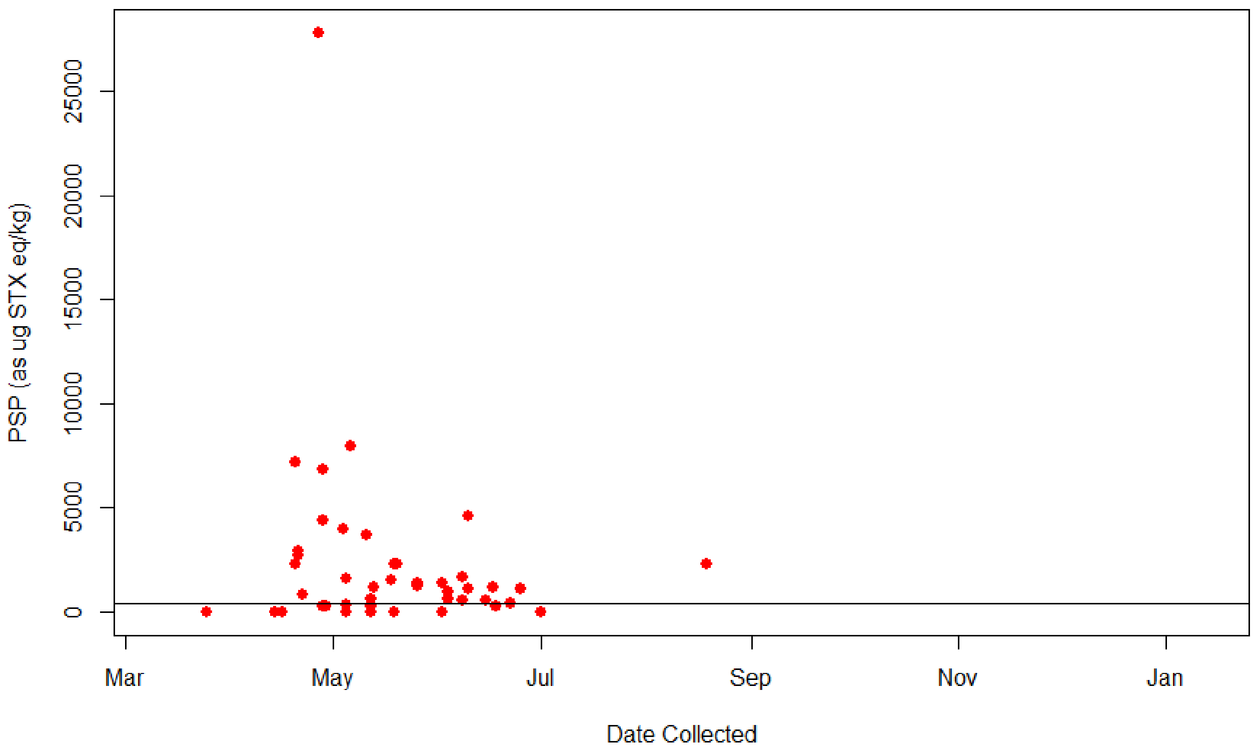


Figure 17. PSP toxins in shellfish collected from shellfish producers and local authorities in Argyll and Bute, Mar 2015 – Jan 2016. The limit allowed in shellfish flesh is shown by the horizontal line, 40 mg/kg.

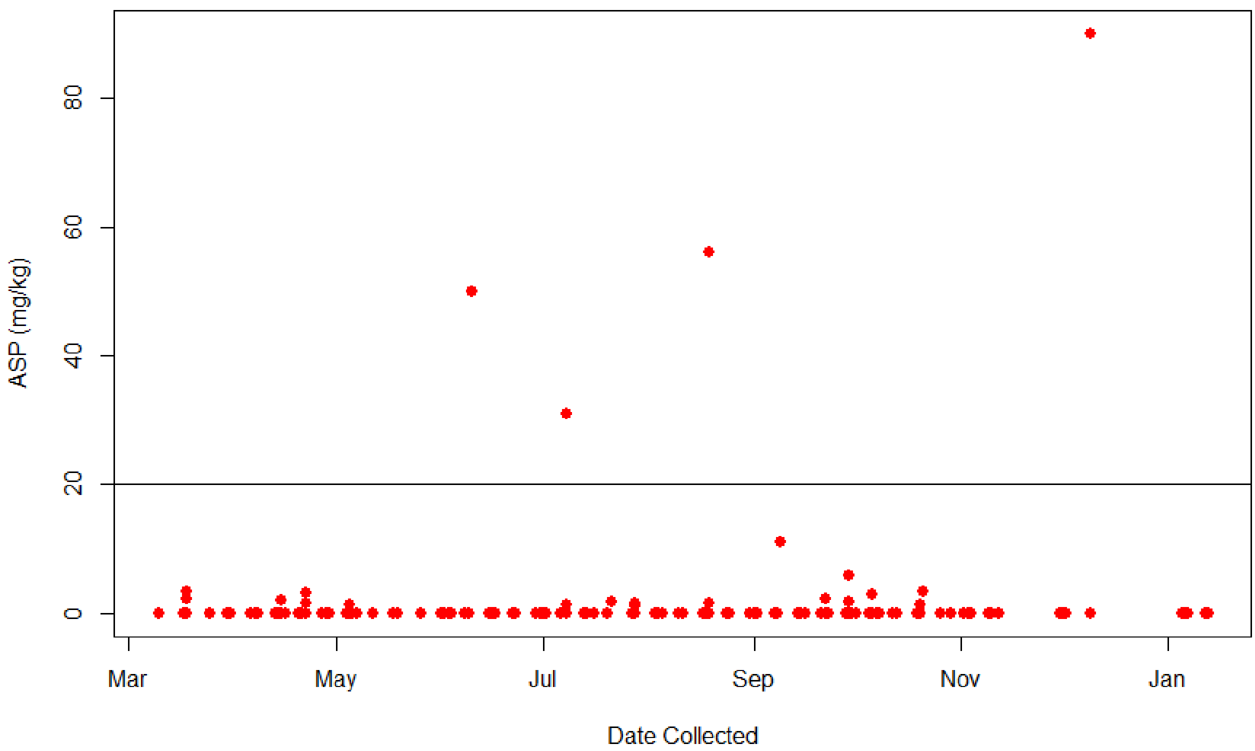


Figure 18. ASP toxins in shellfish collected from shellfish producers and local authorities in Argyll and Bute, Mar 2015 – Jan 2016. The limit allowed in shellfish flesh is shown by the horizontal line, 20 mg/kg.

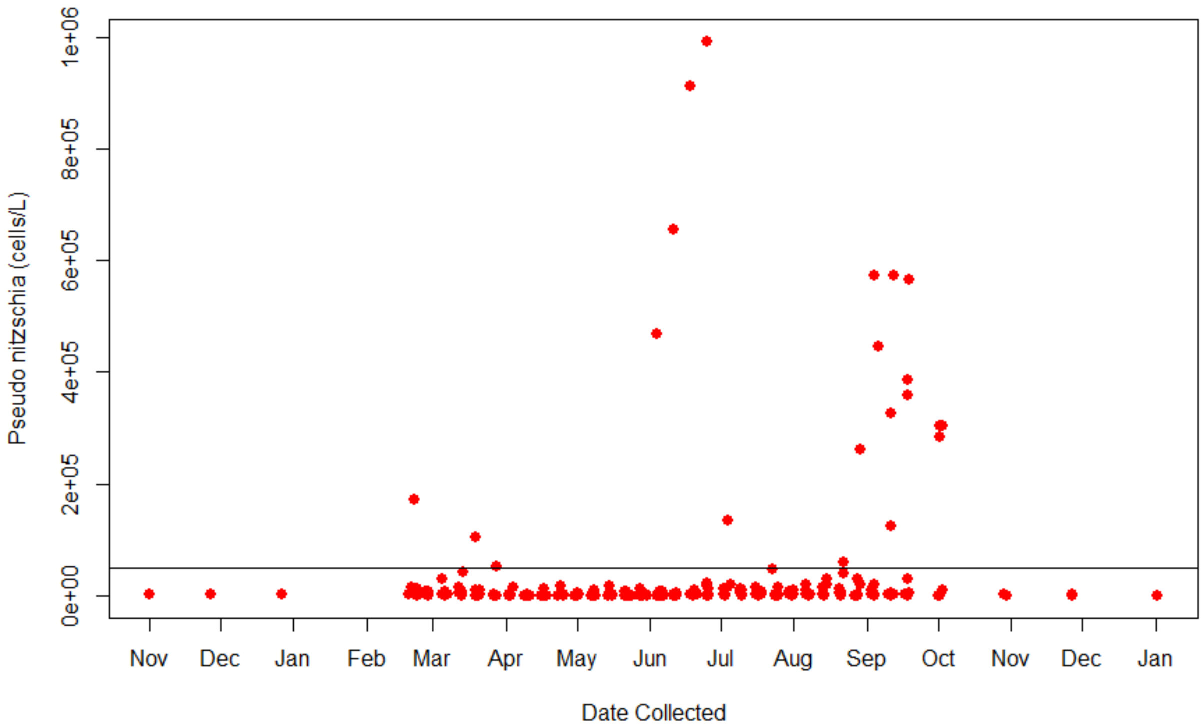


Figure 19. *Pseudo-nitzschia* cells in seawater samples from Argyll and Bute sampling stations, Nov 2014 – Jan 2016. The horizontal line shows the trigger level of shellfish production closure of 50,000 cells/L

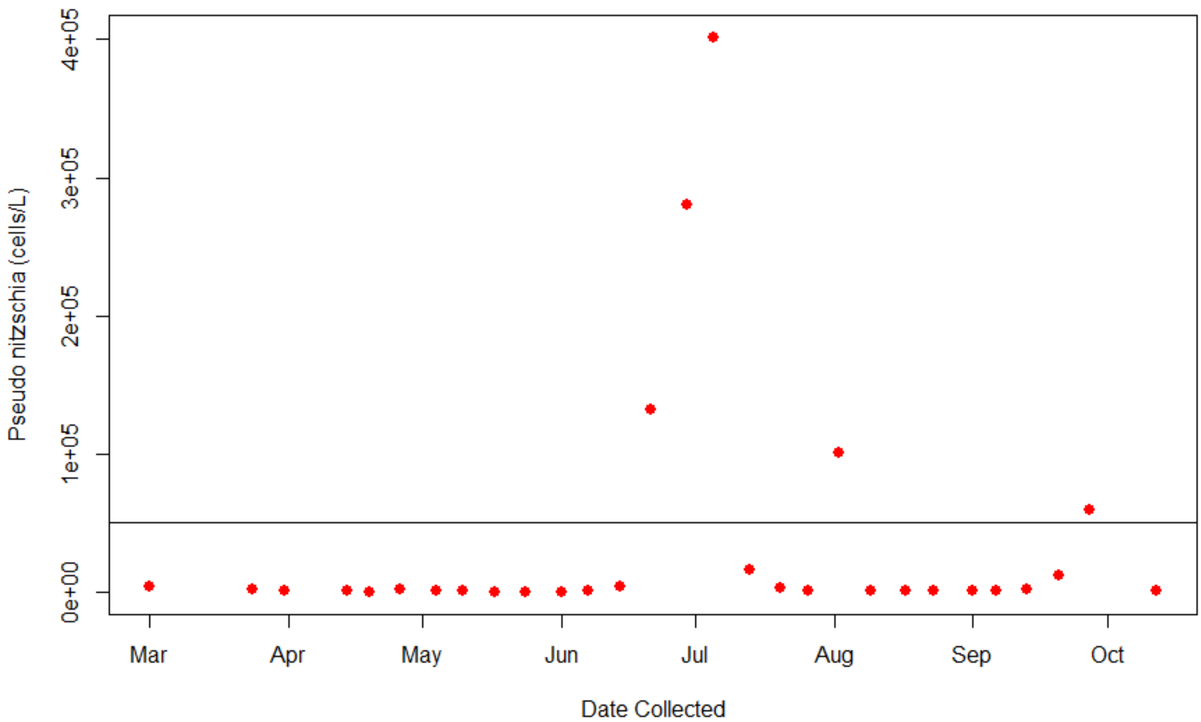


Figure 20. *Pseudo-nitzschia sp.* cells in seawater samples from the Orkney sampling station, March 2015 – Oct 2015. The horizontal line shows the trigger level of shellfish production closure of 50,000 cells/L

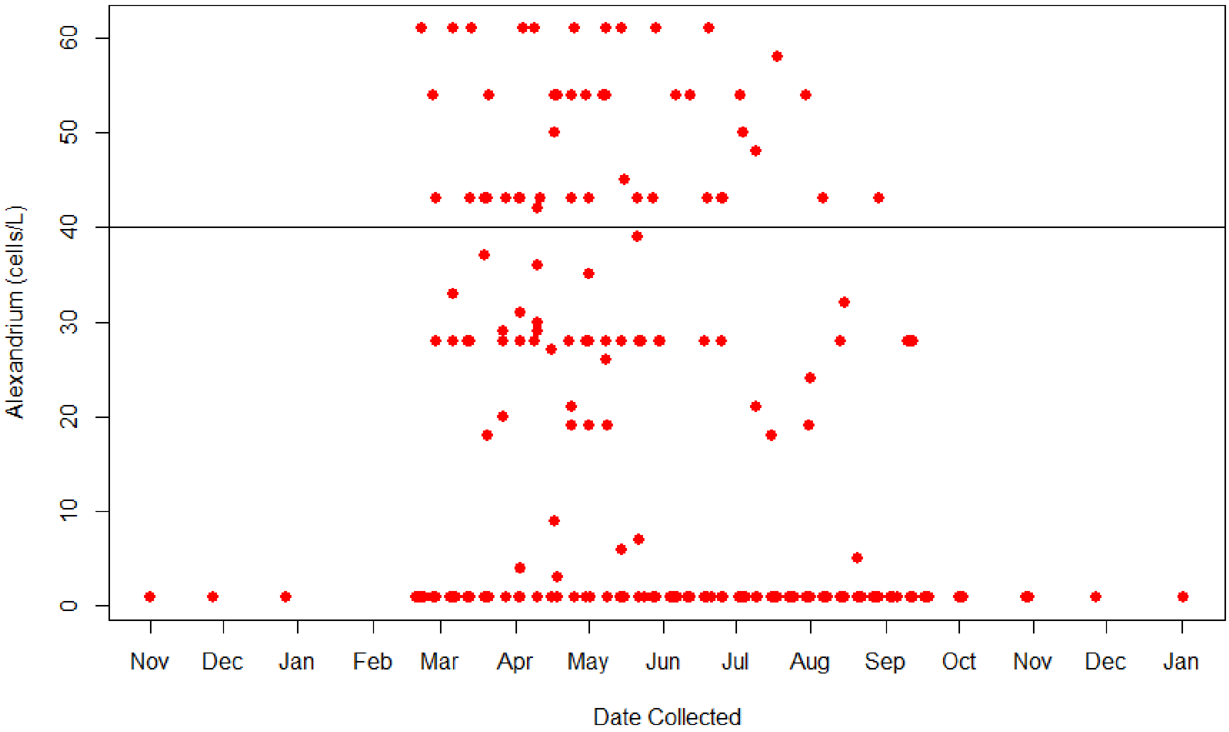


Figure 21. *Alexandrium* sp. cells in seawater samples from Argyll and Bute sampling stations, Nov 2014 – Jan 2016. The horizontal line shows the trigger level of shellfish production closure of 40 cells/L

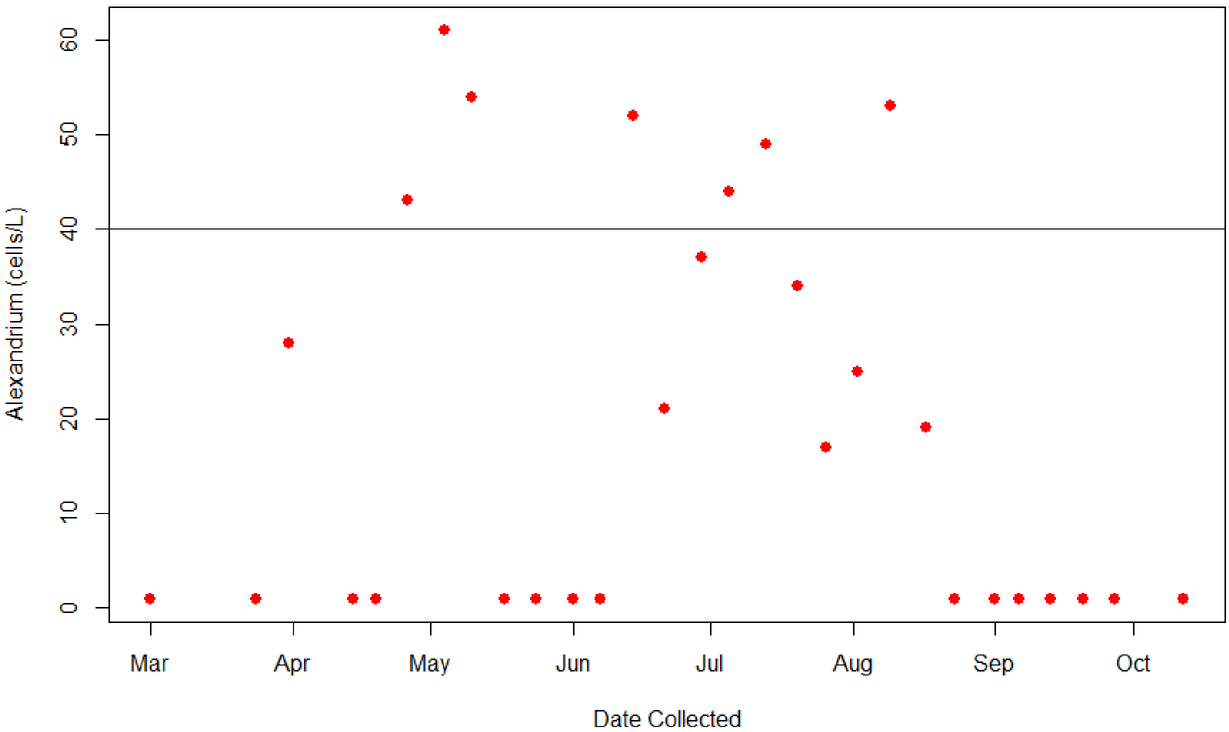


Figure 22. *Alexandrium* sp. cells in seawater samples from Orkney sampling stations, March 2015 – Oct 2015. The horizontal line shows the trigger level of shellfish production closure of 40 cells/L

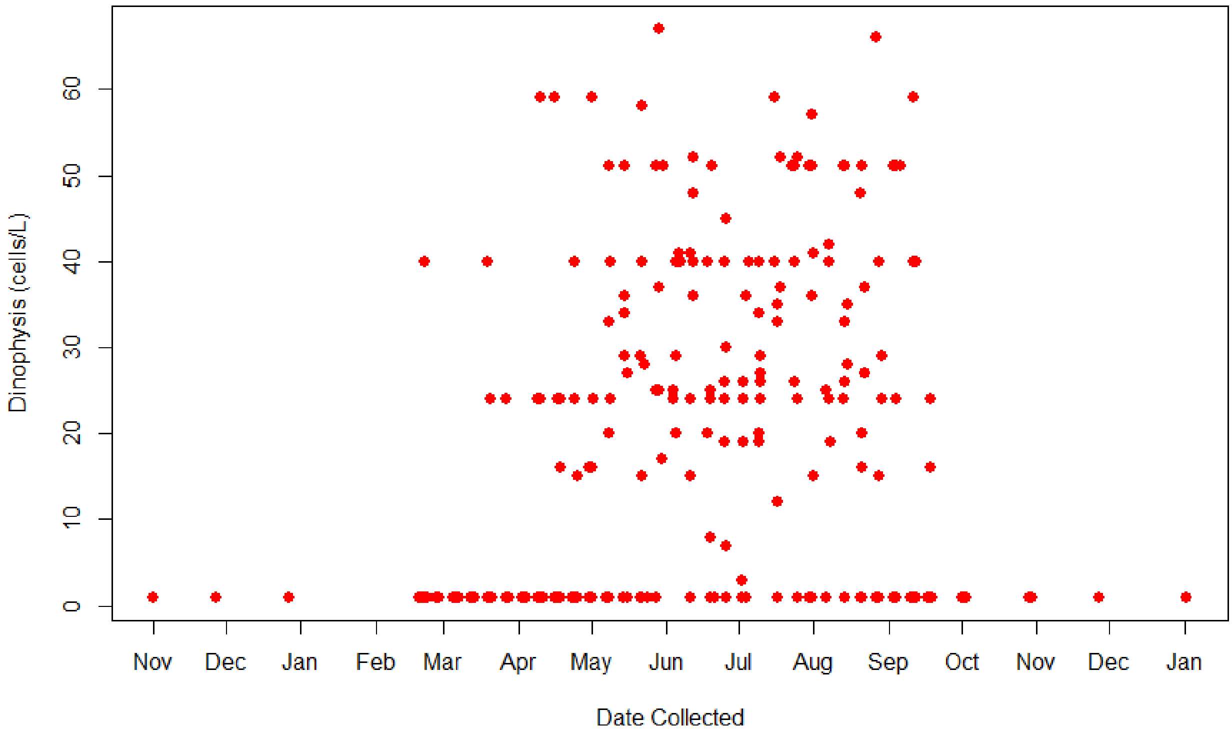


Figure 23. *Dinophysis* sp. cells in seawater samples from Argyll and Bute sampling stations, Nov 2014 – Jan 2016. The trigger level for these phytoplankton is 100 cells/L

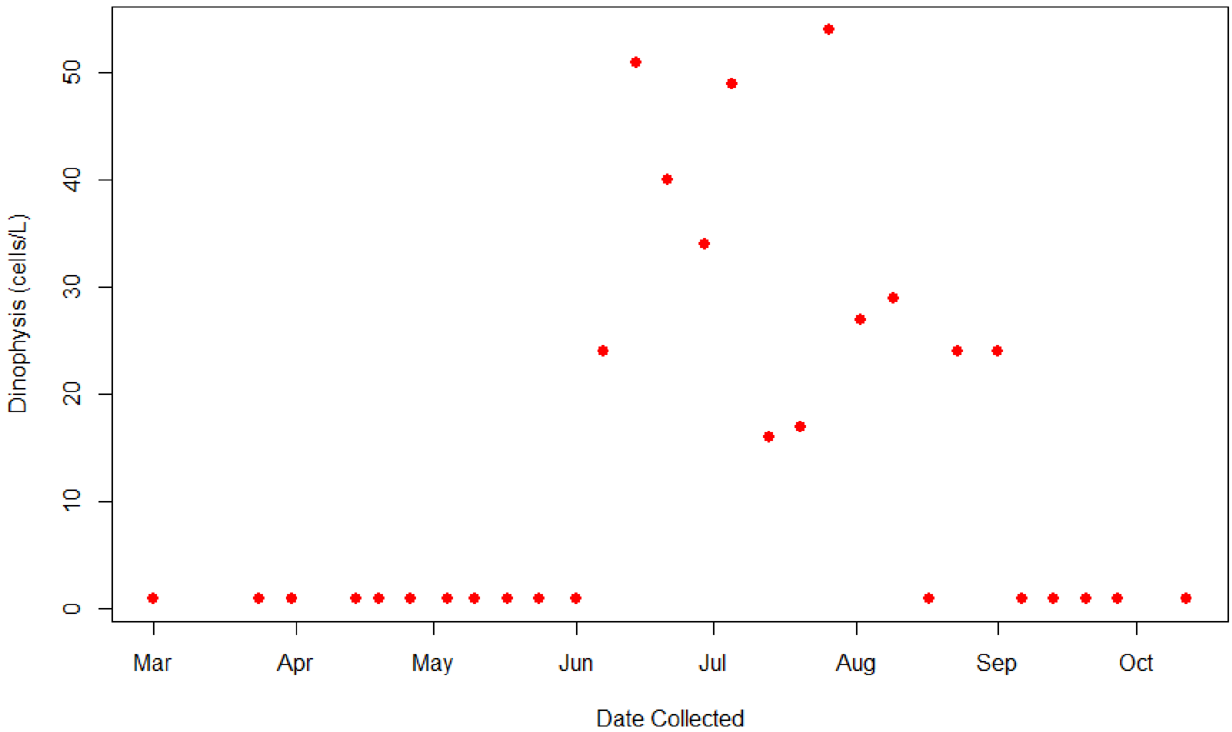


Figure 24. *Dinophysis* sp. cells in seawater samples from the Orkney sampling stations, March 2015 – Oct 2015. The trigger level for these phytoplankton is 100 cells/L

The HAB data presented here (in Figures 19 to 24) indicate the seasonal occurrence of the three major toxin-producing phytoplankton species in the two study regions; Argyll and Bute, and Orkney. Although the sampling station in Orkney is located in the northern Orkney Islands, the results from the phytoplankton monitoring scheme will still give an indication of when blooms are likely to occur in the region of interest and therefore the most important time of year to collect fish prey and seal scats. As results are posted on the web on a weekly basis, this will give us an 'early warning' of potential toxic events and when to particularly target sample collection. The sites in Argyll and Bute are close to the study site and will therefore provide very useful information on bloom occurrence during the period of observation and scat and prey collection. For example, *Dinophysis* and *Alexandrium* blooms tend to occur earlier in the year (April-May) than *Pseudo-nitzschia* (July and September). However, as indicated from the urine and faecal samples collected to date, HAB toxins can also be sequestered into sediments and therefore be detected in prey outwith a large bloom. The prey choice (planktivorous *vs.* benthic for example) of the seals is perhaps the most important factor dictating the seasonality of toxin exposure as the planktivorous fish may take up toxins at the time of the bloom whereas flatfish may concentrate toxins from the sediments. Thus linking HAB blooms, toxin production, prey exposure, prey choice and seal uptake will be a key aspect of the study.

7 Approach 6. Carcass collection

7.1 Introduction

Observations of predation by adult male grey seals on grey seal pups in 2014, and the resulting pathology on the retrieved carcasses, are presented in the appended submitted scientific paper manuscript (Brownlow *et al.*, 2016) (see Section 10.7). Analysis of the wound patterns and comparison with previous records of spiral lacerations suggest that most cases previously attributed to propeller injuries could be explained by grey seal predation. The following report provides an update on the current state of knowledge of the causes of spiral lacerations in seals based on necropsy results of stranded individuals since November 2014. Cases which have occurred around Scotland since November 2014 are summarised along with objective assessments of the cause of the wound patterns based on a weighted scoring system.

7.2 Methods

An attempt was made to collect all reported dead stranded seals with suspected corkscrew lesions or other signs of potential seal predation trauma around the Scottish coast since November 2014, depending on the level of autolysis and the accessibility of the carcass. The assessment of autolysis was carried out subjectively on a case by case basis. If carcasses were not collected, on-site necropsies were carried out to identify likely cause of death, length measurements and photographs of wound margins were taken and seal sex and species was determined if possible.

Carcasses were collected either by a member of the Scottish Marine Animal Stranding Scheme (SMASS) or SMRU. They were stored either in a freezer (-16° C) or a cold store (5° C) prior to laboratory necropsy. Necropsies collected the following information, if the state of the carcass allowed:

- Physical metrics (Figure 25)
    - Length (tip of the nose to tip of the tail *and* tip of the nose to tip of the rear flippers).
    - Axial girth.
    - Mid-sternal blubber thickness.
- Lesion morphometrics
    - Length of cut.
    - Distance between cuts (dorsally and ventrally).
    - Rotation direction (clockwise or counter clockwise, as viewed from muzzle).
    - Inclination of wound edge (perpendicular, caudal or cranial).

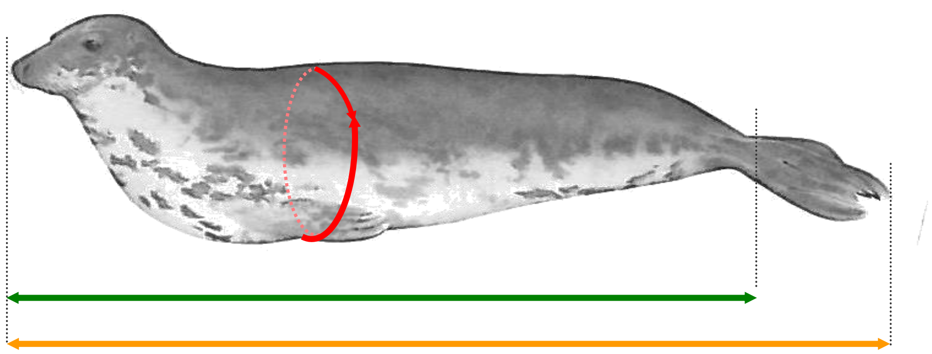


Figure 25. Body metrics taken for each necropsy where the condition of the carcass allowed.

7.3 Results and conclusions

Table 6 shows all cases found during the study window and Table 7 the associated necropsy results. Since November 2014, 34 carcasses with spiral lacerations have been recorded along the Scottish coast. Of these cases, 26 were grey seals, 6 harbour seals and 2 of indeterminate species. Using the objective assessment of the likelihood of grey seal predation being the cause of death, described in Brownlow *et al.*, (2016) (see section 12.7), six of these cases were classed as definite, fourteen as likely, three as probable, ten as possible and one where no data were available to assess the likelihood of grey seal predation. None of the carcasses examined were classed as unlikely. A further 21 cases have yet to be confirmed and scored. However, due to descriptions from volunteers and members of the public, they are all likely to be scored as potential cases of grey seal predation. Lack of empirical evidence precludes their inclusion in the database. Of these, as yet, undetermined cases, 20 are from Orkney and one is from the Western Isles.

The scoring system and assessment which resulted in the classifications in Table 7 (i.e. objective assessment of grey seal predation) is based on an analysis of the results of directly observed predation events on the Isle of May in November and December 2014. A detailed description of these events and analysis of the pathology are presented in Brownlow *et al.* (2016) (see section 12.7). The majority of cases found since the identification of grey seal predation as a likely cause of spiral lacerations have wound characteristics consistent with this theory. Carcass collection, necropsy analysis and observations at key locations will continue to attempt to identify the true extent of the phenomenon, and what possible population consequences this could have on seals around Scotland. Observations at the Isle of May in 2015 attempted to identify further adult males causing spiral lacerations and, although incidences of aggression were observed, no cannibalism events were reported.

The total number of seals reported with spiral wounds around Scotland from 1988 to the date of this report is 170, of which 103 were grey seals, 57 harbour seals, one a hooded seal and 9 of indeterminate species.

Table 6. Species ID, location, date found and morphometrics (where possible) of every potential corkscrew seal reported in Scotland since November 2014.

SMASS ID Number	Species	Date Found	Location	Region	Length (nose to tail, cm)	Length (nose to flipper, cm)	Axial Girth (cm)	Ventral Blubber (cm)
M382/14	Grey seal	01/12/2014	Bu sands, Burray	Orkney	N/A	N/A	N/A	N/A
M409/14	Grey seal	03/12/2014	Isle of May, Kirkhaven	Fife	121	106	93	52
M410/14	Grey seal	03/12/2014	Isle of May, Kirkhaven	Fife	124	107	70	54
M411/14	Grey seal	03/12/2014	Isle of May, Kirkhaven	Fife	115	102	66	30
M412/14	Grey seal	03/12/2014	Isle of May, Kirkhaven	Fife	135	117	87	51
M413/14	Grey seal	03/12/2014	Isle of May, Loan	Fife	124	109	91	45
M414/14	Grey seal	03/12/2014	Isle of May	Fife	122	106	NA	48
M415/14	Grey seal	03/12/2014	Isle of May	Fife	129	111	98	52
M416/14	Grey seal	04/12/2014	Isle of May	Fife	137	119	91	52
M417/14	Grey seal	05/12/2014	Isle of May	Fife	128	111	83	45
M373/14	Grey seal	24/11/2014	Isle of May	Fife	115	99	57	24
M439/14	Grey seal	18/12/2014	Echnaloch Bay, Burray	Orkney	N/A	N/A	N/A	N/A
M443/14	Grey seal	18/12/2014	Echnaloch Bay, Burray	Orkney	N/A	N/A	N/A	N/A
M387/14	Grey seal	02/12/2014	Isle of May, Loan	Fife	120	104	52	52
M431/14	Grey seal	07/12/2014	Isle of May, Loan	Fife	N/A	N/A	N/A	N/A
M432/14	Grey seal	08/12/2014	Isle of May, Loan	Fife	N/A	N/A	N/A	N/A
M433/14	Grey seal	09/12/2014	Isle of May, Kirkhaven	Fife	N/A	N/A	N/A	N/A
M8/15	Grey seal	05/01/2015	Scapa beach	Orkney	N/A	N/A	N/A	N/A
M12/15	Grey seal	07/01/2015	Dunnet beach	Highland	N/A	N/A	N/A	N/A

M29/15	Grey seal	14/01/2015	Sands of Wright	Orkney	N/A	N/A	N/A	N/A
M40/15	Harbour Seal	19/01/2015	South beach, Troon	Strathclyde	N/A	N/A	N/A	N/A
M54/15	Grey seal	26/01/2015	Dornoch Firth	Highland	N/A	N/A	N/A	N/A
M77/15	Grey seal	11/02/2015	Point of Buckquoy, Birsay	Orkney	N/A	N/A	N/A	N/A
M94/15	Grey seal	02/03/2015	Loch Broom	Highland	N/A	N/A	N/A	N/A
M227/15	Harbour Seal	17/07/2015	West Sands, St. Andrews	Fife	189	163	122	49
M249/15	Harbour Seal	27/07/2015	Achiltibuie	Highland	110	93	N/A	10
M251/15	Harbour Seal	26/07/2015	Achiltibuie	Highland	110	94	80	52
M259/15	Grey seal	30/07/2015	Tentsmuir	Fife	171	155	N/A	50
M288/15	Indeterminate species	04/09/2015	Badetarbet bay.	Highland	N/A	N/A	N/A	N/A
M290/15	Indeterminate species	04/09/2015	Dornoch airfield.	Highland	N/A	N/A	N/A	N/A
M349/15	Harbour Seal	26/10/2015	Danna	Argyll and Bute	N/A	N/A	N/A	N/A
M368/15	Harbour Seal	15/11/2015	Braeswick, Sanday	Orkney	N/A	N/A	N/A	N/A
M374/15	Grey seal	14/11/2015	Baleshare	Western Isles	N/A	N/A	N/A	N/A
M381/15	Grey seal	21/11/2015	Evie Beach	Orkney	N/A	N/A	N/A	N/A

Table 7. Wound attributes for every corkscrew seal reported in Scotland since November 2014. A score of 1 denotes presence of the characteristic, -1 denotes absence of the characteristic and 0 denotes an inability to assess presence or absence of the characteristic.

SMASS ID Number	Single linear lesion (one or more rotations)	Absence of skeletal trauma	Skeletal trauma to head	Avulsion of one or both scapula	Skeletal trauma to Scapula	Smooth edged wound	Ragged edged wound	Areas of skin or tissue missing	No obvious tissue defects associated with wound margin	Lesion begins at mouth	Punctate lesions on muzzle	Punctate lesions elsewhere	Rakemarks in blubber	Undermining of blubber	Adjectival assessment for grey seal predation
M382/14	1	0	1	1	1	1	-1	1	-1	0	0	-1	0	1	Possible
M409/14	-1	1	1	-1	-1	-1	1	1	1	1	1	-1	-1	-1	Likely
M410/14	1	-1	1	1	1	1	-1	1	-1	1	1	-1	1	1	Likely
M411/14	1	-1	1	1	1	1	-1	1	-1	1	1	-1	1	1	Likely
M412/14	-1	-1	1	-1	-1	-1	1	-1	1	1	1	1	-1	-1	Likely
M413/14	1	1	-1	1	-1	1	1	1	-1	-1	-1	1	1	1	Likely
M414/14	-1	-1	-1	1	-1	-1	1	1	-1	-1	-1	1	1	1	Definite
M415/14	-1	1	-1	1	-1	-1	1	1	-1	-1	-1	1	1	1	Likely
M416/14	1	-1	-1	1	1	1	1	1	-1	-1	-1	1	1	1	Definite
M417/14	-1	-1	-1	1	-1	1	1	1	-1	-1	-1	-1	1	1	Definite
M373/14	1	1	-1	1	1	1	-1	1	-1	-1	1	-1	1	1	Likely
M439/14	-1	-1	-1	1	0	-1	1	1	-1	0	0	0	0	0	Possible
M443/14	0	0	-1	1	0	-1	1	1	0	0	0	0	0	0	Possible
M387/14	1	-1	-1	-1	-1	1	1	1	-1	-1	-1	1	1	1	Definite
M431/14	1	-1	-1	-1	-1	1	1	1	-1	1	-1	1	1	1	Definite
M432/14	1	-1	-1	1	1	1	-1	1	-1	1	-1	1	1	1	Definite
M433/14	1	1	-1	-1	-1	1	-1	1	1	1	1	1	-1	1	Likely

M8/15	-1	0	0	1	0	-1	1	1	1	0	0	0	0	0	Possible
M12/15	0	0	0	1	0	0	0	0	1	0	0	0	0	0	Possible
M29/15	0	-1	0	-1	-1	-1	1	1	-1	-1	0	0	1	1	Possible
M40/15	1	0	1	1	1	1	1	1	1	0	0	0	0	0	Possible
M54/15	0	0	0	1	0	0	0	0	0	0	0	0	0	0	No data
M77/15	1	0	0	1	1	1	-1	1	1	-1	0	0	0	1	Likely
M94/15	1	0	0	1	-1	1	0	1	1	0	0	0	0	0	Possible
M227/15	1	-1	-1	1	1	1	1	1	-1	1	1	1	-1	1	Likely
M249/15	1	-1	1	1	-1	-1	1	1	1	1	1	1	1	1	Likely
M251/15	1	-1	1	1	1	1	-1	1	1	1	1	1	1	1	Likely
M259/15	1	-1	-1	1	-1	1	-1	1	-1	1	1	0	-1	1	Likely
M288/15	0	0	0	1	0	1	0	0	0	0	0	0	0	0	Possible
M290/15	0	0	0	1	0	0	0	1	0	1	0	0	0	0	Possible
M349/15	1	-1	0	1	1	1	0	1	0	0	0	0	0	0	Likely
M368/15	1	0	-1	0	0	1	0	1	1	1	-1	0	0	0	Probable
M374/15	1	0	0	1	0	1	-1	1	1	1	0	0	0	0	Probable
M381/15	1	0	0	1	0	1	1	1	0	1	0	0	0	0	Probable

8 Harbour Seal Decline Project web blog

A web blog has been set up through the University of St Andrews WordPress Multisite service with information on the harbour seal decline project (Figure 26). The blog aims to provide a link between the science carried through the project within SMRU and the general public, stakeholders and other organizations interested in the project. The blog provides background information on the research being conducted, the scientific questions, the biology of harbour seals, and presents the team of researchers behind it. The main page of the blog (Home page) will be updated regularly with posts about data collection in different regions of Scotland as well as data processing and analysis, mostly during the field season in the spring and summer.

A link to the blog can be found at http://synergy.st-andrews.ac.uk/harbourseals/, and new posts in the blog will be advertised via Twitter using the SMRU account (@_SMRU_).

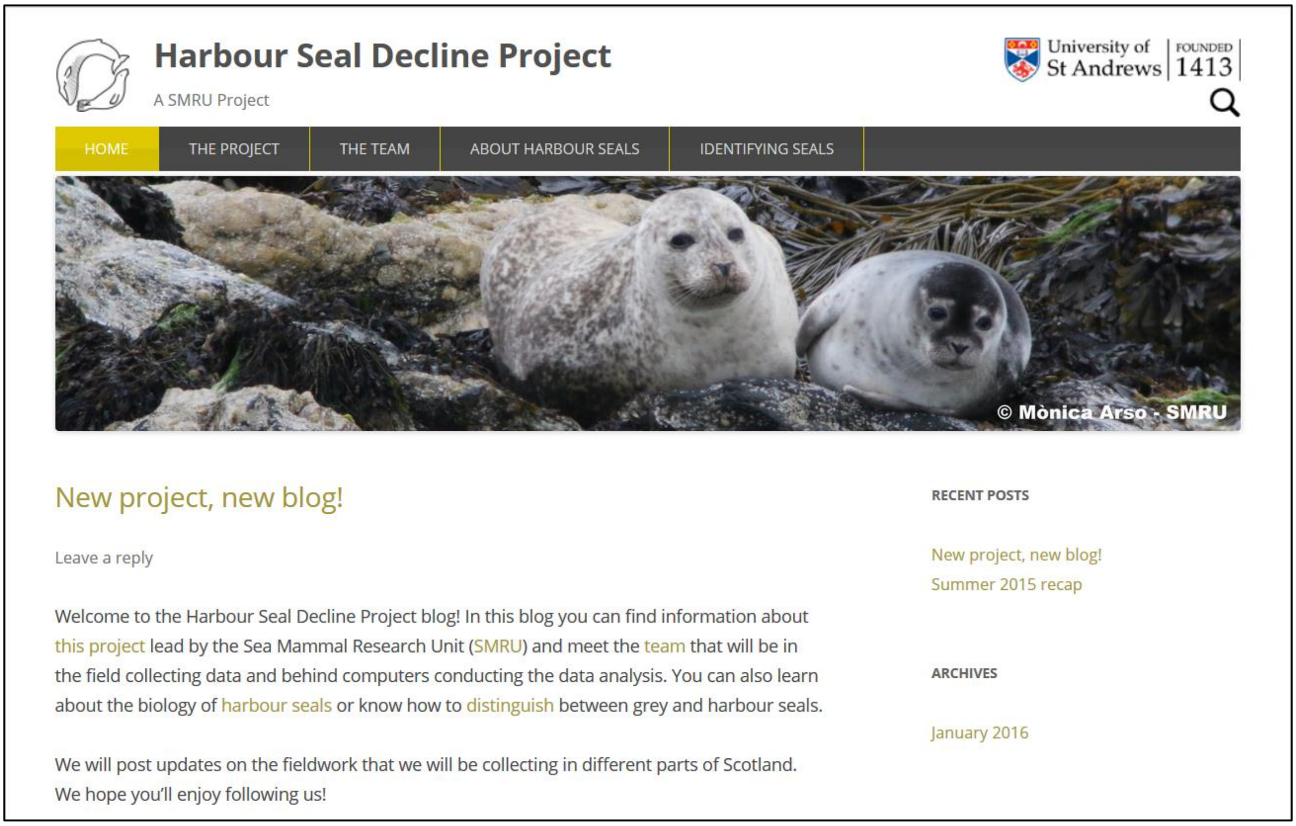


Figure 26. Screen capture of the Harbour Seal Decline Project blog's home page.

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10 Appendices

10.1 Appendix 1: Deliverables for Year 1 (HSD 2)

Approach 1. Integrated population model.

1. Fully commented code for model-fitting, and technical report to support the use of this code (equivalent to a help file)
2. Report outlining the performance of the re-coded model

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

1. A report reviewing the trial sites that have been visited, and recommending which may be suitable for long-term intensive studies under the project.

   These will be the criteria for site selection. Ideally, the sites chosen would have the following characteristics:

   - Harbour seals moult and breed at the same site
   - Logistically accessible
   - There are sufficient animals to allow for robust estimation of population parameters
   - The site is suitable for photography using digi-scoping and/or UAV
   - The site is accessible for scat collection
   - Adjacent grey seal populations, if there are any, are countable
   - Live captures of harbour seals can be carried out at the site
   - Harbour seals can be observed without undue disturbance
   - The site can be monitored so that any carcasses can be collected for necropsy
   - There is good visibility of females during breeding, for estimation of fecundity

2. A report detailing any data collection that has taken place during visits to trial sites. This may include photographs, scats, counts, and necropsy reports from carcasses.

3. A report on the development of low-cost tags for local telemetry studies of harbour seal movement around chosen sites.

Approach 3. Live Captures.

There will be no live captures in year 1

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

1. A report detailing the existing aerial survey data and an assessment of the feasibility of obtaining count data using various methods (e.g. ground counts, UAV and conventional air survey methods) for the trial sites.

Approach 5. Improving understanding of potential drivers of population change

1. For the trial sites surveyed during the first year study, a report detailing:

   - Feasibility of scat collection across trial sites
   - Investigation of the availability of prey samples relevant to seals foraging from trial sites
   - Collate prey abundance data

- Collate data from the monitoring of HABs

The parallel Marine Scotland and Scottish Natural Heritage funded Ardersier project will be providing reports during year 1, these will be seen by a subset of the MMSS steering group, but they are not specific deliverables for this project. If required these reports or a summary of them could be made available to the MMSS project steering group.

Approach 6. Carcass collection

1. Full necropsy reports on any dead seals found and collected within the regions of the trial sites (in collaboration with Scottish Marine Animal Stranding Scheme)
2. A progress report summarizing the initial results of studies of the patterns of occurrence, extent and estimated scale of predation mortality in both harbour and grey seal populations in Scotland.
3. An updated version of the "Current state of knowledge of the extent, causes and population effects of unusual mortality events in Scottish seals."

10.2 Appendix 2: Model and equations

10.2.1 Population model

The age-structured model considers the following common seal age and sex classes:

- Class 1: male pups
- Class 2-4: male juveniles
- Class 5: adult males
- Class 6: female pups
- Class 7-9: female juveniles
- Class 10: adult females

Beginning in the first year with initial number of seals n_0 the population in each category is updated through the processes of survival and reproduction.

Survival rates are calculated based on a logistic function, allowing for time-dependence and for positive or negative effects of conspecifics. $n_{total,t}$ is the total number of harbour seals (non-pups) in the population in year t

$$ss_{i,t} = \frac{exp(s_{o,i} + s_{1,i}(t-22) + s_{2,i}n_{total,t})}{1 + exp(s_{o,i} + s_{1,i}(t-22) + s_{2,i}n_{total,t})}$$

Survival is also impacted by shooting mortality. Maximum shooting mortality is mort, and str_t is a time-dependent scalar that changes the impact of shooting:

$s_{i,t} = ss_{i,t}(1\text{-}str_t\, mort)$

For juveniles

$n_{i+1,t+1} \sim Bernouilli\ (s_{i,t,}\ ,\ n_{i,t})$

Adults are an 'absorbing' age class

$n_{i+1,t+1} \sim Bernouilli\ (s_{i+1,t}\ ,\ n_{i+1,t})$

Pups in year $t+1$ are born if a female survives into year t+1 and also reproduces. Fecundity is based on the preceding year's covariates.

$$f_{i,t} = \frac{exp(b_o + b_1(t-22) + b_2 n_{total,t})}{1 + exp(b_o + b_1(t-22) + b_2 n_{total,t})}$$

Pup births

$n_{0,t+1} \sim Bernouilli\ (f_{10,t}{*}s_{10,t}\ ,\ n_{10,t})$

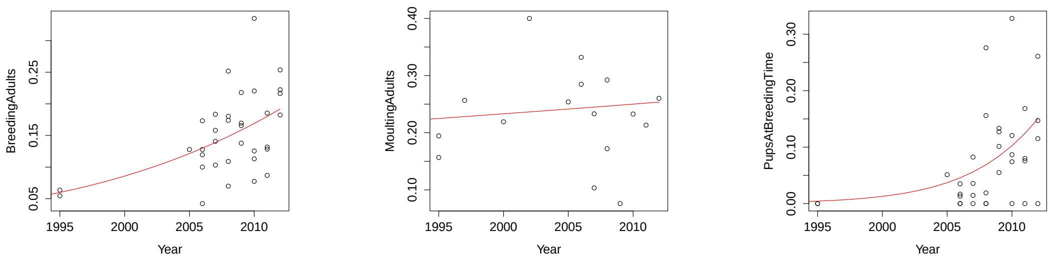
10.2.2 Observations

The number of shot seals that are recovered and counted is a proportion of the total number due to a geographical split between the inner and outer Moray Firth. If ns_{it} is the number of shot seals in class i in year t

$shot_t \sim Poisson(split\ \Sigma ns_{i,t})$

Surveys may take place either at breeding or at moult. Fixed parameters are used to set the expected proportion of animals in class i hauled out at breeding or moult, $pho_{i,k}$.

Surveys covered Brora/Helmsdale, LochFleet/Dornoch, or both sites. There was some support for a change in the proportions at these sites over time. The number expected at each site *psite* was modelled using a binomial glm parameterised outside the main model, based on aerial survey data.



Proportion of seals hauling out at Brora/Helmsdale as a function of time, function fitted using binomial glms to the adult and pup data.

The number of seals in each age class expected hauled out at site s in season k is calculated from

$n_{i,t,s,k} = n_{i,t,k}\ pho_{i,k}\ psite_{i,k}$

In addition, the model includes a random variation in haulout probability. For a survey carried out on occasion d

$err_d \sim dnorm(0,0.2)$

and this error was added to the expected haulout probability on the logistic scale

$q = log(pho_{i,k}/(1+ pho_{i,k}))$

$q^* = q+err$

$pho_{i,k}^* = exp(q^*)/(1+exp(q^*))$

The number of seals (adults or pups) observed in the survey at site s in season k is then modelled as a Poisson process

$adults_{obs,s,k} \sim Poisson(adults_{t,s,k})$

$pups_{obs,s,k} \sim Poisson(pups_{t,s,k})$

10.2.3 Independent population size estimates

Two estimates of the local population size were available, one based on mark-recapture and one on telemetry plus onshore counts. The model's prediction of total population size $n_{tot,t}$ is compared with the observed values $n_{indep,t}$

$$n_{indep,t} \sim dnorm(n_{tot,t}, 0.075 * n_{tot,t})$$

10.3 Appendix 3: Parameters and Priors

10.3.1 Haulout probability by season and age class

	1	2	3	4	5	6	7	8	9	10
Breeding season	0.85	0.5	0.5	0.5	0.5	0.85	0.5	0.5	0.5	0.75
Moult season	0.10	0.5	0.5	0.5	0.6	0.10	0.5	0.5	0.5	0.50

10.3.2 Priors

Parameter	Description	Prior
$s_{0,1}$	intercept coefficient in the linear predictor for survival rate, pups	q~β(2,2) $g_{=}$=0.6+q*0.2 $_1$=log(g_p/(1-g_p))-$S_{2,juv}$*$nindep_2$
$s_{0,2}$	intercept coefficient in the linear predictor for survival rate, juveniles	q~β(2,2) gp<-0.7+q*0.2 $s_{0,2=}$log(gp/(1-gp))- $s_{,uv}$*$nindep_2$
$s_{0,5}$	intercept coefficient in the linear predictor for survival rate, adult males	q~β(2,2) gm=0.94+0.06q $s_{0,10}$=-log(gm/(1-mf))- $s_{2,adults}$*nindep[2]
$s_{0,10}$	intercept coefficient in the linear predictor for survival rate, adult females	gf=0.94+0.06q $s_{0,10}$=-log(gf/(1-gf))- $s_{2,adults}$*nindep[2]
$s_{1,juv}$	coefficient associated with time-dependence in the linear predictor for survival rate, juveniles	(-0.03)+0.06*β(2,2)
$s_{1,adults}$	coefficient associated with time-dependence in the linear predictor for survival rate, adults	(-0.03)+0.06* β(2,2)
$s_{2,juv}$	coefficient associated with population density-dependence in the linear predictor for survival rate, juveniles	(-0.02)+0.04* β(2,2)
$s_{2,adults}$	coefficient associated with population density-dependence in the linear predictor for survival rate adults	(-0.02)+0.04* β(2,2)
f_0	intercept coefficient in the linear predictor for fecundity	β(2,2)
f_1	coefficient associated with time-dependence in the linear predictor for fecundity, adults	β(2,2)
f_2	coefficient associated with population density-dependence in the linear predictor for fecundity	β(2,2)
mort	Baseline mortality from shooting	0.05+ 0.15 β(2,2)
lambda.n_0	initial population size, log scale. n_0=exp(lambda.n_0)	N(4.6, sd=0.46)
strbe	scalar for shooting mortality before the period of intensive shooting	U(0.4,0.6)
straf	scalar for shooting mortality after the period of intensive shooting	U(0.05,0.15)

10.4 Appendix 4: Moray Firth survey data

Site (1=LochFleet & Dornoch, 2=Brora&Helmsdale)	***Season*** (1=breeding, 2=moult)	***Year*** (year 1 is 1988)	***Survey type*** (1=ground, 2=aerial)	***Adult Count***	***Pup Count***
1	1	1	1	528	27
1	1	1	1	513	21
1	2	1	1	542	0
1	1	2	1	443	29
1	1	2	1	183	23
1	1	2	1	156	34
1	1	2	1	148	31
1	1	2	1	135	29
1	1	2	1	330	25
1	2	2	1	363	0
1	1	3	1	357	0
1	1	3	1	385	6
1	2	3	1	453	0
1	2	4	1	437	0
1	2	4	1	327	0
1	1	5	1	468	62
1	1	5	1	363	85
1	2	5	1	590	0
1	2	5	1	441	0
1	1	6	1	489	26
1	1	6	1	556	134
1	1	6	1	532	136
1	1	6	1	642	116
1	1	6	1	528	70
1	1	6	1	489	85
1	1	6	1	562	63
1	1	6	1	582	33
1	2	6	1	656	0
1	2	6	1	614	0
1	1	7	1	534	121
1	1	7	1	380	63
1	1	7	1	449	53
1	1	7	1	388	24
1	1	8	1	343	17
1	1	8	1	380	34
1	1	8	1	497	100
1	1	8	1	547	113
1	1	8	1	411	90
1	2	8	1	511	0
1	2	8	1	464	0
1	1	9	1	419	20
1	1	9	1	531	81
1	1	9	1	428	109
1	1	9	1	401	104
1	1	9	1	421	55
1	2	9	1	415	0
1	2	9	1	405	0
1	1	10	1	293	40
1	1	10	1	427	60
1	1	10	1	331	51
1	1	10	1	243	59
1	1	10	1	253	61
1	2	10	2	834	0

1	1	11	1	379	45
1	1	11	1	479	108
1	1	11	1	470	123
1	1	11	1	462	91
1	1	11	1	226	44
1	2	11	1	521	0
1	2	11	1	472	0
1	2	11	1	399	0
1	1	12	1	518	11
1	1	12	1	363	36
1	1	12	1	451	128
1	1	12	1	374	78
1	1	12	1	333	78
1	2	12	1	262	0
1	2	12	1	446	0
1	1	13	1	437	79
1	1	13	1	408	90
1	1	13	1	417	123
1	1	13	1	282	72
1	1	13	1	247	61
1	2	13	1	328	0
1	2	13	1	318	0
1	2	13	1	325	0
1	2	13	1	317	0
1	2	13	1	335	0
1	1	14	1	338	61
1	1	14	1	435	130
1	1	14	1	423	106
1	1	14	1	396	95
1	1	14	1	348	74
1	2	14	1	280	0
1	2	14	1	373	0
1	2	14	1	365	0
1	1	15	1	306	20
1	1	15	1	378	107
1	1	15	1	374	123
1	1	15	1	349	76
1	1	15	1	275	63
1	2	15	2	470	0
1	2	15	1	302	0
1	2	15	1	336	0
1	1	16	1	349	81
1	1	16	1	410	86
1	1	16	1	266	69
1	1	16	1	302	56
1	1	16	1	213	25
1	2	16	1	272	0
1	2	16	1	206	0
1	1	17	1	330	89
1	1	17	1	326	115
1	2	17	1	313	0
1	2	17	1	294	0
1	1	18	1	266	21
1	1	18	1	230	58
1	1	18	1	231	33
1	1	18	1	226	25
1	2	18	2	445	0

1	2	18	1	295	0
1	2	18	1	240	0
1	1	19	1	195	22
1	1	19	1	209	49
1	1	19	1	207	77
1	1	19	1	213	53
1	1	19	1	134	43
1	1	19	2	219	17
1	1	19	2	283	60
1	1	19	2	189	84
1	1	19	2	268	76
1	1	19	2	190	57
1	2	19	2	491	0
1	2	19	2	481	0
1	1	20	2	218	28
1	1	20	2	234	85
1	1	20	2	223	69
1	1	20	2	199	54
1	2	20	2	174	0
1	2	20	2	386	0
1	1	21	2	257	53
1	1	21	2	229	89
1	1	21	2	183	77
1	1	21	2	282	87
1	1	21	2	184	33
1	2	21	2	349	0
1	2	21	2	250	0
1	1	22	2	358	91
1	1	22	2	305	168
1	1	22	2	296	150
1	1	22	2	230	118
1	2	22	2	250	0
1	1	23	2	297	72
1	1	23	2	292	162
1	1	23	2	271	150
1	1	23	2	295	141
1	1	23	2	203	61
1	2	23	2	434	0
1	1	24	2	207	34
1	1	24	2	296	132
1	1	24	2	319	150
1	1	24	2	259	101
1	2	24	2	408	0
1	1	25	2	305	34
1	1	25	2	261	113
1	1	25	2	340	136
1	1	25	2	276	69
1	2	25	2	392	0
2	1	8	1	22	0
2	1	8	1	28	0
2	2	8	1	123	0
2	2	8	1	86	0
2	2	10	2	214	0
2	2	13	1	91	0
2	2	15	2	188	0
2	1	18	1	34	2
2	2	18	2	113	0

2	1	19	2	28	0
2	1	19	2	49	1
2	1	19	2	8	0
2	1	19	2	32	1
2	1	19	2	19	2
2	2	19	2	163	0
2	2	19	2	264	0
2	1	20	2	40	1
2	1	20	2	37	7
2	1	20	2	23	1
2	1	20	2	28	0
2	2	20	2	18	0
2	2	20	2	90	0
2	1	21	2	28	1
2	1	21	2	16	0
2	1	21	2	33	12
2	1	21	2	71	24
2	1	21	2	32	0
2	2	21	2	102	0
2	2	21	2	43	0
2	1	22	2	78	5
2	1	22	2	42	17
2	1	22	2	49	20
2	1	22	2	39	15
2	2	22	2	19	0
2	1	23	2	23	0
2	1	23	2	33	12
2	1	23	2	34	13
2	1	23	2	65	17
2	1	23	2	68	20
2	2	23	2	101	0
2	1	24	2	18	0
2	1	24	2	38	10
2	1	24	2	42	12
2	1	24	2	48	17
2	2	24	2	87	0
2	1	25	2	66	0
2	1	25	2	58	13
2	1	25	2	62	20
2	1	25	2	70	18
2	2	25	2	102	0

10.5 Appendix 5: Example help documentation

mfmcmc.fn(thin,inits,HPinits,l.fn,sim.fn,iterations)

This is the main function, which runs the mcmc and provides as output a chain of parameters and states sampled from the posterior distribution. Bayesian inference is carried out for a state-space model with parameters

$\boldsymbol{\theta} = (\theta_{1,}\theta_2 \ldots \theta_k)$

and states

$\boldsymbol{x} = (x_1, x_2 \ldots x_f)$

Using an mcmc algorithm is designed to sample from the posterior distribution with probability proportional to

$Pr(\boldsymbol{\theta})Pr(x_1|\boldsymbol{\theta}) \prod_{t=2}^{n} Pr(x_t|\,\boldsymbol{\theta}, x_{t-1}\,) \prod_{t=1}^{n} Pr(\boldsymbol{y}|\boldsymbol{x},\boldsymbol{\theta})$ ……………………………….(1)

In this expression:

$Pr(\boldsymbol{\theta})$ is the prior distribution of the parameters.

$\prod_{t=1}^{n} Pr(\boldsymbol{y}|\boldsymbol{x},\boldsymbol{\theta})$ is the "likelihood function" i.e. the probability of observations, given parameters (and also states).

$(x_1|\boldsymbol{\theta}) \prod_{t=2}^{n} Pr(x_t|\,\boldsymbol{\theta}, x_{t-1}\,)$ is the likelihood of a given state of the chain of hidden states.

Inputs

name	**description**
thin	Integer j, the values of parameters and states in the Markov chain will be saved every jth iteration
inits	Initial values of the parameters
hpinits	Initial values for the hidden states
l.fn	The user must provide l.fn() which evaluates the log of the likelihood given by equation(1) for a given set of hidden states, parameters, priors and data.
sim.fn	The user must provide sim.fn() which simulates a new realisation of the chain of hidden states
iterations	The number of iterations of the mcmc

Value

mfmcmc.fn returns a list of values

name	**description**
Param.chain	Chain of mcmc samples of the full set of parameters
n.chain	Chain of mcmc samples of population sizes. This is vectorised, and can be written into a matrix dimension 10 rows (corresponding to the age/sex classes) and 25 columns (corresponding to the 25 years of the study)
Err.chain	Chain of samples of survey error, each sample containing 123 values (one value for each survey occasion).
HPs	Final states at the last iteration of the for the mcmc

mfLL.fn(parms,hiddenstates)

This function, called by mfmcmc, evaluates the log of the likelihood given by equation (1) for a given set of hidden states, parameters, priors and data. The data (survey counts, shot seals recovered, and independent population estimates) must be attached in the R environment.

Inputs

name	**description**
parms	Vector: full set of parameters
hiddenstates	A list as produced by

Value

mfLL.fn returns a single value, the log likelihood.

mfsim.fn(parms) and pop.fn(bf,bs,firstseals,mort,str)

mfsim.fn is a 'wrapper' that takes as its argument the raw parameter values updated by the mcmc. Some of these are a little difficult to interpret, due to the slightly complex way in which prior distributions have been constructed. The values are transformed in mfsim.fn and passed to pop.fn which simulates the population trajectory (numbers in all age and sex classes over the years of the study). Stochasticity is included in the birth/death and hauling-out process in pop.fn. Haulout probabilities are fixed in the model by age and sex class, but to represent daily variation in hauling-out behaviour, variability is added on the logistic scale, using 'errors' sampled from a normal distribution.

Inputs to pop.fn, passed by mfsim.fn

name	description
bf	Vector of coefficients for the linear predictor that is used in the logistic function to calculate fecundity. Using R notation, the linear predictor is calculated for a given time step *t* using covariates *t* and the total population size n_{tot} Bf[1] + bf[2]*(t-22) + bf[3]*n_{tot}
bs	Vector of coefficients for the linear predictor that is used in the logistic function to calculate survival rates. Using R notation, the linear predictor is calculated for a given time step *t* using covariates *t* and the total population size n_{tot}
firstseals	The total number of seals in the population in the first year of the study. This is estimated by the model. The initial age structure is assumed.
mort	Maximum per capita shooting mortality
str	Shooting parameter, vector of 3 values for periods before, during and after the main period of shooting in the area. This multiplies mort to give the realised value of shooting mortality during each period.

Value

name	description
n	matrix of population sizes, dimension 10 rows (corresponding to the age/sex classes) and 25 columns (corresponding to the 25 years of the study)
shotseals	Vector, the number of seals estimated to be shot in each year of the study
err	Survey variability, vector of 123 values, one value for each survey occasion.

10.6 Appendix 6: R code

Code is given for two functions, mfsim.fn which simulates the trajectory of the common seal population, based on vital rates and initial values, implementing the model described in Appendix 1. mfmcmc.fn estimates parameters and hidden states, given the data (Appendix 2).

```
############################################
pop.fn<-function(bf,bs,firstseals,mort,str)
############################################

{

  ####### PARAMETERS ###########

  ### years for the study ###
  nyear<-25

  ### matrix to represent the seal population structure each year
  # males are 1:5
  # female are 6:10
  # final absorbing age class (aged 5) is "mature animals" for both sexes
  n<-matrix(nrow=10,ncol=nyear,data=0)


  ### starting population size in all age classes
  n[,1]<-round(firstseals*agestructure)

  ### vector to store variation in haulout probability
  err<-rep(0,ncounts)

  ### vector to store total population size
  ntot<-rep(0,nyear)

  ### survival and related matrices
  ss<-matrix(nrow=10,ncol=nyear)
  s<-ss
  shotbyclass<-ss
  ShotSeals<-rep(0,nyear)

  ### numbers hauled out vector
  nHo<-rep(0,10)

  ### survival parameters for the logistic function

  s0<-rep(0,10)
  s1<-s0
  s2<-s0

  s0[1]<-bs[1]          # male pups
  s0[6]<-bs[1]          # female pups
  s0[2:4]<-bs[2]        # male juveniles
  s0[7:9]<-bs[2]        # female juvs
  s0[5]<-bs[3]          # adult males
  s0[10]<-bs[4]         # adult females

  s1[1]<-bs[5]          # pups
  s1[6]<-bs[5]
  s1[2:4]<-bs[6]        # juveniles
  s1[7:9]<-bs[6]
  s1[5]<-bs[7]          # adult males
  s1[10]<-bs[8]         # adult females

  s2[1]<-bs[9]          # male pups
```

```
  s2[6]<-bs[9]          # female pups
  s2[2:4]<-bs[10]       # male juveniles
  s2[7:9]<-bs[10]       # female juvs
  s2[5]<-bs[11]         # adult males
  s2[10]<-bs[12]        # adult females

  ### fecundity parameters

  f0<-bf[1]
  f1<-bf[2]
  f2<-bf[3]


  ################# POPULATION DYNAMICS ##########################

  for(t in 1:(nyear-1)){

    ### total population size in year t (1+ animals only)

    ntot[t]<-sum(n[2:5,t])+sum(n[7:10,t])

    ### survival by age class for this year

    for (i in 1:10)

    {

      # Background survival probability based on covariates, logistic
      ss[i,t] <- logistic.fn(s0[i]+s1[i]*(t-22)+s2[i]*ntot[t])

      # Survival from shooting
      s[i,t]<-ss[i,t]*(1-mort*str[t])

      # deaths from shooting
      shotbyclass[i,t]<-mort*str[t]*n[i,t]

    }


    ### All seals shot in outer Moray Firth
    # value 2 is assumed to scale up to whole MF, original model had a (1.99,2.01)
prior
    ShotSeals[t]<-2*sum(shotbyclass[1:10,t])

    # pups, juveniles and adults survive from year t to t+1
    n[2,t+1]<-rbinom(1,n[1,t],prob=s[1])
    n[3,t+1]<-rbinom(1,n[2,t],prob=s[2])
    n[4,t+1]<-rbinom(1,n[3,t],prob=s[3])
    n[5,t+1]<-rbinom(1,n[4,t],prob=s[5])+rbinom(1,n[5,t],prob=s[5])
    n[7,t+1]<-rbinom(1,n[6,t],prob=s[6])
    n[8,t+1]<-rbinom(1,n[7,t],prob=s[7])
    n[9,t+1]<-rbinom(1,n[8,t],prob=s[8])
    n[10,t+1]<-rbinom(1,n[9,t], prob=s[10])+rbinom(1,n[10,t], prob=s[10])

    # Birth probability
    f[t] <- logistic.fn(f0+f1*(t-22)+f2*ntot[t])

    # the surviving adult females may pup in year t+1 (random, binomial)
    pups<-rbinom(1,n[10,t+1],prob=f[t])

    # 50% of the pups are female (random, binomial)
    femalepups<-rbinom(1,pups,prob=0.5)
    n[1,t+1]<-pups-femalepups
    n[6,t+1]<-femalepups
```

```
  } # end of main loop

  ### calculate shooting in final year

  t<-nyear

  ### survival by age class for this year

  for (i in 1:10)
  {
    ### Background survival probability based on covariates, logistic
    ss[i,t] <- logistic.fn(s0[i]+s1[i]*(t-22)+s2[i]*ntot[t])

    ### Survival from shooting
    s[i,t]<-ss[i,t]*(1-mort*str[t])

    ### deaths from shooting
    shotbyclass[i,t]<-mort*str[t]*n[i,t]
  }

  ### All seals shot in outer Moray Firth
  # value 2 is assumed to scale up to whole MF, original model had a (1.99,2.01)
prior
  ShotSeals[t]<-2*sum(shotbyclass[1:10,t])


  #### simulate seal shooting data ####

  for(i in 1:nshoots){

    # shot animals reported in outer Moray Firth
    #LLS<-LLS+dpois(shot[i],ShotSeals[syear[i]],log=T)
    shot[i]<-rpois(1,ShotSeals[syear[i]])

  } # end of loop over shooting data

#### seal survey count data at Brora/Helmsdale (BH) and LochFleet/Dornoch (LF)

  for(i in 1:ncounts){

    # expected numbers at this site by age/sex class (site 1 is LF, site 2 is BH)

    nn<-rep(0,10)

    psite<-ppnSite[Site[i],year[i],Season[i],]  # expected ppn at this site all
classes

    for(class in 1:10){nn[class]<-n[class,year[i]]*psite[class]}

    # expected probability of hauling out?

    # vector of HO probabilities all classes
      pH <- pHo[Season[i],]

    # logit transform in order to perturb the haulout probabilities
      err[i]<-rnorm(1,0,sd.pHo)
      for(class in 1:10){
      p0H<-log(pH[class]/(1-pH[class]))
      p0H<-p0H+err[i]
      pH[class]<-exp(p0H)/(1+exp(p0H))
    }

    ### expected hauled out animals by class
```

```
    for (class in 1:10){
      nHo[class]<-nn[class]*pH[class]
    } # end of loop over age/sex classes


    ###put animals into aggregated classes for observation
    pups<-nHo[1]+nHo[6]
    adults <-sum(nHo[2:5])+sum(nHo[7:10])

  } ### end of loop over the surveys

### return results as a list

  results<-list(n=n,shotseals=ShotSeals,err=err)

}     ### end of function

#####################################################################
```

```
####################################################################
mfmcmc.fn<-function(thin,initialparams,initialstates,LLfn,simfn,nits)
####################################################################

{

### initial states and parameters
  params<-initialparams
  n<-initialstates$n
  HPs<-initialstates

### set up chains
  n.chain<-as.vector(n)
  param.chain<-initialparams
  err.chain<-initialstates$err
  LLs<-LLfn(initialparams,initialstates)
  LL<-LLs
  nparams<-length(initialparams)
  AR<-rep(0,nparams+1)

### main loop over iterations ###

  for(j in 1:nits){  # loop over iterations

    for(i in 1:nparams) {   # loop through parameter set

      # pull out parameter value
      param<-params[i]

      # copy the parameter vector
      newparams<-params

      ## slightly different methods for bounded/unbounded priors

      if(is.lim[i]==1){                   # bounded prior

        upper<-min(uplim[i],param+stride[i])
        lower<-max(lowlim[i],param-stride[i])
        newparam<-runif(1,min=lower,max=upper)
        lnew<-dunif(newparam,min=lower,max=upper,log=T)

        newupper<-min(uplim[i],newparam+stride[i])
        newlower<-(max(lowlim[i],newparam-stride[i]))
        lold<-dunif(param,min=newlower,max=newupper,log=T)

        newparams[i]<-newparam
        newLL<-LLfn(newparams,HPs)
        log.ratio<-newLL-LL+lold-lnew

        # accept or reject based on ratio and variable "bar"
        bar<-alpha*runif(1,min=0,max=alpha)
        accept<-ifelse (log(bar)<log.ratio,1,0)

      }  else {                           # unbounded prior

        upper<-param+stride[i]
        lower<-param-stride[i]
        newparam<-runif(1,max=upper,min=lower)

        newparams[i]<-newparam
        newLL<-LLfn(newparams,HPs)
        log.ratio<-newLL-LL

        # accept or reject based on ratio and variable "bar"
```

```
        bar<-alpha*runif(1,min=0,max=alpha)
        accept<-ifelse (log(bar)<log.ratio,1,0)

      }  # end of decisions about the new parameter proposal

      ## overwrite the parameter vector if the new parameter is good

      if(accept==1){params<-newparams; LL<-newLL;AR[i]<-AR[i]+1}

    } # end loop over parameters

### now update states ###

    ### starting population size in all age classes ###
      HPs$n[,1]<-round(exp(params[13])*agestructure)

    ## now try a different population trajectory
    newHPs<-simfn(params)

    newLL<-LLfn(params,newHPs)
    log.ratio<-newLL-LL

    ## accept or reject based on ratio and variable "bar"
    bar<-alpha*runif(1,min=0,max=alpha)
    accept<-ifelse (log(bar)<log.ratio,1,0)

    if(accept==1){LL<-newLL;HPs<-newHPs;AR[nparams+1]<-AR[nparams+1]+1}

    ### store the current chain and LL value, depending on thinning

    if((j/thin-floor(j/thin))==0){
    param.chain<-rbind(param.chain,params)
    n<-HPs$n
    n.chain<-rbind(n.chain,as.vector(HPs$n))
    err<-HPs$err
    err.chain<-c(err.chain,err)

    LLs<-c(LLs,LL)}

    if((j/500-floor(j/500))==0){print(j)}

  } ### end of mcmc

  AR<-AR/nits                 # calculate final acceptance rates

### create a list of results and return it
  results    <-list(param.chain=param.chain,  n.chain=n.chain,  LLs=LLs,  AR=AR,
HPs=HPs)

return(results)

}   ### end of function

######################################################################
```

10.7 Appendix 7: Brownlow *et al.* (2016) paper

Brownlow A., Onoufriou, J., Bishop, A., Davison, N. and Thompson, D. (2016) "Corkscrew seals": Grey seal (*Halichoerus grypus*) infanticide and cannibalism may indicate the cause of spiral lacerations in seals *PLoS One*, 11:6, 1-14. http://dx.doi.org/10.1371/journal.pone.0156464 Accessed June 2016.