Marine Mammal Scientific Support Research Programme MMSS/001/11

Task CSD1:

Review of the status, trends and potential causes for the decline in abundance of harbour seals around the coast of Scotland

Sea Mammal Research Unit
Report to
Scottish Government

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Ailsa Hall and Joanna Kershaw

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

1 CONTENTS

2 ABUNDANCE, TRENDS, MOVEMENTS, FORAGING AND DEMOGRAPHY

2.1 Introduction

Key Findings – SCOS (2012)

- Compared with the mid 1990s, some populations have declined by:
  50% in Shetland; 68% in Orkney; and 90% in the Firth of Tay.
- Other populations do not show consistent declines:
  - Strathclyde is unclear having declined slightly after an apparent increase around 2000
  - The west coast of Highland region appears to be stable
  - The Moray Firth count declined by 50% before 2005, remained reasonably stable for 4 years then increased by 40%
  - The Outer Hebrides apparently declined by 35% between 1996 and 2008 but

Harbour (or common) seals (*Phoca vitulina*) in the UK are protected under the Conservation of Seals Act (1970) (England and Wales) and the Wildlife (Northern Ireland) Order 1985. However, in Scotland the new Marine (Scotland) Act (2010) is the primary protective legislation. Section 6 prohibits the taking of seals except under licence. Licences can be granted for the protection of fisheries, for scientific and welfare reasons and for the protection of aquaculture activities. It is also now an offence to disturb seals at designated haulout sites.

They are also listed under Annex II of the EU Habitats Directive, requiring specific areas to be designated for their protection, and 16 such SACs have been designated specifically for seals with 7 additional sites where seals are 'features of qualifying interest'.

The current status of British harbour seals, as reported to the UK's Special Committee on Seals in 2012 is a total of 26,262 counted during the annual moult (August) giving a total population of approximately 36,500; 80% in Scotland, 15% in England and 5% in Northern Ireland.

2.2 Abundance trends and estimates

SMRU carries out surveys of harbour seals during their moult in August each year, with the aim of completing a complete coastline survey every 5 years (using helicopter-mounted thermal imagery for rocky haulouts and photographs from fixed wing aircraft for sandbanks). However, in response to observed declines since the mid-1990s, survey effort has been increased and the majority of

English and Scottish east coast populations are surveyed annually. Counts by region are shown in Table 1.

2.3 *Magnitude and duration of decline*

The Management Areas referenced above are shown in the distribution map, Fig. 1 and the trends in the counts of harbour seals around Scotland are also shown in Fig. 2.

The decline in Scottish harbour seals was first observed following the surveys carried out in the early 2000's and the results were published by Lonergan *et al*., (2007). Since then the decline in some regions has continued and an update of the current status was given at the 2012 Special Committee on Seals meeting (SCOS). Thus further background information and survey details can be found in the SCOS documents available from the SMRU website at http://www.smru.st-and.ac.uk/pageset.aspx?psr=411. A summary from these documents is given below.

1. A complete survey of Orkney in 2010 counted 6.2% fewer seals than during the previous complete count in 2008. These latest results suggest that the Orkney harbour seal population declined by 68% since the late 1990s and has been falling at an average rate >11% p.a. since 2001. The recent counts may indicate a slowing down of the rate of decline, with an average decrease of 3% pa over the last two years.

2. Survey results from 2008 confirmed that the North coast of Highland Region has declined by 35% since the 2005 survey and is approximately 60% lower than in 1997.

3. Counts in the Outer Hebrides in 2008 were 35% lower than the peak count in 1996. Regular surveys over the intervening period suggest that there has been a sustained but gradual decline of around 3% pa since 1996.

4. Only part of Strathclyde region was surveyed in 2009. Counts for that subsection were 15% higher than in 2007. A count of the entire Strathclyde region in 2007 was 25% lower than in 2000 but similar to counts in the mid-1990s. If the subsection counted in 2009 was representative, the overall Strathclyde population would have been intermediate between the 1990s and early 2000 counts.

5. Surveys in 2007 confirmed that the west coast of Highland Region has not shown any decline.

6. The Firth of Tay count in 2011 was the lowest ever recorded (77 seals) and was 38% lower than the 2010 count. This SAC population has declined at an average rate of 20% p.a. since 2002 with the 2011 count 89% lower than the peak count in 2000. An analysis of the likely future trends in population in this population suggests that it will go extinct by 2040 and probably much sooner unless the cause of the additional mortality is removed.

7. In 2011, the Inner Moray Firth (Ardersier to Loch Fleet) count was 674, 30.0% lower than the high August 2010 count (975). This count was still 20% higher than the mean of counts for 2007-2009 suggesting that the long term decline in the Moray Firth population may have been halted.

A recent update of the population trends (Lonergan *et al*. in prep) indicated that the annual rate of decline in Orkney has been 13% 95% confidence interval 11-15%). In Shetland the decline equates to an annual rate of 3.5% (95% CI 1-6%) which means the population in Shetland is probably now larger than the Orkney population. In the Tay the decline has been an annual rate of 18% (95% CI 14-21) whereas in the Moray Firth the decline has been only 3% per year (95% CI 0.5-5) and there are indications that this population is now stabilising. The west coast populations are all more or less now stable.

Figure 1. The number and distribution of harbour seals in Management Areas around the coast of Scotland, from surveys carried out between August 2007 and 2009. All areas were surveyed by helicopter using a thermal imaging camera.

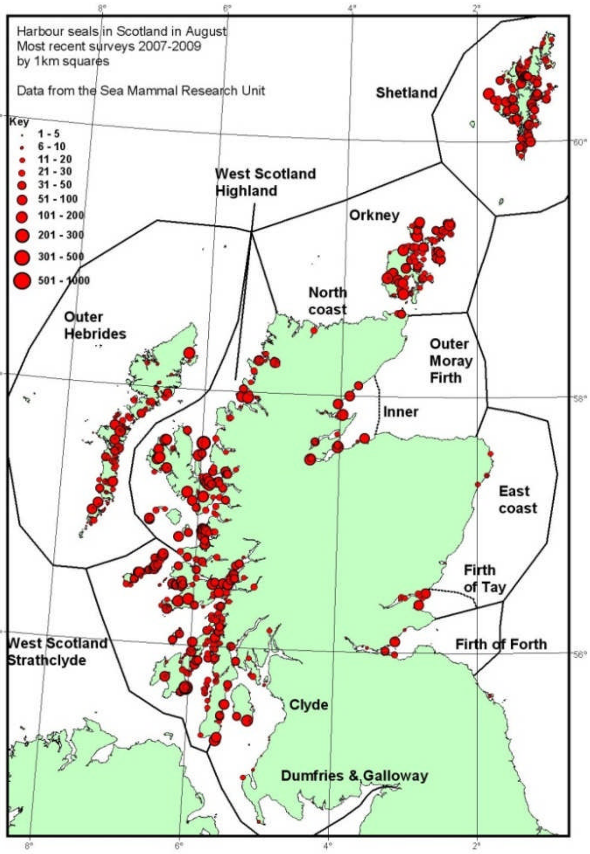
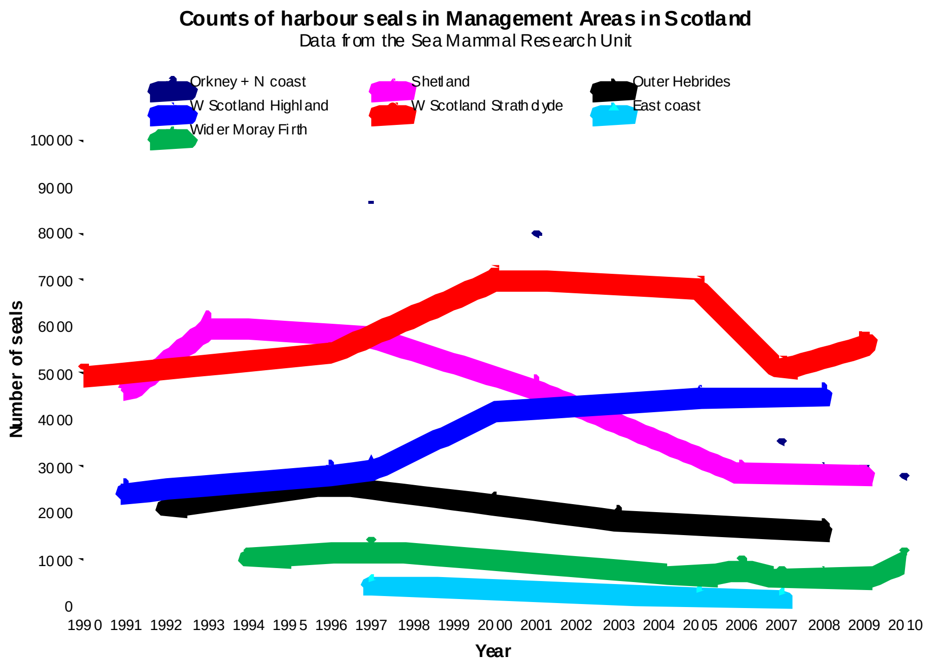


Figure 2. Trends in counts of harbour seals by Management Area in Scotland

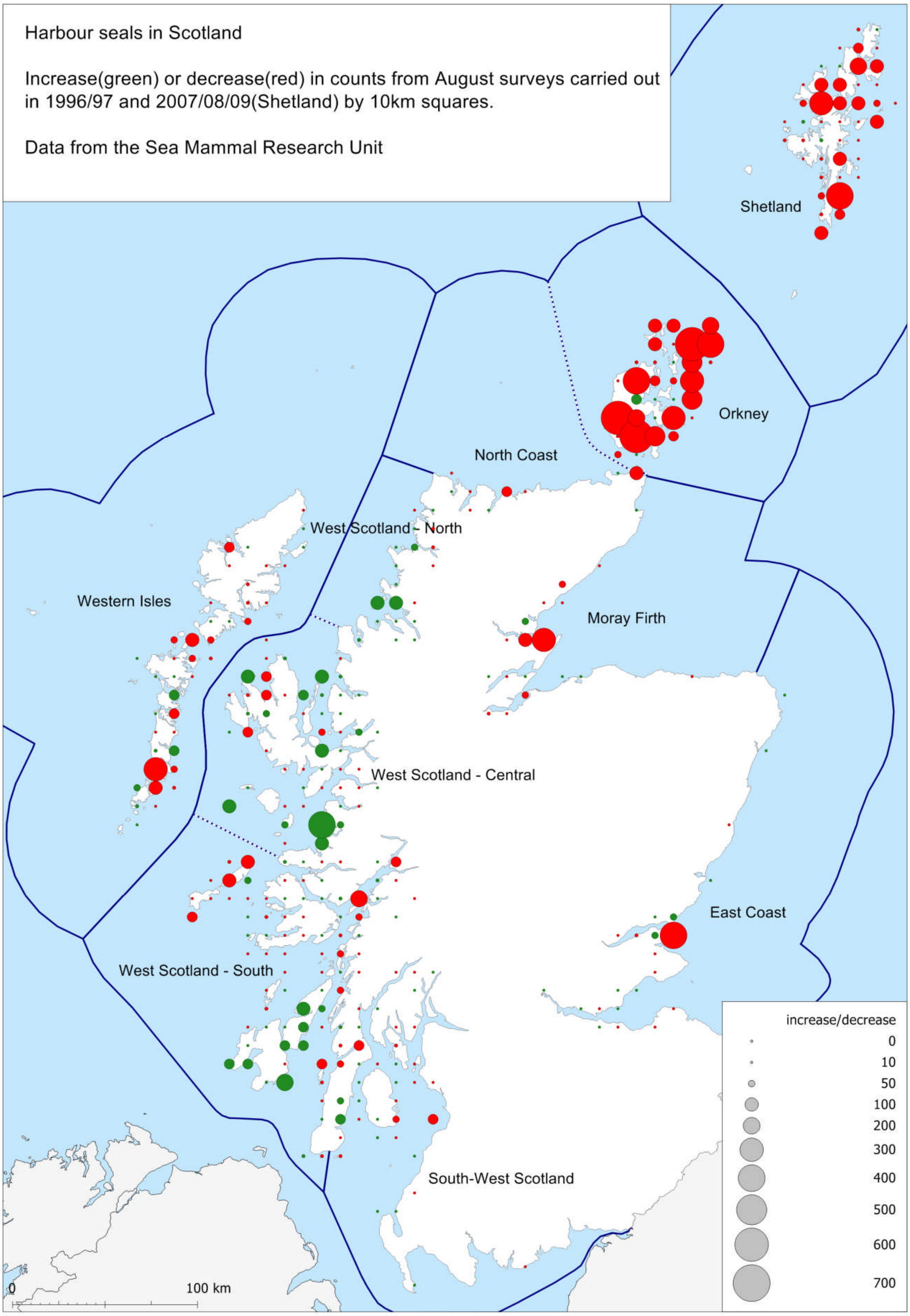


Harbour seal Management Area	Recent counts **(2007-2010)**	Previous estimate **(2000-2005)**	Earlier estimate **(1996-1997)**
Shetland	**3,039**	**4,883**	**5,991**
	2009	2001	1997
Orkney	**2,688**	**7,752**	**8,523**
	2010	2001	1997
Highland	**112**	**174**	**265**
North coast	2008	2005	1997
Outer Hebrides	**2,739**	**2,067**	**2,820**
	2011	2003	1996
West Scotland, Highland	**4,696**	**4,665**	**3,160**
(Cape Wrath to Ardnamurchan Point)	2007, 2008	2005	1996, 1997
West Scotland, Strathclyde	**5,914**	**7,003**	**5,651**
(Ardnamurchan Point to Mull of Kintyre)	2007, 2009	2000, 2005	1996
South-west Scotland, Firth of Clyde	**811**	**581**	**923**
(Mull of Kintyre to Loch Ryan)	2007	2005	1996
South-west Scotland, Dumfries & Galloway	**23**	**42**	**6**
(Loch Ryan to English Border at Carlisle)	2007	2005	1996
East Scotland, Firth of Forth	**148**	**280**	**116**
(Border to Fife Ness)	2007	2005	1997
East Scotland, east coast	**167**	**406**	**648**
Fife Ness to Fraserburgh	2007, 2011	2005	1997
East Scotland, Moray Firth (widest)	**954**	**959**	**1429**
Fraserburgh to Duncansby Head	2007, 2011	2005	1997

TOTAL SCOTLAND	**21,291**	**28,812**	**29,532**
	(2010)	(2005)	(1997)
Blakeney Point	**349**	**709**	**311**
The Wash	**2,894**	**1,946**	**2,461**
Donna Nook	**205**	**421**	**251**
Scroby Sands	**119**	**57**	**65**
		2004	
Other east coast sites	436	**153**	**137**
		1994-2003	1994 –1997
South and west England (estimated)	**20**	**20**	**15**
TOTAL ENGLAND	**4,023**	**3,306**	**3,240**
TOTAL BRITAIN	**25,314**	**32,118**	**32,772**
TOTAL NORTHERN IRELAND	**948**	**1,248**	
	2011	2002	
TOTAL BRITAIN & N. IRELAND	**26,262**	**33,366**	
TOTALREPUBLIC OF IRELAND	**2,905**	**2,905**	
	2003	2003	
TOTAL GREAT BRITAIN & IRELAND	**29,167**	**36,271**	

Table 1. Counts of harbour seals by Management Area (SCOS, 2012)

Figure 3. Comparison of 1997 and 2007 harbour seal count data. Increases in counts are shown in green, decreases in red (Morris *et al*. in prep).



The change in the abundance of harbour seals is also shown in Fig. 3. This is a comparison of the moult counts for the complete Scotland-wide surveys carried out between 1996 and 1997 and those carried out between 2007and 2009. The red dots indicate a negative change and the green dots a positive change. This clearly shows the declines in haulout counts in the Northern isles, east coast and Western isles compared to the stable populations on the west coast. It should be noted however that the recent surveys of the Western isles found an increase in abundance here so the declines in more recent years appear now to be restricted to the north and east coasts. Why there was a temporary decline in the abundance of harbour seals on the Western isles is still unclear.

2.4 Vital rates

2.4.1 First year pup survival

Key Findings – SMRU (in prep)

- In 2007 satellite telemetry was used to investigate relative pup survival rates in areas with declining (Orkney) and stable (Lismore) populations. 24 pups between 3 and 20 days old were tagged with location-only satellite relay data-loggers in each of the two study areas.
- No pre-weaning mortality was detected at either site suggesting the tagging did not disrupt the maternal bond.
- A simple exponential model suggested mortality over the first 100 days was higher in Orkney but fitted a gamma function as a more flexible mortality function and a normally distributed time-to-tag failure function indicated that mortality was **not** significantly different in the two areas.

Until the decline in Scottish harbour seals was detected, very little was known about the survival probability of harbour seal pups in the UK. A study by Harding *et al*., (2005) found that winter survival rates of harbour seal pups in the Skagerrak were significantly correlated with their autumn body mass. The probability of survival to age one was 0.63 for the smallest pups at 17 kg, where pups at 32 kg had a survival probability of 0.96.

The most widely referenced estimates of harbour seal pup survival within European waters are those reported by (Härkönen and Heide Jørgensen, 1990), which gives an estimated juvenile survival of 0.6-0.7, depending on the population growth rate.

Pup survival in areas of Scotland with contrasting population dynamics were estimated by SMRU in 2007 (SMRU, in prep), with the objective that any observed significant differences between regions might provide further clues about the causes of the decline. Any food limitations, either quantity or quality, throughout the winter period following weaning could have significant effects on first year survival rates. Mortality was estimated using small location-only satellite relay data-loggers as other forms of mark-recapture study were not logistically feasible in these regions. Only female pups were tagged and survival was estimated by fitting two model components, tag survival and animal survival. A normal time to tag failure and independent survival estimates in each region was fitted. Survival did not follow simple exponential decay and was best fitted by a gamma distribution which allowed for a gradually increasing probability of death. The model fits to the data found no evidence that the mortality rates in the two areas were significantly different and in both regions survival was low. However there was some indication that pups which moved long distances during the first few weeks after weaning had a lower survival probability. This is the first study to estimate harbour seal pup survival in the UK and such a low survival rate in a region where the population was not declining is also of some note.

The satellite telemetry data demonstrated that some pups dispersed widely from their natal site, a finding also reported in a study by Thompson *et al*., (1994a). From pups tagged in Orkney with flipper tags in the 1980s (n=225) 3% were found dead within a few weeks and ~13% were observed or recovered after the end of the lactation period. The mean dispersal distance was 57km, although this was highly skewed. Six pups were seen or recovered from outside Orkney over 100km from their capture site, but the remainder were found within 50km of their natal site.

2.4.2 Adult survival

Key Findings – Mackey et al., (2008); Cordes (2011)

- Adult survival for harbour seals in the Moray Firth has been estimated using photo-identification mark-recapture methods.
- For animals hauling out in the Cromarty Firth, a Bayesian estimate using a Jolly-Seber mark-recapture model found a high survival probability at 0.98 (with a 95% probability interval of 0.92-1.00) using the photo-identification data alone or 0.97 (0.92-0.99) using an informative prior based on estimates of adult harbour seal survival from North America and other European countries.
- For adults hauling out in Loch Fleet, in the wider Moray Firth estimates ranged

Information on adult survival probabilities for Scottish harbour seals is also limited but estimates have been published for animals in the Moray Firth by (Mackey *et al*., 2008). The resulting survival rates using data collected between 1999 and 2002 (0.97-0.98) were relatively high compared to those published for other harbour seals populations which ranged from 0.8 (Bigg, 1969) to 0.96 (Härkönen and Heide Jørgensen, 1990). There were logistical limitations to the study which resulted in relatively small dataset (95 females and 10 males) so although no differences between survival among the sexes was detected this may have been due to the limited amount of data available for males.

A second study carried out between 2006 and 2010 by Cordes *et al*., (2011) and Cordes (2011) also using photo-identification methods but with a multi-state mark-recapture model fitted to the data resulted in similarly high estimates for females (0.97, 95% confidence interval 0.9-0.99) but lower estimates for males (0.89, 0.71-0.96). In the study 152 individuals were identified, 73 females and 38 males. Sexes were unknown for 41 animals. Recapture probabilities for both sexes were high (0.98-1.00) although again females were more readily identifiable by the presence of a pup during the breeding season than males. It should be noted that the Loch Fleet NNR breeding population has been steadily increasing since about 2000, in contrast to the Dornoch Firth SAC population.

2.4.3 Female fecundity

Key Findings – Cordes (2011)

- Reproductive rates (the proportion of females breeding) were estimated for harbour seals in Loch Fleet using photo-identification methods and an open robust design multi-state model.
- The average unconditional reproductive rate for this population from 2009 to 2010 was 0.88.

Cordes (2011) also estimated female reproductive rates using photo identification methods and an open robust design multi-state model for the Loch Fleet population. This represents the first estimates for UK harbour seals. Overall the estimate was slightly lower than that reported for other populations, which ranged from 0.90 in Norway (Bjorge, 1992) to 0.95 for the population in Eastern Canada (Boulva and McLaren, 1979).

2.5 Mortality - Dead and stranded seals

Key Findings – Brownlow and Reid, (2010)

- Historically the Marine Mammal Strandings Co-ordination and Investigation (Scotland) Scheme has not included seals, except to record strandings reported and to respond during an epidemic or unusual mortality event. However, following the harbour seal decline additional funding from Marine Scotland enabled seals to be included from 2009 onwards. It is therefore not possible to compare stranding proportions between years due to the variation in effort and coverage. However, there has been no evidence, outside the 2002 phocine distemper virus epidemic of an unusual mortality event occurring except for an increase in the number of trauma cases in a localised area (spiral or corkscrew seals – see section 3.5 below on Trauma)
- Between 2003 and 2010 the number of seal strandings (both species) reported ranged from 71 to 242 in 2003 (a peak following the 2002 PDV epidemic). In 2010 the number reported to the scheme was 183 of which 62 were necropsied under the scheme. 26 died of infectious

Whilst historically the Scottish Marine Animal Stranding Scheme has focussed on cetaceans, the Scheme (only in Scotland) now also investigates and carries out necropsies on a number of seals each year. A summary of the findings from the scheme reported in 2010 are given above. Of the seals reported to the scheme in 2010, 53 were grey seals and 58 were harbour seals with 71 unidentified species. Of these 34 grey seals and 20 harbour seals were necropsied. The main finding for the harbour seals was the increase in trauma cases, particularly in the Eden estuary, SE Scotland and details of those findings are given in section 3.5 on Trauma. Outside this cluster of cases, no other notable patterns were reported and no sign of an unusual mortality event.

2.6 Population dynamics

Key Findings – Matthiopoulos et al. (in review)

- In the north and east of Scotland counts of moulting harbour seals have been declining for 10 years. To evaluate the contributions of different proximate causes (survival, fecundity, observation artefacts) to this decline, behavioural, demographic and population data from an intensively studied population in part of the Moray Firth (NE Scotland) were collated. A state-space model comprising age-structured dynamics and a detailed account of observation errors was fitted to the data.
- The results confirm that the trends in the population counts are the result of an underlying decline in population numbers, not an artefact of the observation process.
- After accounting for the effect of culling (estimated by our model as 13% of total mortality), the main driver of the population decline is a decreasing trend in survival, particularly of juvenile individuals combined with (previously unknown) low historical levels of pupping success.
- The model provides evidence for considerable increases in breeding success and consistently high levels of adult survival, hinting that adults are unaffected by the

A recent study by Matthiopoulos *et al*., (in review) focused on the Moray Firth population to investigate the proximate causes of the decline by modelling the population dynamics of the harbour seals in that region using the available demographic data. This allowed for the exploration of changes in fecundity and or survival as being the underlying mechanisms involved in the changes in this region. The study also investigated whether the observed patterns in the count data were due to population decline and not observation artefact, whether they could be explained by trends in known causes of mortality (i.e. shooting in this region) and what the projected population size in 5 years' time might be. They used a state-structured model comprising one pup, three sub-adult and one adult stage for each sex. The model produced a good fit to the count data for all years but pup and juvenile survival parameters were not separately estimable. Estimated demographic trends indicated a 30% increase in fecundity whilst pup and juvenile survival was decreasing. The estimated total population size for the period 1989-2011 varied between 850 and 100 individuals with an initial period of stability followed by a decline down to 50% of the initial size. The model forecasts a slow recovery from 2010 onwards based on the prediction of sustained high fecundity, constant survival and low levels of shooting.

2.7 Behavioural changes

2.7.1 Haulout patterns

Key Findings – Lonergan et al., (in press)

- The numbers of animals counted during aerial surveys of this area have decreased substantially over the period 2001-2010. ARGOS transmitters were attached to flipper tags to rescale the counts into estimates of abundance and confirm the rate of decline of this population.
- Females hauled out for more of the survey window (0.84; bootstrap 95% confidence interval 0.63-0.99) than males (0.61; bootstrap 95% CI 0.34-0.86). The animals hauled out less during weekends (0.57; bootstrap 95% CI 0.40-0.74) than during the week (0.76; bootstrap 95% CI 0.58-0.91).
- The sex–ratio of this population is unknown. Assuming it was close to 1-1, then there were around 3586 (bootstrap 95% CI 2970-4542) harbour seals in Orkney in 2010. A female-skewed sex-ratio would reduce the population estimate, and a changing sex-ratio might mean the counts understate the real decline.
- The mean annual rate of decline in the Orkney population of harbour seals, over the period 2001-2010, is estimated at 12% (95% CI 10.8-14.8). Similar data for Arisaig, on

Where population trends are based on indices of abundance (such as haulout counts) then interpretation of changes in trends is highly dependent on the validity of the assumptions about the proportion of animals being counted. Lonergan *et al*. (in press) carried out a study to estimate the proportion of the population currently counted, to confirm that the proportion has not changed with time and that it does not vary between locations. Moult surveys are carried out by SMRU during the first three weeks of August. This study used transmitters attached to flipper tags to monitor harbour seal behaviour during the moult at low tide, overlapping with the period when air surveys are conducted. Two locations were compared, the declining Orkney population and the West Coast population from Arisaig in 2009. Simple frequentist statistical models were applied to the telemetry data (whether an animal was ashore or not), essentially a bootstrap estimate of the uncertainty in the proportion of animals hauled out. The main findings are given above. The estimates of changes in abundance of harbour seals in Orkney clearly indicate that the population has declined substantially. Over the same period there has been a gradual increase in the numbers of seals at Arisaig. The haulout behaviour in the two regions was indistinguishable suggesting changes in behaviour are unlikely to explain any of the reduction in counts.

2.7.2 Movements and Emigration

VHF tracking and satellite telemetry data

Key Findings –

Thompson et al., (1989);

- Radio telemetry was first used to determine harbour seal activity patterns. In Orkney animals spent more time outside the study area (i.e. offshore) during the winter than the summer with no diurnal haulout pattern as seen in the summer. During the summer months (breeding and moult) they spent more time hauled out during the middle of the day.

Thompson and Miller (1990) and Cordes et al. (2011)

- In the Moray Firth study using radio tracking, seals travelled up to 45km from their haulout sites on feeding trips of up to 6 days.
- A comparison of foraging locations from radio-tracked adult females in the Moray Firth in 1989 with data from animals tagged with GSM/GPS data-loggers in 2009 found that the regions in used were broadly similar.

Sharples et al., (2009)

- Harbour seals in the Tay and Eden Estuary, Southeast coast of Scotland, (n=25) fitted with satellite relay data-loggers between 2001 and 2003 spent 39% (95% CI 34 - 45) of their time within 10 km of the haulout sites (averaged over all seals for November to June)
- The probability of hauling out (conditional on being within 10km of the haulout site) increased as the tide height decreased with hauling out being less frequent in the winter months. Seals were more likely to haulout out around midday in all months.
- The satellite telemetry and count data were then used to estimate total population size. On average estimates were 37% greater than the moult counts carried out by boat or air survey.

Cunningham et al. (2009)

- On the west coast of Scotland a study of 24 harbour seals fitted with satellite relay data-loggers between 2003 and 2005, found the animals hauled out for a mean of 5 h.
- Patterns of movement were observed at two geographical scales, while some seals travelled over 100 km, 50% of trips were within 25 km of a haulout site.
- On average seals returned to the haulout site they last used during 40% of trips although there was wide variation between different sites.

Sharples et al. (2012)

- Harbour seal movements are highly variable among individuals

The earliest studies of harbour seal movement were carried out using VHF radio tracking in Orkney (Thompson *et al*., 1989) and the Moray Firth (Thompson and Miller, 1990) where presence or absence within a study area could be estimated. In Orkney, seals spent more time in offshore waters during the winter, although they regularly returned to the inshore study area to haulout. In addition the tidal cycle appeared to have less influence during the summer than the winter, when diurnal patterns were dominant.

Adult females breeding in the Moray Firth were also radio tracked during the 1989 breeding season (Thompson *et al*., 1994b) and the results compared with the tracks of females fitted with GPS/GSM dataloggers in 2009 (Cordes *et al*., 2011). A comparison of the foraging locations is shown in Fig. 4. There was no difference in the distance travelled by the seals between the two deployments, 17-22 km in 1989 and 7-22 km in 2009.

Between 2003 and 2005, 24 harbour seals from Islay and Skye on the west coast of Scotland were tracked using Argos satellite relay data-loggers (Cunningham *et al*., 2009). The mean travel-trip extent was 10.5 km (95% CI 9.9-11.0) while the maximum was 144 km. About half the trips lasted between 12 and 24 h although a few lasted several days with the longest being 9 days. This study also showed that seals remained within a 25 km radius of haulout sites with almost half the trips lasting between 12 and 24 h. This data confirms that, like harbour seals in other parts of the world, these are coastal species with animals remaining within fairly restricted areas.

Sharples *et al*. (2009) used satellite telemetry and haulout counts to estimate the seasonal abundance of harbour seals in the Tay and Eden estuaries between 2001 and 2003. Fig. 5 shows the main haulout sites with a 10km radius displayed. A graduated kernel of slow at-sea movements (speed <0.5ms^{-1} thought to be associated with foraging behaviour) not associated with haulouts.

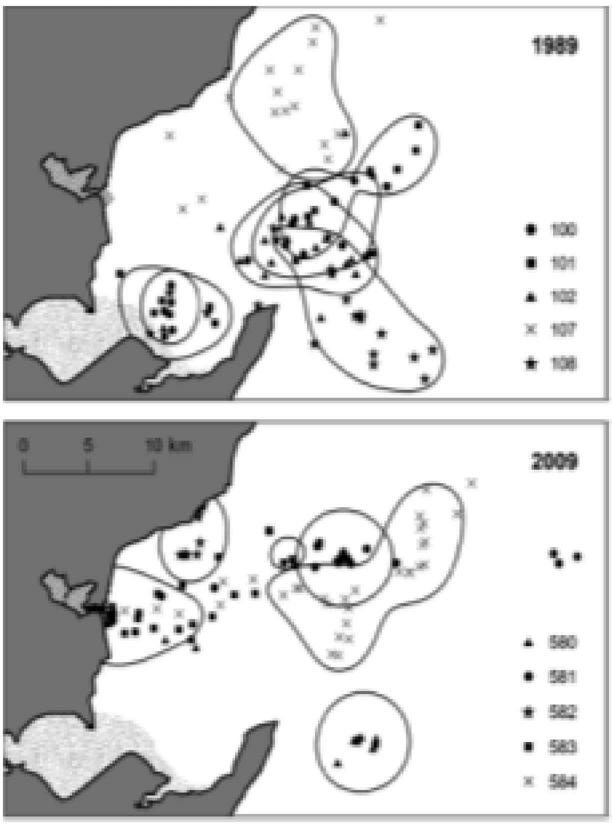


Figure 4. Comparison of adult female foraging locations in 1989 (n=5) and 2009 (n=5). The solid lines show the 50% contours of individual foraging areas as calculated by Kernel analysis. Individuals 100, 101 and 583 each had two separate

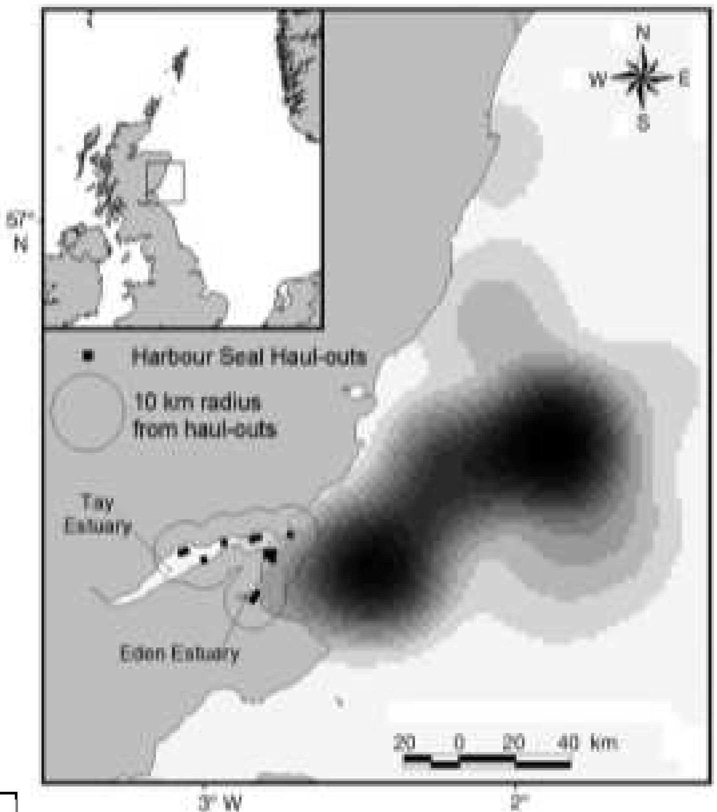


Figure 5. Locations of main harbour seal haulout sites in St Andrews Bay and slow at-sea movements

Each shade represents a different 5% kernel; shade darkens with reduced kernel percentage.

Further analysis of foraging behaviour was carried out by Sharples *et al*. (2012) who found that harbour seals around the UK frequently made wide-ranging movements to sea and also transited between regions. Region and time of year were better predictors of foraging behaviour whereas sex, size and body condition were not important. Animals hauling out in the Moray Firth, St Andrews Bay and the Wash in England made much longer distance and duration foraging trips than those from the Outer Hebrides, Shetland and Orkney. Time of year was found to be an important variable in explaining variation in foraging trip duration and distance travelled. Harbour seals spend more time away from haulout sites during the winter months. This seasonal pattern is apparent throughout their range and is presumably driven by changes in foraging behaviour.

The most recent information on the movements of harbour seals is summarised in Fig. 6. This shows the tracks of all the harbour seals fitted with satellite or GPS/GSM tags deployed by SMRU and its collaborators. These data are still to be fully analysed but the figure illustrates the general movement patterns of these animals in UK coastal waters.

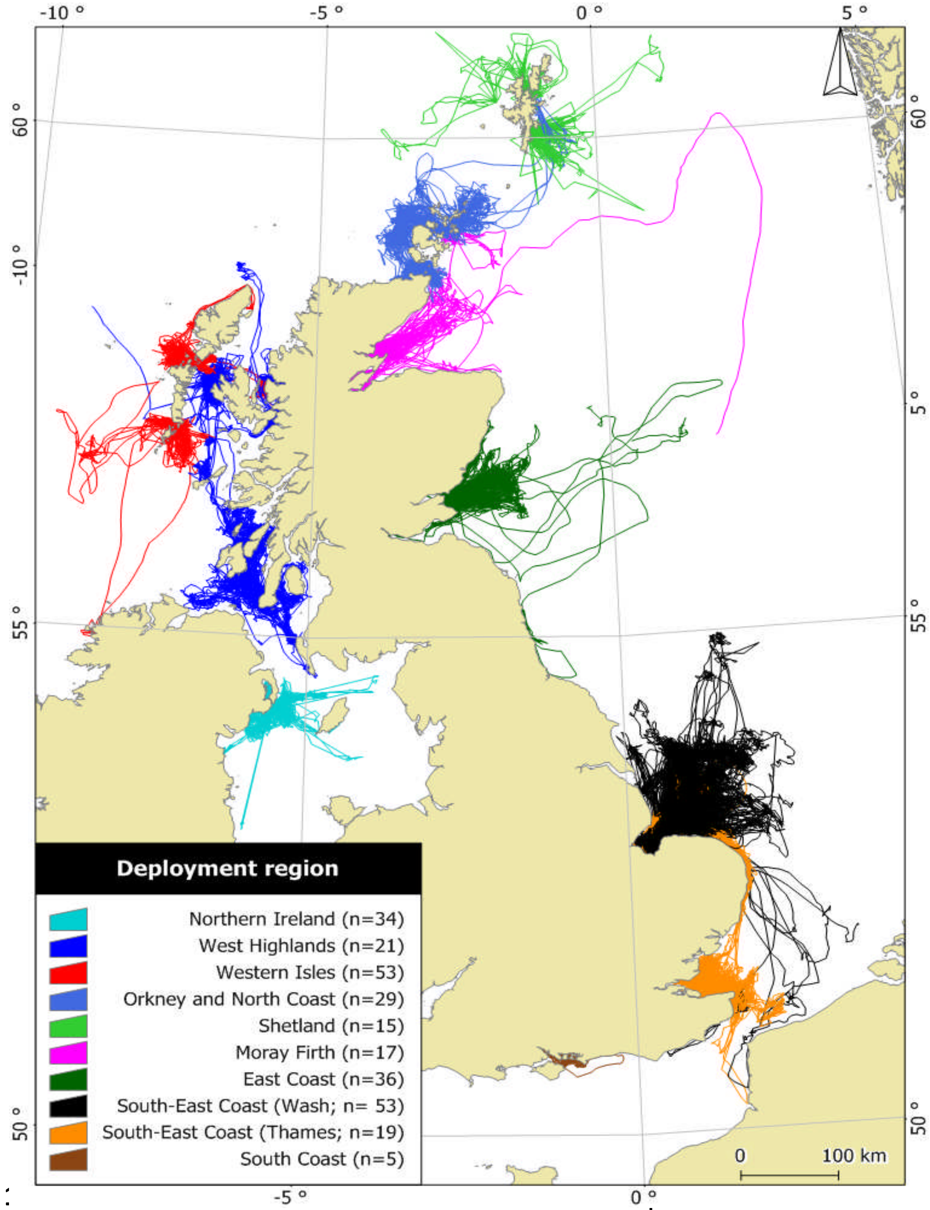


Figure 6. Tracks of harbour seals fitted with satellite or GPS/GSM tags, 2001-2012

2.8 Population structure

2.8.1 Genetic diversity

Key Findings – Islas et al. (in prep)

- Analysis of DNA samples from a total of 453 individuals around Scotland including samples from comparative regions in the UK and Europe (including an out-group of Pacific harbour seals) was carried out.

- Following some initial trials the most appropriate population differentiation analysis comprised 10 putative populations across all the samples analysed. Focusing on Scotland, Bayesian clustering analysis clearly separated Scotland from England, France and the Dutch Wadden Sea.

- In this scenario 3 clusters were generally identified: a) Norway, b)West Coast of Scotland/Northern Ireland and c) Pentland Firth / Orkney / Shetland / Moray Firth / Tay and Eden with some degree of shared individuals between them. Examining the Scottish populations alone indicated there might be some additional separation between the Tay

The population structure of harbour seals around Scotland was investigated using different genetic markers and approaches. This allowed discrete population units or metapopulations to be identified. The population genetic structure is compared to the recently defined harbour seal management regions (SCOS, 2011), ensuring Scottish Government's regional management procedures and plans for harbour seals are based on genetic data as well as the currently employed ecological haulout and pupping site data.

Within the Scottish populations a number of harbour seal Management Areas have been assigned based on haul outs and breeding sites (SCOS, 2011). The result of the genetic analyses clearly supports the designation and definition of these Areas.

Allelic diversity and heterozygosity are standard measures that assess the level of inbreeding which populations display as a reflection of their 'genetic health'. The populations with relatively good sample sizes and low levels of genetic diversity were Shetland (n=2.545, H_O=*0.363*) and the Outer Hebrides (2.467, H_O= *0.331*). It has been widely shown that inbreeding, translated as very low levels of genetic diversity in wild populations is correlated with disease such as cancer (Acevedo-Whitehouse *et al*. 2003) and with susceptibility to pathogens such as parasites (Rijks *et al*. 2008) among others.

2.8.2 Age Structure

Key Findings

- Among the live captured and dead harbour seals sampled around the UK between 1988 and 2012, there was no evidence for a difference in age distribution, asymptotic length or length at age by either year or location.
- In the Moray Firth live captured animals sampled in the early 1990s animals were significantly younger than animals sampled elsewhere during later years. However, this may be due to capture bias.
- However, age length data from juveniles is lacking due to the absence of pups,

The true age structure of the UK harbour seal populations are very difficult to determine as any sampling strategy (from live capture or dead stranded animals) has inherent biases. Recent studies (Hall *et al*., in prep) have investigated the variation in the age of live captured animals sampled around the UK coast since 1989. Animals are aged from the growth layer groups in their teeth which can be visualised following sectioning and staining (one group is equivalent to one year of life). Incisor teeth are taken from live captured animals. Estimates for pups of the year are made in relation to a common birth date.

There was no evidence that the age distribution of all the aged animals (both live capture and dead) varied by region or year (n=276). However, the animals live captured in the Moray Firth by the University of Aberdeen in the late 1980s to early 1990s were significantly younger than the animals sampled more recently. The maximum age of their adults was 11 years for males and 12.5 years for females. By contrast, the maximum age for males from all the other sites was 25 years for males and 28 years for females.

2.9 Diet

Key Findings

- There have been a limited number of studies of harbour seal diet in the North Sea
- Results show that sandeels and whiting are dominant prey in all regions.
- Flatfish, seasonal clupeids and cephalopods are also important
- Seasonal and regional differences have been reported
- In the one study in the Moray Firth comparing grey and harbour seal diet, the prey

2.9.1 Harbour Seal Diet in General in the North Sea

Studies of harbour seal diet in the northwestern North Sea have shown regional variation, but sandeels and whiting were dominant prey species in all regions. Studies conducted in different regions were conducted over different years and some of the variation observed may thus be temporal rather than regional as seasonal variation in harbour seal diet has typically been attributed to variation in prey availability (Tollit & Thompson 1996, Brown & Pierce 1998, Hall *et al*. 1998, Middlemas 2003, Wilson & McMahon 2006). The results of a number of studies (e.g. Harkonen, 1987; Payne & Selzer, 1989; Bowen & Harrison, 1996) suggest that diet composition reflects differences in assemblages of prey species encountered in different habitats, and that harbour seals are able to adjust their foraging patterns and find alternative prey when food conditions change (Tollit and Thompson, 1997). Based on a study by Hall and colleagues (1998), the diet of harbour seals in the Wash, in the SE North Sea differs significantly from the diet of the seal in the NW North Sea.

***Table 1** – Harbour seal diet by region.*

Location	Diet
Moray Firth	- Significant seasonal variation (Tollit and Thompson, 1997). - Significant inter-annual variation (Tollit and Thompson, 1997). - On average, sandeels make up most of their diet – approximately 47% (Tollit and Thompson, 1997). - Diet to be dominated by sandeels (47%), lesser octopus (26%) and whiting (6%). - Diet is very similar to grey seals in the area during the summer (Thompson *et al.* 1996).
St Andrews Bay	- Diet is heavily dominated by sandeels, especially in winter and spring (81 to 94%) and lower in summer and autumn (63%) (Sharples *et al*. 2009).
Firth of Tay	- Salmonids are the dominant prey type, except in winter when sandeels are the dominant prey (Sharples *et al*. 2009). - The only other species recovered from scats were sandeel, flounder and whiting (Sharples *et al*. 2009).

Shetland	- Whiting and other gadoids made up over 60% of harbour seal diet by weight (Brown & Pierce, 1998). - Diet mainly comprised of sandeels (29%), whiting (25%), saithe (11%) and pelagic fishes (14%) (Brown & Pierce, 1998). - Seasonal trends in diet with sandeels being the most important prey in March to June and gadids dominating the diet in much of the rest of the year (Brown & Pierce, 1998). -Predominant prey types during the summer were whiting, herring, sandeel and garfish (Brown *et al*. 2001).
Orkney	- Sandeels dominate harbour seal diet, followed by herring and gadoids (Pierce *et al*. 1990).
The Wash	-Diet consists of mostly whiting (24 %), sole (15%), drayonet (13%) and sand goby (11%). - Other flatfish (dab, flounder, plaice: 12%) other gadoids (bib, cod: 11 %), bullrout (7 %), and sandeels (3 %) are also consumed.

<u>Thompson *et al.* 1996</u> - Comparative distribution, movements and diet of harbour and grey seals from the Moray Firth using telemetry and scat analysis.

The distribution, movements and foraging activity of harbour and grey seals from the inner Moray Firth were compared using a combination of observations at haul-out sites, VHF and satellite-link telemetry, and analyses of diet composition using scat samples collected on haul out sites in the Dornoch Firth during the summer of 1992 (May-August).

Main findings of the study:

- All harbour seals foraged within 60 km of their haul-out sites, but showed seasonal variation in their foraging areas which was related to changes in their terrestrial distribution.
- There was some overlap in the foraging areas used by harbour seals and grey seals in more inshore areas.
- Although harbour seals were present in the study area throughout the year, the importance of different haul- out areas varied seasonally.
- From scat sample analysis, the diet composition of the two species of seals was remarkably similar with sandeels being the major prey item for harbour and grey seals.
- Sandeels, gadoids, flatfish and cephalopods formed over 95% of the diet of both species.

- These results suggest that Moray Firth harbour seals can be considered as a relatively discrete population, with clear links between breeding, feeding and resting areas, and little exchange of adults between this and adjacent breeding areas in Orkney and the Tay Estuary. In contrast, grey seals from several different breeding sites appear to move into the Moray Firth in summer and use the area primarily for foraging and non-breeding haul-out.

Tollit and Thompson, 1997 – Seasonal and inter-annual diet composition in the Moray Firth from scat samples collected between 1989 – 1992.

This study examined the extent of variations in the relative contributions of key prey species between years and between seasons in harbour seal diet in the Moray Firth using scat samples collected between 1989 and 1992. Analyses of fish otoliths and cephalopod beaks collected from 1129 scat samples were used to derive estimates of the contribution made by 35 prey species, based on the number and mass consumed. The percentage of each prey species, by mass, was used primarily to highlight the key prey species and the extent of observed temporal variations.

The key prey species, by mass, were:

- sand eels (*Ammodytidae*) (47%),
- lesser octopus (*Eledone cirrhosa*) (27 %)
- whiting (*Merlangius merlangus*) (6 %)
- flounder (*Platichthys jesus*) (5 %)
- cod (*Gadus morhua*) (4%).

However, there were seasonal fluctuations in the contributions of these species to the diet, and these differences in diet composition appeared to reflect local changes in the availability of food, especially overwintering clupeids, probably as a result of seasonally changing fish distributions. Specifically:

- sand eels contributed 86-20% in summer and 91-49% in winter.
- lesser octopus contributed 0-62% in summer and <5 % in winter.
- whiting and cod contributed 2-34% in winter and 1-4% in summer.

There were also between year differences in diet and it was thought that these changes reflected seals exploiting changes in prey availability in the same local area. For example, whilst the contribution of sand eels in successive winters decreased in all areas, the contribution of gadoids appeared to increase from 0.5 to 43 %. It was thought that the observed increase in the contribution of gadoids in the Moray Firth may be have been related to a decreased availability of clupeids and sand eels. These data suggest that harbour seals adjust their foraging patterns and find alternative prey when food conditions change. The results also highlighted that dietary information obtained from short-term studies can be a poor indicator of subsequent diet composition and should be treated with caution.

Hall *et al.* 1998. – Seasonal variation in harbour seal diet in the Wash using scat analysis.

This paper presents the results of a 2 year study to investigate the seasonal variation in harbour seal diet in the Wash using analyses of faecal material collected from a haul out site between October 1990 and September 1992. Results were also compared with those from a study of the diet of grey seals in an adjacent area (Prime & Hammond 1990) to investigate evidence for separation of foraging niche by area, prey species or prey size. In general, harbour seal diet composition and seasonal changes in diet in particular, appeared mainly to be linked to availability in terms of prey distribution and abundance, feeding or spawning activity and, perhaps, prey size, but this was not always the case. The dominant species in the diet of harbour seals in the Wash in 1990-1992 were whiting and flatfish but these only accounted for about half the diet by weight.

Overall, the diet consisted of :

- whiting (24 %)
- sole (15%),
- drayonct (13%)
- sand goby (11%).
- other flatfish (dab, flounder, plaice: 12%)
- other gadoids (bib, cod: 11 %)
- bullrout (7 %)
- sandeels (3 %)

Strong seasonal variation was apparent over the two year study period, and was consistent between the two years, and can be summarised as: whiting, bib and bullrout dominated from late autumn through early spring; sand goby peaked during winter and early spring; dragonet, sandeels and flatfish (except sole) dominated from late spring to early autumn; and sole peaked in spring. Also, almost all the fish taken by Wash harbour seals were small (<30 cm in estimated length), including individuals of larger species such as cod and sole. The lack of a seasonal pattern in cod consumption by Wash harbour seals and the small size of fish taken could imply that these fish were in inshore waters, but is also consistent with a maximum limit on the preferred size of prey taken by harbour seals. In a comparative study however, much larger fish were taken by grey seals hauled out at the Humber estuary nearby.

Tollit *et al*. 1998 – Foraging and diving behaviour of harbour seals tagged at two sites in the Moray Firth combined with diet studies using scat samples.

In this study, information on the at-sea distribution of radio-tagged seals was used to identify the foraging areas used by harbour seals from two different haulout sites in the Moray Firth; Inverness and Dornoch Firth. Available information on sea-bed sediment characteristics and bathymetry was then used to determine whether seals are more likely to occur over particular sediment types or water depths. Finally, the diet composition of the seals from the two sites was compared using scat samples. Information on the biology of prey species was then used to assess whether the local geographical variations in diet composition seen in the Moray Firth can be related to local differences in available foraging habitat.

The main findings of this study were that:

- The majority of seals foraged within 30km of their haul-out site, and individuals returned consistently to the same areas.
- There was a broad overlap between the foraging areas used by animals from the same site, but little overlap in the areas used by seals from the two different sites.
- Most seals foraged in water depths of 10±50m with mainly sandy sea-bed sediments.
- Few pelagic prey items were consumed and the majority of prey species found in faeces were strongly associated with (e.g. sandeels) or live on (e.g. flatfishes and octopus) the sea-bed. These data further support the findings of the animals deployed with TDRs, that seals forage mainly benthically during the summer period.

- Occasional pelagic dives were seen between the more common benthic dives, and as a whole, the harbour seals in the Moray Firth were seen to feed on species that are found at a variety of depths and habitats.
- Between-site differences in the seals' use of different water depths and sea-bed sediments suggest that local geographical variations in diet were related to local differences in foraging habitats.
- Finally, habitat use also differed between individual seals, and the variety of different foraging habitats used by individual seals may be an indication of individual specialization for particular prey or foraging techniques.

Brown and Pierce 1998. - Monthly variation in the diet of harbour seals in inshore waters along the southeast Shetland using scat analysis.

The aims of this study were to examine monthly variation in harbour seal diets along the southeast coastline of Shetland between May 1995 and April 1996. Any changes in diet composition were then compared to known changes in prey availability to then identify potential competition between seals and local fisheries.

The main findings of this study were:

- Gadids accounted for an estimated 53.4% of the annual diet by weight followed by sandeels (28.5%) and pelagic fishes (13.8%).
- The dominant gadid fishes were whiting (25.3%) and saithe (l1.1 %), and the least dominant was haddock (0.9%).
- Cephalopods were generally of highest importance during November to January. However, overall they were of minor importance, accounting for 2.4 % of the diet by weight.
- The range of species observed in the diet was similar to that recorded in other areas of the UK.
- Garfish (Belone helone) accounting for 34.1 % of the diet in September of 1996, which is a species not previously reported for harbour seal diets in UK waters.
- Strong seasonal patterns were observed in the contribution of sandeels and gadids, with sandeels being important in spring and early summer, and gadids in winter.
- Pelagic species - mainly herring, garfish and mackerel were important in late summer and autumn. Herring was most common from June to August and lowest during winter.
- Observed seasonal patterns are similar to those previously recorded for harbour seal diets in the Moray Firth area of Scotland and appear to coincide with changes in prey availability.
- In general, the fish eaten by the seals in Shetland were larger than those reported in other studies. However, the question remains as to whether harbour seals around Shetland are deliberately selecting larger prey in Shetland waters or if the fish available are generally larger than elsewhere. It is possible that some of the fish eaten include discarded fish.

The results show strong seasonal trends in diet, with sandeels being the most important prey in March to June and gadids dominating the diet in much of the rest of the year. The importance of garfish in the diet is worthy of comment, since this species had not been reported in seal diets in other areas of the North Sea. Garfish are occasionally by-caught with herring and mackerel by pelagic fishing vessels and have been observed in inshore around Shetland. Overall their results suggested that the 5 main commercial species (haddock, whiting, ling, saithe and cod) account for 45 % of the annual diet of harbour seals in this area.

Brown *et al*. 2001 - Interannual variation in the summer diets of harbour seals at Mousa, Shetland using scat analysis.

- The main prey species in the summer (July–September) diets of harbour seals on the Island of Mousa between 1994–1997, were whiting, herring, sandeel and garfish.
- There were marked between-year fluctuations in the relative importance of these prey, with whiting comprising 16–34% (by weight) of the diet, herring 12–28%, sandeels 7–18% and garfish 7–22%.
- During the spring (April–June), sandeels were the most important prey by in all three years (51–60% of the diet), while herring (8–48%) and gadids (2–22%) varied in importance.
- The average size of fish eaten was larger than that reported in comparable studies from other areas: harbour seals appear to have selected larger sandeels, whiting and Norway pout than the average size available in the area, as indicated by survey trawls, although between-year changes in the size of Norway pout in the diet did to some extent reflect availability.
- Interannual variation in the importance of Norway pout in the diet appeared to track trends in abundance, although the short time series precluded detection of a statistically significant correlation.
- Thus, some of the results are consistent with harbour seals feeding opportunistically while others point to selectivity, particularly for prey size.

Pierce and Santos 2003 – Diet of harbour seals in Mull and Skye (Inner Hebrides, western Scotland)

Diet data from these two islands for 1993 and 1994 were presented. The diet included a range of fish and cephalopod species of which the most important were gadoids, particularly whiting along with pelagic scad and herring. There were significant temporal and spatial differences in diet, the relative high importance of pelagic species and low importance of sandeels is consistent with previous studies on grey seals in the Inner Hebrides but differs from studies in other parts of Scotland.

Wilson *et al.* 2002 – Diet of harbour seals of Dundrum Bay, north-east Ireland

This study showed that the main constituents of the diet of harbour seals from Dundrum Bay, County Down, northeast Ireland between 1995 – 2000 have been small flatfish and gadoids particularly whiting and haddock/pollock/saithe.

Sharples *et al*. 2009 – Harbour seal diet in the Firth of Tay and St Andrews Bay using scat analysis.

This study aimed to estimate the diet and prey consumption of a population of harbour seals in southeast Scotland, using analysis of hard prey remains recovered from scats collected between 1998 and 2003. In particular, the study aimed to investigate the importance of sandeels in the diet of harbour seals in southeast Scotland and, in particular, determine whether their contribution to the diet increased following the closure of the Firth of Forth sandeel fishery. Secondly, the importance of salmon in the diet of harbour seals in the Firth of Tay and surrounding areas was investigated, and the extent to which predation by harbour seals could be impacting the vulnerable salmon stock in this area was considered.

The main findings of in St Andrews Bay were that:

- Diet was heavily dominated by sandeels, especially in winter and spring (81 to 94%) and lower in summer and autumn making (63%).
- Gadoids (whiting, cod) and flatfish (dab, plaice, flounder) were the other main prey.
- The proportion of sandeels in the diet was remarkably consistent over time (71 to 77%).
- The average size of sandeels consumed increased significantly following the closure of the fishery in 2000.
- Salmon contributed little to the diet during spring, autumn and summer, averaging 1.27%.

The main findings from the Firth of Tay were that:

- Salmonids were the dominant prey type, except in winter, comprising an estimated 78% of the diet in spring (salmon 32%, smelt 17% and sea trout 28%), 47% in summer (salmon only) and 40% in autumn (sea trout only).
- Most of the salmon consumed were in the size range taken by the rod and line fishery for mature fish.
- Sandeel, flounder and whiting were the only other prey species recovered.
- Estimated sandeel consumption was highest in winter and lowest in spring and summer.

Thus, marked differences in diet were evident at a fine spatial scale between the Firth of Tay and St Andrews Bay. The effects of the sandeel fishery closure on harbour seals were equivocal, but harbour seals that haul out in SE Scotland are clearly dependent on sandeels.

3 ENVIRONMENTAL VARIATION

3.1 Regime Shifts in the North Sea

Key Findings

- Between 1988-1989 and 1998-2002, two major regime shifts occurred in the North Sea resulting in large scale ecosystem changes in phytoplankton/zooplankton/fish community structures and abundance.
- Regime shifts in the North Sea are associated with an inflow of oceanic water and rising sea water temperatures.
- Regime shifts in the North Sea have occurred when the North Atlantic Oscillation Index is positive.
- Since the late 1980s regime shift, the planktonic community has shown a considerable shift and has remained in a warm-water state with more warmer/sub-tropical species.
- Sea bird populations are declining.
- All commercially exploited fish stocks are considered to be in seriously depleted condition.
- Little information is available regarding long term population trends of other marine mammals, although there do not appear to be any significant declines and some evidence suggests a shift in distribution of some small cetacean species toward the southern North

3.1.1 Regime Shifts and the North Atlantic Oscillation

A 'regime shift' occurs when large-scale changes take place at various levels of the marine ecosystems. These are likely to have been triggered by a shift in the state of the atmosphere–ocean climate system (Philippart *et al.* 2000). Regime shifts remain poorly understood in terms of the long term consequences associated with the abrupt changes in the ecosystem resulting in major biological modifications, and may not be recognised until long after they have actually occurred (Reid *et al*. 2001).

Evidence is growing that the North Sea periodically experiences changes in physical and ecological conditions associated with different inflow rates of oceanic waters. Long-term monitoring using a Continuous Plankton Recorder (CPR) survey since 1938 has revealed ecological shifts of varying magnitude, effect and frequency. Marked interannual shifts have occurred at least twice in the last three decades in the North Sea. The first shift occurred in the late 1980s and was then followed by a more recent one in the late 1990s. These two shifts appear to reflect an increased inflow of both oceanic water and oceanic species into the North Sea. It has been suggested by Reid *et al.* (1998), on the basis of biological evidence and model results that these higher flows of oceanic water into the

North Sea have occurred during periods with a high positive North Atlantic Oscillation (NAO) Index. The NAO oscillates between negative and positive indices caused by a change in the pressure difference between Iceland and the Azores, and with the exception of 1996, it has been positive since 1988 (Reid *et al.* 2001). The extent to which the NAO influences the North Sea quickly by atmospheric heating, and more slowly through the inflow of water around Scotland and the English Channel is still relatively unknown. Thus, the nature of the interaction of the North Sea with North Atlantic waters is still poorly understood. To date, there are no published direct observations of the temporal variation of total inflow from the Atlantic into the North Sea either through the Channel or from the North via Shetland, Orkney and Norway. However, biological data and model evidence have been used to infer periods of increased oceanic inflow, even though it was not directly measured.

3.1.1.1 1988-1989 Regime Shift

Evidence suggesting a regime shift in the North Sea in the late 1980s came from observed changes in both biological measurements and oceanographic modelling (Holliday and Reid, 2000).

1. **Biological Data**

After 1987, Phytoplankton Colour (a visual estimate of chlorophyll) measured on water samples taken by the Continuous Plankton Recorder (CPR) in the North Sea increased substantially both in level and seasonal extent, compared to earlier years since 1946 (Fig. 7) (Reid *et al*. 2001). As such, phytoplankton biomass increased and the growing season was extended (Alheita *et al.* 2005). Other changes in biological data implied that there had been an unusual incursion of oceanic water into the North Sea, but that the incursion was in the form of a pulse rather than a prolonged period of increased transport (Holliday and Reid, 2000). For example, there was an unusual incursion of oceanographic species into the North Sea, including the short-lived occurrence of doliolids (gelatinous zooplankton) that are normally only found in oceanic waters (Lindley *et al.* 1990).

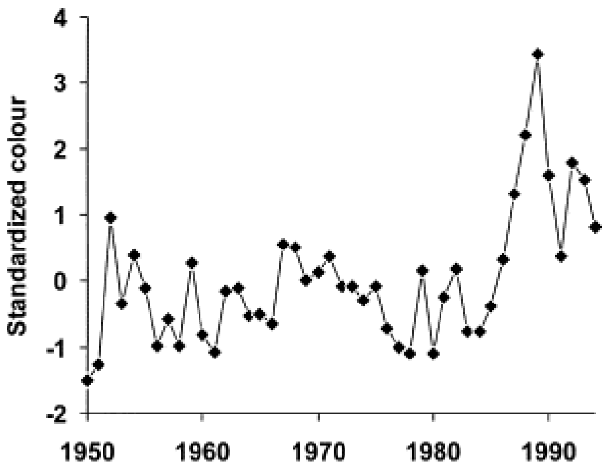


Figure 7. Phytoplankton Colour: annual means for the period 1950–1994 averaged for the whole North Sea (CPR survey). (Adapted from Reid *et al.* 2001)

Many other species of phytoplankton and zooplankton also showed marked changes in distribution and abundance at around the same time. As such, the composition of phyto- and zooplankton communities in the North Sea changed substantially with an increase in dinoflagellate abundance and a decrease in the abundance of diatoms (Alheita *et al.* 2005). Furthermore, key copepod species that are essential in fish diets experienced pronounced changes in biomass. For example, the abundance of *Calanus finmarchicus* fell to low levels, whereas *C. helgolandicus* and *Temora longicornis* were persistently abundant. These changes in biomass of different copepod species had wide-ranging consequences on the biomass, and therefore the landings of key fish species, notably the number of North Sea cod which declined dramatically (Alheita *et al*. 2005). However, these changes coincided with a large increase in catches of the western stock of the horse mackerel (*Trachurus trachurus L.*) in the northern North Sea reflecting a northerly expansion of the stock after 1987 (Reid *et al*. 2001). Following these changes, it is thought that the benthic response to the changes observed in the phytoplankton took from one to two years to take effect (Krönke *et al*. 1998). This suggests delayed and/or longer lasting effects of these incursions of oceanic water affecting the ecosystem over a prolonged period. As such, the planktonic community of the North Sea has remained in a position of post regime shift characteristic of a warm-temperate zooplankton community structure since 1989.

2. Oceanographic Modelling

Oceanographic modelling has demonstrated a link between altered rates of inflow of oceanic water into the northern parts of the North Sea, and the subsequent regime shift in 1988-1989 (Reid *et al*. 2001). Specifically, using a 3D hydrodynamic model, with input from measured wind parameters, monthly transport of oceanic water into the North Sea was been calculated for the period 1976–1994. Results from the modelling process indicate that since 1988, the flow of oceanic water into the North Sea across a section of water between Orkney, Shetland and Norway, had increased by around 50% in the winter months (Reid *et al*. 2001). Further evidence suggesting that there was an increase in inflow over this time period is provided by observations of exceptionally high salinity in the North Sea in 1989-91, as well as higher sea surface temperatures measured after 1987, especially in spring and summer months. It was suggested that this increase in oceanic inflow brought about the observed regime shift (Reid *et al*. 2001).

3.1.1.2 1997-2002 Regime Shift

Less information is available regarding the changes that occurred during this shift although analyses conducted by several groups suggest that a shift occurred between 1997 and 2002 (Weijerman *et al.* 2005, Holliday and Reid, 2000. SAHFOS Annual Report, 2002) which was separate from the shift in the late 1980s.

1. Biological Data

Similarly to the changes seen in the shift of the late 1980s, another incursion of oceanic water occurred in late 1997 revealed by the presence of oceanic indicator species observed by the CPR survey (Edwards *et al*.1999). Again, doliolids were found east of Scotland and between the Netherlands and Denmark in September 1997. And, at the same time, copepods normally occurring west of the UK were found in the North Sea including the mesozooplanktonic copepods *Metridia lucens* and *Candacia armata* for example *(*Edwards *et al*.1999). Later, in 2002, the plankton community had unusually high numbers of warm-water/sub-tropical species as well as oceanic species including doliolids. In particular the shelf-edge copepod, *Pareuchaeta hebes* recorded its highest ever abundance in the North Sea during 2002. The sub-tropical cladoceran *Penilia avirostris* has increased considerably in abundance in the North Sea since 1997 (SAHFOS Annual Report, 2002).

Using Principal Component Analysis, a ‘striking change’ in the zooplankton community of the North Sea was identified from 1998 to 2002 compared to previous years (SAHFOS Annual Report, 2002).

Specifically, holozooplankton (organisms that are planktonic for their entire life cycle) showed a strong decline in abundance, particularly the small copepods *Para-Pseudocalanus* spp. and *Oithona* spp. as well as other copepods such as *Calanus spp.* What is particularly worth noting is that while *Calanus helgolandicus* is becoming more abundant in the North Sea, the overall *Calanus* abundance has declined considerably which has important implications for other trophic levels (Fig. 8) (SAHFOS, 2004).

Conversely, meroplankton (organisms that are planktonic for only a part of their life cycles, usually the larval stage) showed a huge increase in abundance over the same five year time period, particularly dominated by echinoderm larvae. These changes in community structure have persisted in subsequent years (SAHFOS Report, 2004).

Finally, the plankton community in 2002 had unusually high numbers of warm-water/sub-tropical species as well as oceanic species. In particular the shelf-edge copepod, *Pareuchaeta hebes* recorded its highest ever abundance in the North Sea during 2002. The sub-tropical cladoceran *Penilia avirostris* had also increased considerably in abundance in the North Sea over the same time period.

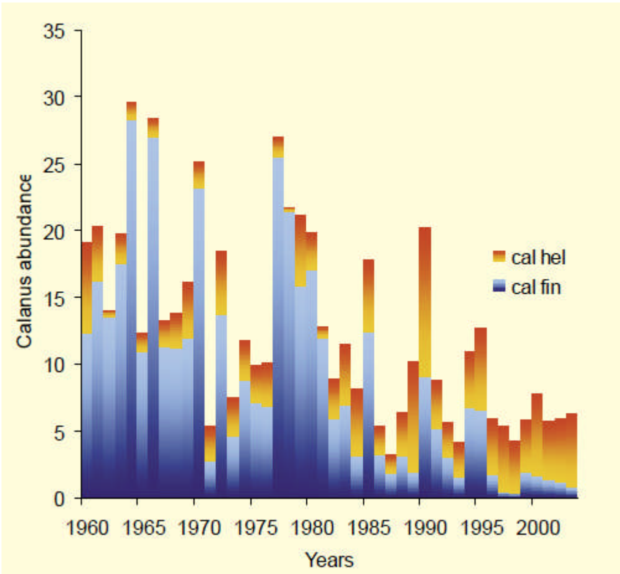


Figure 8. The abundance of *Calanus* populations in the North Sea from 1960 to 2003. The percentage ratio of *Calanus finmarchicus* (blue) and *Calanus helgolandicus* (red) are shown in relation to total *Calanus* abundance in each annual bar. (Adapted from SAHFOS Annual Report, 2004)

2. Oceanographic Modelling

The pulses of oceanic water into the North Sea in 1997-1998 occurred at similar times to unusual circulation in the Rockall Trough, to the west of the British Isles. Holliday *et al.* (2000) analysed a time series of a hydrographic sections across the northern Rockall Trough, and showed that the mean geostrophic transport (horizontal movement of ocean surface waters) of upper water (above 1200m) had increased (Reid and Holliday, 2000). These periods of high transport were also observed during the regime shift in early 1989 and then again in spring 1998. Oceanographic modelling has demonstrated a link between altered rates in water circulation in the Rockall Trough and the inflow of oceanic water into the North Sea via the English Channel and over the Northern parts of Scotland.

3.1.2 General Health Assessment of the North Sea Ecosystem

In an attempt to assess the health of the North Sea ecosystem, a set of biological attributes were evaluated (McGlade, 1989 in Sherman and Skjoldal, 2002). These were biodiversity, level of pollution and trophic stability (abundance, size-classes and life-span). Each attribute may have more than one measure associated with it, and the time periods that were chosen for analysis were pre-1957 and then 1958 to present, to coincide with the establishment of the European Commission, and the extension of the industrial activities in the North Sea. The combined results of these three attributes all indicated a general decline in the health of the ecosystem (McGlade, 1989 in Sherman and Skjoldal, 2002). It was concluded that the economic outputs derived from the North Sea have been obtained at some cost to the environment. The measures also suggested that the changes observed in the trophic structure are indicative of a trend towards decreasing resilience. It was thought that this trend was not only a result of increasing fishing pressure and resource exploitation, but also to the inter-annual changes in the physical oceanography of the North Atlantic (McGlade, 1989 in Sherman and Skjoldal, 2002).

3.1.2.1 Seabirds

Approximately 110 species of birds utilise the North Sea and can divided into three main groups; those that feed primarily intertidally, those using nearshore shallow waters and those feeding offshore. During the 20th century, most species of sea birds in the North Sea have greatly increased in numbers as they establish new colonies and/or expand their range (Sherman and Skjoldal, 2002). It is believed that the increases seen in most species are the results of reduced exploitation for the adults and their eggs (eg. black-legged kittiwake), reduced persecution and also the benefits of offal produced by many fisheries (eg. northern fulmar). It has also been suggested that seabirds have benefitted from changes in the abundance of small fish arising from the activities of commercial fishing that have resulted in a change in the size composition of many exploited species (Sherman and Skjoldal, 2002). It has been estimated that a substantial part of the energy requirements of the more common species like the northern fulmar, the herring gull, the great-backed gull, the kittiwake and the guillemot in fact come from the discards of fishing vessels (Sherman and Skjoldal, 2002).

However, recent reports by the RSPB (RSPB, 2011) and SNH have indicated that breeding seabirds in the UK have declined since 1986 and substantial declines have occurred in populations of breeding shags, Actic skuas, herring gulls, kittiwakes and roseate terns. Key factors affecting abundance and productivity are food availability, weather conditions and the impact of predators. Changes in the food chain are thought to have contributed to reductions in size, abundance and energy content of sandeels in the North sea. Fisheries also have an impact on the abundance and breeding success of some bird species via competition for food. For example, the breeding success of several sea bird populations in the Shetlands declined dramatically through the 1980s at the same time as a noticeable drop in the landings of sandeels from an industrial fishery in the area. The numbers of seabirds increased again in 1991 when there was a large sandeel year class, giving rise to the suggestion that these birds are directly competing with industrial fisheries for food. The controversy surrounding the size and therefore the impact of the industrial fishing on the birds in this area still persists.

3.1.2.2 Fish Stocks

In general, there has been a decline in the abundance of demersal species, particularly haddock, since the beginning of the century (Sherman and Skjodal, 2002). There has also been a change in the size composition resulting in fewer larger fish, and an increasing proportion of smaller individuals. Fluctuations and trends in fish numbers and biological characteristics have been attributed to fisheries, eutrophication, quality of nursery areas and alterations in wind components affecting the transport rates of larvae (Sherman and Skjodal, 2002). Some species appear to be more sensitive than others which has led to concern over the loss of certain species as a result of human activities. For example, elasmobranchs appear to be especially sensitive as two species of dogfish have decreased in numbers dramatically as have rays and skates, while the greater weaver is now extinct in the North Sea (Sherman and Skjodal, 2002).

Changes in the abundance of the commercially important fish stocks in the North Sea have been monitored since the 1950s. All are now heavily exploited, and the majority of those landed for human consumption are considered to be in seriously depleted condition, either outside Safe Biological Limits or below their Minimum Biologically Acceptable Level (a level of spawning stock size below which the stock may be in danger of severe depletion) (Sherman and Skjoldal, 2002).

3.1.2.3 Marine Mammals (excluding harbour seals)

Trends in small cetacean numbers in Europe show a historical decline in many areas, with notable drops in the numbers of harbour porpoises in southern North Sea and the English Channel. In the Channel in particular, there has been a 95% decline in sightings rates of harbour porpoises and bottlenose dolphins from the coast in the last 50 years coinciding with the use of monofilament gillnets (Sherman and Skjoldal, 2002). However, two side-scale surveys in the UK and adjacent waters (Hammond *et al.* 2002, SCNS II 2008) found no evidence for a change in abundance but perhaps a distributional shift towards the southern North Sea.

A study conducted by the North East Cetacean Project (NECP) however, has found that the community structure of small cetaceans in the North Sea may be changing, with more bottlenose, common and Risso's dolphins being sighted. These are all dolphin species associated with warm waters while sightings of the white-beaked dolphin and harbour porpoise, associated with colder water, are decreasing. Thus, there is some evidence that some species of small cetaceans are showing shifts in distribution, possibly as a result of increasing sea temperatures.

Grey seals and harbour seals are the two most abundant pinniped species in the North Sea although other species occasionally occur in coastal waters, including the ringed seal (*Phoca hispida*), harp seal (*Phoca groenlandica*), bearded seal (*Erignathus barbatus*) and the hooded seal (*Cystophora crystata*) all of which are Arctic species. Approximately 45% of the world's grey seals breed in the UK and 90% of these breed at colonies in Scotland. Although the number of grey seal pups throughout Britain has grown steadily since the 1960s when records began, there is clear evidence that the growth is levelling off in some colonies particularly on the west coast of Scotland (SCOS, 2012). Declines in the numbers of animals at some large colonies have been seen while increases in the number of individuals have been recorded at others. Overall, the population of grey seals in the UK and the rest of the North Sea is thought to be healthy and stable.

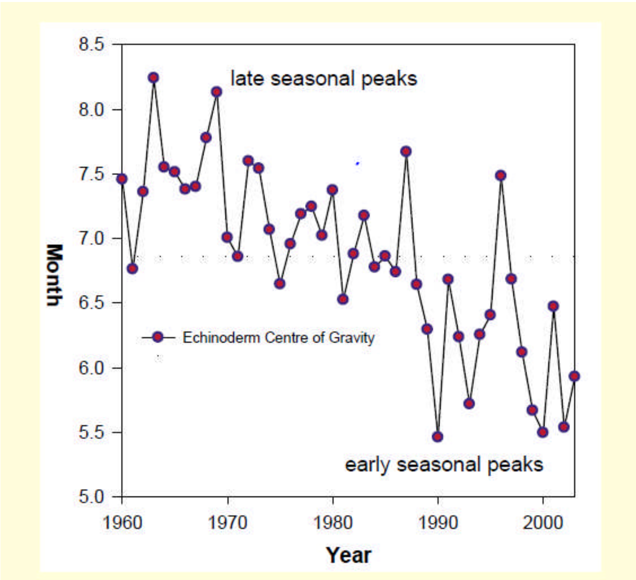


Figure 3. Inter-annual variability in the peak development of echinoderm larvae (an indicator of plankton phenology) from 1960-2003. (Adapted from SAHFOS Annual Report, 2004)

3.2 Phenology

As a representative of phenological changes in shelf environments of the North Sea, the peak seasonal abundance of echinoderm larvae were modelled over time due to the sensitivity of their physiological development to temperature (SAHFOS Annual Report, 2004). Although considerable interannual variability was seen between 1946-2003, a major pattern emerged from 1988 onwards in that the seasonal development of echinoderm larvae has occurred much earlier than the long-term average. The seasonal cycle was 4-5 weeks earlier in the 1990s compared to the long-term mean. This trend towards an earlier seasonal appearance of meroplanktonic larvae from 1988 to 2003 is highly correlated to spring sea surface temperature (SAHFOS Annual Report, 2004). This is a trend that many other planktonic taxa also share (Edwards & Richardson, 2004). The change in the timing of these natural phenomena will have knock-on effects through the rest of the ecosystem, although what these consequences are for other marine organisms is little understood.

4 POTENTIAL CAUSES OF THE DECLINE IN SCOTTISH HARBOUR SEALS

4.1 Infectious disease

4.1.1 Bacterial infections

Brucella : *Brucella* spp. recovered from marine mammals were first reported in 1994. Since then, both culture and serological analysis have demonstrated that the infection occurs in a wide range of species of marine mammals inhabiting a vast amount of the world's oceans. The first marine mammal isolations of *Brucella* came from harbour seals, a harbour porpoise (*Phocoena phocoena*) and a common dolphin (*Delphinus delphis*) in Scotland (Ross *et al.* 1994) and a captive bottlenose dolphin (*Tursiops truncatus*) in the USA (Ewalt *et al.* 1994).

While *Brucella* has been isolated from Scottish harbour seals, there is little evidence that it is causing disease amongst the populations. Mainly young animals have been examined however, but it could be that *Brucella* is causing reproductive problems in adults, which is going unnoticed due to a lack of appropriate diagnostic material. There is currently no information on the levels of abortion in seals (Foster *et al.* 2002). However recent data on the prevalence of positive cultures from stranded seals suggests harbour seals may be affected more often than grey seals.

Infection by marine *Brucella* spp. has also been identified in Pacific harbour seals in Washington State (USA) and in British Columbia (Canada) (Garner *et al.* 1997. Lambourn *et al.* 2001. Ross *et al.* 1994). One of the harbour seals from which *Brucella* spp. were isolated in 1997 in the U.S.A was infected with *Parafilaroides* lungworms, and it was suggested that transmission of brucellosis to pinnipeds by infected lungworms is possible. If *Parafilaroides* infection has a commensal relationship with *Brucella*, it seems that *Brucella* infections might be endemic in some populations of harbour seals.

Leptospirosis : The first report of leptospirosis in marine mammals was published in 1971, and since then, several reports of this infection in pinnipeds have been published. A retrospective study of leptospiral antibody serum titers in two rehabilitated harbour seals at the Marine Mammal Centre, California, indicated both seals had elevated titers to *Leptospira interrogans* serovar *grippotyphosa* (Stamper *et al*. 1998). It was suspected that these individuals had become infected while at the rehabilitations centre. A third seal, which died about the time when the index cases occurred, also had elevated titers to *L. interrogans* serovar *grippotyphosa* (Stamper *et al*. 1998). Following these cases, in 1999, an additional case of leptospirosis was reported in a stranded harbour seal that was thought to have become infected in the natural environment (Stevens *et al.* 1999). It appears that California sea lions are more affected than harbour seals however, as epizootics as a result of leptospirosis infection occur on a regular basis in the sea lions in California (Lloyd Smith, 2007).

Harbour seal serum samples from animals captured or stranded dead around the coast of the UK between 1991 and 2005 were screened for the presence of Leptospire antibodies (Zachariah *et al*., unpublished). Of the 123 live harbour seal serum samples analysed, 9 (7%) had positive titres against *leptospira interrogans serovar australis*. This was the only serovar that produced a reaction in any of the live sera tested. Interestingly all the positive animals were sampled in the same year (2003). The prevalence was higher in the dead harbour seals (22%) and these were all animals that stranded during the 2002 PDV epidemic. However, to our knowledge, no cases of disease have been reported. It is possible that there was some interaction between leptospira and PDV during the outbreak, in the same way that herpesvirus is a prevalent secondary infection because of the immunosuppressive effects of PDV.

Mycoplasma : The isolation of *Mycoplasma* spp. has been reported only in pinnipeds. No other marine mammal has been reported as a host for these bacteria (Higgins, 2000). Following a pneumonia epizootic that killed over 400 harbour seals along the New England coast between 1979 and 1980, mycoplasma isolates were recovered from the respiratory tracts of six of the animals, and it was found to be distinct from any previously described species *(*Ruhnke and Madoff, 1992*)*. This new strain of *mycoplasma* was named *Mycoplasma phocidae (*Ruhnke and Madoff, 1992). Mycoplasma was also isolated in the respiratory tract of a large number of harbour seals that died during the PDV epidemic in Europe in 1988 (Giebel *et al*. 1991). The *Mycoplasma* isolates did not belong to the *M. phocidae* species, or to any of the other known *Mycoplasma* species. They were characterized and classified into 2 new species, *M. phocarhinis* and *M. phocacerebrale*. Even if these mycoplasmas were not the primary cause, they might have been involved in the production of pathological changes and in the general disease, leading to the deaths of the seals (Giebel *et al*. 1991).

Mycobacterium : The presence of Mycobacterium spp. in marine mammals is poorly documented, but appears to be limited to pinnipeds. Tuberculosis was diagnosed in 6 strandings of two otariid species between 1989 and 1992 in Argentina, and was the first time tuberculosis had been diagnosed in wild seals from the south western Atlantic (Higgins, 2000). Cutaneous mycobacteriosis due to *mycobacterium s*pp. has since been reported in a captive harbour seal in the USA in 1990 (Wells *et al*. 1990)

Multiple drug resistance : In a study by Lockwood *et al.* (2006), bacterial cultures collected over 12 years from stranded harbour seal pups and weanlings located in the North Puget Sound and San Juan Islands region of Washington were analysed to identify the most common pathogenic isolates and to describe their antimicrobial resistance patterns. The most frequent isolates were *Escherichia coli* (17%), hemolytic *Streptococcus* spp. (15%), *Enterococcus* spp. (11%), and *Pseudomonas aeruginosa* (11%). It was also so seen that all four isolates exhibited resistance to more than 50% of the antimicrobials tested.

4.1.2 Viral Infections

PDV : In 1988, approximately 20,000 harbour seals died off the coast of northern Europe within the space of 8 months as a result of viral infection. The virus was first reported in April 1988, when widespread abortions and deaths among harbour seals were reported in the Kattegat area between Denmark and Sweden. The infection then spread to the North, Wadden, and Baltic seas. The virus was subsequently classified as a species of the genus *Morbillivirus*, and named *Phocine distemper virus* (PDV). Another more recent outbreak occurred in Europe in 2002. An estimated 30,000 harbour seals died during this epizootic.

PDV disease in the United States was first described in harbour seals on the east coast during the winter of 1991–92 (Duignan *et al.* 1993). Serologic testing of grey and harbour seals suggested that a PDV-like strain or strains were circulating enzootically in the region. During the spring of 2006, the number of deaths of harbour, grey and hooded seals increased along the coasts of Maine and Massachusetts, and was classified as an unusual mortality event (UME). Investigations indicated that the pathologic changes were consistent with morbillivirus infection, and PDV was later isolated from seal tissues (Duignan *et al.* 1995. Earle *et al.* 2011).

Harbour seals screened for CDV on Sable Island, Nova Scotia, in 1988, 1989 and 1991, were shown to have virus neutralising antibodies to CDV (Ross *et al*. 1992). Serological testing then suggested that the virus which infected the Canadian seals was most closely related to the virus which caused the 1988 epizootic in Europe. The results suggested that the virus is currently enzootic in the harbour seal populations of south eastern Canada (Ross *et al*. 1992). Finally, antibodies to PDV have also been detected in a small population of Kuril harbour seals from Hokkaido, Japan (Fujii *et al*. 2006). Sporadic infections of the virus are thought to have occurred in this population in recent years (Fujii *et al*. 2006).

Influenza A : Over 400 harbour seals, most of them immature individuals, died along the New England coast between December 1979 and October 1980 of acute pneumonia associated with influenza virus A. The virus has avian characteristics, replicates principally in mammals, and causes mild respiratory disease in experimentally infected seals (Geraci *et al.* 1982). Although antigenic analyses and characterization of the RNAs show that all of the genes and gene products are closely related to different avian influenza viruses, biologically the virus behaves more like a mammalian strain (Webster *et al.* 1981). Potentially, this may be an example of the adaptation of avian viruses to mammals, which would represent an intermediate step in the evolution of new mammalian strains (Hinshaw *et al.* 1984). The incubation period during epidemics in harbour seals is approximately 3 days, and many factors probably contribute to the explosive nature of the reported epidemics. It is thought that high population densities and unseasonably warm temperatures contribute to high mortality. Since the original epidemic in 1979, five outbreaks of influenza have been reported along the coast of New England.

What renders harbour seals sensitive to disease from influenza is not understood. Cross-species transmission from birds may occur because of the close contact with sea birds at haul out sites. Transmission was thought to occur either through direct physical contact including ingestion of infected bird carcasses or indirect contact with bird faeces, or a contaminated environment through the inhalation of virus particles excreted by birds as aerosols (Reperant *et al*. 2009). However, it has since been seen that attachment of avian influenza A viruses and human influenza B viruses to trachea and bronchi of harbour seals is consistent with reported influenza outbreaks in this species (Ramis *et al*. 2012), suggesting that transmission is primarily through the inhalation of viral particles.

Herpesvirus : Phocid herpesvirus-1 (PhHV-1, subfamily Alphaherpesvirinae), an α-herpesvirus similar to canine herpesvirus, was isolated from harbour seals in the Netherlands in 1985, and was subsequently identified in Pacific harbour seals from California in the 1990s by Gulland *et al*. (1997). PhHV-1 associated pathology was then recognised in harbour seal carcasses in British Columbia, Canada, in 2000 and then again in 2008. A review of these cases indicated that PhHV-1–associated disease is widespread in harbour seals in the wild along the coastal northeastern Pacific including

British Columbia, Canada, and Washington. Morbidity and mortality occurred primarily in neonatal and weanling pups, and was due to PhHV-1 alone, or in combination with other disease processes. All cases occurred between July and October, corresponding to the pupping and weaning seasons in this area (Himworth *et al*. 2010).

Poxvirus : Sealpox infections have been described in young captive harbour seals (Wilson *et al*. 1972. Dunn and Spotte, 1974) maintained at Mystic Marineland Aquarium in the USA. An epizootic of seal pox also occurred at the rehabilitation centre, the Marine Mammal Centre, in California during the summer of 1986. The chronology of the outbreak suggested transmission of the virus as a propagating epizootic among harbour seals and then passage to both elephant seals and a California sea lion (Hastings *et al*. 1989). Finally, poxvirus was also present in one harbour seal that died in an epidemic of unknown cause in New Jersey in 1991 (Gulland and Hall, 2007).

Parapoxvirus : The presence of parapoxvirus was confirmed in 26 young harbour seals from a rehabilitation centre in Germany in 2000. The seals showed spherical dermal elevations with ulceration on various parts of the body and inside the mouth. Although DNA analysis revealed that the causative agent can clearly be distinct from terrestrial parapoxviruses, lesions resembled parapoxvirus infections in other terrestrial species (Muller *et al*. 2003).

Influenza B : An influenza B virus was isolated from a naturally infected harbour seal in Germany, and was then found to be infectious to seal kidney cells in vitro. Sequence analyses and serology indicated that the influenza virus B strain was closely related to strains that circulated in humans 4 to 5 years earlier. Therefore, it has been suggested that this animal reservoir harboring influenza B viruses that have circulated in the past, may pose a direct threat to human health (Osterhaus *et al*. 2000).

4.1.3 Parasites

Sucking Lice : Prevalence and intensity of infection by sucking lice (Echinophthirius horridus) on harbour seals captured in the Moray Firth, Scotland, varied in relation to host age but not sex. Burdens were highest on immature seals, but both prevalence and intensity of infection were significantly higher in years when food availability was low. There was a significant negative correlation between intensity of infection and several erythrocyte parameters, suggesting that high burdens of lice may compromise diving ability (Thompson *et al*. 1998).

Heartworms : The seal louse is suggested to play an important role as an intermediate host transmitting the heartworm, Acanthocheilonema spirocauda, among seals. The heartworm infects nearly the same species of seals as the seal louse, except for the grey seal Halichoerus grypus, where the heartworm is absent. And as for seal lice, heartworms mainly infect immature seals, and after infection the prevalence seems to decrease with increasing age of the host (Leidenberger *et al*. 2007).

4.1.4 Protozoans

Toxoplasma : The recent discovery of *Toxoplasma gondii* in marine mammals might indicate natural infections that were previously unknown because of lack of study, or they might indicate a recent contamination of the marine environment from the terrestrial environment by natural or anthropogenic activities (Measures *et al*. 2004). Clinical reports of toxoplasmosis for harbour seals were first reported by van Pelt and Deitrich in a very young seal in Alaska (1973). Later, Miller *et al*. (2001) isolated viable *T. gondii* from a diseased Pacific harbour seal. Antibodies to *T. gondii* were identified in serum samples from harbour seals in Puget Sound, Washington. These results indicated natural exposure of these wild harbour seals to *T. gondii* oocysts (Lambourn *et al*. 2001). Antibodies to *T. gondii* were also detected in 11 of 311 blood samples collected from Pacific harbour seals in Alaska (Dubey *et al*. 2003). Finally, antibodies to *T. gondii* were also detected in blood samples from harbour seals from the east coast of Canada (Measures *et al.* 2004).

Cabezon *et al*., (2011) tested 56 harbour seal sera from the animals live captured in the UK, only 3 (5%) had low titres (1:25) against *Toxoplasma gondii*. These animals were from the Moray Firth, Orkney and the Tay Estuary respectively.

4.2 Non-infectious disease

4.2.1 Persistent organic pollutants

4.2.1.1 Effects on Immune Function

POP–induced Immunosuppression in Marine Mammals

It has been shown in a variety of experimental studies using a range of different species that exposure to PCBs can render animals more susceptible to viral and bacterial infections by compromising the immune system. PCB-induced immunosuppression has been shown to result in a higher sensitivity of experimental animals to a variety of infectious agents including bacteria, protozoa and viruses. For example in PCB-treated mice, their sensitivity is increased to endotoxin, malaria (Loose *et al*. 1978) and bacteria (Thomas and Hinsdill, 1978). Mice have also been shown to be more sensitive to challenge by herpes simplex and ectromelia (mousepox) (Imanishi *et al*. 1980). PCB-treated rabbits have been shown to synthesise fewer antibodies after being challenged by pseudorabies virus (Koller and Thigpen, 1973), and the resistance of PCB-treated ducks to duck hepatitis virus was also shown to be impaired (Friend and Trainer, 1970). Together, these results demonstrate the association between increased levels of pathogen infection with exposure to PCBs.

While similar studies of exposing marine mammals to pathogens have not been conducted for ethical reasons, it is thought that they too would suffer similar increases in susceptibility to infectious diseases as a result of PCB exposure. It is assumed that the increased risk of infectious disease in relation to PCB levels in the blubber is mediated through effects on immunity of the animal. Thus, to characterize cellular immunity of marine mammals, assays have been developed and applied to various immune parameters, including natural killer cell activity, phagocytosis, cytokine expression, and lymphocyte proliferation among others (De Guise *et al.* 1995. Pillet *et al*. 2000. Lalancette *et al*. 2003. Hammond *et al.* 2005. Camara Pellisso *et al.* 2008. Fonfara *et al.* 2008. Frouin *et al.* 2008). Various studies have been conducted to investigate the changes in cellular immunity of marine mammals in response to PCB and heavy metal exposure, as well as other persistent organic pollutants. Through a combination of *in vitro* and *in vivo* studies using blood samples taken from both captive and wild marine mammals, immune parameters have been assessed to evaluate the potential effects of contaminants on their immune function. Overall, these studies have suggested that marine mammals exposed to high levels of environmental contaminants may be immunocompromised, and as such, suffer from a reduction in resistance to disease.

While we do not have good dose–response data for immune function effects in marine mammals in terms of PCB exposure, the published data do indicate that the effects become more severe as exposure increases. It is therefore assumed that at the highest exposure levels, the effects on both innate and acquired immunity, and thus on cell-mediated and humoral functions, could result in more severe immunosuppression. And, as a result of this immunosuppression, the animals could suffer from increased infection after pathogen exposure resulting in premature mortality.

POP-induced Immunosuppression in Harbour Seals

There is a growing body of literature describing both the contaminant levels found in free-ranging harbour seals across the northern hemisphere, and also the adverse health effects associated with these high contaminant burdens. Ross and colleagues (1994) undertook a two and a half year feeding experiment of 22 captive harbour seals where half of them were fed contaminated Baltic Sea herring, while the other half were fed less contaminated herring from the North Atlantic. Blood samples and blubber biopsy samples were taken throughout the experiment and a series of immune function assays and tests were performed on the seals over the experimental period. The results showed an impairment of natural killer cell activity, in vitro T-lymphocyte function, antigen-specific in vitro lymphocyte proliferative responses and in vivo delayed-type hypersensitivity and antibody responses to ovalbumin in the seals fed the contaminated Baltic herring. These data indicate that present levels of PCBs in the aquatic food chain are immunotoxic to harbour seals.

A review of contaminant levels in free-ranging harbour seals inhabiting polluted areas of Europe and North America suggests that many populations may be at risk to immunotoxicity (Ross *et al*. 1996). It was reported that of the harbour seal populations from which there are blubber contaminant load data, a number of populations in Europe and North America have blubber concentrations of PCBs at, or exceeding those seen in the Ross *et al*. (1994) captive harbour seals with contaminant-related immune impairment. This could result in diminished host resistance and an increased incidence and severity of infectious disease in these populations.

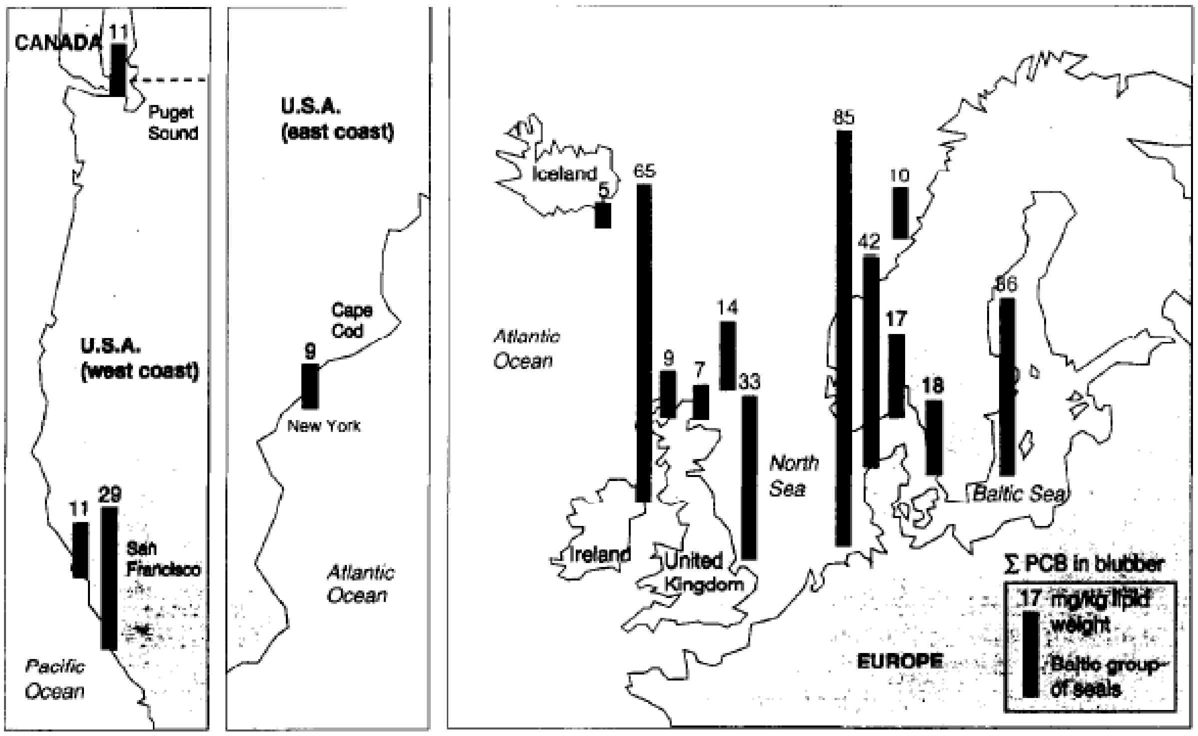


Figure 1 (Adapted from Ross *et al*. 1996). Mean blubber levels of PCBs (mg/kg lipid weight) in harbour seals. Blubber levels of PCBs in harbour seals are even higher in many areas of northern Europe and North America than in the immunosuppressed harbour seals fed Baltic herring in the Ross *et al*. 1994 study.

Atlantic : De Swart *et al*. 1995. Baltic: De Swart *et al*. 1995. USA: San Francisco Bay and Monterey coast (Kopec and Harvey, 1995). Puget Sound (S. Shaw). Long Island (Lake *et al*.1995). Iceland: Luckas *et al*. 1990. United Kingdom: N. Ireland, W. Scotland, Moray Firth, Orkney, and The Wash (Hall *et al*. 1992). Germany: Wadden Sea (Luckas *et al*. 1990). Norway: West and south coast

(Skaare *et al*. 1990). Denmark: Wadden Sea (Storr-Hansen and Spliid, 1993). Sweden: Kattegat and Baltic Sea (Blomkvist *et al*. 1992).

Mos and colleagues (2006) conducted a study on free ranging Pacific harbour seal pups aged between three to five weeks. These were captured at four haulout sites, two urban and two remote sites of varying sizes, human population density and agricultural activity in British Columbia and Washington State. Blood and blubber samples were collected to quantify hematology, innate immune function, adaptive immune function and PCB accumulation. Along with the other immune parameters that were assessed, mitogen induced T-lymphocyte proliferation was negatively correlated with PCB concentrations in the seal pups providing additional evidence of the immunotoxic effects of these contaminants in wild seals. In addition to this reduced functionality, the more contaminated seals had decreased circulating numbers and decreased percentages of lymphocytes in their total white blood cell counts. It was concluded that PCBs appear to be affecting both the quality and quantity of lymphocytes, and therefore, the adaptive immune system as a whole may be less able to respond to infectious agents (Mos *et al*. 2006).

Estimates of individual POPs and their toxic risks were derived by Mos and colleagues in 2010 with respect to free-ranging harbour seals in the north-east Pacific. They were able to generate a new toxicity reference value (TRV) for the protection of marine mammal health. In their case study of harbour seals in British Columbia, Canada, and Washington State, PCBs were the single most abundant POP and were correlated with several adverse health effects, and their levels consistently exceeded regulatory toxicity thresholds for fish-eating wildlife (Mos *et al.* 2010). Nursing seal pups were found to be at particular risk, reflecting their greatly increased dietary intake of PCBs and their sensitivity to developmental toxicity. New TRVs (consisting of 5% tissue residue concentration and dose) of 1.3 mg/kg lipid weight tissue residue in blubber and 0.05 mg/kg lipid weight tolerable daily intake in prey were proposed. These TRVs were lower than previously established TRVs and other regulatory guidelines, thus highlighting the previous underestimation of risks associated with PCBs in high-trophic-level marine wildlife (Mos *et al.* 2010).

Following the 1988 phocine distemper virus epidemic, largely among harbour seals in the North Sea, samples of blubber were taken from animals that died of the disease and levels of contaminants were compared with samples taken from live captured animals that were survivors (Hall *et al*., 1992). Concentrations were compared by region with the hypothesis that levels would be higher in the victims than the survivors due to the immunosuppressive effects of the POPs, thus animals affected by the virus were more likely to have higher blubber contaminant levels. There was indeed a significant difference, after accounting for seasonal differences in blubber thickness, where levels were higher in animals that died of PDV than those in the same region that did not.

4.2.1.2 Effects on Reproduction

<u>*POP–induced Fecundity Changes and Offspring Survival in Marine Mammals*</u>

The high concentrations of POPs are of concern because a growing body of experimental evidence has linked PCBs to deleterious effects on reproduction in various species. Some of these deleterious effects include a reduction in ovulation, mating, implantation failure, abortion and sterility for example that have been documented for other mammal species, notably mink. These results may be due to a hormonal disturbance, to direct dominant-lethal action or to an embryo lethal effect caused by the toxins (Reijnders, 1986). High POP concentrations may also affect reproduction through decreased offspring survival, as demonstrated in a study on first-year survival in grey seal pups by Hall *et al*. (2009) where there was evidence that higher levels of blubber contaminants reduced survivorship. Overall, reproductive failures have been documented in four populations of marine mammals; Californian sea lions (*Zalophus californianus*), Bothnian Bay ringed seals (*Pusa hispida*), Dutch Wadden Sea harbour seals, and most recently, Gulf of St. Lawrence beluga whales (*Delphinapterus leucas*). These failures have been attributed to the effects of contamination by organochlorine residues (Addison, 1989).

The mechanisms by which POPs can cause reproductive failure are still relatively poorly understood. However, an early study in pinnipeds by Helle and colleagues (1976a) demonstrated that high levels of DDT and PCBs in female ringed seals are associated with pathological changes of the uterus. About 40% of a sample of Baltic ringed seal females of reproductive age showed pathological changes of the uterus including uterine horns that were closed by stenosis and occlusions thus preventing any passage from the ovary out through the horn (Helle *et al.* 1976a). These changes resulted in deceased fecundity, implantation failure and sterility in the ringed seals (Helle *et al.* 1976b) and thus explained the low reproduction rate of these seals in the Baltic at the time. Animals showing these changes had significantly higher levels of DDTs and PCBs than normal, pregnant females (Helle *et al.* 1976a). It was strongly indicated that PCBs were responsible for the reproductive failure of the seals in the Baltic area (Helle *et al.* 1976a). PCBs and associated DDT-like compounds have also been linked to premature pupping in sea lions (Delong *et al.* 1973). In addition, like the Baltic seal population, reduced reproductive capacity due to POP exposure has been proposed as the primary cause for the lack of recovery of the St. Lawrence beluga whale population that has really high concentrations of POPs compared to other marine mammal populations (Martineau *et al*. 1987).

POP–induced Fecundity Changes in Harbour Seals

Helle *et al.* (1976a) showed that high levels of DDT and PCBs in female harbour, ringed and grey seals are associated with pathological changes of the uterus. Harbour seals from along the Swedish west coast showed these pathological changes of the uterus, and it was hypothesised that PCBs were responsible for the reproductive failure of the harbour seals in the Baltic area.

The population of harbour seals in the westernmost part of the Wadden Sea, The Netherlands, collapsed between 1950 and 1975 when the population dropped from more than 3,000 to less than 500 individuals (Reijnders, 1986). A comparative toxicological study on the levels of heavy metals and organochlorines in tissues of seals from the western and northern parts of the Wadden Sea, where the declines were at their greatest, showed that only the polychlorinated biphenyl (PCB) levels differ significantly from other populations. It was thought that this was predominantly a result of PCB pollution from the river Rhine, which mainly affects the western part of the Wadden Sea. PCBs were thus suspected to be responsible for the low rate of reproduction in Dutch harbour seals. Reijnders (1986) conducted feeding experiments with two groups of harbour seals fed fish from either the polluted Dutch Wadden sea or from the less polluted north-east Atlantic. He reported reproductive failure in the seals fed the Wadden Sea fish as the reproductive process was disrupted in the post-ovulation phase. Therefore, he concluded that reproductive failure in the wild seals from the Dutch Wadden Sea is related to feeding on fish from that polluted area (Reijnders, 1986). Since then, this population of seals has become extinct.

However, in the most recent study of lipophilic contaminant concentrations in the blubber of harbour seals (Hall and Thomas., 2007) indicated that the levels of various POPs (PCBs, DDTs and PBDEs) were lowest in the regions of greatest decline (such as Shetland, Orkney and the SE coast of Scotland) and were well below the thresholds indicated as being deleterious to health (with the exception of adult males in particular from Islay where they may be foraging on contaminated prey from the well-identified hotspot of PCB contamination in the Clyde estuary). This suggests that POP contaminant levels are unlikely to be either a direct or indirect factor involved in the recent decline in abundance.

4.3 Biotoxin Exposure

In the late 1990s domoic acid (DA) toxicity was identified as the major cause of a mass mortality event among California sea lions. This potent neurotoxin (which causes amnesic shellfish poisoning in humans) is produced by diatoms of the genus *Pseudo-nitzschia* that has since bloomed on a more or less annual basis along the coast of California, causing major mass mortality events among sea lions and other marine mammals. Blooms of various species of toxic algae (so-called Harmful Algal Blooms or HABs) appear to be on the increase worldwide (Hallegraeff, 1993) and are now occurring regularly in Scottish waters (Swan and Davidson, 2010). These toxins, if ingested at levels above the toxic threshold can cause severe neurological effects, paralytic effects and gastrointestinal effects. Effects are often seen very rapidly with high levels of mortality.

Starting in 2008 we began monitoring harbour seals for signs of exposure. Low levels of DA were found in the faeces and urine (indicating animals had been exposed to domoic acid) of live captured animals from various sites around the Scottish coast (Hall and Frame, 2010). Given the very short half -life of these toxins (24h in urine and a few days in faeces) this probably represents recent exposure. The highest proportion of positive samples (~70%) and animals with the highest levels were found in the seals captured in the Eden estuary on the east coast of Scotland.

A follow up study then screened additional urine and faecal samples from live captured animals (n=108) and a wider geographical spread of faecal samples from harbour seal haulout sites (n=262) collected as part of the Scotland-wide diet study in 2010 (Hall *et al*, 2010). Again all regions contained some positive samples but interpretation of the absolute concentrations is difficult given the time of exposure is unknown.

We did not find any signs of DA toxicity among the live captured animals (signs of seizure or neurological effects) although there was a positive correlation between blood eosinophilia and urinary concentration of DA, as has been reported in California sea lions.

In some regions, such as Shetland and the southeast coast, the proportion of positive harbour seal faecal samples was ≥70% and these regions are among those where the rate of decline in harbour seals has been highest (SCOS 2010). Other regions showed between 30-45% positive in the Outer Hebrides, with the Inner Hebrides having the lowest numbers of positive seals, between 6-13%. The regions of greatest decline coincide with the highest proportion of positive seals but this is merely an observed correlation at this stage.

Domoic acid is most likely to have been ingested by seals which prey on demersal benthivores such as flatfish and squid, as higher levels of DA were found in the guts of these fish and cephalopods than other species from the same area sampled at the same time. This is also in line with the diet of harbour seals in this region (see Diet section above). Grey seals appear to be less exposed with fewer positive samples (20% were positive in the Tay estuary, n=33) and with lower concentrations.

Preliminary results also suggest that harbour seals are also ingesting saxitoxin, a potent biotoxin produced by dinoflagellates from the genus *Alexandrium*, which affects the nervous system and causes Paralytic Shellfish Poisoning in humans.

Further exposure, metabolism, effect and risk assessment studies are currently being carried out as part of a MASTS Prize PhD studentship in conjunction with Scottish Association for Marine Science who are responsible for the phytoplankton monitoring around Scotland and Marine Scotland Science Aberdeen laboratory to analyse excreta, fish and water samples for various toxins, to determine the impact such exposure (and the impact of exposure to multiple toxins from different HAB species) is likely to be having on harbour seal health and survival.

4.4 Nutritional Stress

This is also a difficult issue to address from live capture studies due to inherent biases in capture methods and in the nature of the animals hauled out and available for capture. However, we analysed the morphometric, condition and clinical blood chemistry information for harbour seals captured between 1988 and 2006 (Hall *et al*., 2009) and then again from 1988 to 2012.

As was reported in the age distribution data, overall the number of juveniles captured over the years has declined although this is potentially confounded by captured method and target animals.

We used a set of generalised linear models fitted to the data to explore differences in morphometric and blood chemistry indicators of condition, and investigating or controlling for the effects of sex, region, month and year. The animals from Orkney were significantly longer than those from the other sites (west coast of Scotland, Moray Firth, Tay, SE England and Northern Ireland) and although longer animals had larger absolute girths, the girths increased less than linearly with length so that longer animals were relatively 'thinner'. Orkney animals were denser than other animals which may indicate they have less lipid and are in poorer 'condition' but there was no indication from the results of the clinical blood chemistries that animals were nutritionally stressed. Their circulating protein, triglyceride, non-esterified fatty acid and urea levels were all within normal ranges and were not significant when included as additional explanatory variables in the morphometric models.

4.4.1 Prey quality

Changes in prey quality have been identified as important aspects affecting seabird breeding failures. For example in 2004 (Wanless *et al*., 2005) common guillemots, the most abundant seabird species in the North sea, showed greatly reduced breeding success and those chicks that did survive were in poor condition. The main prey item fed to the chicks was sprat rather than the usual sandeels. Nutrient analysis of fish collected from birds in 2004 found they were significantly lower in energy quality than expected. Poor food quality therefore appeared to be the proximate cause of breeding failure. However, these species are single prey loaders and as such are very sensitive to such variations and harbour seals may be less vulnerable as they feed on a variety of species.

This potentially important factor does need further investigation and following the harbour seal diet study that is currently being conducted, research into prey quality changes should certainly be investigated.

4.4.2 Prey quantity

Fishing pressure in the North Sea has changed the marine environment such that the total biomass of the major fishery species has declined over the past century by between 50 and 98% and some species have become locally extinct. Populations of large predatory fish such as cod, haddock, plaice, turbot and halibut are estimated to have been reduced by 90% since 1990 (Christensen *et al*. 2003). The abundance of forage fish species such as herring, blue whiting and Norway pout have been reduced by 50% or more (Jennings and Blanchard 2004). The collapse of bottom-living species in the North Sea has reduced direct predation on prey species such as herring. Bundy (2005) estimated that fish which feed in the water column made up 30% of the total biomass of fish prior to recent decades. This has increased the supply of these fish to commercial fisheries for fishmeal and has shifted foodwebs from dominance by bottom fish to pelagic fish (Roberts and Mason, 2008).

During the late 1990s a study investigating the link between sandeel abundance and predator relationships (Harwood *et al*., 1998) found seabirds, seals and predatory fish responded to changes in sandeel abundance and availability, brought about by increased removal of sandeels by fisheries. For bird predators and grey seals it was possible to demonstrate a relationship between sandeel availability (at an appropriate spatial scale) and breeding performance. Thus local depletion of sandeel aggregations at a distance less than 100km from seabird colonies may affect some species of birds, especially black-legged kittiwake and terns, whereas more mobile marine mammals and fish may be less vulnerable (ICES, 2011). However there does not appear to be any information on the relationship between sandeel abundance and harbour seal population trends.

It is difficult to determine the effect of prey quantity and availability on Scottish harbour seals until the comprehensive round-Scotland diet information and analysis is complete. However, following the completion of that study, further investigations into the link between recent data on prey and current diet will be forthcoming.

4.5 Trauma

4.5.1 Vessel interactions

Recent evidence of interactions between harbour seals and vessels has emerged. Severely characteristically damaged seal carcasses have been found on beaches in eastern Scotland (St Andrews Bay, Tay and Eden Estuaries and Firth of Forth), along the North Norfolk coast in England (centred on the Blakeney Point nature reserve), and within and around Strangford Lough in Northern

Ireland (SCOS, 2010). A more detailed report on these extensive lacerations can be found at http://www.smru.st-and.ac.uk/documents/366.pdf.

All the seals had a distinguishing wound consisting of a single smooth edged cut that starts at the head and spirals around the body. In most cases the resulting spiral strip of skin and blubber was detached from the underlying tissue. In each case examined so far the wound would have been fatal. The extremely neat edge to the wound strongly suggests the effects of a blade with a smooth edge applied with considerable force, while the spiral shape is consistent with rotation about the longitudinal axis of the animal.

The injuries are consistent with the seals being drawn through a ducted propeller such as a Kort nozzle or some types of Azimuth thrusters. Such systems are common to a wide range of ships including tugs, self-propelled barges and rigs, various types of offshore support vessels and research boats. All the other explanations of the injuries that have been proposed, including suggested Greenland shark predation are difficult to reconcile with the actual observations and, based on the evidence to date, seem very unlikely to have been the cause of these mortalities.

There are also various older reports, of carcasses with wounds to the head and thorax, from these and other areas around the UK. Such animals have often been assumed to have died in fishing nets and sustained lacerations when being cut out of nets. However some of these wounds may be consistent with a rotating blade strike and warrant further investigation in light of our more recent observations.

4.6 Shooting

Under the Conservation of Seals Act (1970) and the Marine (Scotland) 2010 Act, seals cannot be shot during the breeding season or when Conservation Orders are in place. And outside this seals in Scotland can only be taken under licence. Thus prior to 2010 and still in English waters outside any existing Conservation Orders, seals can be legally shot with no requirement to report the number of animals killed. Thus statutory information on the number of UK seals shot each year is not available (Thompson *et al*., 2007).

However, an estimate of the number of seals shot in the Moray Firth by the Spey District Salmon Fishery Board enabled Thompson *et al*., (2007) to investigate the impact of this culling on population trends. They showed that the abundance of harbour seals in the Moray Firth declined by 2-5% per annum between 1993 and 2004. Records from the local salmon fisheries and aquaculture sites indicated that 66-327 seals were shot each year between 1994 and 2002. Matric models and estimates of potential biological removal indicated that this level of shooting was sufficient to explain the observed declines. Nevertheless, uncertainty over the number and identity of the seals shot means that other factors may be contributing. Recent conservation measures in the form of the Moray Firth Seal Management Plan have markedly reduced the level of shooting and this coordinated plan to protect salmon fisheries interests has proved so successful that it's approach was taken up Scotland-wide as part of the conservation measures under the recent Marine Scotland (2010) Act.

Thus under Part 6 of the Marine (Scotland) Act 2010, it is an offence to kill or injure a seal except under licence or for welfare reasons, thus outlawing unregulated seal shooting that was permitted under previous legislation.

In 2012, Marine Scotland received 62 applications for seal licences and 60 licences were granted. The maximum number of seals involved was 873 grey and 290 harbour seals, the majority of which are in the West of Scotland. The maximum number of harbour seals allowed on licences granted in 2012 represents a 10% reduction on numbers involved in the previous year's licences. However, comprehensive monitoring of future population trends and improved regulation of shootings are still required to provide more robust assessments of the impact of human persecution on harbour seal populations around the UK.

Table 1 – Breakdown of harbour seal licences in 2012. Source : http://www.scotland.gov.uk/

Seal Management Area	Harbour seal Licences Applied For	Potential Biological Removal	Harbour Seal Licences Granted
East Coast	106	2	0
Moray Firth	82	20	19
Orkney and North Coast	58	18	7
Shetland	32	18	6
Western Isles	120	54	43
South West Scotland	104	35	30
West Scotland	308	442	185
Grand Total	810	589	290

4.7 Spatial and ecological overlap with other marine mammals

4.7.1 Direct exclusion

Grey seals - no current information is available. However, the data and maps from Task MR5 will indicate spatial, at-sea overlap between grey and harbour seals. These taken in conjunction with the results of the diet studies will assist in assessing the likelihood of inter-specific competition. However, some evidence for spatial overlap between the species in the Moray Firth has been reported (Thompson *et al*. 1996), evidence for direct exclusion is lacking. Some anecdotal information from observations of seals around salmon nets (Harris personal communication) may suggest exclusion in that when grey seals arrive at the nets, harbour seals leave. However, much more information on this behavior is required before any firm conclusions can be drawn.

4.7.2 Indirect effects

Competition for prey - no current information is available; see section on Diet for studies on contemporaneous diet in grey and harbour seal in the Moray Firth. A Marine Scotland funded project is currently underway to comprehensively investigate the diet of harbour seals around Scotland and the overlap between grey and harbour seal prey.

4.8 Human disturbance

Human disturbance can cause females seals to abandon their pups and thus reduce their reproductive success (Hoover-Miller 1994). In addition, animals may abandon their haulout and breeding sites in favour of less disturbed areas. For example recreational yachting was though to reduce the harbour seals in the Rhine delta area from the 1970s (Reijnders, 1985). However, good empirical data on the level of disturbance required to produce a major population decline is lacking and as many of the regions in decline are in relatively remote areas with low human population densities and no evidence of major increases in boat or other vessel traffic (as has been seen in other regions), disturbance as a major causal factor alone may be difficult to envisage. But as a cumulative factor on top of various other stressors disturbance could be locally very important.

4.9 Predation

Bolt *et al*., (2009) reported sightings of killer whales around Shetland between 1991 and 2006 for around Scotland for 2007. There was a strong seasonal peak in Shetland in June and July coinciding with the harbour seal pupping season but there was no clear trend in annual sightings during the study period. The authors estimated that harbour seal consumption ranged from 0 to a maximum annual estimate of 828 harbour seal pops for the year 2000 with most killer whale sightings(57 days killer whales were sighted, 294 killer whale days) assuming that killer whale diet comprised 100% harbour seal pups. However, there was no correlation between harbour seal counts and killer whale sightings.

A further study (Deecke *et al*., 2010) also investigated the potential for increased killer whale predation, again focussed particularly in Shetland waters, to be a factor involved in the recent decline. In almost all encounters with killer whales in Shetland during the summers of 2008 and 2009 (Deecke, *et al*., 2010) were in nearshore waters where the killer whales exhibited behaviour consistent with hunting for seals e.g. hugging the coastline tightly, particularly around seal haul-outs. Evidence for feeding behaviour, including lunges towards seals, both grey and harbour, could be obtained in 9 encounters. Group size ranged from 1 to 6 for groups seen to attack sea mammals and from 25-50 estimated for groups documented to feed on fish. So far, none of the individuals involved in marine mammal predation have been observed feeding on fish, which may suggest some degree of dietary specialisation consistent with our characterisation of type 1 killer whales based on stable isotope values (Foote *et al*. 2009).

Further evidence of seals being primarily targeted as prey by killer whales in nearshore waters around Shetland came from analysing their acoustic behaviour. In addition, the small number of confirmed kills documented was mainly harbour seals.

Bioenergetic modelling suggests that each adult female/sub-adult male will require approximately one adult harbour seal a day, adult males will require twice this and juveniles approximately half this (Bolt *et al*. 2009). The group composition and the number of seals consumed during the "follows" averaged out at 0.6 seals per day per adult female or sub-adult male.

The study estimates suggest approximately 30 whales in Shetland waters during 2008-2009 with 36 individuals identified within this nearshore seal-eating community. They are primarily observed around Shetland, Orkney and Caithness from May-Aug (Bolt *et al*. 2009), e.g. 120 days, but identified individuals have been seen as early as March around Shetland. If these individuals take harbour seals at the observed predation rate throughout this time period then the number of harbour seals taken annually will be in the upper range of, or larger than, the Bolt *et al.* (2009) estimate of 828 pups per year.

4.10 Fisheries Interactions

The fishing industry's collective view is that seals are damaging to the industry in two ways; firstly they are competitors for economically valuable fish (biological interactions) and secondly, they damage both fishing gear and catch (operational interactions) in attempts to feed on the fish caught in nets, traps and cages. Interference problems appear to be more prevalent around static gear, such as fixed nets, long lines and gill nets, than around actively-fished gear, such as trawls and seines (Harwood, 1987). It is thought that the grey seal is the fishing industry's principal problem, since it is the more numerous species in UK, its population has been increasing for several decades, and it appears to be more opportunistic than the harbour seal in its predatory habits in most areas. For this reason, most of the investigations into fisheries interactions have focused on grey seals, and as such, there is little up to date information available examining the interactions between the fishing industry and harbour seal populations in the UK. Based on a few studies however, it is thought that bottom set nets may cause the greatest problems in terms of by-catch of harbour seals, although the numbers of by-caught animals are thought to be low, and entanglement in marine debris has been recorded around the UK, but the extent of the problem is currently unknown. However, there is concern over the potential impact of unrecorded shooting of harbour seals associated with the salmon fishing industry in particular, as while the number of seal licences granted continues to decline, the number of seals shot illegally remains unknown (Thompson *et al.*, 2007).

4.10.1 By-catch

It appears that in most cases the seal by-catch level in the UK does not appear to be a threat to seal populations, and may be considered more of a problem of animal welfare. For instance, overall, estimates for the percentage of grey seal yearlings dying in nets vary from about 1–2% in Scotland and the Farne Islands and 12% on the west of Ireland (Wickens, 1995). However, in Cornwall in the early 1990s, it was estimated that almost 70% of pups were drowned in nets, and as a consequence, the population was thought to be declining by about 8% per year (Glain, 1998), the problem may therefore have been affecting the conservation status of the population, and was not merely an animal welfare issue.

Another fishery that used to catch unusually high numbers of seals compared to fisheries in the rest of the UK, was the Barra crayfish fishery in the early 1980s (Northridge, 1984). When this fishery was first begun on an experimental basis in 1980, 107 harbour seals were caught in two months. The majority of these seals were juveniles probably only one or two years old. These nets were set flat and loosely on the seabed, and it was thought that harbour seals foraging on the seabed do not see these nets until it is too late, on account of the dark background of the seabed and the absence of a float (Northridge, 1984). Once caught, they cannot escape because of the thick multifilament mesh used for these nets.

Seals may also be caught in anti-predator nets. Anti-predator nets are common on many salmon farms in Scotland and seals sometimes drown in these nets (Ross, 1988). Furthermore, seals occasionally drown in salmon bag and stake nets set around river estuaries in Scotland. While some are still able to surface inside the net to breathe, if found in the trap when fishermen come to remove the salmon they are usually clubbed (Northridge, 1984). A survey of 47 Scottish salmon farms in 1988 revealed that 319 seals were reported killed in one year. Of these, approximately one third were caused by entanglement, which in some cases appeared to be deliberate. The figure for Shetland is less, estimated at about 100 seals killed between 1991–92, about one fifth of which died as a result of entanglement (Ross, 1988). These data are over 15 years old, and more up to date research and monitoring of by-catch of harbour seals especially in certain coastal areas of the UK is necessary.

In a long-term study investigating the by-catch of seals along the Norwegian coast between 1975 and 1998, it was estimated that a minimum of 6% of yearlings of grey and harbour seals are by-caught annually in these nets (Bjørge, *et al*. 2002). Bottom-set nets were the single most important cause of by-catch (5% of all tagged pups), followed by traps set for cod. The pups were most vulnerable to by-catch during the first 3 months after birth (25% of the grey seals and 14% of the harbour seals), but high incidental mortality prevailed until about 8 months in grey seals and 10 months in harbour seals. Older animals appeared to be less vulnerable. It was hypothesised that harbour seals may be especially vulnerable to being tangled in bottom set nets because they swim rapidly along the seabed when searching for prey (Bjørge *et al.* 1995), whereas grey seals tend to dive directly to the seabed and then remain more stationary (Thompson *et al*. 1991). It was suggested that yearlings and young seals may fail to escape because of their limited physical strength and less well-controlled diving responses when compared to adults. It was also thoughtthat naive curiosity may also attract them to investigate nets. Overall by-catch mortality is not thought to threaten Norwegian populations of harbour or grey seals, although local depletions may occur. However, the levels of by-catch are sufficiently high to warrant further monitoring of by-catches in Norwegian coastal fisheries (Bjørge, *et al*., 2002).

4.10.2 Entanglements in Marine Debris

Entanglement of seals in pieces of discarded netting is a major problem for various seal species in some parts of the world. A seal may drown, or become entangled in a piece of net, which causes constriction, wounding and eventually death. Entanglement of grey and harbour seals in the UK has been widely reported but not documented and published (Emery & Simmonds, 1995). Information obtained from five sources (Skomer Island, Orkney, the Hebrides, Norfolk and Cornwall) all reported several seals over a four-year period from 1991 to 1995 that had been constricted or wounded by debris still attached. Most had rope, cord or netting around the neck, either embedded in blubber or causing raw flesh wounds (Emery & Simmonds, 1995). The extent of this problem for seals in the UK and Ireland has yet to be assessed on any quantitative basis, but deliberate or negligent discarding of netting should be prevented. It has been suggested that a survey should be carried out, in conjunction with seal sanctuaries, to define the extent of the problem.

5 POPULATION DYNAMICS OF HARBOUR SEALS WORLDWIDE

5.1 Harbour Seal Subspecies Distribution and Abundance

Harbour seals are one of the most widespread of the pinnipeds, and it is estimated that there are currently between 300,000 and 500,000 harbour seals worldwide consisting of 5 different subspecies. Harbour seals are found throughout the coastal areas of temperate, subarctic, and arctic waters of the North Atlantic and North Pacific, and Figure 1 shows the approximate distributions of the 5 subspecies. Each subspecies is geographically separated, so it is thought that they are reproductively isolated.

Figure 1. *Worldwide distributions of the 5 subspecies of harbour seal. In red are the areas that have recently, or are currently experiencing unexplained population declines.*

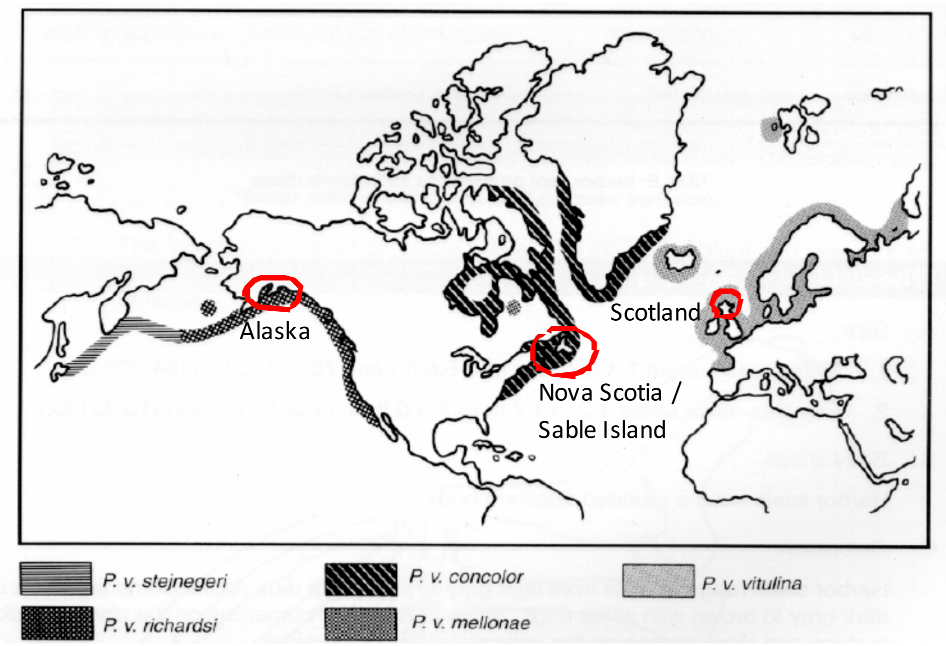


Table 1. *Harbour seal subspecies population sizes and distribution.*

Subspecies	Population Size	Distribution
P. v. richardsi	120,000 – 150,000	Eastern Pacific – From the Pribilof Islands at the end of the Alaskan Peninsula, to Baja California, Mexico.
P. v. stejnegeri	12,500 – 13,500	Western Pacific – From the Bering Sea, along the Kuril Islands in Alaska to Hokkaido, Japan.
P. v. vitulina	68,000 -100,000	North-eastern Atlantic – Along the European coast from Finland to Portugal and Iceland.
P. v. concolor	90,000 – 100,000	Western Atlantic – Greenland to the central United

		States.
P. v. mellonae	100 - 600	Seal lakes in Quebec, Canada.

5.2 Harbour Seal Subspecies Population Trends

P. v. richardsi

Overall the *P. v. richardsi* population has been stable or increasing since the early 1990s although population dynamics of regional subpopulations vary dramatically.

Alaska: Large-scale, long-term declines of over 60% in Gulf of Alaska and Prince William Sound from the 1970s to the early 1990s have apparently stabilized, with the population experiencing slight increases since the early 1990s (Pitcher 1990, Frost *et al*. 1999, Jemison and Kelly 2001, Boveng *et al*. 2003, Mathews and Pendleton 2006, Jemison *et al*. 2006). However, numbers in a few specific areas in Alaska continue to decline and although part of this decline may be related to the effects of the Exxon Valdez disaster, the overall decline in Gulf of Alaska is unexplained. Declines of the Alaskan harbour seal population coincide with similar declines seen in the Stellar sea lion (*Eumetopias jubatus*) populations in the same areas, the reasons for which are also still unknown.

British Columbia to California: Following the cessation of state-financed bounty programs in 1960 and the implementation of the Marine Mammal Protection Act in 1972, long-term population increases occurred in the 1970s up to the late 1990s when the numbers of harbour seals in B.C., Washington and Oregon increased ten-fold and were considered to be at an optimum sustainable level (Jeffries *et al*. 2003). These population increases appear to have reached an asymptote where the population is now thought to be stable and probably at carrying capacity (Brown *et al*. 2005). Harbour seal numbers in California have shown a similar trend whereby increases through the 1970s to the 1990s appear to have now stabilised (NWFSC - NOAA, 2009).

P. v. stejnegeri

The population dynamics of this subspecies are not well documented.

Russia: The population in the Kuril Islands appears to have increased slightly from 2,000-2,500 animals in the early 1960s to around 3,000-3,500 individuals in 2000 (Thompson and Härkönen, 2008). Similarly, in the Commander Islands, the subpopulation increased from around 2,000 in the early 1960s to around 3,000-3,500 individuals in the early 1990s and is thought now to be stable (Thompson and Härkönen, 2008). Low levels of human activity in the Kurils, and the protected status of the seals within nature reserves in the Commander Islands means that there are no obvious anthropogenic threats to the bulk of the population.

Japan: The population in Japan is very small, estimated at only 350 individuals in late 1980s, having declined due to heavy hunting pressure (Hayama, 1988). This population is still thought to be subject to high by-catch rates in trap net fisheries (especially salmon fisheries), and the animals are shot by fishermen in coastal areas (Wada *et al*. 1991). These high mortality rates associated with the fishing industry are a cause for concern for this small and declining population.

P. v. vitulina

Overall the population of *P. v. vitulina* has increased since the 1970s, but population dynamics of regional subpopulations vary dramatically.

UK: In the southern populations there have seen increases in numbers punctuated by population crashes caused by PDV outbreaks in 1988 and 2002, but these populations appear to be recovering (Thompson *et al*. 2005). Case mortality from the PDV outbreaks appear to have been highly variable across the British populations, with the southern populations experiencing the most dramatic declines (Lonergan *et al*. 2010). Unlike the southern populations however, there have been recent large-scale declines in the northern UK populations, particularly in Scotland, the reasons for which are still unknown (Thompson *et al*. 2001, Lonergan *et al*. 2007).

Netherlands, Denmark, Germany, Sweden: Similarly to the southern UK populations, populations of European harbour seals increased exponentially until 1988 when there was a major population crash due to a PDV outbreak in the Wadden Sea, Kattegat and Skagerrak populations. (e.g. Heide-Jorgensen and Harkonen 1988, Harkonen *et al*. 2002, 2005, 2006). These populations of harbour seals then increased in numbers following the epizootic (Harkonen *et al*. 2002), but were reduced again after a second outbreak of PDV in 2002. In 2008, following aerial surveys of the areas, it was estimated that the population of seals in the Wadden Sea was back to pre-epizootic levels and continuing to grow (Trilateral Seal Expert Group, 2008). Seals in the Skagerrak and Kattegat are counted annually (Teilmann *et al*. 2010), and these populations have also shown annual positive growth rates since 2002 (Teilmann *et al*. 2010).

Baltic: Historically, harbour seals were found throughout the Baltic sea, but are now only found in the southern Baltic (Ojaveer *et al*. 2010). Harbour seals form two distinct populations in the southern Baltic both of which have faced steep declines in the first half of the twentieth century through a combination of hunting and pollution, and as a result, their abundance was very low by the early 1970s (Ojaveer *et al*. 2010). Multiple PDV outbreaks since the late 1980s have also caused mass die-offs in the Baltic seals with a very small population of only approximately 400 animals counted in 2004 (Härkönen *et al*. 2006). This population is now protected, but more recent estimates suggest that the Eastern population continues to decline (SMRU, 2009).

Norway and Svalbard: The Norwegian population is estimated at approximately 3,800 individuals (SMRU, 2009), although the overall trend in population growth is uncertain as estimates in the 1980s suggested over 4,000 seals (Bjorge, 1991). It has been suggested that the Norwegian harbour seal population is declining as a result of hunting (Thompson and Härkönen, 2008), and it was advised by the NAMMCO Scientific Committee in 2008 that Norway needs a management plan for its hunting industry and more efficient monitoring of by-catch in all fisheries. The total population size on Svalbard, the most northerly population of harbour seals, is not currently known, but a minimum estimate of this population conducted in the early 1980s suggested that there were between 500 and 600 animals (Prestrud and Gjertz, 1990). It is likely that there are currently less than 1,000 individuals and the population is on the national Red List for Norway and is afforded complete protection (Lydersen and Kovacs 2005).

Iceland: The Icelandic population has declined by 5% p.a. since 1980, which is thought to be a direct result of hunting (Thompson and Harkonen, 2008. Ministry of Fisheries and Agriculture, 2010). The total population size is estimated at approximately 12,000 individuals with around 100 seals harvested each year (Ministry of Fisheries and Agriculture, 2010). In 2006 the NAMMCO Scientific Committee showed that this species is at risk in Iceland due to a substantial decrease in the population size as a result of unsustainable takes, and a formal assessment of the stock is required along with a management plan that establishes clear objectives (NAMMCO, 2008).

P. v. concolor

Overall the population of *P. v. concolor* has been stable since 1980 (COSEWIC, 2007).

Atlantic Canada: Canadian populations declined during the 1970s from approximately 12,700 (Boulva and McLaren, 1979), mostly found on Sable Island and Nova Scotia, to 4,000 individuals (Thompson and Harkonen, 2008). While it is difficult to produce reliable range wide estimates of abundance across the entire Canadian population, most subpopulations have been increasing since the early 1980s when the bounty program ended (COSEWIC, 2007). One exception however is the Sable Island subpopulation that declined from a maximum pup production of 600 in 1989 to less than 10 pups per year by the early 2000s (Bowen *et al*. 2003). In the late 1980s, the Sable Island population was the largest in eastern Canada, and the recent declines have been thought to be due to shark predation and competition with grey seals (Lucas and Stobo, 2000. Bowen *et al*. 2003).

Greenland: It is thought that populations in west Greenland, even in protected areas are depleted as a direct result of hunting (Teilmann and Dietz, 1994). Since 1960, adult harbour seals have been protected during the breeding season from May until September, and certain municipalities have local sanctuaries and further hunting regulations. However, wide scale hunting still occurs for sub adults and pups however (Teilmann and Dietz, 1994). An aerial survey conducted in 1992 indicated that only seven of 14 known harbour seal haul outs may still be in use (Teilmann and Dietz, 1994). As such, it was recommended in 2008 by the NAMMCO Scientific Committee that Greenland enforces a total ban on the hunt of harbour seals (NAMMCO, 2008). It is thought that the remote geographical position of Greenland may cause limited possibilities for immigration, should the harbour seal disappear from Greenland waters.

Eastern U.S.A: Harbour seals in the eastern USA have increased at 6.6% p.a. since 1981, recovering from the effects of bounty hunting which ceased in the 1960s (Gilbert *et al*. 2005). The population along the coast of Maine alone increased significantly by 28.7% between 1997 and 2001 to a total of over 38,000 individuals (NOAA, 2009). This population has been subject to several Unusual Mortality Events over the last decade however. A UME for harbour seals in the Gulf of Maine was declared between 2003 and spring 2005 (NOAA, 2009). No consistent cause of death was determined. Another UME was declared in the Gulf of Maine in 2006 as a result of an infectious disease outbreak (NOAA, 2009), and another one was declared in November 2011 following the deaths of over 160 juvenile harbour seals along the coast of Maine, New Hampshire and northern Massachusetts. It cause of this UME is still unknown.

P.v.mellonae

Seal Lakes (Québec)*:* This subspecies lives in a few lakes and rivers of the Ungava Peninsula in northern Québec, known as the Seal Lakes, that drain into the Hudson and James Bays. Geological features prevent these seals from leaving this freshwater habitat. This population is thought to number between 120 and 600 individuals, and is the subspecies most at risk from anthropogenic threats as its small population size combined with the potential effects of James Bay II hydroelectric development which may reduce the water level in the seal lakes by 20cm, makes this population vulnerable to extinction. The hydroelectric development might have impacts on mortality of seals in winter and altered hydrographic conditions could potentially affect the seals' prey (Smith, 1997). The population currently has minimum legal protection in Canada and none of its habitat is protected, but the Québec government is considering legal protection for part of the habitat (COSEWIC, 2007).

6 REASONS FOR HARBOUR SEAL DECLINES WORLDWIDE – LESSONS TO LEARN

6.1 Major Threats to Harbour Seal Subspecies Worldwide

Major Threats	Affected Areas
Oceanographic Regime Shifts	Large scale oceanographic shifts eg. Pacific Decadal Oscillation, El Niño, La Niña etc have large scale effects on the entire ocean system and its food chain. This affects the abundance and distribution of harbour seal prey, potential predators as well as pathogens.
Over-fishing	The depletion of fish stocks through over-fishing affects the abundance and distribution of important prey species for harbour seals in some areas.
Fisheries Interactions *Shooting and entanglements in fishing gear.*	In areas where harbour seals are causing damage to fishing gear, small shooting quotas are permitted in the UK, Norway and Canada. Overall however, an unknown level of illegal killing of harbour seals, mainly by fishing interests, also takes place throughout the species' range. **Japan**: Both shooting and entanglement in gear is particularly a problem for the small population in northern Japan, and is thought to be the major cause of the decline in this population (Burns, 2002). **Eastern USA**: Fisheries and aquaculture-related mortality of the west Atlantic *population* is also high. An estimated average total of 873 seals were killed each year by fisheries in the United States between 1994 and 1998, mostly as a result of entanglement in nets of the Northeast multispecies sink gillnet fisheries in the Gulf of Maine and southern New England. A number of seals are also killed by deliberate shooting as a result of increasing interactions with aquaculture in the United States, but the level of this mortality is currently unknown. **Canada**: In Canada, seals are primarily entangled in nets of groundfish gillnet fisheries in Newfoundland and Labrador, the Gulf of St. Lawrence and the Bay of Fundy. Seals are also known to become entangled in the nets of the Atlantic Canada salmon gillnet fishery and in nets of the Spanish deep water trawl fishery off the Canadian coast. The overall numbers of seals entangled decreased significantly after the Greenland salmon gillnet and Atlantic Canada cod trap fisheries were ended in 1993. However, an unknown number of seals are still shot at herring weirs in the Bay of Fundy and the Canadian government has implemented a pilot programme to allow aquaculture installations to shoot seals. **Alaska**: A minimum estimate of 103 harbour seals are killed each year by entanglement in

Alaskan fisheries, particularly gillnet fisheries, but this estimate is thought to be an underestimate and the figure could be much higher.

California: The vast majority of fisheries-related mortality in California is caused by entanglement in gillnet fisheries although the extent of this problem is currently unknown.

Mexico: Harbour seals in Baja California are known to have been killed as bait for the shark long line fishing industry. They are also sometimes found entangled in gillnets.

Hunting

Organised population reduction programs including bounty schemes and culling operations occurred historically throughout the harbour seals' range but were stopped in the 1970s.

Commercial and Subsistence

Hunting of harbour seals still takes place in Iceland, Norway, Greenland, Canada and Alaska. Native subsistence hunting of harbour seals occurs specifically in Greenland, Alaska and also in Canada on a smaller scale with fairly constant numbers taken from year to year.

Harbour seals are hunted in Greenland for both subsistence and commercial purposes, and as a consequence, the population has disappeared in recent years from some of its former sites, and its numbers are still declining even in several protected areas.

Oils Spills and Marine Debris

Both chronic oil spills and discharges as well as episodic large scale spills cause direct mortality and have long term impacts on harbour seal health and their environment. The risk to harbour seals from oil and hydrocarbon contamination may be locally significant at certain times of year.

Exxon Valdez: In 1989 the oil spill from the tanker *Exxon Valdez* in Prince William Sound, Alaska, affected some of the largest harbour seal haul out sites in the area. It is thought that about a third of the harbour seals using oiled haul out sites were killed, and that pup production and survival were also affected. Not only did the seals become coated with oil and inhale volatile substances, but the oil was also incorporated into their tissues, and as a result, abnormal behaviour was reported and pathological brain damage was observed in dead seals.

Marine debris: Harbour seals are killed throughout the species' range by entanglement in marine debris, particularly in fishing nets and plastics. In the Channel Islands in California for example it is estimated that at least 0.1% of harbour seals were or had been entangled in marine debris. Most animals that become entangled probably die at sea however, so the extent of the problem is unknown.

Industrial Activity

Rapidly increasing development of both onshore and offshore renewable energies, such as wind generated power, means that the levels of industrial activity and noise are increasing in the foraging areas of resident harbour seals. To date, there is little information available to assess the potential impacts of such disturbance.

Human Disturbance on Haul-outs

Human disturbance has been known to cause problems to harbour seal populations, particularly because of the tendency of the species to inhabit coastal areas where activities such as vessel traffic, construction, bait collecting and leisure pursuits both on shore and in the water are common. The costs of disturbance may be two-fold in that it can cause the exclusion of animals from vital haul out sites, and there may be an energetic cost to the individual when disturbed.

For example, disturbance, recreational yachting in particular, was believed to be one of the main contributors to the decline of the harbour seal population in the Rhine delta area from about 1950 until its extinction in the 1970s (Reijnders, 1985).

Disturbance during the pupping season can cause the deaths of some pups as they become separated from their mother, while haul outs experiencing a high level of disturbance may be abandoned completely (Hoover-Miller, 1994). This is particularly a problem in California where harbour seals haul out in places routinely accessed by humans.

In Alaska, a study of the disturbance caused by cruise ships to harbour seals breeding on ice floes has shown that approach by ships increased the risk of seals entering the water which could lead to low-temperature thermal stress in pups that incur an energy deceit (Jansen *et al*. 2010).

Infectious Disease

Outbreaks of infectious disease have occurred on both sides of the Atlantic. The potential for exposure to disease may be increased by the natural behaviour of this species as it hauls out on near shore and coastal mainland sites. As a result, the frequency with which they come into contact with terrestrial carnivores, waste from human populations as well as human pets and feral animals is increased which may create a greater risk of exposure to infectious diseases.

1979-1980 – 400 harbour seals died in Massachusetts infected with an Influenza A virus (Geraci *et al.* 1982).

1982 – An unknown number of individuals also died along the Massachusetts coast with Influenza A (Hinshaw *et al*. 1984).

1988 - 20,000 European seals died with PDV (Kennedy *et al.* 1988).

1994 – 40 harbour seals died of an unknown infectious disease in New Jersey, U.S.A.

1992 – 30 harbour seals died of an unknown cause in Oregon, Washington.

1997 - An unidentified pathogen, possibly a virus, appeared to be the cause of the death of about 90 harbour seals in California (Gulland and Hall, 2007).

1997 – A viral pathogen killed approximately 80 harbour seals on Anholt and a further 100 along the Swedish North Sea coast in the summer of 1997 (Härkönen *et al*. 2008). It was initially feared that this infection would spread further, but fortunately it did not do so.

2000 – 40 harbour seals died in California from an unknown pathogen. A viral pneumonia was suspected.

2002 – 30,000 seals died in Northern Europe with PDV (Jensen *et al.* 2002)

2003-2004 – An unknown number of harbour seals died in the Gulf of Maine from an unknown infectious disease (Gulland and Hall, 2007).

2006 – Another UME took place in the Gulf of Maine killing an unknown number of harbour seals (Gulland and Hall, 2007).

2007 – An outbreak of disease of viral origin killing approximately 100 seals in Kattegat and Skagerrak took place over the summer, but PDV was not thought to be the cause.

2011-2012 – A current UME is took place in the Gulf of Maine and along the New Hampshire and Massachusetts coasts. An Influenza virus has been identified in some individuals.

6.2 Case Studies of Unexplained Declines

While a number of harbour seal subpopulations worldwide are experiencing declines, they have largely be attributed to one or more causative factors. For example, in Greenland, the declines are thought to be the result of unsustainable hunting practices, and the declines seen in Northern Japan are a direct result of interactions with the fishing industry either as by-catch or deliberate shooting. There are three large-scale declines however, where the underlying cause of the population crashes are still unknown. These declines are occurring in Scotland, in Nova Scotia, specifically on Sable Island, and also in Alaska, specifically in Glacier Bay National Park and the surrounding areas. There have been various hypotheses put forward to explain the declines seen in harbour seal numbers in these areas.

6.3 Alaska Harbour Seal Declines from 1970s to Present

There has been a significant decline in the harbour seal population in the Gulf of Alaska and the Aleutian Islands since the 1970s. Tugidak Island and Prince William Sound populations in particular have decreased by over 90%. The Exxon Valdez oil spill in Prince William Sound in 1989 killed an estimated 33% of the harbour seal population using haul out sites contaminated by the oil spill, but the continued declines are thought not to be related to the spill. The cause for this decline is unknown, but it is suspected to be related to the factors that are also driving the declines in the Steller's sea lion and northern fur seal populations in the region. Declines in these species generally parallel the spatial and temporal trends of the harbour seal population crashes. Some recovery has been seen in a few subpopulations since the 1990s, notably in Prince William Sound. Numbers remain low but stable in other subpopulations while declines continue in others, particularly in Glacier Bay. Research efforts are now being focused on the seals in the recovering Prince William Sound population compared to the declining population in Glacier Bay in attempts to identify factors that could be contributing to the declines.

CAUSE	EXPLANATION	PAPER

Shift in the Pacific Decadal Oscillation	Major declines in the populations of harbour seals as well as Steller sea lions and northern fur seals, starting in the 1980s, coincide with the ecological changes observed after the 1976 to 1977 shift in the Pacific Decadal Oscilliation. This shift meant substantial changes in the ocean ecosystem that could significantly affect the populations of top marine predators. However, the proximate causes of the declines have not been determined and it hasn't been determined exactly when the declines began.	Hoover-Miller *et al.* 2011
Diminishing Glacial Fjord Systems	Within the Alaskan harbour seal population, some individuals use glacial fjords / tide water glaciers for pupping, mating and moutling, while others use terrestrial sites. Tidewater glaciers are rapidly retreating in Alaska, reducing ice availability for harbour seals that use the ice at various stages of their life cycle. Glacial seals show 97% fidelity to their glacial haul-out sites, so with the disappearing ice cover, vital habitat for these seals is no longer available.	Blundell *et al.* 2011. Womble *et al.* 2010
Interspecific Competition	**Steller sea lions**: The number of Steller sea lions increased at their only haul-out site in Glacier Bay between 1992 and 1998. They may affect the harbour seal population directly through predation, or indirectly through competition for food or haul out sites. **Humpback whales**: The number of humpback whales also increased in Glacier Bay between 1992-1995 which suggests that the harbour seals may have experienced competition with humpbacks because they both feed on small schooling fish like herring, capelin, sand lance and walleye pollock. **Sea Otters**: The population of sea otters has increased in Glacier Bay over the same time period, but it is unlikely that they present a significant competitor for food.	Matthews and Pendleton, 2006 Womble *et al.* 2010
Change in Prey Availability	Change in the trophic structure of the ecosystem has changed the availability of important prey species of the harbour seals. There have been both seasonal and area-specific changes in prey concentrations. **Walleye Pollock**: From the late 1970s to mid 1980s there was an increase in numbers of walleye pollock - their main prey source, which was then reduced again in the 1990s. **Herring**: Pacific herring had a peak biomass is 1988 then dropped by 95% by 2001. It's apparent recovery did not begin until 2003, and the population still	Frost *et al.* 2001 Pitcher, 1990 Thomas and

remains considerably smaller than it was before the huge decline. Thorne, 2003

Lower Quality Prey

There is some evidence that seals in Glacier Bay feed on lower quality prey compared to those in Prince William Sound where the population has started to recover. The seals in Glacier Bay feed primarily on lower quality intertidal fish species which have a poorer fat content (eg. rockfish and sculpin), while those in Prince William Sound feed on higher quality pelagic fishes. Herreman *et al.* 2009

Parasitic Infections

Seals in Glacier Bay have a higher prevalence of lung worms than the Prince William Sound seals. Whether the higher prevalence resulted from compromised nutritional status and whether such infection influenced the health of individuals is unknown. Herreman *et al.* 2011

Predation

There has been some suggestion that alterations in resource availability makes the seals take more risks when foraging which ultimately means they are more heavily predated on. Theoretical predictions based on model simulations suggest that compensatory foraging effort by seals will mitigate potential loss of energy reserves when resources decline, but only at the cost of higher predation rates, even if predator densities remain constant. The main predators being killer whales, that attack in shallow waters while the seals feed on species like herring, and sleeper sharks that attack in deeper waters while the seals feed on deeper species like pollock. Herreman *et al.* 2009; Frid *et al*. 2006

Killer whales: Harbour seals are the main prey of transient killer whales in the north Pacific, but further analysis is needed to determine if rates of predation have increased sufficiently to be significant contributors to the seal declines. Matthews and Pendleton, 2006

Steller sea lions: Predation by the sea lions increased in Glacier Bay between 1992 and 2002. But, the predation rate was not proportional to the number of predators. Predation by the stellers is a new source of mortality contributing to the declines, but it is unlikely that it is the sole factor. Mathews *et al.* 2010.

Sleeper sharks: In a study on their distribution, sleeper sharks were located near the largest harbour seal breeding area in Glacier Bay suggesting that Pacific sleeper sharks and harbour seals may co-occur. One hypothesis explaining their overlap in distribution is that sharks may be scavenging or preying on marine mammals as both harbour seal and cetacean tissues have been found in the stomach contents of sharks caught in the long-line fishery. Sleeper sharks may be preying on the harbour seals and may thus be contributing to the decline in Glacier Bay. The observations, however, are too few to be conclusive and this hypothesis warrants further testing. Womble & Conlon. 2010; Taggart *et al.* 2005

Subsistence Hunting	Alaskan native subsistence hunting of harbour seals is estimated at more than 2,500 seals each year. Subsistence hunting is not authorised in Glacier Bay however, but some of the seals may leave the bay during fall and winter when most subsistence hunting occurs and are thus no longer protected.	Matthews and Pendleton, 2006
Human Disturbance	Private and commercial vessels likely have multiple impacts on seals, but the most visible effect of disturbance is to cause seals to escape into the water from haul-outs.	Matthews and Pendleton, 2006
	Cruise Ships: The average number of cruise ships allowed into glacier bay increased from 161 in 1996 to 210 in 2002. But, these are too big to get close to haul outs and they are limited to 2 a day. They are also not allowed close to shore between May and August, so some suggest that these are not a major source of disturbance. However, a study of disturbance by cruise ships to harbour seals breeding on ice floes has shown that approach by ships within 500m increased the risk of seals entering the water. The risk rose to 90% at less than 100m. They also showed that the pups in the glacial Alaska environment are likely to incur an energy deficit if they spend more than 50% of their time in the water, and it is likely that they will experience low-temperature thermal stress.	Jansen *et al*. 2010
	Smaller Vessels: Smaller vessels and kayakers may be altering hall-out behaviour.	
	People: Disturbance by people visiting Glacier Bay National Park may be causing seals to abandon their haul out sites. Mother and pup may become separated when disturbed by beach walkers which lower the pup's chances of survival.	
Seals Emigrating	It was thought that declines in Glacier Bay may be driven by the seals emigrating to other areas resulting in a redistribution of seals to other haul-out sites. However, tagging studies have shown that seals typically remain within 50km of their capture sites, and females show strong site fidelity to their breeding areas. In addition, there is no evidence of comparable increases in adjacent areas.	Matthews and Pendleton, 2006
Entanglement in Marine Debis	Entanglement in marine debris has been suggested as a contributing cause to explain the Northern fur seal decline through the gathering of information on abundance and distribution of debris (mostly nets), and observations of entangled animals.	Pitcher, 1990
	However, this is not thought to be a problem for the Stellers or the harbour seals because they have low entanglement observations, but it could possibly	

present a problem for young animals. The true extent of the problem remains unknown as most animals that become entangled will die at sea.

6.4 Sable Island Harbour Seal Declines from 1990s to Present

Throughout the 1970s, censuses and a tagging study by DFO suggested that pup production was roughly stable on Sable Island at around 350 births per year. Annual censuses on Sable Island then showed an increasing population of harbour seals in the 1980s followed by a rapid decline through the 1990s from a total of 625 pups born in 1989 to only 32 pups born in 1997 (Bowen *et al.* 2003). Weekly surveys of the island during the breeding seasons between 1991 and 1998 showed that the number of both adults and juveniles declined during this period, and that the age structure of parturient females increased significantly, indicating reduced recruitment into the breeding population (Bowen *et al.* 2003). There was then an even further decline of pup production in 2001 and 2002 (Bowen *et al.* 2003). By 2002, there was no longer a breeding population of harbour seals on Sable Island. It is generally agreed that a combination of reduced fecundity and juvenile survival leading to reduced local recruitment to the breeding population drove the decline of the harbour seal population on Sable Island. At the same time however, the grey seal population on Sable Island has been increasing by about 13% annually for approximately 40 years. It was previously thought that the decline was a result of increased shark predation and competition with grey seals for food, although this hypothesis is being reconsidered.

CAUSE	EXPLANATION	PAPER
Nutritional Stress	**Nutritional Stress:** A study on maternal and newborn life-history traits showed that mean birth date increased by 7 days during the early 1990s which suggests later implantation caused by nutritional stress of females. Changes in prey availability as a result of environmental change, or increased competition, may in turn affect maternal condition, which could result in lower fecundity or reduced lactation performance resulting in smaller offspring. Smaller offspring are likely to have reduced survival. Nutritional stress may therefore have played a role in the decline of the population through effects on both fecundity and juvenile survival.	Bowen *et al*. 2003.
	Environmental Changes: Fluctuations in the physical oceanography on the Scotian Shelf causes changes in prey availability. Cooling of ocean temperatures on the eastern Scotian Shelf from about 1983 to the early 1990s, and continued low water temperatures after this point, have been implicated in shifting distributions of fish and invertebrates, with an increased abundance of colder	Frank, Simon

water species such as capelin, Greenland halibut and checker eelpout as well as invertebrates (snow crab, shrimp) that are usually more prevalent in the colder Gulf of St. Lawrence and Newfoundland waters. As well as causing changes in the species distributions, colder temperatures are also implicated in the reductions in growth rates seen in some demersal fishes in the area such as haddock.

& Carscadden, 1996.

Zwanenburg *et al*. 2002

Even with an increase in capelin, it was not identified as part of the diet of harbour seals from sites along eastern Nova Scotia from 1988 to 1990, but then accounted for approximately 9% of the diet by 1992.

Continuous plankton recorder data of phytoplankton colour index (visual estimation of the green colour used to describe the major temporal and spatial patterns of phytoplankton), diatoms and *Calanus* species, show significant decadal scale changes between 1961 and 1998, with a significant influx of arctic species during the 1990s.

Sherman and Skjoldal, 2002

Sameoto, 2001

Competition with Grey Seals: The grey seal population on the island has been growing exponentially for the last 40 years with a doubling time of approximately 6 years. At the beginning of the decline, grey seals outnumbered harbour seals by 20:1, but by the end of the 1990s, they outnumbered them by approximately 500:1, thus it seems probable that interspecific competition with grey seals for food, or possibly haul-out sites, must have increased during the 1990s.

However, analyses of stomach and scat contents have not shown strong dietary overlap between harbour and grey seals, both inshore and on Sable Island.

Bowen *et al.* 2003

Competition with Fisheries: The dominance of fishery development objectives over conservation objectives has resulted in documented over-exploitation of fish resources. Fishing effort, which increased rapidly following the 1977 establishment of Canada's 200-mile exclusive economic zone, was negatively correlated with community size structure.

Bowen and Harrison, 1994.

Bowen and Harrison, 1996.

There was a change in the average size of a suite of exploited fish species which was inversely related to fishing effort. This decrease in size occurred both on the eastern shelf where temperatures decreased in the late 1980s and through the 1990s, and on the western shelf where temperatures remained fairly stable over the same time period. Average size of demersal fishes has decreased by 60 - 70% since 1970 in both systems.

Zwanenburg *et al*. 2002

Large fisheries are therefore removing the larger fish from the ecosystem, and this, combined with the colder waters reducing the growth rates of haddock for example, means that only smaller fish are left as potential prey. This may require seals to spend more time foraging in order to catch a larger number of smaller fish to meet their daily energy intake requirements at the expense of other vital activities. Sherman and Skjoldal, 2002

Shark Predation Bite wounds on individuals, and carcasses washed ashore indicate that shark predation affects all age classes. Lucas & Stobo, 2000

There was a rapid increase in the minimum shark-inflicted mortality rate of pups from <10% to between 30% and 50% after 1993. Even more significantly, the estimated total mortality from sharks on adults was greater than that of pups during the same period. Adult females were killed disproportionately. Between 1993 and 1997, all adult female harbour seals killed by sharks between March and June (the pre-pupping period), whose reproductive status could be determined, were carrying foetuses at the time of death. Furthermore, the minimum number of females killed in 1994, 1995 and 1996 (i.e. 42, 52 and 32, respectively) can account for about half of the observed decline in the number of pups born in the following years. It was therefore thought that shark-inflicted mortality accounted for a considerable fraction of the decline of harbour seals on Sable Island. However, more recent evidence suggests otherwise.

Cork-Screw Injuries Severely damaged seal carcases with characteristic spiral injuries have washed up along the shores of east Scotland and England. The extremely neat edge of the wound strongly suggests that a blade with a smooth edge applied with considerable force created the injuries, while the spiral shape is consistent with rotation about the longitudinal axis of the animal. The injuries are consistent with the seals being drawn up through a ducted propeller. Thompson *et al*. 2010

Seals with these characteristic spiral or 'corkscrew injuries' have been reported from Sable Island for the last 15 years and have been attributed to shark attacks. It is now thought that what previously appeared to be shark attacks on harbour seals in Nova Scotia are in fact seals that have been drawn through ducted propellers as is the case in the UK. The shark predation hypothesis at Sable Island was proposed in part because of a perception that there were few boats in the surrounding area. However this is not consistent with the construction, continued development and operation of an extensive network of gas rigs in the coastal waters off Sable Island. The development and maintenance of such an

	industry will have involved a wide range of shipping activity. The presence of these types of vessels appears to be a common feature of the UK and Canadian experiences of spiral cuts to seals.	
Emigration	It was thought that there could have been emigration of adult females or female recruits to mainland Canada as a result of the interspecific competition with greys. There is some evidence of immigration to Sable Island in the 1980s, so it is possible that some seals emigrated to mainland colonies. But, there is no long-term data from Canadian mainland colonies to test this hypothesis, and given that the smaller ranges of harbour seals compared to the grey seals, this hypothesis is thought to be unlikely.	Lucas & Stobo, 2000
Human Disturbance	Human disturbance to harbour seals may be a problem for colonies worldwide. It was suggested that on Sable Island, increased human disturbance from small numbers of visitors and especially scientists conducting life-history studies, which began in 1987, may have caused females to abandon Sable Island. Disturbance was very limited to certain sites however and declines occurred across the entire island, so this hypothesis has largely been disregarded.	Bowen *et al*. 2003 Lucas & Stobo, 2000
Inbreeding Depression	Inbreeding-like effects have been observed in harbour seal pups from the Sable Island population, and although probably not the original cause of the decline, reduced pup survival as a result of inbreeding may have contributed to the disappearance of Sable Island as a harbour seal breeding colony. As the population declined, its small size and geographical separation from other harbour seal populations in Atlantic Canada by over 200 km of open ocean, suggested the potential for genetic variability to be lost and homozygosity to increase as a result of genetic drift. Perhaps as a consequence of this limited migration and small population size, harbour seals at Sable Island appear to have relatively low levels of genetic variability. Pups which survived until weaning had a significantly higher level of genomic diversity than pups which died, independent of birth weight. These effects are consistent with inbreeding depression in this population.	Coltman *et al*. 1998.

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