ICES Journal of Marine Science Advance Access published February 11, 2010



# Optimizing survey design for Scandinavian harbour seals: population trend as an ecological quality element

Jonas Teilmann, Frank Rigét, and Tero Harkonen

Teilmann, J., Rigét, F., and Harkonen, T. 2010. Optimizing survey design for Scandinavian harbour seals: population trend as an ecological quality element. – ICES Journal of Marine Science, 67: 000–000.

To be successful, conservation and management programmes require accurate data on abundance and population trends. Noise caused by within- and among-year variance should be minimized to optimize the statistical power for detecting changes in abundance. A total of 30 years of monitoring data from seven distinct subpopulations of harbour seals (*Phoca vitulina*) in southern Scandinavia was used to investigate the relative contributions of factors affecting the power to detect trends in abundance. The power is typically doubled under the conditions tested when carrying out annual surveys compared with every second year. The power also increases substantially when carrying out replicate surveys during the annual moult. The gain in power increases steeply up to three annual replicates, but then levels off, and it is further increased when the mean of the two highest counts of three annually repeated counts is used. We propose that harbour seal haul-out sites are surveyed every year during the moult, with at least three replicate surveys per year. This would provide robust data for analyses of population trends, facilitating management and identification of potential influences of diseases and anthropogenic activities.

**Keywords:** aerial surveys, *Phoca vitulina*, statistical power, survey interval, survey replicates, trimmed mean.

Received 14 May 2009; accepted 14 December 2009.

*J. Teilmann and F. Rigét: National Environmental Research Institute, University of Aarhus, Frederiksborgvej 399, DK-4000 Roskilde, Denmark. T. Harkonen: Swedish Museum of Natural History, Box 50007, S-10405 Stockholm, Sweden. Correspondence to J. Teilmann: tel: +45 46301947; fax: +45 46301914; e-mail: jte@dmu.dk.*

## Introduction

Increasing awareness of environmental changes caused by human activities has resulted in many international initiatives and agreements focusing on marine ecosystems. Monitoring seal populations is mandated as one aspect of environmental quality. The Convention for the Protection of the Marine Environment of the North-East Atlantic (OSPAR Convention) has been ratified by all North Sea countries. This convention lists a number of Ecological Quality Objectives (EcoQOs) for the North Sea, which were developed in collaboration with the International Council for the Exploration of the Sea (ICES) and aim to define a desirable state for the North Sea. EcoQOs have been developed for some components of the ecosystem, e.g. commercial fish species, threatened and declining species, and marine mammals. An EcoQO is a measure of real environmental quality in relation to a reference level where anthropogenic influence is minimal. The ecological quality elements "population trends" and "utilization of breeding sites", which have been suggested for seal populations, may serve as suitable tools for evaluating current population status. The term "population trend" is defined for this purpose as a change in abundance of a population, increasing or decreasing within a specified area over a certain number of years.

The EU Water Framework Directive (WFD) includes status categories for coastal waters as well as environmental and ecological objectives, whereas the EU Habitats Directive (European Commission, 1992) specifically states that long-term management objectives should not be influenced by socio-economic considerations, although they may be considered during the implementation of management programmes provided the long-term objectives are not compromised. In line with both the OSPAR Convention and the Marine Strategy Framework, the Helsinki Commission (HELCOM) in the Baltic Sea region is developing a framework using EcoQOs for the Baltic ecosystem. The Trilateral Cooperation on the Protection of the Wadden Sea is managing the nature of the Wadden Sea, including a coordinated monitoring of the harbour seal population (http://www.waddensea-secretariat.org/). All seals in Europe are also listed under the EU Habitats Directive Annex II (European Commission, 1992), and member countries are obliged to monitor the status of seal populations.

The reliability of using population trend as a status parameter in the context of both EcoQOs and the EU Habitats Directive is directly related to the quality of monitoring programmes. The accuracy or precision of available data on distribution, abundance, and trends in study populations is also relevant in developing seal conservation and management programmes.

Relatively long time-series of abundance data are available for many species and populations of seals, but strict power analyses of population trends have only been made in the Moray Firth and the Orkney Islands in Scotland (Thompson *et al.*, 1997), where the feasibility of using single annual surveys was addressed. Using 30 years of survey data for harbour seals (*Phoca vitulina*)

**Table 1.** Average number of seals counted in the seven subareas of southern Scandinavia during the period 1979–2004.

| Year | A1 | A2 | A3 | A4 | A5 | A6 | A7 |
|---|---|---|---|---|---|---|---|
| 1979 | 568 (1, –) | 1 623 (1, –) | 153 (1, –) | – | – | – | 421 (1, –) |
| 1980 | 674 (1, –) | 1 863 (1, –) | 233 (1, –) | – | – | – | 671 (1, –) |
| 1981 | 709 (1, –) | 2 102 (1, –) | 284 (1, –) | – | – | – | 656 (1, –) |
| 1982 | 696 (1, –) | 1 255 (1, –) | 236 (1, –) | – | – | – | 789 (1, –) |
| 1983 | 1 062 (1, –) | 2 235 (1, –) | 247 (2, 76) | – | – | – | 924 (1, –) |
| 1984 | 1 127 (1, –) | 2 358 (2, 297) | 213 (2, 32) | – | – | – | 853 (1, –) |
| 1985 | 1 336 (1, –) | 3 261 (1, –) | 699 (1, –) | – | – | – | 958 (1, –) |
| 1986 | 1 333 (1, –) | 3 863 (1, –) | 595 (1, –) | – | – | – | 1 261 (1, –) |
| 1987 | – | – | 623 (1, –) | – | – | – | 1 477 (1, –) |
| 1988 | 732 (6, 18) | 1 957 (5, 59) | 271 (3, 22) | – | 232 (2, 1) | 112 (2, 4) | – |
| 1989 | 1 007 (3, 53) | 1 892 (3, 48) | 237 (3, 21) | – | 393 (3, 66) | 97 (3, 8) | 860 (1, –) |
| 1990 | 724 (3, 55) | 1 944 (3, 92) | 157 (3, 22) | 157 (5, 157) | 425 (3, 22) | 73 (3, 5) | 1 048 (1, –) |
| 1991 | 1 155 (3, 27) | 2 590 (3, 183) | 159 (3, 36) | 166 (3, 166) | 493 (3, 61) | 135 (3, 5) | 1 097 (1, –) |
| 1992 | 1 036 (2, 230) | 2 547 (2, 206) | 268 (3, 52) | 176 (3, 8) | 450 (3, 95) | 68 (3, 26) | 1 168 (1, –) |
| 1993 | 1 788 (3, 131) | – | – | – | – | – | 1 433 (1, –) |
| 1994 | 1 974 (3, 131) | 3 254 (3, 273) | 327 (3, 64) | 172 (3, 16) | 405 (3, 125) | 109 (3, 33) | 1 507 (1, –) |
| 1995 | 2 218 (3, 321) | – | – | – | – | – | 1 508 (1, –) |
| 1996 | 2 089 (3, 250) | 3 806 (3, 44) | 421 (3, 76) | 250 (3, 27) | 623 (3, 30) | 81 (3, 9) | 1 632 (1, –) |
| 1997 | – | – | – | – | 828 (2, 76) | 129 (2, 9) | 1 803 (1, –) |
| 1998 | 3 020 (3, 247) | 5 154 (3, 126) | 732 (3, 179) | 276 (3, 78) | 847 (4, 143) | 113 (4, 16) | 2 256 (1, –) |
| 1999 | 2 632/3 413 (3, 74) | – | – | – | 1 301 (2, 149) | 144 (2, 39) | 2 183 (1, –) |
| 2000 | 3 568/3 979 (3, 176) | 4 964 (3, 153) | 783 (3, 67) | 362 (3, 28) | 540 (5, 86) | 102 (5, 7) | 2 145 (1, –) |
| 2001 | 4 578/5 412 (3, 443) | – | – | – | 746 (2, 299) | 109 (2, 10) | 2 261 (2, 60) |
| 2002 | – | – | 439 (3, 19) | 251 (3, 12) | 829 (3, 43) | 249 (3, 77) | 2 564 (1, –) |
| 2003 | 2 204/2 538 (3, 163) | 4 138 (3, 194) | 465 (3, 122) | 386 (3, 26) | 597 (2, 38) | 206 (2, 28) | 1 230 (2, 125) |
| 2004 | 2 478/2 692 (2, 18) | – | 60 (1, –) | 464 (1, –) | 684 (1, –) | 281 (1, –) | 1 686 (1, –) |
| 2005 | 3 335/3 561 (3, 55) | 4 829 (3, 114) | 532 (3, 149) | 549 (3, 16) | 422 (3, 125) | 214 (3, 20) | 2 040 (1, –) |
| 2006 | 2 550/2 754 (2, 272) | 4 882 (2, 9) | 559 (2, 13) | 448 (2, 31) | 515 (3, 63) | 295 (3, 23) | 2 243 (1, –) |

From 1999, Norwegian locations in the Skagerrak were included. The totals for area A1 including the Norwegian locations are given after the slash. The parentheses indicate the number of surveys in August in a given year, and the s.e.

from seven subpopulations in southern Scandinavia, we analyse how the power to detect changes in abundance is affected by survey interval, numbers of replicate surveys, and treatment of collected data. We provide guidelines on how to improve survey design to optimize detection of changes in trends.

## Material and methods

### Study populations and survey methods

Harbour seals are distributed along the coasts of Denmark, Sweden, and Norway, where they use a variety of habitats to haul-out, breed, moult, and rest. They are found on rocky shores in the Skagerrak, on large stones, stone reefs, and sand banks in the Kattegat and the western Baltic, and they haul-out on sandbanks, stone reefs, and intertidal sandbanks in the Limfjord, and on intertidal sandbanks in the Danish Wadden Sea. The number of harbour seals present on land is affected by several factors, such as season (Thompson, 1989), time of day (Stewart, 1984; Thompson *et al*., 1989; Watts, 1996), tidal cycle (Schneider and Payne, 1983; Thompson and Miller, 1990), and weather conditions (Kreiber and Barrette, 1984; Watts 1992). Hayward *et al.* (2005) modelled the optimal conditions for harbour seal surveys, but concluded that site-specific condition needed to be taken into consideration. Assessments of the significance of abundance trends therefore require systematic time-series of counts that take these sources of variability into account.

Systematic aerial surveys in southern Scandinavia have been conducted since 1979, but regional coverage and survey intensity have increased over the years (Table 1). All surveys were conducted during the moult in the latter part of August, when there is a peak in the proportion of the seal population hauling-out (Heide-Jørgensen and Harkonen, 1988). Surveys were flown between 09:00 and 15:00 local time, and timed to cover low tides (only relevant for the Wadden Sea and the western Limfjord). To standardize conditions, surveys were only carried out when the windspeed was $<10$ m s$^{-1}$, and there was no precipitation (Heide-Jørgensen and Harkonen, 1988).

The surveys were flown with a single-engined high-winged Cessna 172, and photographs were taken through an opened window. Two observers on the same side of the aircraft took photographs of all haul-out sites using hand-held cameras equipped with 135–200 mm lenses, recording colour slides, monochrome prints, or digital images. Photographs were taken from an altitude of 100–150 m (300–500 ft), flying at 110 km h$^{-1}$ (60 knots). The numbers of seals were subsequently determined from the photographs by at least two enumerators.

The study region was divided into seven areas (Figure 1): Area 1, Skagerrak (A1); Area 2, central Kattegat (A2); Area 3, southwestern Kattegat (A3); Area 4, southwestern Baltic Sea (A4); Areas 5 and 6, central and western Limfjord (A5 and A6), respectively; and Area 7, Danish Wadden Sea (A7). The areas are geographically separated and represent subpopulations of harbour seals with no or limited exchange of animals (Harkonen *et al*., 1999; Olsen *et al*., in press).

### Temporal trend analyses of the population

Harbour seals in Europe experienced two recent epidemics of phocine distemper seal virus (PDV) that killed ~23 000 and

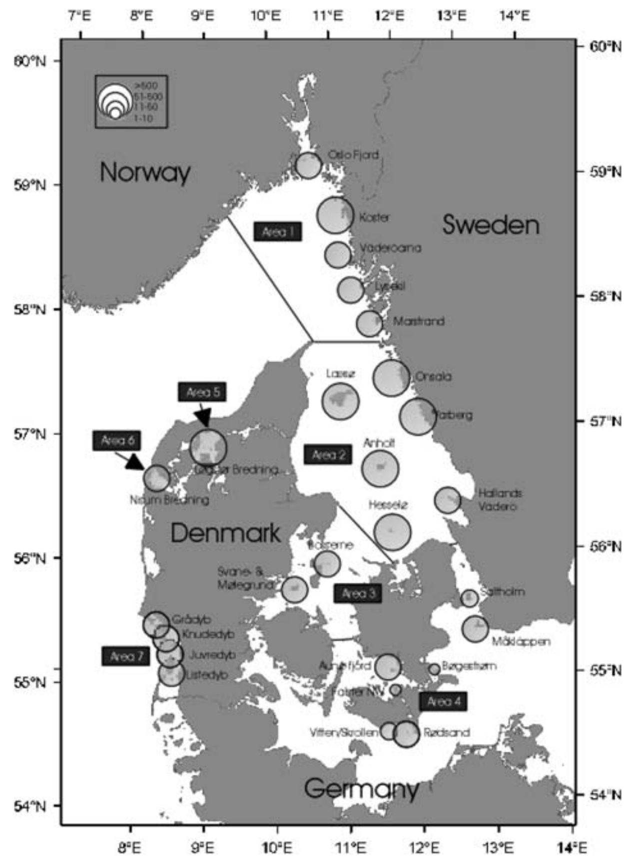


**Figure 1.** Map of the study area. The size of the circle indicates the average number of harbour seals hauling-out at the different locations in 2003.

30 000 seals in 1988 and 2002, respectively. About 50% of the harbour seal populations living along mainland Europe died on both occasions, although UK populations were less affected (Harkonen *et al.*, 2006). Before the first epidemic in 1988, between the two epidemics (1989–2001), and after the second epidemic in 2002 (Harkonen *et al.*, 2006), the average annual growth rate of the subpopulations was estimated using an exponential growth model. The number of seals counted was log-transformed (to the base e) before analysis. The average annual growth rate was derived by linear regression of each subpopulation based on the annual mean of all counts in each year and the trimmed mean, where the lowest count in each year was deleted. Counts from 1988 and 2002 were excluded, because it was suspected that the epidemics affected the number of seals resting on land.

### Power analyses

Statistical power analyses were conducted on survey data from the seven subpopulations. The power of a statistical test is defined as the probability of rejection of the $H_0$ hypothesis and hence accepting the $H_A$ hypothesis when the $H_0$ hypothesis is false (Cohen, 1977). The results of power analyses rely on several assumptions, including the availability of appropriate estimates of within- and between-year variation. Single outliers may also influence the results.

The probability of detecting an annual exponential change then becomes the power of a log-linear regression analysis. The power to detect a linear trend depends on the number of samples per year, the number of years in the time-series, the magnitude of the trend, the residual variance, the significance level chosen, and whether the test is one- or two-tailed. We used the power analysis of log-linear regression including both within- and between-year variance, as described in detail by Fryer and Nicholson (1993), who also argued for the importance of incorporating random between-year variation in the model. Between-year variation results from annual variations in general weather conditions during the moulting season, or age-dependent haul-out behaviour (Harkonen *et al.*, 1999), or different rates of population growth from year to year. The log-linear model and error structure are as follows (after Fryer and Nicholson, 1993):

$$E[y_t] = \mu_t + \beta(t-1), \tag{1}$$

where $E[y_t]$ is the expected population index (on a log-scale) in year $t$, $\mu_t$ the mean population index in year $t$, and $\beta$ the slope of the regression

$$\omega_t + \frac{1}{R}\sum_{r=1}^{R}\varepsilon_{tr}, \quad t = 1, \ldots, T, \tag{2}$$

and total variance

$$\psi^2 = \tau^2 + \frac{\sigma^2}{R}, \tag{3}$$

where $\omega_t$ represents between-year error with zero mean and constant variance $\tau^2$, and $\varepsilon_{tr}$ represents within-year error with zero means and constant variance $\sigma^2$. $R$ is the number of surveys conducted each year. Further, it is assumed that $\omega_t$ is independent of $\varepsilon_{tr}$. The linear trend is tested by regressing the annual mean log-index on year, and the power of the test is calculated according to the formulae provided by Fryer and Nicholson (1993).

Random between-year variation cannot be calculated directly, but it can be estimated indirectly based on the within-year and total variation. The within-year variance was estimated for each area based on the years when more than one survey was conducted. The residual standard deviation from a regression of the mean population index (on a log-scale) in the periods with exponential increase gave an estimation of the sum of within- and between-year standard deviations. The total variance ($\psi^2$) of the error structure was consequently estimated as the squared value of the sum of standard deviations. The between-year variance was then estimated from Equations (2) and (3), using $R = 3$, which was the most usual number of surveys carried out during the study.

## Results

### Changes in the Danish and Swedish seal populations

Growth rates were similar whether based on all surveys or the trimmed mean values (excluding the lowest count in each year; Table 2), except for area A3 for 2003–2006, but the *CV*s were considerably smaller when based on trimmed mean values (Table 2). We therefore used the growth rate of the trimmed mean in subsequent analyses, except for the areas and periods where only one or two surveys were conducted per year. In those cases, the mean growth rate was used instead.

After the protection of harbour seals in 1976/1977, the subpopulations in all areas surveyed (A1–A3 and A7) increased

**Table 2.** Estimated annual population growth rates based on the exponential growth model for periods before, between, and after the two seal epidemics of 1988 and 2002.

| | | Mean | | | Trimmed mean | | |
|---|---|---|---|---|---|---|---|
| Area | Period | CV (%) | Annual growth rate (%) | s.e. | CV (%) | Annual growth rate (%) | s.e. |
| A1 | 1979–1986 | – | 13.3[a] | 1.5 | – | – | – |
| A2 | 1979–1986 | 17.8[b] | 11.0[a] | 1.7 | – | – | – |
| A3 | 1979–1987 | 33.1[b] | 16.9[a] | 4.1 | – | – | – |
| A7 | 1979–1987 | – | 12.9[a] | 1.6 | – | – | – |
| A1 | 1989–2001 | 14.1 | 13.3[a] | 1.3 | 5.4 | 13.2[a] | 1.3 |
| A2 | 1989–2000 | 6.1 | 9.5[a] | 0.8 | 4.5 | 9.1[a] | 1.1 |
| A3 | 1989–2000 | 29.0 | 14.7[a] | 2.2 | 11.4 | 15.0[a] | 2.1 |
| A4 | 1990–2000 | 15.5 | 8.2[a] | 1.0 | 9.8 | 8.0[a] | 1.2 |
| A5[c] | 1989–1999 | 26.8 | 10.1[a] | 1.9 | 16.9 | 10.0[a] | 1.8 |
| A6 | 1989–2001 | 25.4 | 2.4 | 1.8 | 16.1 | 2.4 | 1.8 |
| A7 | 1989–2001 | 5.2[b] | 8.1[a] | 0.5 | – | – | – |
| A1 | 2003–2006 | 7.5 | 7.4 | 8.1 | 4.3 | 8.5 | 6.4 |
| A2 | 2003–2006 | 3.9 | 5.2 | 1.9 | 2.2 | 3.6 | 2.7 |
| A3[c] | 2003–2006 | 31.3 | 6.2 | 0.5 | 16.4 | 1.4 | 6.6 |
| A4 | 2003–2006 | 10.6 | 6.1 | 6.6 | 11.6 | 6.5 | 6.0 |
| A5 | 2003–2006 | 24.7 | −9.2 | 9.2 | 14.0 | −6.3 | 3.9 |
| A6 | 2003–2006 | 15.8 | 8.1 | 8.3 | 6.0 | 7.3 | 6.3 |
| A7 | 2003–2006 | 14.4[b] | 19.9[a] | 3.5 | – | – | – |

The coefficient of variation (*CV*) of the annual population index, the growth rate, and the standard error (s.e.) are given for both mean (of all surveys in that year) and trimmed mean (excluding the day with the lowest number of seals counted) of the annual population index.
[a]Growth rates were significant at 5%.
[b]Based on data from only 1 or 2 years where more than one survey was conducted.
[c]Year 2000–2001 excluded from the growth rate as outliers in A5 (owing to food limitations), and 2004 excluded as an outlier in A3 (owing to disturbance; see text and Table 1).

annually by between 11 and 17% until the outbreak of the first PDV epidemic in 1988 (Tables 1 and 2). After the epidemic in 1988, population growth resumed and all seven subpopulations grew, although annual growth rates were highly variable (2–15%; Table 2). The numbers of seals in area A5 decreased dramatically in 2000 as a consequence of a lack of food, so years 2000–2003 were omitted from the analysis (Tables 1 and 2; Olsen *et al.* in press). After the second epidemic in 2002, all seal populations, except for that in area A5, which decreased by >6% per year, showed annual growth rates varying between 4 and 20%.

## Power to detect an annual change

In all areas except A1, the within-year variance was greater than the between-year variance (Table 3). The number of surveys per year ($R$) influences the within-year variance, because when $R$ increases, the factor $\sigma^2/R$ will decrease, and the between-year variance component will not be affected. Therefore, the effect on the total variance of the number of surveys per year depends on the relative contribution of the two components of variance. Given 10 years of surveying and a power of 0.8, a 2–3% annual change in abundance can be detected in A2, showing the least variance (Table 3). The annual change in abundance would have to exceed 4% in A4, showing intermediate variance, whereas the annual change would have to exceed 10–11% to be detected in A3, which showed the greatest variance (Figure 2).

**Table 3.** Estimates of total variance ($\psi^2$), within-year variance ($\sigma^2$), and between-year variance ($\tau^2$) for the population indices divided by area.

| Area | $\psi^2$ | $\sigma^2$ | $\tau^2$ |
|---|---|---|---|
| A1 | 0.023 | 0.015 | 0.018 |
| A2 | 0.006 | 0.009 | 0.003 |
| A3[a] | 0.076 | 0.078 | 0.050 |
| A4 | 0.015 | 0.021 | 0.008 |
| A5 | 0.042 | 0.064 | 0.020 |
| A6 | 0.045 | 0.057 | 0.026 |
| A7 | 0.008 | 0.008 | 0.005 |
| Mean | 0.031 | 0.036 | 0.019 |

$\psi$ was calculated as the mean of residual standard deviation derived from the growth regression analyses shown in Table 2.
[a]Year 2004 excluded from the estimations as an outlier (Table 1).

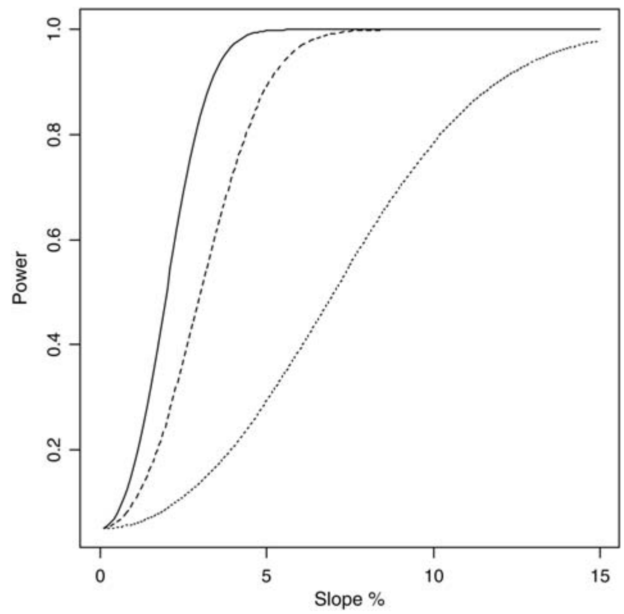


**Figure 2.** Power to detect a significant change in abundance at a 5% level after 10 years of annual surveying. The slope percentage indicates the annual change in abundance. The three graphs show the area with the highest power (area A2, left curve), intermediate power (area A4, middle curve), and worst power (area A3, right curve).

Given an annual change in abundance of 10% with a significance level of 5% (i.e. if the probability of rejecting $H_0$ is <5%), the power is positively correlated with the number of survey years (Figure 3), and a power of 0.80 is not reached for 8 years with ≥2 annual surveys or after 9 years with one annual survey. Further, the gain in power by increasing the number of annual surveys is most pronounced when increasing from one to two annual surveys. The gain in power by increasing from three to four or from four to five surveys per year is minimal (Figure 3). At a power of 0.8 and a significance level of 20%, i.e. if the probability of rejecting $H_0$ is <20%, a change in abundance can be detected after 6 years, whereas it would take 8 years with a 5% significance level (Figure 4).

As aerial surveys are expensive, it is important to have an optimal survey design with regard to survey interval and numbers of surveys annually. Annual surveys will detect

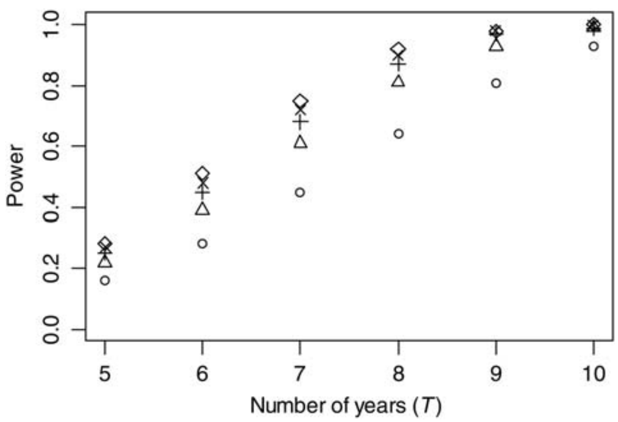


**Figure 3.** The power to detect an annual change in abundance of 10% with a significance level of 5% in relation to the number of years in the time-series and the number of surveys per year. One to five surveys per year are shown with different symbols (bottom symbols, one survey; top symbols, five surveys, i.e. more surveys giving higher power). The power estimates are based on the mean of the between- and within-year variances from Table 3 ($\tau^2 = 0.019$ and $\sigma^2 = 0.036$).

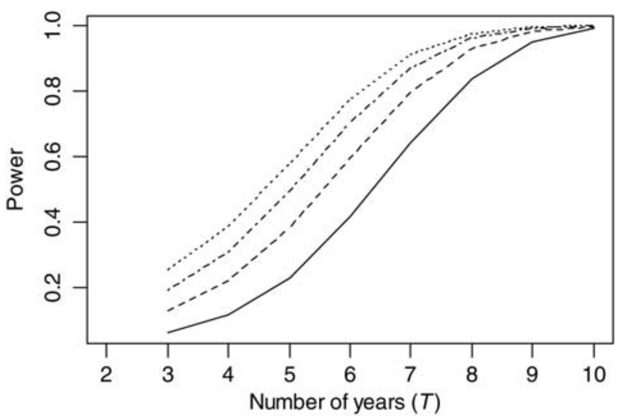


**Figure 4.** The power to detect an annual change in abundance of 10% with three annual surveys in relation to the number of years in the time-series. The four lines indicate significance levels of 5% (solid line), 10, 15, and 20% (dotted line). The power estimates are based on the means of the between- and within-year variances from Table 3 ($\tau^2 = 0.019$ and $\sigma^2 = 0.036$).

population changes that are half the magnitude of those detectable by surveying every second year, regardless of the number of surveys conducted per year. Increasing the number of annual surveys from one to four also increases the power to detect population changes, but less so than surveying every year (Figure 5).

## Discussion

Harbour seals have a circumpolar distribution at temperate latitudes in the northern hemisphere, and a variety of survey methods for estimating harbour seal abundance are currently used throughout the range of their distribution. However, most survey designs share some basic components. Harbour seal abundance is mainly monitored during the peak moulting season (Ries *et al.*, 1998; Bjørge *et al.*, 2007), which for most regions is August (Harkonen and Heide-Jørgensen, 1990). The moulting season is the time of year when most harbour seals haul-out and also the time when the proportion of the seal population present on land is most constant (Harkonen *et al.*, 1999). Therefore, the moulting season should allow for the highest power to detect population trends. Surveys during the pupping season in June can be used to estimate pup production in areas where pups are easily detected, such as the Wadden Sea (Ries *et al.*, 1998), where seals haul-out on mudflats or sandbars, and where tidal cycles synchronize haul-out patterns.

Survey intensity differs substantially among regions, depending on practical circumstances. Harbour seals around Scotland and Norway are surveyed generally every fifth year, without replicates, whereas seals in the Skagerrak, Kattegat, and the Baltic are counted annually, using two or three replicate counts. More detailed counts are also carried out in areas such as the Wash, England (Thompson *et al.*, 2005), the Moray Firth, Scotland (Thompson *et al.*, 1997), or in specific survey areas along the American east coast (Gilbert *et al.*, 2005).

### Optimal survey design

We investigated how the power to detect trends in abundance is affected by survey interval, numbers of replicate surveys, and treatment of collected data.

The length of survey period necessary to detect an annual change in abundance may be shortened by reducing within- and among-year variation, by standardizing as many factors as possible in the data-collection process, using the same observers, pilots, aircraft, photographic equipment, weather conditions, time of day,

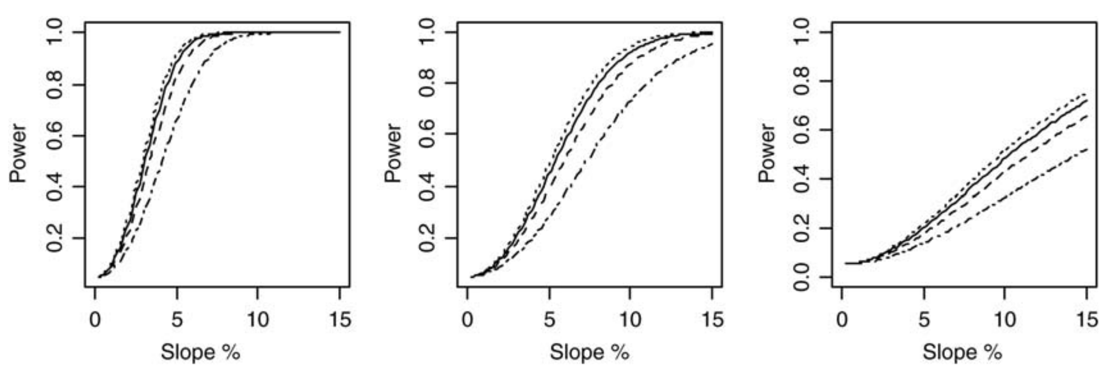


**Figure 5.** The detectable power over a 12-year period with a significance level of 5%. Slope % indicates the annual change in abundance. In the left panel, surveys are conducted every year, in the middle panel every second year, and in the right panel every third year. The four graphs in each panel indicate 1, 2, 3, or 4 surveys conducted each year (increasing number of surveys from right to left). The power estimates in all panels are based on the mean of the between- and within-year variances from Table 3 ($\tau^2 = 0.019$ and $\sigma^2 = 0.036$).

risk of disturbance, etc. Despite such standardization efforts, disturbance at one or more haul-out sites will often result in outliers, where substantially fewer seals haul-out during one survey compared with replicate surveys. If three annual surveys are carried out, the use of the trimmed mean value, where the flight with the fewest seals is omitted, reduced the average *CV* of slopes by 41%, in just one case increasing the *CV* slightly (Table 2).

Human disturbance is probably the reason for the variation in some areas, especially in populated areas sheltered by many islands, e.g. A3, A5, and A6, where leisure craft and small fishing vessels are often seen during surveys. Another reason could be that areas with smaller populations of seals have more variable haul-out patterns.

The number of years between sets of surveys was the parameter that most affected the power to detect trends in abundance (Figure 5). Consequently, in populations where intervals between sets of surveys were more than 1 year, the greatest improvement in programme design would be to carry out sets of surveys annually. If surveys are conducted every year, the second best improvement would be to conduct three annual replicate surveys and to omit the lowest count by the trimmed mean procedure.

Article 17 of the EU Habitats Directive (European Commission, 1992) requires a reporting period of 6 years. However, at a power of 0.8, it will only be possible to detect an annual change of 10% in abundance after 6 years with a 20% significance level, and after 8 years with a 5% significance level (Figure 4). However, these power calculations are based on the mean variances with great variability (as indicated in Figure 2), suggesting that higher power to detect changes in abundance can be achieved within a 6-year period in some areas, whereas a longer time-series is required in other areas.

The Bergen Declaration of the 5th North Sea Conference identified "trends in seal populations" as one EcoQ element, and adopted "No decline in population size or pup production exceeding 10% over a period up to 10 years" as an EcoQO. This has served as a guideline for later work on this issue within the OSPAR Commission (OSPAR Commission, 2005). The optimal survey design suggested in our study would meet the needs of the OSPAR proposal for EcoQOs in seal management.

### Biases in abundance estimates

There are considerable behavioural differences between sexes and among age classes of harbour seals, so the composition of the hauled-out fraction would not be representative of the whole population at any time during summer (Harkonen *et al.*, 1999). The proportion of the population hauled-out during surveys may change among years in populations with non-stable structures, as was the case with harbour seals after the 1988 and 2002 seal epidemics (Harkonen *et al.*, 2002, 2007). This results in transient effects where the observed rate of increase temporarily can exceed the maximum long-term rate of increase in harbour seals (13% per year), as seen in Table 2 (Harkonen *et al.*, 2002). Consequently, survey data on abundance may not be directly compatible in the time-series, which will increase the among-year variance.

### Proposals

Power analysis should be used to attain management goals such as being able to detect changes in abundance of a certain magnitude within a specific time-frame. To reach such goals, it is important to designate the most efficient survey design with respect to survey interval and numbers of replicate surveys. Our results show that the power to detect changes is greater when one survey is conducted every year instead of two surveys every other year. The most efficient survey design requires surveys every year with at least three replicates during the moulting period. Finally, the use of the mean of the two highest (of three) counts (the trimmed mean) provides the most powerful survey design. In cases where the proposed method for surveying cannot be followed for financial or logistic reasons, the power to detect changes will decrease, and management actions would then need to be more conservative and rely on longer time-series of data.

## Acknowledgements

The study was funded by the Danish Ministry of Environment and the Swedish Environmental Protection Agency. We thank the skilled pilots and observers participating in aerial seal surveys since 1979. Funding to pay the Open Access publication charges was provided by the National Environmental Research Institute, Aarhus University, Denmark.

## References

Bjørge, A., Øien, N., and Fagerheim, A. 2007. Abundance of harbour seals (*Phoca vitulina*) in Norway based on aerial surveys and photographic documentation of hauled-out seals during the moulting season, 1996 to 1999. Aquatic Mammals, 33: 269–275.

Cohen, J. 1977. Statistical Power Analysis for the Behavioural Sciences. Academic Press, New York.

European Commission. 1992. EC Habitats Directive. Council Directive 92/43/EEC of 21 May 1992 on the conservation of natural habitats and of wild fauna and flora. http://www.central2013eu/fileadmin/user_upload/Downloads/Document_Centre/OP_Resources/HABITAT_DIRECTIVE_92-43-EEC.pdf.

Fryer, R. J., and Nicholson, M. D. 1993. The power of a contaminant monitoring programme to detect linear trends and incidents. ICES Journal of Marine Science, 50: 161–168.

Gilbert, J. R., Waring, G. T., Wynne, K. M., and Guldager, N. 2005. Changes in abundance and distribution of harbor seals in Maine, 1981–2001. Marine Mammal Science, 21: 519–535.

Harkonen, T., Dietz, R., Reijnders, P., Teilmann, J., Thompson, P., Harding, K., Hall, A., *et al.* 2006. Review of the seal epizootics in Europe. Diseases of Aquatic Organisms, 68: 115–130.

Harkonen, T., Harding, K. C., and Heide-Jørgensen, M. P. 2002. Rates of increase in age-structured populations: a lesson from the European harbour seals. Canadian Journal of Zoology, 80: 1498–1510.

Harkonen, T., Hårding, K. C., and Lunneryd, S. G. 1999. Age- and sex-specific behaviour in harbour seals *Phoca vitulina* leads to biased estimates of vital population parameters. Journal of Applied Ecology, 36: 825–841.

Harkonen, T., Harding, K., Rasmussen, T. D., Teilmann, J., and Dietz, R. 2007. Age- and sex-specific mortality patterns in an emerging wildlife epidemic: the phocine distemper in European harbour seals. PLoS ONE, 2: e887.

Harkonen, T., and Heide-Jørgensen, M. P. 1990. Comparative life histories of east Atlantic and other harbour seal population. Ophelia, 32: 211–235.

Hayward, J. L., Henson, S. M., Logan, C. J., Parris, C. R., Meyer, M. W., and Dennis, B. 2005. Predicting numbers of hauled-out harbour seals: a mathematical model. Journal of Applied Ecology, 42: 108–117.

Heide-Jørgensen, M. P., and Harkonen, T. 1988. Rebuilding seal stocks in the Kattegat–Skagerrak. Marine Mammal Science, 4: 231–246.

Kreiber, M., and Barrette, C. 1984. Aggregation behaviour of harbour seals at Forillon National Park, Canada. Journal of Animal Ecology, 53: 913–928.

Olsen, M. T., Andersen, S. M., Teilmann, J., Duffy, D. C., Edren, S. M., Linnet, A., and Härkönen, T. Status of the harbour seal (*Phoca vitulina)* in southern Scandinavia. NAMMCO Scientific Publications (in press).

OSPAR Commission. 2005. North Sea Pilot Project on Ecological Quality Objectives. Background Document on the Ecological Quality Objective for Seal Population Trends in the North Sea. Publication Number 2005/245. 13 pp. http://www.ospar.org/documents/DBASE/Publications/p00245_Background%20Document%20EcoQO%20-%20seals.pdf.

Ries, E. H., Hiby, A. R., and Reijnders, P. J. H. 1998. Maximum likelihood population size estimation of harbour seals in the Dutch Wadden Sea based on a mark-recapture experiment. Journal of Applied Ecology, 35: 332–339.

Schneider, D. C., and Payne, P. M. 1983. Factors affecting haul-out of harbour seals at a site in southeastern Massachusetts. Journal of Mammalogy, 64: 305–520.

Stewart, B. S. 1984. Diurnal hauling pattern of harbour seals at San Miguel Island, California. Journal of Wildlife Management, 48: 1459–1461.

Thompson, D., Lonergan, M. E., and Duck, C. 2005. Population dynamics of harbour seals (*Phoca vitulina*) in England: growth and catastrophic declines. Journal of Applied Ecology, 42: 638–648.

Thompson, P. M. 1989. Seasonal changes in the distribution and composition of common seal (*Phoca vitulina*) haul-out groups. Journal of Zoology, London, 217: 281–294.

Thompson, P. M., Fedak, M. A., McConnell, B. J., and Nicholas, K. S. 1989. Seasonal and sex-related variation in the activity pattern of common seals (*Phoca vitulina*). Journal of Applied Ecology, 26: 521–535.

Thompson, P. M., and Miller, D. 1990. Summer foraging activity and movements of radio-tagged common seals (*Phoca vitulina*. L.) in the Moray Firth, Scotland. Journal of Applied Ecology, 27: 492–501.

Thompson, P. M., Tollit, D. J., Wood, D., Corpe, H. M., Hammond, P. S., and Mackay, A. 1997. Estimated harbour seal abundance and status in an estuarine habitat in north-east Scotland. Journal of Applied Ecology, 34: 43–52.

Watts, P. 1992. Thermal constraints on hauling out by harbour seals (*Phoca vitulina*). Canadian Journal of Zoology, 70: 553–560.

Watts, P. 1996. The diel hauling-out cycle of harbour seals in an open marine environment: correlation and constraints. Journal of Zoology, 240: 175–200.

doi:10.1093/icesjms/fsq001