Estimating the Barents Sea polar bear subpopulation size

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Running headline:

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Abstract

A large scale survey was conducted in August 2004 to estimate the size of the Barents Sea polar bear subpopulation. We combined helicopter line transect distance sampling surveys in most of the survey area with total counts in small areas not suitable for distance sampling. Due to weather constraints we failed to survey some of the areas originally planned to be covered by distance sampling. For those, abundance was estimated using a ratio estimator, in which the auxiliary variable was the number of satellite telemetry fixes (in previous years). We estimated that the Barents Sea subpopulation had approximately 2650 (95% CI approx 1900 to 3600) bears. Given current intense interest in polar bear management due to the potentially disastrous effects of climate change, it is surprising that many subpopulation sizes are still unknown. We show here that line transect sampling is a promising method for addressing the need for abundance estimates.

Key-words: Helicopter surveys, distance sampling, line transects, polar bear, Barents Sea, subpopulation size.

Introduction

Polar bears were heavily hunted during the first half of the 20th century all over the Arctic. In the early 1960's scientists and managers from the five polar bear nations (Canada, Denmark (Greenland), Norway, Soviet Union, and USA) started to work on an international plan for conservation of polar bears. The outcome of this work was the international "Agreement on the Conservation of Polar Bears", signed in 1973 (see Prestrud and Stirling 1994). One central statement in the agreement is that "Each Contracting Party... shall manage polar bear populations in accordance with sound conservation practices based on the best available scientific data." Monitoring change in population size is the most direct method for monitoring population status. The importance of using scientifically derived population estimates in the management of polar bears has recently been stressed (Wiig 2005, Aars *et al*. 2006).

The Barents Sea polar bear subpopulation, shared between Norway and Russia, has not been harvested since 1956 in Russia and since 1973 in Norway (Prestrud and Stirling 1994). Persistent pollutants (Bernhoft *et al*. 1997, Norstrom *et al*. 1998, Andersen *et al*. 2001), climate change (Derocher 2005), and oil development (Downing and Reed 1996, Isaksen *et al*. 1998) are possible threats to the subpopulation. No meaningful estimate of the size of the subpopulation based on any study that covers the whole area in question has been available until now (Wiig and Derocher 1999). In the early 1980's, Larsen (1986) suggested that the Barents Sea polar bear subpopulation size was between 3000 and 6700 (dependent on subpopulation definition). This was based on data from multiple sources including den counts and spatially restricted, non-random air surveys, and extrapolation to larger areas.

With recent statistical developments, distance sampling is one of the most widely used methods for estimating animal abundance (Buckland *et al*. 2001), and is today considered to be more cost efficient than capture-recapture to achieve a given precision (Borchers *et al*. 2002), in particular for populations occurring at low densities over large areas. Wiig and Derocher (1999) advocated a line transect study for the Barents Sea area to estimate the subpopulation size, due to the large area and the lack of logistical bases needed for capture-recapture based estimates. Pilot studies on polar bears in Norway and the United States have examined the applicability of aerial surveys over sea ice, employing both strip transects and line transects. However, density estimates have not been extended to subpopulation estimates due to small sample sizes, restricted coverage, and methodological uncertainties (Wiig and Bakken 1990, Wiig 1995, Manly *et al*. 1996, Wiig and Derocher 1999, Evans *et al*. 2003).

Wiig and Derocher (1999) reviewed aerial survey attempts in the Barents Sea, comparing them with mark-recapture techniques, and concluded that line transect surveys would be the most economical and effective means to estimate and monitor the polar bear subpopulation size. In the present paper we report on a large-scale line transect survey of polar bears that was conducted in the Barents Sea in August 2004.

Materials and Methods

STUDY AREA

The aerial survey was conducted between 26th of July and 1st of September 2004, in the Barents Sea area (Fig. 1). The Barents Sea polar bear subpopulation has earlier been defined as the animals occupying the area between longitudes of 10°E and 60°E, and latitudes of 72°N and 83°N including the Svalbard (Norway) and Franz Josef Land (FJL, Russia) archipelagos (Wiig and Derocher 1999), but we chose to include both the whole of Franz Josef Land, and areas extending slightly west of 10°E and east of 60°E allowing parallel survey lines extending north from the ice edge (Fig. 1). The latitudinal boundaries vary seasonally with the sea ice extent, and in August bears are not found south of about 76° 30'. In 2004, there was less sea ice around the islands than in most recent years, and the sea ice edge was in most places further north with a very distinct edge, and very stationary during the period of survey. Movements of bears are lowest at the time of year the survey was conducted (Mauritzen et al. 2003), and they are not expected to be directional as in spring or late autumn when bears move between hunting and denning areas, or earlier in summer when sea ice distribution changes considerably.

SURVEY DESIGN

Before the survey was conducted, we used capture and satellite tracking data, as well as historical knowledge, to plan the survey design. Bears could be encountered either on or around islands (land, glaciers or on land fast sea ice) or in the pack ice in the Arctic Basin (hereafter termed pack ice or PI). The Svalbard areas were considered to be either: a_0 areas were bears were unlikely to be encountered in late summer, or a_p areas were there could be polar bears present. Areas in category a_0 were excluded from the survey (bear density assumed 0). For areas where polar bears could be present, a further sub-division was made: a_{pc} small areas not well suited for line transect sampling, with expected high densities of polar bears and a_{pd} areas well suited for line transect sampling, mostly with presumed intermediate densities. Areas a_{pc} were either small islands or relatively narrow strips of land between fjords and steep cliffs, and were free of snow. It was therefore possible to conduct complete counts (with variance assumed to be zero) of these areas.

Areas a_{pd}, together with areas of sea ice and all the islands of FJL, were surveyed using line transect sampling.

The distance sampling survey design for areas a_{pd} was created using the survey design engine in Distance (Thomas et al. 2006). Line spacing was 3km for all islands and sea ice areas. This spacing was chosen according to flight hours and survey time available. In different sub-areas line orientation was determined to minimize transects along shore areas, placing lines perpendicular to any potential density gradients. The line transect coordinates were imported into Arcview (www.ESRI.com), and from there uploaded into a GPS unit that was used in the helicopter during the survey.

When transects were flown over land and glaciers, they were continued over the sea wherever there was ice (fast ice or drift ice) present. Around Svalbard, there was virtually no sea ice left. Only 41 km of transect line was flown to cover what was left, and no bears were observed. Thus we ignored these transects in the analyses (bear density assumed 0). Also some very open drift ice (Fig. 1) was not covered due to safety considerations.

While most of the land areas were surveyed according to the planned 3 km line spacing pattern, the line spacing of glaciers on FJL was often changed. Because fog often prevented flying across glaciers, every 2^{nd} or 3^{rd} line were flown (Fig. 1), resulting in respectively 6 or 9km line spacing. In Svalbard, the coverage on glaciers was even more sporadic than on FJL (Fig. 1), because of almost continuous dense fog over the glaciers during the survey period.

For the PI area, 89 transect lines 9 km apart were laid roughly northward from the ice edge, with the most western and eastern lines running from respectively 9°39.4'E, 81°26.0'N to 6°13.2'E, 82°30.3'N and 60°28.4'E, 81°54.5'N to 63°48.6'E, 82°41.0'N (see Fig. 1). These lines extended 185km north from the ice edge. Due to time and fog-induced safety constraints, 17 lines were not covered, and most surveyed lines were shorter than 185km (Fig. 1).

For analysis we considered 7 geographic strata, based on the interaction of administrative regions (Russia and Norway) and habitats (Pack Ice, Land, Glacier and Sea Ice, the latter around islands, only in Russia) (Fig. 1).

FIELD METHODS

Two one-engined helicopters (Eurocopter AS350 Ecureuil) were used for flying total counts and line transects. One helicopter was stationed at Longyearbyen, Svalbard, covering the Svalbard archipelago from 26th – 31st of July, and 14th –26th of August. The second helicopter was stationed onboard the research vessel RV Lance (from 1st – 31st of August) operating along the ice edge in the Barents Sea and in the FJL archipelago area. The helicopters operated with four observers including the pilot. The two observers in the front seats focused on the transect line in front of the helicopter, while the two rear observers focused to each side of the helicopter further away from the transect line, but with some overlap with the front observers' search areas. The helicopters generally flew at 200 feet (61 m) above ground and at 100 knots speed (185 km/hour). Due to weather conditions, other combinations of altitude and speed were used for one transect at the PI, and at a few transects above glaciers at FJL.

The speed and altitude for flying were chosen after a pilot study (Aars et al., unpublished data) to ensure that the probability of observing a bear on the transect line, g(0), was maximized. We tested different altitudes and varying speed and found that a speed of 185 km/hour and altitude of 60 m was optimal.

The predetermined transect lines were flown using the GPS unit to which the survey design had been previously uploaded. This GPS unit also recorded a detailed track of the actual flight path. Details can be found in Marques et al (2006). The helicopter that operated from the research vessel in the Russian area and along the PI had two complete survey teams including two pilots, to allow transects to be flown almost continuously in periods of good weather.

When single transect lines covered different habitat types (land, glacier, fast ice, drift ice), each stretch of one habitat type was categorized as a section. For analysis, all sections of the same habitat type along a single line were then pooled (e.g. a flown line with 10 km ice + 10 km land + 10 km ice was considered as 2 transects, 1 with 20 km ice and 1 with 10 km land). For each bear observation, habitat structure was recorded as a covariate and scored as: 1 = relatively flat surface with only minor or no structure of the size that could make it difficult to spot a polar bear; 2 = habitat with some structure that could make it harder to spot a bear in the area (e.g. some screwed sea ice or crevasses on glaciers); 3 = major structures present that make it considerably more difficult to detect polar bears (e.g. heavily screwed sea ice).

DATA ANALYSIS:

We used distance sampling (DS) as described by Buckland *et al*. (2001, 2004) to estimate bear abundance.

For populations which potentially occur in well defined clusters, like polar bears, the perpendicular sighting distances to the center of detected clusters allows the modeling of a detection function, g(y), which represents the probability of detecting a cluster, given that it is at distance y from the transect line (Buckland *et al*. 2001). Parametric models are assumed for this detection function, and their parameters estimated via maximum likelihood, with the possibility to include adjustment terms for fit improvement. The probability of detecting a cluster in the covered areas, P, is the mean value of the detection function with respect to the available distances. While conventional methods use only the perpendicular distance y for detection function modeling, multiple covariate distance sampling (MCDS) extends the methods to include additional covariates z to help model the detection function. The scale parameter of the detection function becomes a function of these additional covariates (Marques and Buckland 2003). If MCDS is used, the probability of detection associated with cluster i, $P_a(z_i)$ (i=1,2,…,n, where n is the total number of detected clusters) is conditional on the corresponding covariate values z_i. An estimate of cluster abundance in the covered area (corresponding to the covered strips of width 2w, i.e. extending a distance w either side of the lines) of size *a* is then obtained by (e.g. Marques and Buckland 2003)

$$\hat{N}_{cs} = \sum_{i=1}^{n} \frac{1}{\hat{P}_a(z_i)}.$$

To estimate animal abundance, this estimate can be multiplied by an estimate of mean cluster size, using the regression method (Buckland, 2001: 73-75) to correct for size bias.

Given an appropriate random sample of lines (see Strindberg *et al*. 2004 for design details), one can extrapolate the results obtained in the covered area, based on the design properties, to the wider survey region. In our case, purely design-based extrapolation was not possible for the entire PI because it was not possible to survey all the transect lines, so that an additional procedure was required (see below). We define the surveyed area as the area within which a systematic sample of surveyed transects was conducted, and for which we can estimate abundance using line transect sampling alone. Other areas within the study region, to the north of covered strips or within the gap in survey coverage (areas D,E and F, Fig. 1) are referred to as the unsurveyed area.

The conventional methods used in our survey rely on a set of assumptions (Buckland *et al*. 2001), the most important being: (1) a large number of transects are randomly allocated in the study area independently of the distribution of the population of interest; (2) all animals on the line are detected with certainty (g(0)=1); (3) Animal movement is slow with respect to observer movement; (4) Distances are measured without error. An evaluation of the extent to which each of these was fulfilled is provided in the Discussion.

Preliminaries

Both the tracks and the waypoint files from the transects flown were downloaded to a computer and analyzed using the program GPS Map Explorer version 2.34 (http://home.tiscali.no/gpsii/). Perpendicular distances to bear clusters required for distance sampling analysis were obtained by calculating the shortest distance from the line flown, as recorded by GPS, to the waypoint representing the location of the bear (or bear cluster) (Marques *et al*. 2006).

Extensive plotting of detected distances, number of detections, encounter rates and cluster sizes was done during the survey, allowing the removal of virtually all typos and recording errors.

Analysis in Distance 5.0

The line transect data were analyzed using program Distance 5.0. (Thomas *et al*. 2006). A preliminary analysis of all the data with half-normal and hazard-rate detection functions showed a well-behaved detection function decreasing with distance and no evidence of any major problems. Preliminary analyses showed that truncation of 5% of the largest distances (w = 1068m) was adequate to preclude fitting spurious bumps in the tail of the detection function, and that was the truncation used in subsequent analysis.

A number of candidate covariates were available for modeling the detection function: habitat, structure (around the position the bear was observed), cluster size and helicopter altitude. Habitat was a factor covariate with 3 levels, structure was considered both as a factor with 3 levels and as a continuous covariate (with values 1, 2, or 3), and the remaining two were continuous covariates. Their inclusion was assessed by using minimum Akaike's Information Criterion (AIC), and the overall fit evaluated using the standard Chi-square, the Kolmogorov-Smirnov and the Cramér-von Mises tests available in Distance. A priori, it was thought that altitude could reflect overall flying conditions (since under ideal conditions the altitude would be 61m). The perception based on the fieldwork was that cluster size would not be relevant, because clusters tend to act as single cues. Both habitat and structure were believed to be potentially useful for modeling the detection function. As well as testing the inclusion of cluster size as a covariate, we used size bias regression methods, namely by regressing the log of the detection function on the log of cluster size (e.g. Buckland et al. 2001, 73:75), to evaluate and correct for the eventual presence of size bias. For abundance estimation, we considered a common detection function model across strata, with density estimated by stratum conditional on the observed covariate values.

CORRECTION FOR AREAS NOT SURVEYED

Despite the carefully planned survey design, it proved impossible to survey 17 lines in the Russian region, leaving a gap in the coverage of the PI region between Svalbard and FJL (see area F, Fig. 1). This was due to bad weather and related safety considerations arising from flying a one motor helicopter in a remote area. Additionally, the average length of the lines flown in this area was 125 km (range 43 – 232 km, Fig. 1) instead of the 185 km planned. Rather than assuming that density in the surveyed areas could be extrapolated to these areas, we opted for a ratio estimator. Considering boxes as described below, we used the auxiliary variable number of telemetry fixes (from adult females, see below) within each box, to predict the number of bears that would have been detected had the lines been flown.

The 89 lines from the study design, including the 17 that were not covered by line transects, were considered to be the centerlines of rectangles or ‘boxes’, each 9 km wide (4.5 km either side of the line) and 336 km long (north from the ice edge). Each box was divided into two, the southern portion corresponding to the surveyed centerline, and the northern portion extending the box from where survey effort stopped to the boundary 336 km north of the ice edge (the maximum distance recorded by telemetry fixes). The 17 lines not covered by the survey in the Russian sector were divided into two; a southern part was 92 km long (the average length of the Russian transects flown) and a northern part was 244 km long (= 336 - 92 km). Thus, the size of the study region north of the ice edge was 269,136 km^2 (89 x 9 km x 336km), of which 80,839 km^2 (30%) was surveyed by line transect sampling, with abundance for the remaining 188 297 km^2 (70%) being estimated using the ratio estimator, as described below.

The telemetry data are well described in Mauritzen *et al*. (2001, 2002). Satellite telemetry fixes have high position accuracy compared to the scale on which polar bears operate. The telemetry accuracy was estimated to be less than 1400 meters for 92% of the positions (Mauritzen et al, 2001). We used only positions from the period when the ice edge is furthest north (July-September) from 44 different bears tracked between 1989 and 1999. Only positions north of 79º N and at least 20 km from land were used (169 data points). If more than one position was available for a given bear, only positions a minimum of 6 days apart were used to reduce dependence between bear locations. The average distance between 93 pairs of fixes 6 days apart in time was 57 km (SD = 28 km), and thus relatively large compared to the distance between lines (9 km). Using standard ANOVA (p-values > 0.1), there was no significant yearly difference in the distribution of bears relative to the distance from the ice edge, despite the latitudinal position of the ice edge varying substantially among years. There was also no significant difference in the distance from the ice edge when comparing data for July plus September with data for August. Each point was allocated to the appropriate box. As a box was defined in terms of distance from the ice edge, a fix of say 20 km north of the ice edge in 1989 would be placed 20 km north of the ice edge in our survey, even though the ice edge was in a different absolute position.

The number of bears that would have been detected if transects had been flown in the areas not surveyed, $\hat{n}_{uns}$, was estimated using the following ratio estimator

$$\hat{n}_{uns} = r\sum_{i=73}^{178} X_i$$

where

$$r = \frac{\sum_{i=1}^{72} Yi}{\sum_{i=1}^{72} Xi}$$

and X_i is the number of telemetry fixes within box *i* and Y_i the number of bear groups detected within box *i* during the survey. Note *i* = 1, 2,…, 72 (Fig. 1, area A+B+C) represents boxes associated with transect lines surveyed while *i* = 73, 74,…, 178 (Fig. 1, area D+E+F) represents boxes corresponding to transect line segments not surveyed.

The estimated number of animals for the unsurveyed areas ($\hat{N}_{uns}$) is then calculated by

$$\hat{N}_{uns} = \frac{\hat{E}(s)\hat{n}_{uns}}{P_d P_{c|s}}$$

where the relevant quantities were obtained in the distance sampling component of the survey, i.e. $\hat{E}(s)$ is an estimate of mean cluster size, obtained using the regression method (Buckland, 2001: 73-75) to allow for size bias, $\hat{P}_d$ is estimated probability of detection of animals that are within the truncation distance w (this is obtained as the average estimated probability of detection within each stratum, conditional on the observed covariates in that stratum) and $P_{c|s}$ is the probability that a bear is within a distance w from the survey lines, given that it is within the surveyed areas (= 2w/box width).

Total estimate and variance estimation

The total estimated number of bears was obtained as the sum of: (1) the estimated numbers in the surveyed area, (2) the estimated numbers in the unsurveyed area and (3) the numbers obtained by total counts. Although the final population estimate is made up of 3 components (total count, surveyed areas and unsurveyed areas), the first of these does not contribute to the variance, as by definition a total count has no variance.

To obtain estimates of variance for the estimated abundances we used a non-parametric bootstrap (999 bootstrap resamples). Variance estimates were obtained by resampling lines within strata, as described in Buckland *et al*. (2001). In the case of the PI strata, the 336 km long transects were resampled, along with all the information contained in them (survey data and telemetry fixes). To incorporate the variance involved in estimation for both surveyed and unsurveyed areas, the bootstrap procedure had to be implemented outside Distance, using software R (version 2.0.1, R Development Core Team 2004), with Distance called from R; in this way, for each bootstrap resample, an estimate of all random quantities involved both in the distance sampling component and the ratio estimator component were obtained. As both detections and fixes are resampled together within the bootstrap, no assumption of independence is made between the estimate for the unsurveyed and surveyed areas when calculating the variance of the whole subpopulation. Confidence intervals were obtained by the percentile method (Buckland *et al*. 2001). By bootstrapping all the information within the boxes (around each line), we ensure comparability across the two components of estimation. As shown by Davison and Hinkley (1997), it is theoretically superior not to bootstrap at lower levels when data are hierarchical, hence we do not bootstrap fixes within boxes in addition to boxes. In this way, we also avoid having to assume that fixes are independent, replacing this by the weaker assumption that data for different boxes are independent.

Results

TOTAL COUNTS

A total of 31 polar bears were observed during total counts on the island of Spitsbergen. An additional 27 bears were observed on different small and medium sized islands in Svalbard. On Kvitøya, in the north-east of the Svalbard area, 32 bears were observed. In addition to these observations from areas that we allocated to a total count survey, we added six bears that were observed from RV Lance or from the helicopter in the Russian area, in areas of loose drift ice not surveyed by line transects. Thus total counts add up to 96 bears.

LINE TRANSECTS

We flew 20,975 km of transect lines distributed in seven strata (Table 1). These were considered to be 1018 independent transect units for variance estimation. A total of 189 polar bear clusters were detected. These clusters consisted of 139 lone bears and 50 adult females with 1-3 (average 1.48) juveniles. The mean cluster size was 1.39 and the total number of bears observed was 263.

In Table 2 we present summary statistics for the candidate models considered for the detection function, with combinations of the covariates available (models shown only if $\Delta AIC<2$). This table provides further reassurance on the quality of the data. Despite using different key functions (half-normal and hazard rate) with several combinations of covariates, the global density estimates, and corresponding associated measures of precision, were remarkably close. Additionally none of the three absolute goodness of fit measures considered indicated that any of the top models gave a poor fit.

AIC did not indicate that cluster size affected detectability (ΔAIC of 5.35 and 8.44 for the half-normal and hazard rate models respectively). This was in accordance with field perception. We were rarely able to distinguish between a family group and a lone animal before we were very close, and hence at the spatial scale we were operating, bear clusters seemed to offer a single cue independently of their size. Similarly, altitude was not important for detection function modeling based on AIC, and hence was subsequently ignored in the analysis.

Overall, conditional on the covariates, the half-normal key function was usually more parsimonious than the hazard rate. Although the model with lowest AIC included only structure as a covariate, we opted to use the next best model (ΔAIC=0.1), which included the habitat covariate, for further inference. This was justified because we were interested in estimation over different strata with considerably different habitats, and from the field there was a clear perception that the detection process was different in different habitat types.

Fig. 2 shows the distribution of observed detection distances in different habitats and areas. Similar trends across strata made it possible to fit the half-normal detection function to all strata, with habitat and structure as covariates.

Based on this model, we estimated bear abundance (and corresponding variances) for the seven strata (Table 1). In total 1394 (95% CI: 1060 – 1743) bears were estimated to be in the areas surveyed by line transects. Bear densities were much higher in Russian than Norwegian areas, and higher on land than in other habitat types (Table 1).

PACK ICE AREAS NOT SURVEYED

The ratio estimator was r=0.875 based on 56 observations and 64 telemetry fixes within the PI areas covered by line transects (Fig. 3). Based on line transect data, the size bias regression estimate of mean cluster size was 1.389, probability of detection within the covered strip of half-width 1068m was 0.472 (Russia) and 0.442 (Norway), and the proportion of the surveyed area covered was 1068/4500. Based on this, the number of bears in the unsurveyed areas of the PI was estimated to be 1154 (95% CI: 659-1845, see Table 3). The wide confidence interval obtained was partly due to the considerable spatial variation in numbers of observations and fixes (Fig. 3).

THE TOTAL ESTIMATE

Adding the estimated numbers of bears detected by total counts, those predicted to be within line transect survey areas and those predicted to be in unsurveyed areas of the PI, the total is 2644 bears (95% confidence interval of 1899 - 3592).

Discussion

POPULATION ESTIMATE

We estimated the Barents Sea area to host between approx. 1900 and 3600 polar bears, combining total counts (in small, easily surveyed areas), estimates from line transects (over large areas) and a ratio estimator (where planned line transects were not implemented due to safety and weather constraints). The ratio estimator approach used to estimate abundance in areas not surveyed was the best of a number of non-ideal alternatives, and the potential problems are discussed at length in a separate section below. However, it is unlikely that any such survey, covering such a large area of quickly changing weather conditions, in a necessarily narrow time window, will avoid similar difficult choices. We have attempted to represent the considerable uncertainty in our estimate fairly, resulting in a rather wide confidence interval. It is assumed that the Arctic has 19 relatively discrete subpopulations with a total of about 20,000 to 25,000 polar bears (Aars *et al*. 2006). Thus, the Barents Sea subpopulation contains a considerable fraction of the world's population. Larsen (1986) suggested there were close to 2000 bears in the Svalbard area, and 3000 to 6700 in the area between East Greenland and FJL in 1980. Uncertainties around his and our estimate preclude a direct comparison. Derocher (2005) assumed that the subpopulation had increased in size until recently.

EVALUATION OF METHODOLOGICAL ASSUMPTIONS

Total count

The relatively low number of bears observed during the total counts had little influence on the total estimate. The failure to detect bears during these counts is therefore likely to have negligible effect on the total abundance estimate. A few bears were also missed in areas of very open drift ice which we did not cover by helicopter. These areas were of minor extent, and we were fortunate to encounter a rather distinct ice edge that moved little during the period of the survey. Larger movements of the habitat during the survey would certainly have complicated the study. Six bears were seen from RV Lance in the FJL region, in areas that were not covered by line transects. This was in areas with very open water not suited for search by a one engine helicopter, and where we beforehand had decided densities of bears would be too low to justify surveying. These observations suggest that a considerable number of bears might have been outside the areas we covered, and hence missed. In the absence of contemporaneous maps showing distribution of areas having very loose drift ice, it is not possible to provide a data-based number for individuals in these areas. As an educated guess we believe that this might account for 100 – 200 bears.

Distance sampling

The large number of randomly allocated line transects guarantees that the design was adequate for estimating abundance within the surveyed area. Avoidance movement before detection would lead to a biased estimate, but is likely to generate negligible bias due to the slow speed of the bears relative to the helicopter. Another possible problem would be if movement away from a surveyed line generated a temporarily higher density around neighbouring survey lines before the helicopter reached these areas. All experience we have with polar bear behavior after disturbance is that they only react for a short period of time when the helicopter approaches. Also, in most cases, the helicopter traveling at 185 km/hr would reach the next line before a polar bear, averaging a maximum of 4 km/hr (Andersen et al. 2008), even when fueling or switching observational teams, and hence this is unlikely to be a significant issue. The adequacy of the measurement procedure was evaluated in Marques *et al*. (2006), and it is reasonable to say that, at the scale we were working, measurements were virtually error free. Therefore, it is unlikely that any of these assumptions might have had an impact on the final estimates. The most important issue regarding the reliability of the distance sampling population estimate is g(0). If, say 10% of bears on the line passed undetected, then we expect our estimate to be only 90% of true abundance (Buckland *et al*. 2001). Our own perception was that bears were unlikely to be missed on land (grey or brown background), on most areas of glaciers, and on flat, newly formed sea ice. We think that along transects covering these habitats, g(0) was either 1 or very close to 1. However, in some sections of transects in the PI, with heavily packed ice, it is possible that polar bears close to the line could be missed. Heavily packed ice was most commonly found close to open water, at the ice edge. Two polar bear observations out of 56 in the PI area were in structure 3 habitat, and this habitat accounted for a small proportion of the total area covered. Even if g(0) was considerably lower than 1 in structure 3 habitat, we think that g(0) was close to 1 when averaged over all transects. However, in accordance with recommendations from e.g. Borchers et al. (2006), estimation of g(0) as an integral part of the study should be a priority for future similar surveys. An eventual $g(0)<1$, coupled with some underestimation on the areas covered with total counts and areas assumed to have no bears, means that, if anything, our estimate might underestimate the subpopulation size. Nonetheless, it is our belief that provided, as expected, g(0) was not considerably lower than 1, it is unlikely that these factors were enough to seriously affect the quality of our estimate.

Area not surveyed

The most challenging problem resulted from the large number of transects not surveyed in the Russian part of the PI and the restricted coverage in areas more than 90 km north of the ice edge. Fixes of tagged females showed a tighter longitudinal spread than did observations made in the line transect sampling, which were relatively uniform in distribution from east to west (Fig. 3). This is presumably linked to non-random selection of animals for tagging – tagging effort was concentrated in eastern Svalbard. Because there was no survey effort in the north, we cannot assess whether there might be a similar mismatch between north and south; we must assume that the tagged bears have a representative distribution in late summer with respect to latitude, for the ratio estimator to be approximately unbiased. The bears can walk more than 50 km in a day (Amstrup 2003). Bears tagged in Svalbard can have home range areas of many thousand square km, and use the sea ice of the PI as far as the most easterly areas surveyed (Mauritzen et al.

2002). Thus the geographic distances per se are unlikely to limit where they can be found along the PI. Nonetheless it is plausible to believe that bears from FJL are more commonly found at the areas further to the east, and also that areas furthest west had more bears from northern Svalbard rather than from eastern Svalbard. Furthermore, some bears seen furthest west and east are likely to be from neighboring subpopulations, East Greenland to the west and Kara Sea to the east. This would explain the mismatch of distributions of telemetry fixes and observations from east to west (Fig. 3). This mismatch in longitudinal distributions raises the concern about whether the ratio estimator will give a biased estimate for the southern area (Rus Uns Fig. 1 and Fig. 3, area F) not surveyed. The number of fixes (22) in this area predicts an average 1.3 detections per line segments had they been covered. This is similar to what we had in the Russian sector to the west (1.5) and east (1.3). Thus we have no indication of which direction a bias for this area would be directed, and it seems unlikely that the bias is substantial given densities recorded were similar in neighboring areas. It is thus of greater concern whether the latitudinal distribution of fixes (converted to distance north of the ice edge) from several years match with how the bears were distributed. A possible source of bias would be if polar bears were found closer to the ice edge in years where the ice edge was located far north. Due to the high mobility of the polar bears, it is not likely that such a relative switch in positions relative to the edge would be caused by an increased distance from the islands per se. However, polar bears prefer areas of more shallow water with higher productivity (Ferguson et al. 2000). Areas further north from the ice edge have deeper water. The ice edge in 2004 was further north than average, and thus it could be that the ratio estimator using distributions from earlier years overestimated the number of bears in the uncovered areas to the north. However, the failure to reveal any heterogeneity in distances from the ice edge in fixes among years, despite a large year to year variation in the position of the ice edge, means that such a bias might be small. Another indication of this is the fact that 65 of the telemetry fixes used were from 1999, a year with a very similar ice edge location to 2004. The average distance of fixes from the ice edge was 57 nm in 1999, only slightly shorter that that for all the 169 fixes used in the analyses (61 nm). Other potential sources of bias are the possibility that males and females or animals at different age classes have different distributions. Little is known about this, because telemetry data are almost exclusively available for adult females. To avoid all the possible sources of bias, it would obviously have been preferable to have a representative sample of collared bears with respect to both area and status, and from the year of the survey. In our case, given that such data are not available, it might be possible to improve the estimate during coming years by adding new information from telemetry fix data if polar bears in the future are fitted with satellite transmitters in areas from where we currently have low coverage (northern part of Svalbard and Russian areas).

Comparison with other studies

In our study, the average density of polar bears was 1.1 per 100 km^2 in the areas surveyed by line transects (125,000 km^2). In comparison, Taylor and Lee (1995) estimated an average density of 0.4 (range 0.1 - 1.0) bears per 100 km^2 on the pack ice in the Canadian Arctic in April. In the Chukchi Sea, Evans *et al*. (2003) estimated an average of 0.7 bears/100km^2 in August. Average densities of polar bears across different types of habitat in the Barents Sea are close to these estimates. However, we found a profound geographic variability. Densities on fast ice and pack ice in the Russian area were much higher (> 2 bears/ 100 km^2) than farther west in the Norwegian area. Such spatial patterns however will vary a lot with both seasons and years. Polar bears in the Barents Sea show high seasonal fidelity (Mauritzen *et al*. 2002), and many of the polar bears that are present around the islands of Svalbard in the spring, will be hunting along the ice edge, particularly further north-east in the Russian area, and around FJL in August. During our survey there were three times as many bears in the Russian area as in the Norwegian area. Both the number of maternity dens (Larsen 1986) and the relatively high number of recaptures of bears in the Svalbard area (Derocher 2005) indicate that many more polar bears are present in the Svalbard area in spring. The fact that a large proportion of the subpopulation seems to migrate regularly across territorial borders emphasizes the need for a joint management between the two nations.

CONCLUSIONS

With the challenge of a warmer Arctic climate and significant habitat loss, it is a serious concern that several of the 19 existing subpopulations of polar bears still do not have reliable population size estimates (Aars *et al*. 2006). This is the first large scale line transect study aimed at estimating the size of a polar bear subpopulation. Difficulties and limitations were clearly demonstrated, particularly connected to icing conditions and fog preventing helicopter flying, which forced us to use a ratio estimator comparing telemetry data from earlier years to line transect observations to estimate bear densities in areas not surveyed. In future studies, time should be allocated to ensure a good coverage by transects independent of weather conditions, and ideally, helicopters capable of flying further north of the ice edge should be used. In face of the increasing demand for reasonable estimates of polar bear subpopulation sizes in the near future, we argue that line transect surveys are the best estimation method for such widely distributed populations.

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Table 1. Estimates of polar bear density and abundance within areas of seven different strata covered by line transect surveys, based on analyses in the program Distance. Nor = Norwegian area, Rus = Russian area, G = Glacier, L = Land, SI = Sea Ice around FJL, PI = Pack Ice, obs = number of distance observations used to fit the curves after 5% truncation of observations, $\hat{D}$ = estimated bear density (per 100 km^2), $\hat{N}$ = estimated number of bears in surveyed areas.

Strata	Km lines	Obs	$\hat{D}$	$\hat{D}$ 95% CI	$\hat{N}$	$\hat{N}$ 95% CI	Km^2
Nor G	1055	3	0.5	(0.0; 1.2)	67	(0; 160)	13,271
Nor L	2771	25	1.0	(0.6; 1.5)	84	(49; 121)	8,082
Nor PI	6903	16	0.4	(0.2; 0.6)	212	(106; 318)	57,877
Rus G	1757	16	1.6	(0.8; 3.1)	226	(106; 424)	13,714
Rus L	888	38	5.7	(3.3; 8.8)	137	(79; 212)	2,421
Rus PI	4706	39	2.1	(1.3; 3.0)	483	(305; 678)	22,962
Rus SI	2895	43	2.3	(1.4; 3.4)	185	(113; 271)	8,009
TOTAL	20975	180	1.1	(0.8; 1.4)	1394	(1060;1743)	126,336

Table 2. Details of the MCDS models considered for the detection function, with combinations of the available covariates. Available covariates were habitat (Hab), structure as factor (Str) or as a continuous covariate (nfStr), cluster size (CS) and altitude (Alt), used to describe the model. HN corresponds to half-normal and HR to hazard rate. Columns are Akaike Information Criterion (AIC), and the difference between lowest AIC and model AIC (ΔAIC), number of parameters in the model (par), global density estimate pooled across strata (D), the corresponding 95% confidence interval (95% CI) and coefficient of variation (CV), as well as 3 goodness of fit (GOF) measures, a chi-square test (ChS), a Kolmogorov-Smirnov (KS) and a Cramér-von Mises test (CvM).

Name	Par	ΔAIC	AIC	D	95% CI	D CV	GOF ChS	GOF KS	GOF CvM
HN+nfStr	2	0.00	2417.75	0.013	(0.01,0.017)	0.129	0.145	0.518	0.5
HN+nfStr+Hab	4	0.09	2417.84	0.014	(0.011,0.018)	0.130	0.087	0.568	0.7
HN+Str	3	0.10	2417.86	0.014	(0.01,0.017)	0.129	0.115	0.472	0.6
HR+nfStr	3	0.43	2418.19	0.014	(0.011,0.018)	0.130	0.092	0.635	0.9
HN+Str+Hab	5	1.09	2418.85	0.014	(0.011,0.018)	0.130	0.064	0.451	0.7
HR+nfStr+Hab	5	1.15	2418.91	0.014	(0.011,0.018)	0.131	0.051	0.474	0.9

Table 3. The estimated number of bears in areas of the pack ice not surveyed by line transects (area D+E+F, Fig. 1) $\hat{N}$, together with confidence intervals based on a ratio estimator. Exp # Groups = the number of bear groups expected to have been detected if the areas had been surveyed, based on the detection functions for the PI line transect strata.

	Exp # Groups	$\hat{N}$	95% CI for N
Nor Uns	17.5	232	133; 377
Rus Uns	74.4	922	527;1480
Nor+Rus Uns	91.9	1154	659;1845

Figure 1. Study area. Line transects are marked with solid lines. The seven strata used in distance sampling analyses were: (1) Glacier and (2) Land in Norway (area G), (3) Glacier, (4) Land and (5) Sea ice in Russia (area H), and (6) Pack Ice in Norway (area A) and in (7) Russia (areas B+C). Dotted lines show planned survey lines not covered or extensions of these lines north to 336 km from the ice edge, in areas were telemetry fixes from collared bears were used to estimate bear densities (areas D+E+F).

Figure 2. Histograms of all 189 observations grouped into 200 meter distance classes from survey lines. Detections are divided by habitat (glacier = G, land = L, pack ice = PI, and sea ice around islands = SI) and by region (Nor = Norwegian Arctic, Rus = Russian Arctic). The histogram to the upper right shows all 189 observations pooled. Observations truncated in the distance analyses are also shown.

Figure 3. The number of observations by line transect flown (Obs S, in square A+B+C), the corresponding number of telemetry fixes allocated to boxes associated with the same transects (Fixes S, in square A+B+C), and the number of telemetry fixes in unsurveyed areas, extended from where transects terminated to 336 km N of the ice edge (D+E) and in the gap not surveyed (F). The area codes A – F correspond to those in Fig. 1.