Quantifying spatial characteristics of the Bowhead Whale Aerial Survey Project (BWASP) survey design

Megan C. Ferguson

National Marine Mammal Laboratory, Alaska Fisheries Science Center, NOAA Fisheries, 7600 Sand Point Way NE, F/AKC3, Seattle, WA 98115-6349, USA.

Contact e-mail: Megan.Ferguson@noaa.gov

ABSTRACT

The Bowhead Whale Aerial Survey Project (BWASP) has been conducted annually since 1979 in the Alaskan Beaufort Sea to monitor the distribution and relative abundance of the Bering-Chukchi-Beaufort (BCB) stock of bowhead whales (*Balaena mysticetus*) during their autumn migration. BWASP was created to specifically address broad-scale research and management questions related to bowhead whale ecology, with particular interest in the potential effects of oil and natural gas exploration, development and production activities on the BCB bowhead whales. With elevated concerns about climate change, increasing oil and gas activities and the forecasted increase in vessel traffic, it is expected that interest in the BWASP dataset will also increase in order to evaluate effects of these anthropogenic activities on BCB bowhead whales and indigenous whaling. The following analysis quantified the spatial characteristics of the BWASP survey design and provided guidelines for the types of investigations that the BWASP data can potentially address. Sampling lags (transect spacing) in the BWASP survey design of approximately 20km along the east/west axis of the study area limit the spatial scale of phenomena that can be detected using data from a single BWASP survey. Therefore, BWASP data are relatively uninformative for studying variability in distribution or relative abundance along the east/west axis over short time scales (one survey) and within small areas measuring less than approximately 20km. In addition, computer simulations showed spatial heterogeneity in the long-term survey coverage probability (the probability that a given location will be included in a survey having an assumed effective search width under the BWASP survey design). Pooled transects created from simulated surveys resulted in a repeating diamond pattern in which coverage probability was low. Analyses incorporating data from many BWASP surveys should account for this spatial heterogeneity, via either the survey coverage probabilities or quantification of survey effort; otherwise estimates of variables such as relative density, density, or habitat use may be biased. The BWASP surveys have increased understanding of the broad-scale patterns of bowhead distribution, relative abundance and behaviour. The utility of this dataset in informing other questions will depend upon the scale of the ecological phenomena under investigation and the analytical scales used to address the questions.

KEYWORDS: BOWHEAD WHALE; ARCTIC; SURVEY – AERIAL; MODELLING; DISTRIBUTION; BEAUFORT SEA; LINE TRANSECT; NORTHERN HEMISPHERE

INTRODUCTION

The Bering-Chukchi-Beaufort (BCB) stock of bowhead whales (*Balaena mysticetus*) undertakes spring migrations northward and eastward from the Bering Sea, following the receding seasonal sea ice across the Chukchi Sea to the eastern Beaufort Sea; in the autumn, these whales return via the Chukchi Sea to winter in the Bering Sea (Moore and Reeves, 1993). Understanding the ecology of the BCB bowhead whales is of concern to many including indigenous subsistence whalers, scientists, representatives of the oil and natural gas industry, and natural resource managers. Aerial surveys can be a valuable source of insight into BCB bowhead whale ecology, especially their distribution and relative abundance, and the spatial and temporal variability therein (e.g. Givens, 2009; Moore, 2000; Moore *et al.*, 2000; Schweder *et al.*, 2010). The utility of data from a given aerial survey for addressing a specific question is largely determined by details of the survey's design (transect layout and number) and field protocol (data collection methods). Matching the spatiotemporal scale of the question to the sampling resolution of the data is critical.

Bowhead Whale Aerial Survey Project (BWASP) surveys and their predecessors have been consistently conducted in the Alaskan Beaufort Sea annually from 1979 to the present and they coincide with the westward autumn migration of BCB bowheads (late August through late October or early November). BWASP was created to address broad-scale research and management questions related to bowhead whale ecology, with particular interest in the effects of oil and natural gas exploration, development and production activities on the BCB bowhead stock. When developing the BWASP survey design, 'particular emphasis was placed on regional surveys to assess large-area shifts in the migration pathway of bowhead whales and on the coordination of effort and management of data necessary to support seasonal offshore-drilling and seismic-exploration regulations' (Treacy, 2002). The ongoing goals of BWASP are as follows (Monnett and Treacy, 2005).

(1) Define the annual fall migration of bowhead whales, significant inter-year differences, and long-term trends in the distance from shore and water depth at which whales migrate;

(2) Monitor temporal and spatial trends in the distribution, relative abundance, habitat, and behaviours (especially feeding) of endangered whales in arctic waters;

(3) Provide real-time data to MMS [the US Minerals Management Service, now the Bureau of Ocean Energy Management] and NMFS [the National Marine Fisheries Service, National Oceanic and Atmospheric Administration (NOAA)] on the general progress of the fall migration of bowhead whales across the Alaskan Beaufort Sea, for use in protection of this Endangered Species;

(4) Provide an objective wide-area context for management interpretation of the overall fall migration of bowhead whales and site-specific study results;

(5) Record and map beluga whale distribution and incidental sightings of other marine mammals; and

(6) Determine seasonal distribution of endangered whales in other planning areas of interest to MMS.

The BWASP survey design and protocol were based on line transect methods, and have not changed substantially since 1982. BWASP has collected a wealth of data over nearly three decades. Heightened interest by the oil and gas industry to explore and extract resources from the Arctic, in addition to heightened awareness of the pressures of climate change and other anthropogenic activities on Arctic ecosystems, has provided increased motivation to identify, predict and quantify the potential effects of these factors on bowhead whales.

Dungan *et al.* (2002) provided an overview of the importance of scale in spatial statistical analyses. They identified three components to which the concepts of spatial scale pertain: (1) the phenomenon (system) under investigation; (2) the sampling units used to acquire information about the phenomenon; and (3) the analysis used to summarise information or make inferences. The phenomenon being studied can be characterised by its physical structure (patch size or patterns of objects) and the dynamic processes that act upon it. A process can be described by measures of the distance across which it can act (its range of action) and the area over which it can or does act (its potential or actual extent, measured in two dimensions) (Dungan *et al.*, 2002). The authors highlight four elements used to describe fundamental spatial characteristics of phenomena, sampling units or analyses: size; shape; lag (the spacing or interval between neighbouring phenomena, sampling or analysis units); and extent (the total length, area or volume that exists, is observed or is analysed).

The concepts outlined by Dungan *et al*. (2002) were applied to examine issues of spatial scale relevant to BCB bowhead whales and the BWASP survey design. The phenomena of interest were the spatial distribution and relative abundance of bowhead whales in the Alaskan Arctic, including the associated variability. The spatial scales that are relevant for understanding bowhead whale ecology span three orders of magnitude, from ocean basins (thousands of kilometers) to mesoscale features such as eddies, canyons, and fronts (tens to hundreds of kilometers) to prey patches (tens to hundreds of meters). Examples of processes acting upon the Arctic ecosystem that potentially affect bowheads include oceanic circulation (currents, eddies, upwelling and downwelling, and the energy and objects that these features transport); sea ice dynamics; movements of predators and prey; generation and transmission of sound from marine organisms, wind, ice, vessels, drilling, acoustic (seismic) surveys, etc., that contribute acoustic signals or noise which may help bowhead whales interpret their environment or hinder their ability to function in their environment (e.g. via masking communication or, in extreme cases, causing temporary or permanent hearing loss); and physical disturbances due to the movement of vessels. The objectives were as follows:

(1) Quantify the spatial characteristics of the BWASP survey design. To do this, the magnitude and spatial distribution of the long-term survey coverage probability was investigated, which is the probability that a given location will be included in a survey having an assumed effective search width under the BWASP survey design. This aspect of the BWASP survey design has not been examined until now. The spatial lags that are inherent in the BWASP survey design were also examined;

(2) Inform researchers and resource managers about some of the ecological questions and analytical scales to which the BWASP data can be appropriately applied.

METHODS

The BWASP study area is located in the Alaskan Beaufort Sea, stretching from 140°W to 157°W, and from the northern coast of Alaska (located within a latitudinal range of approximately 69.5° to 71.5°N) to 72°N (Fig. 1). It encompasses 107,500km^2, including the continental shelf and slope, and extending into the Arctic Ocean basin with depths approaching 3,600m. The isobaths in the study area tend to parallel the coastline; one prominent exception is Barrow Canyon, which cuts across the shelf near 71.5°N, 155°W (Fig. 1).

BWASP survey design

The BWASP study area was divided into geographic blocks of variable size and shape (Fig. 1), upon which the survey design was based (Treacy, 2002). The BWASP survey design comprised six to eight transects per block, depending on the width of the block. The northern and southern endpoints of each transect were randomly placed at minute marks along the survey block boundaries, independent of each other and of all other transects, within a fixed 0.5° longitudinal bin (Fig. 2). Paired northern and southern endpoints were connected by linear transects so that adjacent transects never crossed. Transects were generally oriented along a north/south axis, but the exact orientation for each transect depended upon the location of the randomly generated northern and southern endpoints (Fig. 2).

Simulation exercise to compute long-term survey coverage probabilities

The simulation procedure developed for this analysis comprised four basic steps.

(1) Define the study area, including the shoreline and boundaries of the BWASP survey blocks.

(2) Create a fine-scale grid (500m × 500m) overlaying the entire study area.

(3) Generate transects for the study area using the BWASP survey design. Transform transect lines into strips 2,000m wide and centred on the transect line. (A 2,000m strip width was chosen because preliminary analyses suggested that the effective search half-width for these surveys was close to 1km.) Overlay the fine-scale grid (produced in step 2) onto the transect strips to determine

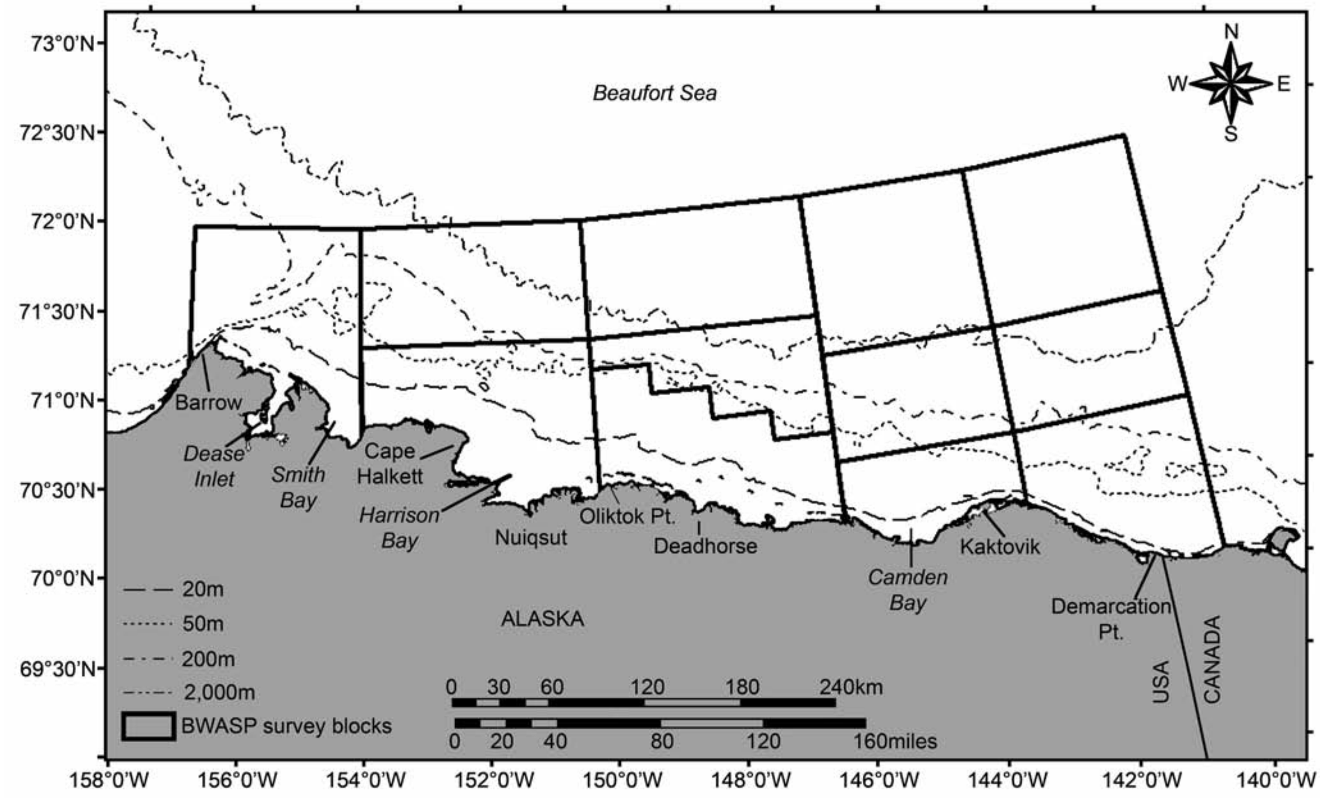

Fig. 1. Study area for the BWASP aerial surveys in the western Beaufort Sea. Solid lines represent the survey block boundaries; dashed and dotted lines represent the 20, 50, 200, and 2,000m isobaths.

which grid cells contain transect segments. Repeat this step 5,000 times.

(4) Compute the cumulative number of times (across all iterations) that the midpoint of each cell in the study area was found within a strip of transect. Divide these cumulative counts for each cell by the total number of iterations in the simulation (5,000 in this case) to compute cell-specific long-term survey coverage probabilities.

Survey blocks and associated 0.5º longitudinal bins used for the simulation were identical to those used to generate transects for actual BWASP surveys. During each iteration, one transect was placed inside each 0.5° bin by drawing random numbers from a uniform distribution to determine attachment points along the northern and southern boundary of the survey block within which the transect was located. Random numbers were independently drawn for each attachment point throughout the BWASP study area. The southern attachment points for transects in survey blocks bordering the Alaskan coastline were located on a 'modified coastline' having 52 straight-line segments that approximate the actual coastline (Fig. 2). This is the same modified coastline used to generate transects for an actual BWASP survey.

All analyses for this investigation were coded in R version 2.10.1 (*R* Development Core Team, 2009), using the packages maptools (Lewin-Koh *et al.*, 2009), rgdal (Keitt *et al.*, 2010) and sp (Pebesma and Bivand, 2005). Spatial analyses were computed only after re-projecting the spatial objects into a Lambert Azimuthal Equal Area projection as defined by the PROJ.4 projection library by the following parameterisation:

- Latitude at projection center: 70.0°N, Longitude at projection center: 154.5°W
- False Easting: 0, False Northing: 0.

An equal area projection was chosen for the spatial analyses because fidelity to the true surface area covered by each of the fine-scale grid cells in the simulation exercise was important for computing accurate estimates of survey coverage. R code for the analysis is available from the author upon request.

RESULTS

The long-term survey coverage probabilities across the BWASP study area were spatially heterogeneous (Fig. 3), ranging from 0.0 to 0.238 with a mean of 0.109 and CV of 0.432 (Fig. 4). Transects could not cross any of the borders of the 0.5° bins. In addition, the probability of a transect cutting at any angle across the bin was greater than the probability of a transect being oriented along a straight north/south axis at the edges of a bin, producing long-term survey coverage probabilities in the eastern and western margins of the bins that were at least half as large as those towards the interiors of the bins. As a result, when transects for many simulated surveys were pooled, the sampling coverage exhibited a pattern of repeating diamonds (associated with the longitudinal boundaries of the 0.5° bins used for transect placement) in which coverage probability was relatively low (Fig. 3).

Examination of the spatial lags inherent in the BWASP survey design was also informative. Sampling along the north/south axis of the study area could be considered continuous because transects cut across the bathymetric

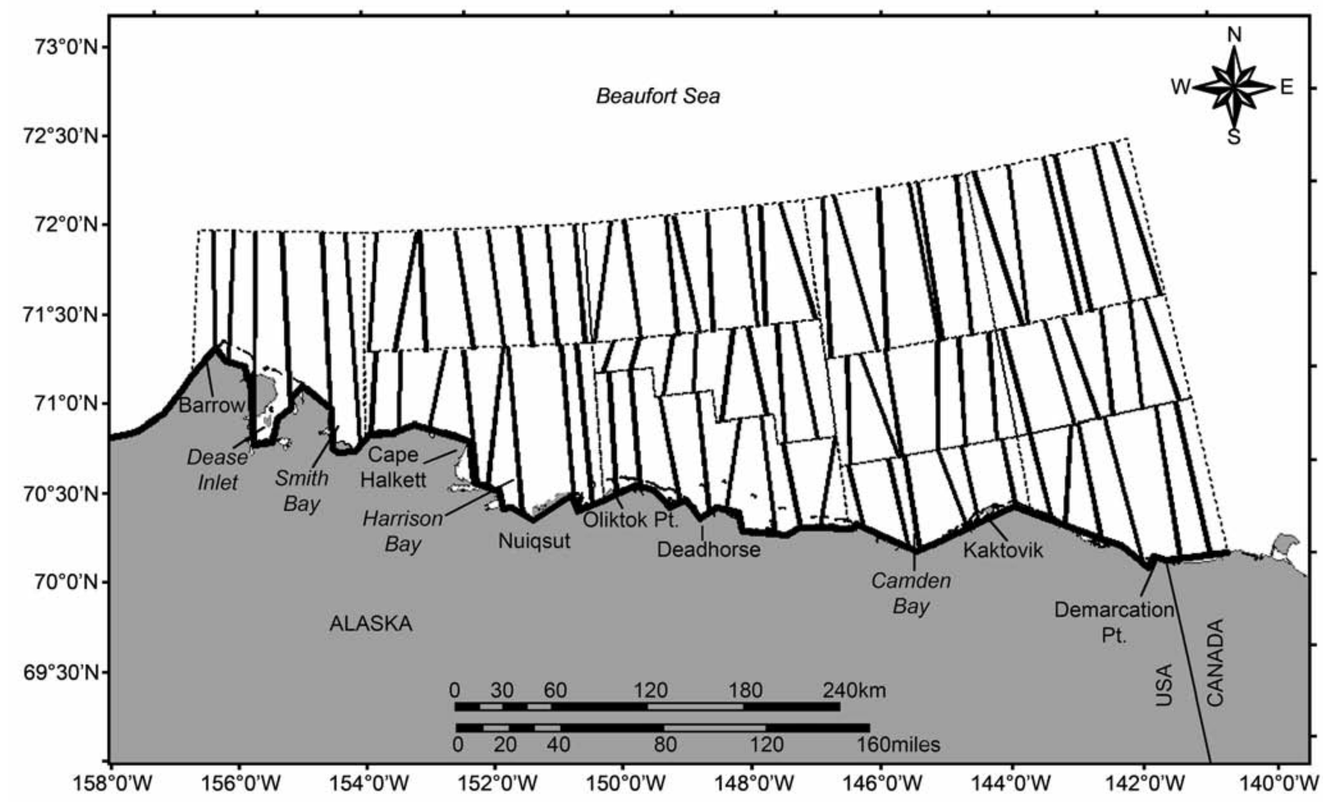

Fig. 2. Example of BWASP transects from one iteration of the simulation exercise, which corresponds to one complete survey. Bold line represents the modified coastline used as attachment points for BWASP transects.

contours from the coast to the offshore limit of the study area. The spatial lag along the east/west axis associated with a single survey corresponds to the width between the longitudinal bins within which transects are generated. This lag averages 0.5° of longitude, resulting in a range of 17.25 to 19.5km from the northern to southern borders of the study area, respectively.

DISCUSSION

Two fundamental spatial characteristics are inherent in the BWASP survey design: (1) sampling lags along the east/west axis arising from the spacing between adjacent transects; and (2) heterogeneity in the long-term survey coverage probabilities. The first characteristic should be considered when examining phenomena that are concurrent with a single survey, as stated in Dungan *et al.'s* (2002) fourth guideline for designing a field survey or experiment:

'The sampling lag (or spacing) should be smaller than the average distance between the structures resulting from the hypothesised process. Otherwise one may fail to recognise the structures (e.g. patches) as separate from one another….'

It is not possible to detect patches or variability along the east/west axis of the BWASP study area on scales smaller than the average distance between transect lines for a single survey. In contrast, the scale of investigations into one-dimensional phenomena that can be measured along a north/south axis, such as the median depth at which bowhead whales migrate, are limited only by sample size, temporal distribution of survey effort and the variability in whale distribution. These, in turn, affect the ability of a statistical analysis to separate ecological signal from noise (sampling error or effects of unobserved or unmodeled phenomena) (Houghton *et al.*, 1984). For certain analyses, such as estimating density, relative density, or habitat use, it might be possible to pool the BWASP data across years (or across time periods within a single year) to achieve higher sample (transect) density and therefore reduce the spatial lag associated with the transect spacing on a single survey. However, such an analysis may be biased if the spatial variability in long-term survey coverage probabilities and the temporal variability in effort across years (discussed below) are not accounted for. One simple method for accounting for the former is to incorporate a measure of survey effort (e.g. transect length) into the analysis.

Scientists and resource managers who are interested in whether the BWASP data can adequately inform their research or decision-making processes should ask the following two questions below.

(1) What scales of variability in bowhead whale distribution or relative abundance are relevant to the question under investigation?

(2) What is the range of scales over which the process under examination (for example, eddies, fronts, prey patches, or anthropogenic disturbance) could influence bowhead whale distribution or relative abundance?

If the scales of interest are smaller than the relevant sampling lags identified above for the BWASP data set, and if ecological arguments exist for not pooling survey effort across surveys in order to reduce the sampling lags, then another sampling method or survey design should be used to address the question.

There is a need for a similar examination of the BWASP survey design and field protocol with respect to: (1) time;

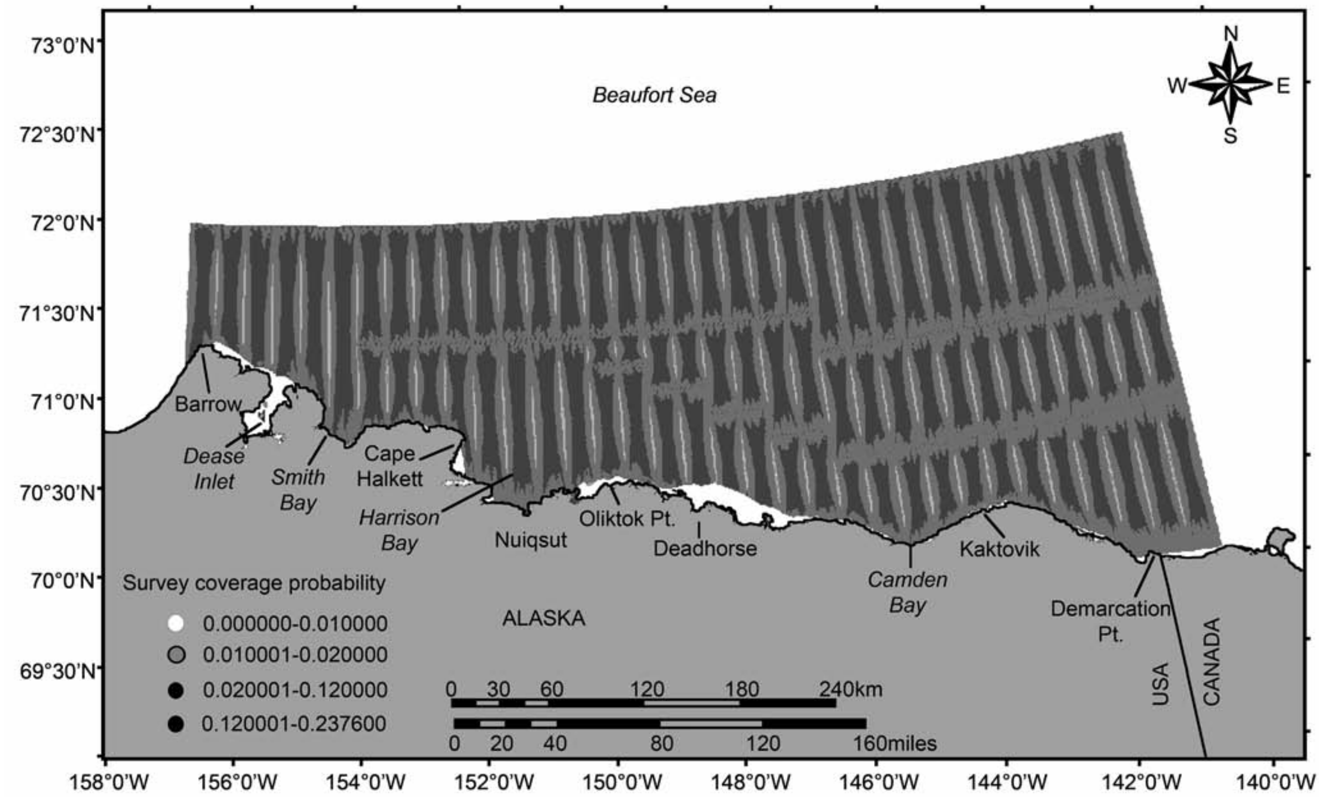

Fig. 3. Spatial distribution of survey coverage probability under the BWASP survey design within fine-scale (500m × 500m) grid cells computed by the simulation exercise with 5,000 simulated surveys.

and (2) space and time. The BWASP surveys do not encompass the entire duration of the autumn bowhead whale migration. Although the timing of the surveys has been relatively consistent across the years, the spatiotemporal coverage (the specific times at which certain regions within the study area are surveyed) has been neither consistent nor systematic. Factors that influenced the decision of where to fly included the following: reported or observed weather conditions; distribution of offshore seismic or drilling activity; occurrence of whaling near Cross Island in the central Alaskan Beaufort Sea and Kaktovik in the eastern Alaskan Beaufort Sea (the aerial surveys avoided these areas during the indigenous hunts); and, for the early survey years, an informal weighting of effort allocation by survey block based on the spatial variability in the relative abundance of bowhead whales throughout the study area during previous survey years (Monnett and Treacy, 2005). For the early survey years, examples exist where the decision to fly on a given day was dependent on sighting locations from the previous day, resulting in disproportionate and unplanned survey effort in areas of relatively high bowhead density and temporal autocorrelation in the data. In addition, areas such as the northeastern survey blocks that had low sighting rates in the early years tended to be undersampled in later years. Givens (2009) used sensitivity analyses to determine how the results of his spatiotemporal analysis of relative density of BCB bowheads based on the BWASP data would be affected by three hypothetical scenarios: (1) oversampling in the western region of the BWASP study area; (2) concentration of survey effort in areas where bowhead whales were thought to be present; and (3) oversampling in the western region plus concentration of survey effort in areas where bowhead whales were thought to be present in the western region. Sensitivity analyses such as Givens' (2009) are helpful in identifying the strengths and weaknesses of specific analyses when interpreting BWASP data, which were sometimes collected using complex spatial and temporal sampling schemes.

In conclusion, the BWASP surveys have increased understanding of the broad-scale patterns of bowhead whale (and other cetacean) distribution, relative abundance and

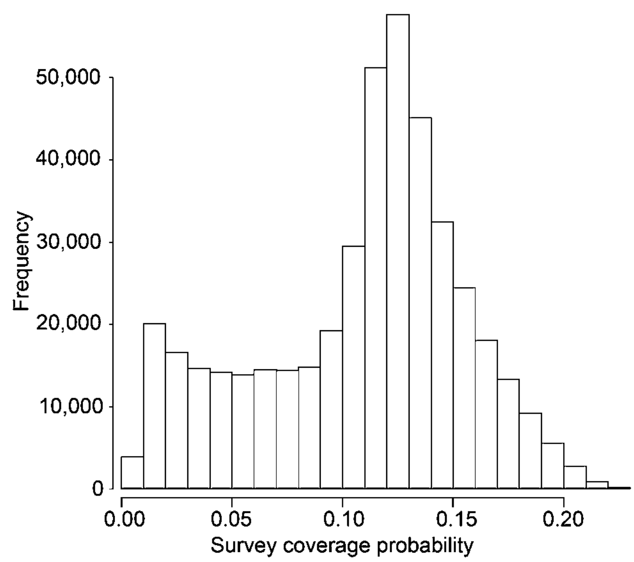

Fig. 4. Frequency histogram of survey coverage probabilities throughout the BWASP study area under the BWASP survey design. The frequencies indicate the number of times a simulated transect crossed through a 500m × 500m cell.

behaviour in the Alaskan Beaufort Sea during the autumn. Quantification of the spatial characteristics of the BWASP survey design has provided greater understanding of the utility and limitations of the BWASP data for other applications. Sampling lags in the BWASP survey design of approximately 20km along the east/west axis limit the spatial scale of phenomena that can be detected using data from a single BWASP survey. Depending upon the research question, it may be possible to pool data across surveys in order to conduct analyses on finer spatial scales, although results from some analyses might be biased if the spatial heterogeneity in the long-term survey coverage probabilities (or survey effort) and the temporal variability in the data are not accounted for. Investigations into smaller scale (less than 20km) phenomena oriented strictly in a north/south (offshore/onshore) direction might be possible using data from a single survey, depending on sample sizes and variability in the data, due to the continuous sampling along this axis (Houghton *et al.*, 1984). To put these numbers into perspective, spatial scales spanning hundreds of meters to hundreds of kilometers are typically relevant to bowhead whale feeding studies (Ashjian *et al.*, 2010); scales of the order of kilometers to hundreds of kilometers are often appropriate for studies into the effects of sea ice distribution on bowhead whale migration (Moore, 2000; Moore *et al.*, 2000; Moore and Laidre, 2006); similarly, examination of scales ranging from kilometers to hundreds of kilometers are often necessary for conducting research into the effects of anthropogenic disturbances on bowhead whale behaviour, distribution, and relative density, depending on the range of action or the extent of the disturbance and the characteristics of the effects that are of concern (Givens, 2009; Manly *et al.*, 2007; Schick and Urban, 2000). Hierarchical or nested sampling designs may provide valuable insight into phenomena relevant to bowhead whale ecology: broad-scale sampling, as implemented by BWASP, provides a regional context within which to interpret fine-scale data and analyses; fine-scale sampling is necessary to identify and understand local changes in small areas over short time periods. Similar investigations into other ecological systems, sampling designs, and data sets should be encouraged prior to undertaking spatial analyses.

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