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Methods for estimating density of bowhead whales (Balaena mysticetus) in the Beaufort Sea during fall migration: A review of progress and a proposal for future efforts

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INTRODUCTION

The bowhead whale, _Balaena mysticetus,_ inhabits the Bering, Chukchi, and Beaufort Seas. Bowheads migrate annually in the spring (April, May, and early June) from the Bering Sea north and east into the Beaufort Sea, and east to the MacKenzie Delta - Banks Island and Amundsen Gulf area located in Canadian waters. In early or mid-September, they make a westerly return migration near shore from Canadian waters past Point Barrow, and south to the Bering Sea.

These migrations take bowheads through or near areas currently being assessed as potential sources of mineral and oil resources. The bowhead whale is protected under both the Endangered Species Act and the Marine Mammal Protection Act and there is concern that resource related development may effect it.

From 1979 to the present, the Bureau of Land Management has funded the Naval Ocean Systems Center to conduct a study to determine the distribution and estimate population densityof bowheads in the vicinity of the Beaufort Sea oil lease areas (Ljungblad et al 1980, 1981, 1982).

Determining the distribution and occurrence of a species provides an evaluation of the relative importance of an area to that group. The density estimate for a particular area is useful when assessing how a portion of a species' range is utilized by the population. Sequential density estimates provide an invaluable tool when determining a population's response to its environment through time.

This paper describes the line transect technique used to calculate a density estimate of bowhead whales utilizing proposed Beaufort Sea oil lease areas during the fall migration of 1979 and 1980. This method of analysis is compared to the alternative technique of strip transect sampling. Summary recommendations describe stratified random quadrat sampling for future derivation of bowhead whale population density estimates.

METHODS

Aerial surveys were implemented as the best means of repetitively sampling a marine mammal population over a short period of time.

Line transect is one of the available methods that can be applied to aerial surveys, from which statistical inferences can be made. A density estimate for an animal population can be obtained when counting the entire population is not feasible. Populations do not have to be distributed randomly to use line transect methods, however, the position of the line must be selected randomly (Cochran 1963).

The areas for which the density estimate is calculated are illustrated in Figure 1 for 1979 and 1980.

Each study area was divided into rectangular, 18.5 km wide sections. The north-south transects were drawn by randomly picking two numbers between 1 and 20, matching these numbers to corresponding numbers marked at the top and bottom of the mapped rectangular section and drawing a line between these two points. An example survey flight track is illustrated in Figure 2. This basic design is adopted from Leatherwood (1979).

Prior to each survey flight, the randomly selected transect positions (turning points) were programmed into the aircraft's navigation system (Global Navigation System) which was then calibrated at a known location. Surveys were flown at an average altitude of 150 m. The intention was to maintain 305 m of altitude, but flights varied according to weather conditions. Airspeed varied between 183 and 201 km/h.

Figure 1. Study area for 1979 and 1980.

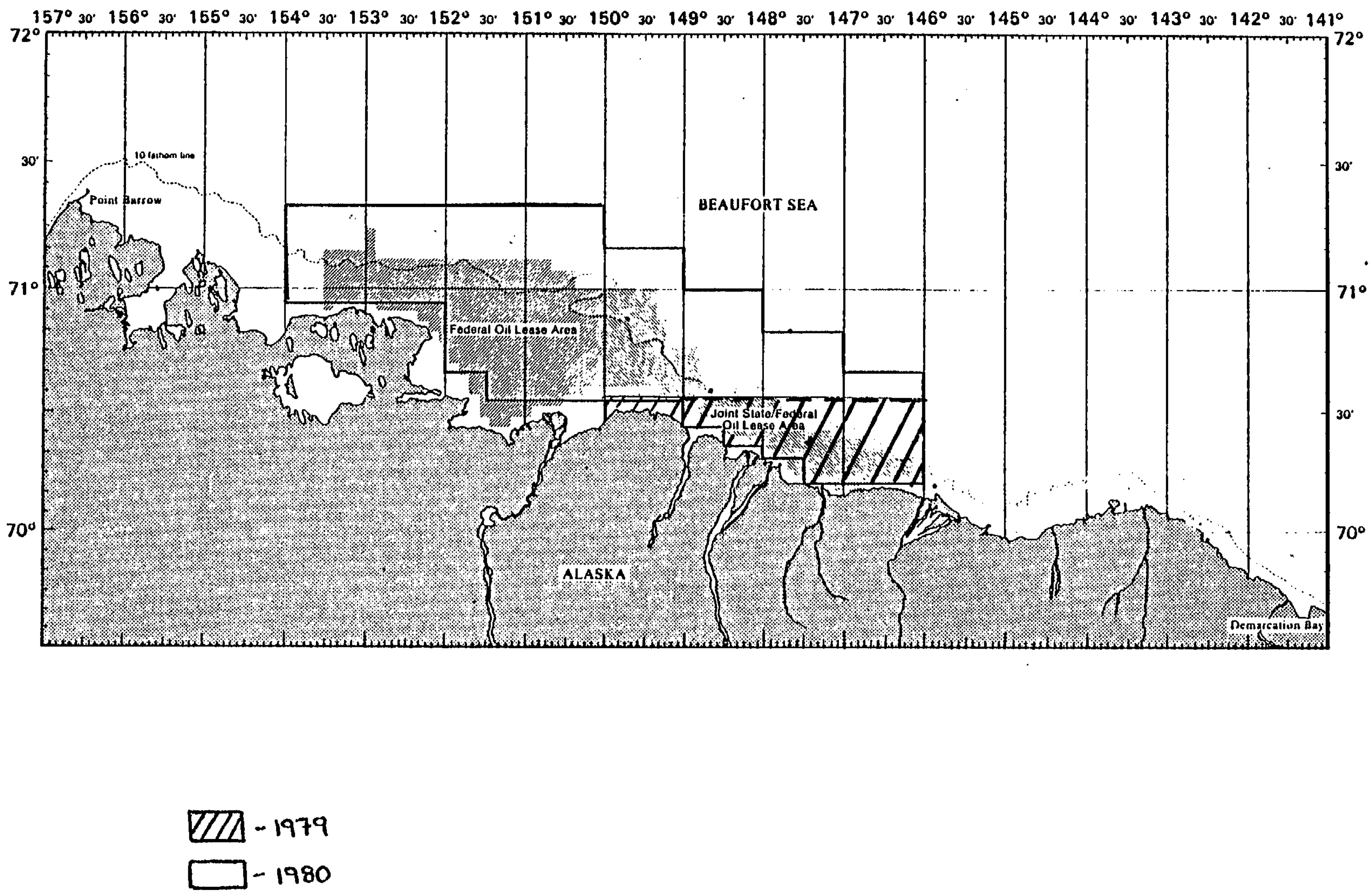
157° 30' 156° 30' 155° 30' 154° 30' 153° 30' 152° 30' 151° 30' 150° 30' 149° 30' 148° 30' 147° 30' 146° 30' 145° 30' 144° 30' 143° 30' 142° 30' 141°
72°
30'
71°
70°
10 fathom line
Point Barrow
BEAUFORT SEA
Federal Oil Lease Area
Joint State/Federal Oil Lease Area
ALASKA
Demarcation Bay
- 1979
- 1980

Figure 2. Sample survey design

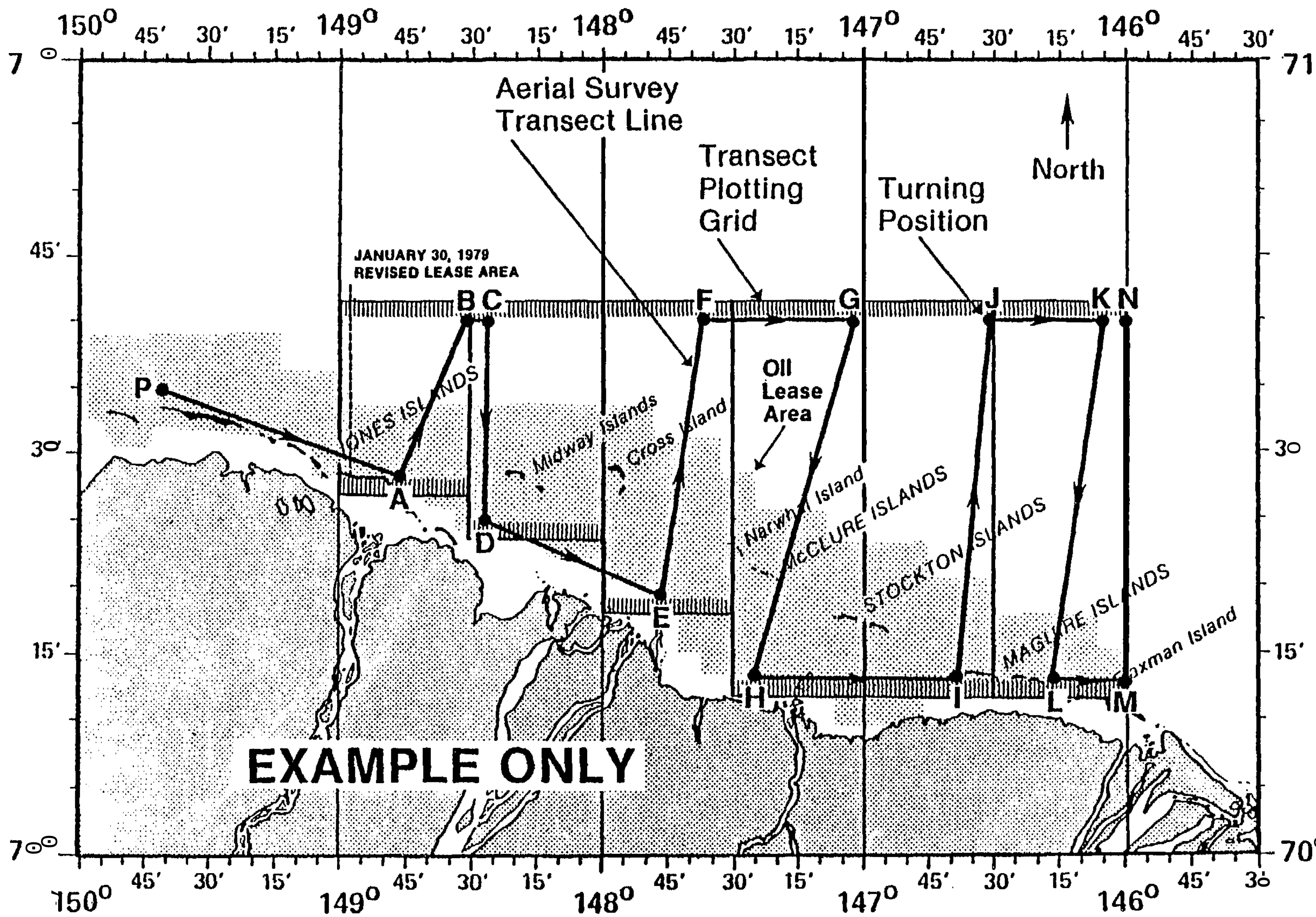

Figure 2. Sample survey design.

For all bowhead whales sighted, a clinometer angle was taken when the sighting was abeam of the aircraft. The altitude of the aircraft, the heading of the whale, the whales' behavior and group size were recorded also.

Assumptions

Estimating population density requires calculating the portion of that population which is never sighted. In order to correctly estimate density of any population, four underlying assumptions must be made and strictly adhered to. These assumptions are as follows: (1) there are no measurement errors and no rounding errors, (2) sightings are independent events, (3) individuals are fixed at an initial sighting position and no individuals are counted twice, (4) a sample of the population is collected at random; no individual is biasly selected during a count (Cox 1958, Anderson et al 1976).

In addition to these assumptions, several new assumptions specific to this study are required. Two factors inherent to a study of cetaceans that cause an individual to be missed during a count are sightability and submergence. Sightability means an individual may be surfaced, but missed by the observer. As the distance increases between the observer and a whale, the chance of sighting the whale decreases (Doi 1974, Doi 1975). Transect estimators are designed to work in planar situations. Hence, it is the portion of a population surfaced but not sighted, that is calculated when estimating total population. Secondly, whales are not sighted because they are submerged. A distinction must be made between whales at the surface, but not sighted and submerged whales that cannot be sighted. Submerged whales are never calculated in the total population estimate. These whales represent a source of known but currently unmeasurable error in the total population estimate (Eberhardt et al 1979).

A fifth assumption based on these two conditions is that only surfaced animals are counted and density estimates are calculated for the population of whales not submerged during an observation period[1].

A sixth assumption is that the whales' behaviors do not change over the period for which an estimate is calculated, (i.e., whales' maintain the same swimming speeds and dive patterns throughout the migratory period). This assumption is critical, yet difficult to uphold. Whales' behaviors do change with respect to ice cover and the period of migration (Ljungblad et al 1980, 1981, 1982).

A seventh assumption is that observers are equally effective on both sides of the aircraft and in all areas of the sighting sector. This assumption is necessary since each observer's sightings are weighted equally by formulas used in calculating population size. Any deviaiton from this assumption will cause a negative or downward bias on the final estimate.

An eighth assumption is that group size does not affect detection of whales. A violation of this assumption would cause a negative bias, since some classes of groups would not be sighted. This assumption is probably violated since larger groups are indeed easier to sight because the larger the group the higher the probability of having a whale at the surface.

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1 A combined estimate of the population of surfaced and submerged whales can be calculated if a ratio of dive time to surface time is known. This ratio is a correction factor which permits one to adjust the population estimate to incorporate submerged whales. Presently no good correction factor exists for all behavioral situations. Reliable dive time/surface time ratios have been calculated for non-migrating whales (Ljungblad et al 1982, Mate unpub.). Whales counted during the fall in the Beaufort Sea can either be actively migrating, moving slowly or milling and feeding depending on ice conditions. Dive time ratios have been calculated for milling and feeding patterns only. Existing ratios, therefore, cannot be used as correction factors.

A ninth assumption is that whales evade the aircraft. This assumption is upheld because the speed of the aircraft is extremely fast relative to the whales'. The aircraft probably approaches a whale before the whale can evade it by diving.

The final assumption is that unity of detection occurs on the flight track. All whales are sighted if they are on the transect line. The only whales that an observer fails to sight are those that are some distance away from the survey aircraft (Burnham et al 1980).

Line Transect

Line transect methods are based on the following formula to estimate density:

$$D = \frac{n\ f(o)}{2L},$$

where D is the estimated density, n is the number of animals sighted while surveying from a transect, f(o) is the detection function or the probability of sighting and animal and L is the total transect length surveyed.

The number of animals sighted and the transect length surveyed are known parameters. The detection function is the probability of sighting a surfaced whale at a known distance from the transect, and must be estimated for density to be calculated. It is used to determine the number of animals on the surface that are not seen.

The previously mentioned critical assumption that must be satisfied to validate the detection function is unity at the transect line; all individuals that occur on the transect line are counted.

This assumption was violated because the aircraft's design prevented searching between clinometer angles of 90° and 70° from the horizon. To compensate, all perpendicular distances were adjusted by subtracting a distance from the transect's centerline to a parallel line drawn by the 70° angle specific for the highest altitude flown. The original assumption of unity is modified to assume unity of sightings at these two parallel lines (Figure 3). The lines are placed at a position equidistant from the transect line; the distance being the perpendicular distance for a 70° clinometer angle at the highest altitude surveyed.

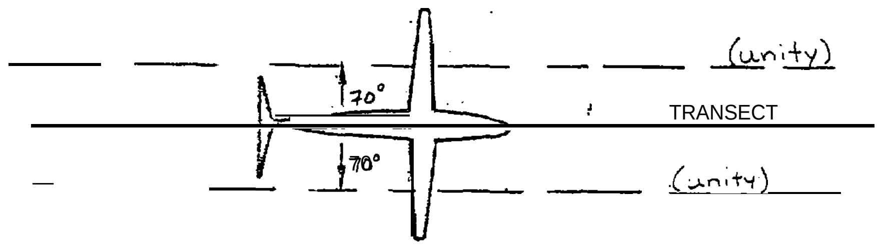
Previous studies have shown both the accuracy and precision of line transect estimators rely on the ability to determine the exact distance of an individual sighting from the transect line. A fundamental problem now arises. The transect line has been transformed to represent two parallel lines determined by a 70° clinometer angle at the highest altitude surveyed. If a sighting occurs at an altitude lower than the altitude used to attain the parallel transect lines, but at a 70°, the sighting will occur in a mathematical "blind spot". The blind spot being the area between the two parallel lines. A blind spot confuses any effort to mathematically model the true probability of detecting whales at varying distances from the survey aircraft. A negative bias or under estimation of the true population is the result of a mathematical blind spot.

Another assumption that may be violated is that there are no measurement errors and no rounding errors. Exact sighting angles are difficult to obtain. A deviation of several degrees from the true sighting angle will significantly alter the density estimate.

As long as sampling is completed with respect to random transects, the detection function, f(o), is the critical estimation made. Determining which specific mathematical model best fits the detection function is most easily done by program computer models. TRANSECT

Figure 3. Due to aircraft design, assumption of unity at centerline is modified to assume unity at two parallel lines drawn by the 70° angle for the highest altitude flown.

A.



B.

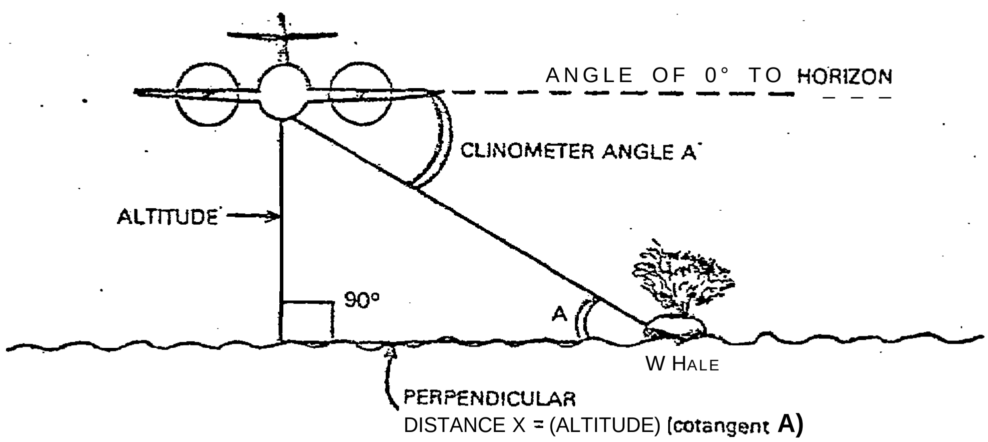


Figure 3 A.) Diagram of an aircraft flying a line transect showing two parallel lines (at 70° from horizon) that replaces transect line as line(s) along which every animal is counted (unity).

B.) Diagram showing the trigonometric relationships used to obtain the perpendicular distance X from clinometer angle A and aircraft's altitude

(Burnham et al 1980) is a program inclusive of parametric and non-parametric mathematical models applicable to fitting curves to data comprised of perpendicular distances.

We used this program when calculating our bowhead density estimates for 1980 and 1981.

Strip Transect

Strip transect estimators are an alternative to line transect estimators. The fundamental difference is strip transect sample a strip defined by boundaries, where line transect samples an area without boundaries. Both methods sample from a predetermined, randomly selected transect. The basic formula for strip transect estimators (Hayne 1949) is as follows:

$$N = \frac{nA}{2LH},$$

where N is the estimated animal population, n is the number of individuals counted, A is area of strip, L is the transect length and H is the mean sighting distance. Strip transect have a predetermined strip width, within which the observer is required to be certain of counting all individuals. This method does not utilize a detection function that incorporates sightings to the horizon. Individuals outside the strip are not counted, even if seen. For this reason, strip transect methods are recommended when the species density is high and individual counts are large. Line transect estimators should be used when densities are sparse so that every individual sighted is used in the estimate. The detection function removes restraints of distance and permits every individual sighted to be incorporated into the population estimate. Line transects are conceptually a strip transect with infinite strip width.

When using strip transect estimators, the number of bowheads that migrated through an area (N) is determined by the formula:

$$N = \frac{D \cdot A \cdot M}{R},$$

where D is the density estimate derived from the either method previously described, A is the study area of the interest, M is the migration period, and R is the migration speed over the migration route.

We did not use this method because bowhead densities are sparse and we could not ensure that every whale within a strip would be counted.

RESULTS

The 1979 and 1980 bowhead density estimate was derived using the computer program TRANSECT (Burnham et al 1980). This program evaluates aerial survey data with respect to the assumptions and parameters of line transect density estimators.

In 1979 the study area and the near vicinity was surveyed from 2 August until 20 October. The survey area (A), was 4,519 km^2. Sightings were made in the area from 26 September to 17 October. A 25-day migration period was defined from 26 September to 20 October.

Bowheads began migrating through the study area at low numbers. The number of whales gradually increased until a peak was reached, then migration quickly fell off, leaving a few stragglers in the area.

This migration pattern illustrates the difficulty of determining the influence of migratory behavior on the estimated number of bowheads utilizing the study area. The density of bowheads is, therefore, calculated only for the 10 day period of peak migration and does not reflect density over the entire migratory period.

If the full 25-day migration period is used, the number of bowheads, N, would be positively biased. For 1979, M becomes 10 days and N is newly defined as the number of bowheads that utilize the study area during peak migration.

The average length of time to migrate through the study area, R, is estimated to be 7.5 days and was derived by drawing a straight line through the study area that intercepted the greatest number of sighting positions. This variable is a result of two independent factors; swimming speed (including the effect of currents) and migration route. The migration route was estimated to be 82.2 km. Swimming speed was estimated below 1 knot.

Twenty individual sightings were made while flying transects. The cumulative transect length was 3,121 km. The half-normal series yielded the most appropriate detection function for the 1979 bowhead data. The resultant density of 17.4 bowheads present at any one time during peak migration was calculated for the survey area. Confidence limits from 14.0 to 20.8 bowheads were calculated at the 95-percent level.

The study area for 1980 was expanded to include Federal Sale 71. This increased the size of the study area to 17,719 km^2.

Sightings were made on 22 survey flights from 9 September to 9 October. A 31 day migration period was concluded.

Bowheads migrated through the study area in constant low numbers. There appeared to be no peak in migration, as evident in 1979. Therefore, a density estimate calculated for 1980 need not be restricted to a specific time period within the migration period.

Swimming speed was estimated at 2.5 knots. Compared to 1979, 1980 was a heavy ice year perhaps forcing the whales to move through the area faster. The estimated migration route was 294.8 km. The resultant rate R, was 2.7 days. The density estimate for 1980 was calculated for the period 20 September to 9 October because only flights made during this period satisfy the assumption of line transect estimation.

Thirteen sightings were made while flying a cumulative transect length of 7,248 km. Again, the half-normal series yielded the most appropriate detection function. A density estimate of 14.5 bowheads present at any one time during the migration period was calculated for the study area. Confidence limits from 11.5 to 17.5 whales were calculated at the 95-percent level.

No attempt was made to determine a density estimate in 1981 as the main effort this season was to study behaviors and dive profiles.

DISCUSSION

The densities calculated for 1979 and 1980 are not directly comparable. Two criteria changed each year which makes it statistically incorrect to directly compare density. First, the ice or surface habitat differed between years. In 1979, the study area remained nearly ice free during the fall migration period. Solid ice did not form until late in the season (15 October). In 1980, ice formedearly.Ice coverage accumulated to an average of 7/10 during early September. By 16 September freeze-up began. During the remainder of the 1980 survey ice coverage ranged from 7/10 to 9/10 in and about the study area. The probability of sighting whales was not constant between years with different ice cover because of the constraints of transect sampling.

The second criteria that changed because of ice conditions was the whales' behavior and speed. Fall swimming speeds, for 1979, were estimated to be 1 knot or less. Whales were observed apparently feeding lying or milling about at the surface. The overall behavior of the population was that of an unhurried, westerly migration. During the fall of 1980, bowheads were noted constantly migrating through the study area exhibiting swimming speeds from 1.5 to 3.0 knots. Whales seen were swimming rapidly and diving quickly. This is an extremely important point. For in actuality, our calculations are not the total densities of bowhead whales occupying the 3-dimensional waters of the study area, but the densities of whales occurring at the planar surface of the water. Therefore, our calculations are the minimum density of bowheads present in the 3-dimensional waters of the study area. Whales on the transect line, but beneath the surface of the water cannot be accounted for using the present survey technique. If our calculations are extrapolated to the entire population migrating through the study area, primary statistical assumptions would be violated. Our calculations are valid in respect to techniques used and do establish minimum values from which projections can be made to the entire population.

The two most important factors affecting sightability are submergence and surface conditions. If sightibility is biased, the population estimate is lowered. Investigators (McLaren 1961, Eberhardt et al 1979) have suggested correction factors for transect estimators to account for submergence. Attempts to date have been futile and Eberhardt et al (1979) recognized submergence (dive profiles) patterns of cetaceaus as the main factor preventing reliable estimates. A correction factor for transect estimators must adjust the probability of sighting to incorporate the probability of a whale being at the surface. The following formula describes this relationship:

$$P' = \frac{S}{S + U} \times \hat{P}.$$

P′ is the probability of sighting a whale given it is in the study area. $\hat{P}$ is the probability of sighting a whale that is surfaced.

This $\hat{P}$ is the detection function. S is the whales' average surface time. U is the whales' average dive time. Therefore, S/(S + U) is the probability of a whale being surfaced. The validityof this model is based upon a binomial distribution of dive time or constant dive times. Ljungblad et al (1982) showed dive times are not constant for bowheads whales when comparing three seasons. The validity of a correction factor cannot be upheld, therefore a correction factor for submerged whales cannot currently be applied to transect data.

Finally, variability in weather, sea conditions and ice coverage changes the probability of sighting whales at the surface. The change increases as the distance increases from the transect line. The bias is negative and cannot be measured.

Density estimates calculated for 1979 and 1980 are absolute estimates. These estimates are not relative estimates or population indices.

Relative estimates or population indices are ratios. The number of bowhead whales sighted per 1,000 transect kilometers for 9/10 ice coverage is an example of an index or relative estimate. These estimates indicate general trends of a population between sampling periods.

Absolute estimates not only indicate population trends, but supply a means of determining the demographic importance of an area to a population. Because we do not yet know enough about bowhead dive profiles in varying ecological conditions these density estimates underestimate the true population by an unknown amount.

The distribution, behavior and density estimate information gathered over the last 3 years provide a sound data base for stratified random quadrat sampling. Reliable strata boundaries required in random quadrat sampling can be drawn using the biogeographic data accumulated in the last 3 years. We discuss stratified random quadrat sampling in the next section as a recommendation because we feel it is the best method for future density estimates of bowhead whales in this area.

Recommendation

Problems associated with determining reliable density estimates are mainly a result of rigid statistical assumptions not being compatible with the behavior of cetaceans. The reliability of density estimates would increase if the statistical assumptions could be more closely related to cetaceans behavior. A sampling technique which partially achieves this objective is stratified random quadrat sampling. Stratification has reduced error variance in wildlife population studies by up to 30% (Blankenship et al 1971, Grier 1977, Seber 1980).2

2 The following example illustrates how error variance is reduced when stratification is implemented. Let p equal the probability of sighting a whale. The probabilityof not sighting a whale is q or 1 - P. The known population of whales is N. The variance about N is Var[N] = Nq/p. Table 1 illustrates how error is related to probabilityof sighting, even when the population is known.

Table 1. Example of error variance.

P	q	N	Nq/P
.80	.20	500	125
.70	.30	500	214
.50	.50	500	500
.30	.70	500	1,167
.20	.80	500	2,000
.10	.90	500	4,500

The variance increases as the probability of sighting decreases. The probability of sighting automatically decreases if the distribution is not homogeneous because of averaging. Strip and line transect

Line and strip transect estimators assume that a population's distribution is homogeneous, and unchanged throughout the entire study area. If distribution is not homogeneous (i.e., if in one portion of the study area it is distributed uniformly and in another portion of the study area it has a clumped distribution), but hetergeneous,. a large error variance will result.

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[2] (Continued) estimators average the probability of sighting whales in both low and high concentrations to estimate the overall probability of sighting (known as the detection function in line transect).

Table 2 illustrates the reduction in error with stratified sampling when the study area does not have a homogeneous distribution.

Table 2. Comparison of error variance between strip/line transect sampling techniques and stratified sampling technique given a known population that does not have a homogeneous probability of sighting. Population is 500 individuals.

Study Area = Unit A and Unit B

P		q		N	
Unit A	Unit B	Unit A	Unit B	Unit A	Unit B
.60	.50	.40	.50	400	100
.60	.40	.40	.60	400	100
.60	.30	.40	.70	400	100
.60	.20	.40	.80	400	100

Variance: Strip line	Variance: Stratified
$Var[N] = \frac{N_a + N_b}{P_a} \bullet \frac{q_a + q_b}{P_b}$	$Var[N] = \frac{N_a q_a}{P_a} + \frac{N_b q_b}{P_b}$
409	367
500	417
611	500
750	667

This simple example illustrates an error variance reduction of 11% by using stratified random sampling.

Stratified random sampling upholds the basic statistical assumptions of randomization, yet permits the sampling technique to be adjusted with respect to the ecology and behavior of cetaceans. The design has five steps that are listed below. The method blocks the study area into homogeneous units, hence adapting to heterogeneous changes in distribution. This yields a more reliable measurement of the probability of sighting individuals.

Step 1. Determine the distribution and/or concentration of whales to be sampled.

Step 2. Divide the study area into four stata. Each strata is an internally homogeneous, non-overlapping subpopulation of whales. Strata boundaries are drawn where the concentration of whales changes. The size of a strata must be small enough to be covered in one flight.

Step 3. Determine how many times each strata is to be sample to complete the study. Sampling effort will be optimally allocated to reflect the relative density of whales in the stata. It is assumed the greater the concentration of whales, the greater the relative density (Eberhardt 1968, Cochran 1963). Sampling effort increases as the concentration of whales among strata increases. Strata with high concentrations of whales will be surveyed more than strata with low concentrations of whales. Hence, the probability of sighting whales increases, lowering error variance and increasing flight time efficiency.

Step 4. Grid the entire study area without respect to strata.

Step 5. Randomly select the grids to be sampled, reflecting individual strata sampling effort. Only grids inclusive of strata are sampled.

Figure 4 is an example of how this design may be adapted to the Beaufort Sea oil lease areas. Strata 1 contains the highest concentration of whales and concentration decreases to stata 4. Strata 1 will have the greatest sampling effort applied towards it. However, strata 1 contains the fewest grids. Grids in strata 1 will be repetitively sampled, where as not all grids in strata 4 will be sampled. The number of grids to be sampled per strata is determined by the following formula:

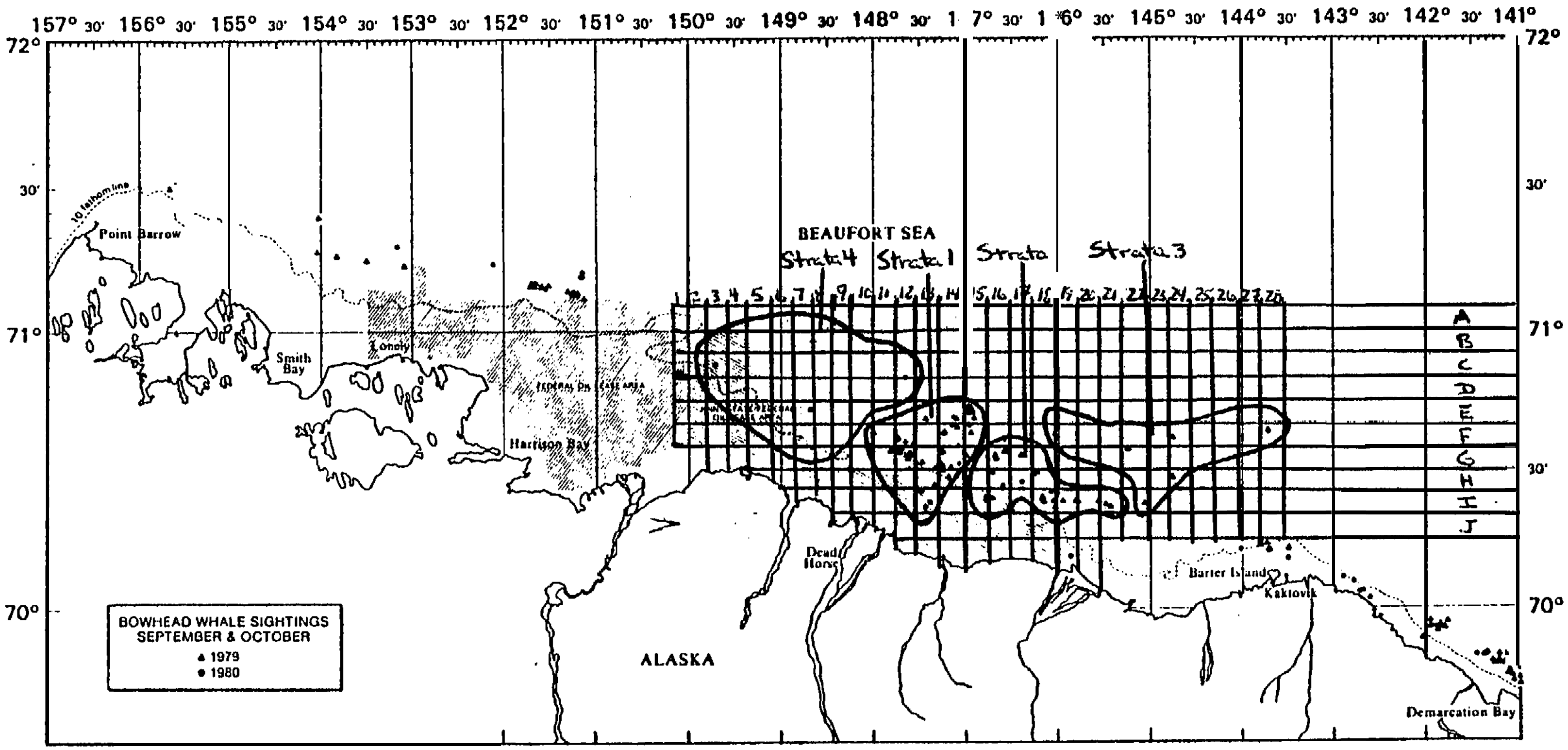
$$N_h \cdot W_h \cdot S_h = T_h \; .$$

N_h is the number of grids overlaid onto strata h, W_h is proportion of grids in strata h of the total number of grids for all strata, S_h is the relative density or concentration of whales in strata h and T_h is the number of grids to be sampled in strata h.

Once a grid is randomly selected it is sampled without the restrictions of a transect. Quadrat sampling involves surveying the respective grid by the most efficient pattern possible. The important point is the grid is intensively sampled. An absolute count of animals in then determined per grid. The advantage is a grid can be circled without time or flight limitations so that submerged whales can have time to surface and be counted. Also, since transects are not flown, a detection function is not estimated and the blind spot no longer exists. All whales sighted are used in the estimate. Hence, quadrat sampling is a direct count method.

Grids are selected randomly and independently, yet individual flight track patterns do not have to be random. Density is determined by adding the individual counts for each strata and mathematically weighing each count proportional to its respective strata sampling effort.

Figure 4. Example application of stratified random quadrat sampling to the Beaufort Sea study area.



(Combined distribution of bowheads for the falls of 1979 and 1980)

Siniff and Skoog (1964) state three reasons why quadrat sampling is preferred to transect sampling for estimating wildlife population from aerial surveys. First, deviation of the aircraft from a constant transect heading and altitude due to air currents and piloting limitations increases error. Second, dissimilar habitat conditions result in a disproportionate number of animals missed because of variable sighting conditions when flying transects. Third, the rather fast coverage of census area from a transect makes searching and retracing difficult. Laws et al (1975) expands upon these three reasons by listing five advantages of quadrant sampling. First, an area can be searched with no fixed time limit. Second, quadrant sampling removes the problems of animal movement with respect to transect placement. Third, the detection function is not estimated. Fourth, altitude and flight speed can be adjusted. Fifth, circling a quadrat increases the probability of sighting animals, thus error variance is reduced.

Stratified random quadrat sampling has not been used for cetaceans surveys because of the lack of preliminary information required to draw strata boundaries representative of relative densities (Estes 1976, Eberhardt et al 1979). However, quadrat sampling can be used to determine the density of bowhead whales in the Beaufort Sea study areas because this information is known (Ljungblad et al 1980, 1981, 1982). The capability to determine a more meaningful density estimate of bowhead whales in the Beaufort Sea study areas now exists.

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