Spatial components of bowhead whale (*Balaena mysticetus*) distribution in the Alaskan Beaufort Sea

R.S. Schick and D.L. Urban

Abstract: Bowhead whales (*Balaena mysticetus*) on their fall migration are exposed to oil exploration activities in the Alaskan Beaufort Sea. While previous research into the effect of industrial noise on whale behavior and distribution has noted significant responses, this research has often proceeded from a parametric statistical framework. To account for the presence of spatially autocorrelated and intercorrelated data, we propose a suite of spatial analysis techniques to assess the distribution of bowhead whales relative to oil exploration activities. Using random resampling techniques and Mantel tests, we analyzed the distribution of bowhead whales around active drilling rigs in 1993. Results from the resampling tests indicated that whales were distributed farther from the drilling rig than they would be under a random scenario. Results from the Mantel tests indicated that in 1993, the spatial pattern of bowhead whale distribution was highly correlated with distance from the drilling rig, indicating that the presence of the drilling rig resulted in a significant temporary loss in available habitat. These techniques offer a new perspective on spatial analysis in the marine realm.

Résumé : La baleine boréale (*Balaena mysticetus*) est, au cours de sa migration automnale, exposée aux activités de prospection pétrolière dans les eaux alaskiennes de la mer de Beaufort. Si des recherches antérieures concernant les effets des bruits industriels sur le comportement et la distribution des cétacés ont relevé des réactions significatives, ces travaux sont souvent partis d'un cadre statistique paramétrique. Pour rendre compte de la présence de données spatialement autocorrélées et intercorrélées, nous proposons un ensemble de techniques d'analyse spatiale permettant d'évaluer la distribution des baleines boréales par rapport aux activités de prospection pétrolière. À l'aide de techniques de rééchantillonnage et de tests de Mantel, nous avons analysé la distribution des baleines boréales autour de plates-formes de forage en activité en 1993. Les résultats des tests de rééchantillonnage ont indiqué que les baleines étaient distribuées plus loin de la plate-forme qu'elles ne le seraient selon un scénario aléatoire. Les résultats des tests de Mantel ont indiqué qu'en 1993 le patron spatial de distribution des baleines boréales était hautement corrélé à la distance par rapport à la plate-forme, ce qui montre que la présence de la plate-forme de forage causait une perte temporaire no table d'habitat disponible. Ces techniques ouvrent de nouvelles perspectives à l'analyse spatiale dans le domaine marin.

[Traduit par la Rédaction]

Introduction

Westward-migrating bowhead whales (*Balaena mysticetus*) in the Alaskan Beaufort Sea travel through areas of oil industry exploration and are exposed to its associated noises. Ascertaining the degree to which industrial activity affects these and other marine mammals has been a goal of researchers and managers alike for 20 years (Richardson and Malme 1993), with research activities ranging from direct observations of behavioral response to industrial noise (Richardson et al. 1985) to playback experiments (Richardson et al. 1990) to geographic information system (GIS) based analysis (Davies 1997). Results have been varied, but several conclusions have been reached. Bowhead whales exhibit stronger responses to consistent noise than to pulsed noise, even if the latter is significantly louder, as it is with seismic exploration (Richardson and Malme 1993). In addition, bowhead whales exhibit greater response to sound sources with increasing sound levels as produced, for example, by an approaching ship (Richardson and Malme 1993). Finally, there seems to be interannual variation in bowhead whale response to fixed drilling units. Bowhead whales seem to respond differently to drilling units during autumn migration than during summer feeding (Richardson and Malme 1993). Richardson and Malme (1993) suggested that whales migrating out of the Beaufort Sea may to be more sensitive to drilling noise than summering bowheads; however, they cautioned that corroboration of this conclusion is needed. Although much remains to be determined in this area, significant short-term behavioral responses have been documented and remain an area of concern for managers and researchers (Richardson and Malme 1993).

Bowhead whales are found in several of the world's arctic oceans and are managed as separate stocks (Moore and Reeves 1993). The Bering–Chukchi–Beaufort stock, which is the focus of this study, migrates into the Bering and Beaufort seas in late spring and early summer after the ice pack retreats.

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R.S. Schick[1] and D.L. Urban. Nicholas School of the Environment, Duke University, Durham, NC 27708, U.S.A.

[1]Author to whom all correspondence should be sent at the following address: Edgerton Research Laboratory, New England Aquarium, Central Wharf, Boston, MA 02110-3399, U.S.A. e-mail: rschick@neaq.org

Bowhead whales spend the summer feeding primarily in the Canadian Beaufort Sea and begin their westward migration along the coast out of the Beaufort Sea in late August and early September (Moore and Reeves 1993). It is on their westward migration that bowhead whales encounter oil industry exploration and extraction activities as they swim close to shore.

Previous research into habitat use by bowhead whales in the Beaufort Sea has noted several factors, both natural and anthropogenic, that contribute to observed distributions. These factors include time of year relative to when whales start their migrations in and out of the Beaufort Sea (Moore and Reeves 1993), physical oceanography, in terms of how ocean currents, wind, and ice interact to generate areas of high primary productivity (Moore and DeMaster 1998), and ocean depth, as the geographic character of the ocean bottom can indicate potential areas of upwelling and resulting productivity (Ljungblad et al. 1986; Moore et al. 1989; Moore and DeMaster 1998). Additional factors, such as the presence of anthropogenic activity, also contribute to observed patterns (Moore and Clarke 1993). In terms of pattern-generating agents (Delcourt et al. 1983; Urban et al. 1987), abiotic processes include oceanographic processes, ice pack movements, and wind-driven ocean currents in the Beaufort Sea, while biotic processes include migration and feeding patterns. The effect of offshore drilling rigs can be postulated as a disturbance stimulus that interacts with and modifies the abiotic and biotic patterns.

While some previous research into noise effects on bowhead whales has indicated a significant effect of oil exploration on species distribution (for a comprehensive review, see Richardson and Malme 1993), few of these studies addressed the problems posed by spatial autocorrelation of ecological data. Spatial autocorrelation is exhibited where, at some distance apart, the variables have values that are more similar (positive autocorrelation) or less similar (negative autocorrelation) than would be expected randomly (Legendre 1993). Attempts to document a causative reason for an observed distribution using traditional parametric statistics seldom adequately address the problem of spatial autocorrelation (Sokal and Oden 1978; Legendre and Fortin 1989). Previous research into the effect of anthropogenic noise on bowhead whales has often proceeded from a parametric framework, which assumes independence of data. The use of such statistics can lead to excessive Type I errors, where differences may be claimed significant when in fact they are not (Legendre and Fortin 1989).

Landscape ecology is concerned with understanding and quantifying the interaction between the environment and species distribution at large scales (Risser et al. 1984; Urban et al. 1987; Turner 1989). Despite a terrestrial bias in the field, the techniques are germane to marine applications and are of interest here.

The Mantel test (Mantel 1967; Legendre and Fortin 1989; Legendre and Legendre 1998) has been proposed as a way to test whether observed spatial patterns are controlled by environmental variables while accounting for spatial autocorrelation. Several terrestrial studies have used a Mantel test as a way of discerning which environmental variables have the strongest effect on species distribution in plants (Leduc et al. 1992; Fortin and Gurevitch 1993). Here, the use of the Mantel test allowed us to assess how much of the observed spatial variation in bowhead whale distribution was explained by the spatial distribution of measured ecological variables and how much of the spatial variation remained to be explained by other factors.

In this study, we analyzed data collected by a marine mammal observation program conducted in conjunction with an oil exploration prospect in the Alaskan Beaufort Sea (Coastal Offshore and Pacific Corporation (COPAC) 1994). Nonparametric randomization techniques as well as simple and partial Mantel tests were used to test the correlation between bowhead whale distribution and interpolated variables, including water depth, distance to shore, and distance to the drilling rig. These techniques have broad application in the marine realm.

Methods

Study area

The study area lies due north of the North Slope of Alaska in the Beaufort Sea region of the Arctic Ocean (Fig. 1). The Beaufort Sea is characterized by a narrow continental shelf and a steep continental slope. The predominant Beaufort Undercurrent flows west to east seaward of the 50-m isobath (Aagard 1984). Shoreward of the 50-m isobath, the ocean currents are primarily wind driven, moving from east to west (Aagard 1984). The Beaufort Sea is covered by ice from December through July (Moore and DeMaster 1998).

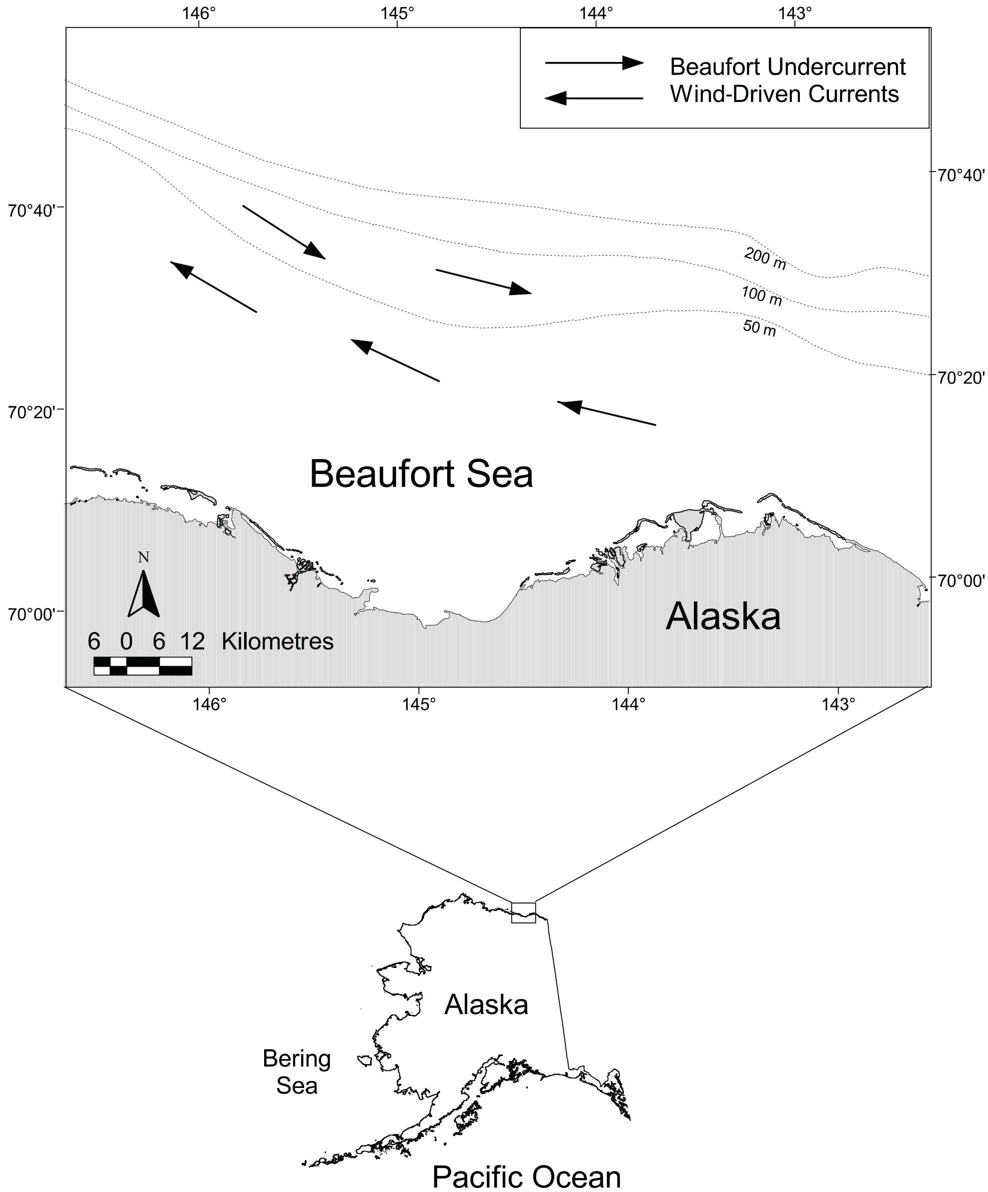
Sampling

A marine mammal monitoring program was required as part of an oil exploration lease agreement to Arco Alaska Incorporated. This research program was conducted by COPAC for Arco, and it is their data that provide the foundation for the present study (COPAC 1994). This monitoring program included several phases: (*i*) a drilling rig based observation program and (*ii*) an aerial survey program of the area around the drilling rig. In addition to these formal programs, observers aboard support vessels, such as icebreakers and supply transport ships, were required to take note of each marine mammal sighting in the vicinity of the drilling operation.

Aerial surveys in 1993 included both a proximal grid of survey lines around the well and a second grid some distance to the east (Fig. 2). The distant grid was designed to enable comparison of marine mammal distribution between the prospected area and an environmentally similar area where no industrial activities had taken place (COPAC 1994). For the purposes of this analysis, the distant grid and its associated whale sightings were not included. Although both survey grids were environmentally similar, comparison of the two areas was not useful because we could not assume that the distribution in the proximal grid would equal that of the distant grid in the absence of the drilling rig. Since we were trying to test whether the presence of the drilling rig altered the spatial pattern of whale distribution, the lack of a drilling rig in the distant grid precluded direct comparison for this variable.

In 1993, aerial surveys were flown between August 17 and October 28. The 1993 surveys coincided with the drilling of three separate wells, and the data used here were collected during the Kuvlum No. 3 prospect (August–October 1993) and overlap with the fall bowhead migration (Moore and Reeves 1993). Surveys were flown on north–south transect lines 12.9 km apart. Transects were flown at altitudes of 257–457 m at an average speed of 222 km·h^{-1} (COPAC 1994). As marine mammals were sighted, aircraft position was recorded, as were declination angles to the center of the group, number of animals, group composition, behavior, travel direction, and estimated swim speed (COPAC 1994). Pod

Fig. 1. Study area and locator map with relevant oceanographic features highlighted. Isobaths are indicated by dotted lines.



sightings were filtered to exclude those seen >3 km from the transect line, those seen during surveys that covered less than the entire length of the prescribed transect legs, and those seen in high-fog conditions (Buckland et al. 1993; Davies 1997). This filtering method reduced the total number of sightings in the analysis from 76 to 56 (Fig. 2). With regard to the drilling status of the drilling rig, 45% of these pods (n = 25) were seen while the rig was tripping, 31% while the rig was idle (n = 17), and 17% while the rig was drilling (n = 10), and no drilling status was available for 6% of the sightings (n = 4) (COPAC 1994). High levels of sound (>150 dB re 1 μPa at 1 m) were reported for both tripping and drilling, but no sound levels were reported for times when the rig was idle (COPAC 1994). Aerial surveys were also flown in 1992 (Fig. 2), yet were not sampled with the same rigor as the 1993 data (COPAC 1993). The whale pods seen in 1992 (n = 27) were analyzed as the 1993 whales were, yet due to the increased rigor with which the 1993 data were collected, these data present a more robust sample of whale distribution and afford us increased confidence in the associated results. The 1992 data will be referred to in the Discussion only.

A GIS (ArcInfo; Environmental Systems Research Institute, Inc. 1998) was used to construct a spatial database of whale sighting locations in relation to associated cartographic features such as coastline and depth contours. All GIS coverages (layers) were projected into the Lambert Azimuthal projection to minimize polar distortion. Had the data been left unprojected in decimal degree units, distance calculations would have been distorted because of the high latitude at which these data were sampled.

GIS coverages were constructed for three variables: water depth, distance to shore, and distance to the drilling rig. Distance to the drilling rig was used as a proxy for received sound level because measured data for sound levels were not available for each sighting. Because sound decays in an inverse square fashion but bottom topography, water depth, Beaufort Sea state, and ice presence can alter the sound, this is not an exact measure of sound at a given location but is nevertheless a useful approximation (Davies 1997). We hasten to add that because no data exist for sound level at each sampled location, we are not explicitly testing the effects of industrial sound on whale distribution; rather, we are using distance to the rig to test for the influence of the rig on the spatial pattern of bowhead whales.

The depth layer was created using data from the U.S. Geological

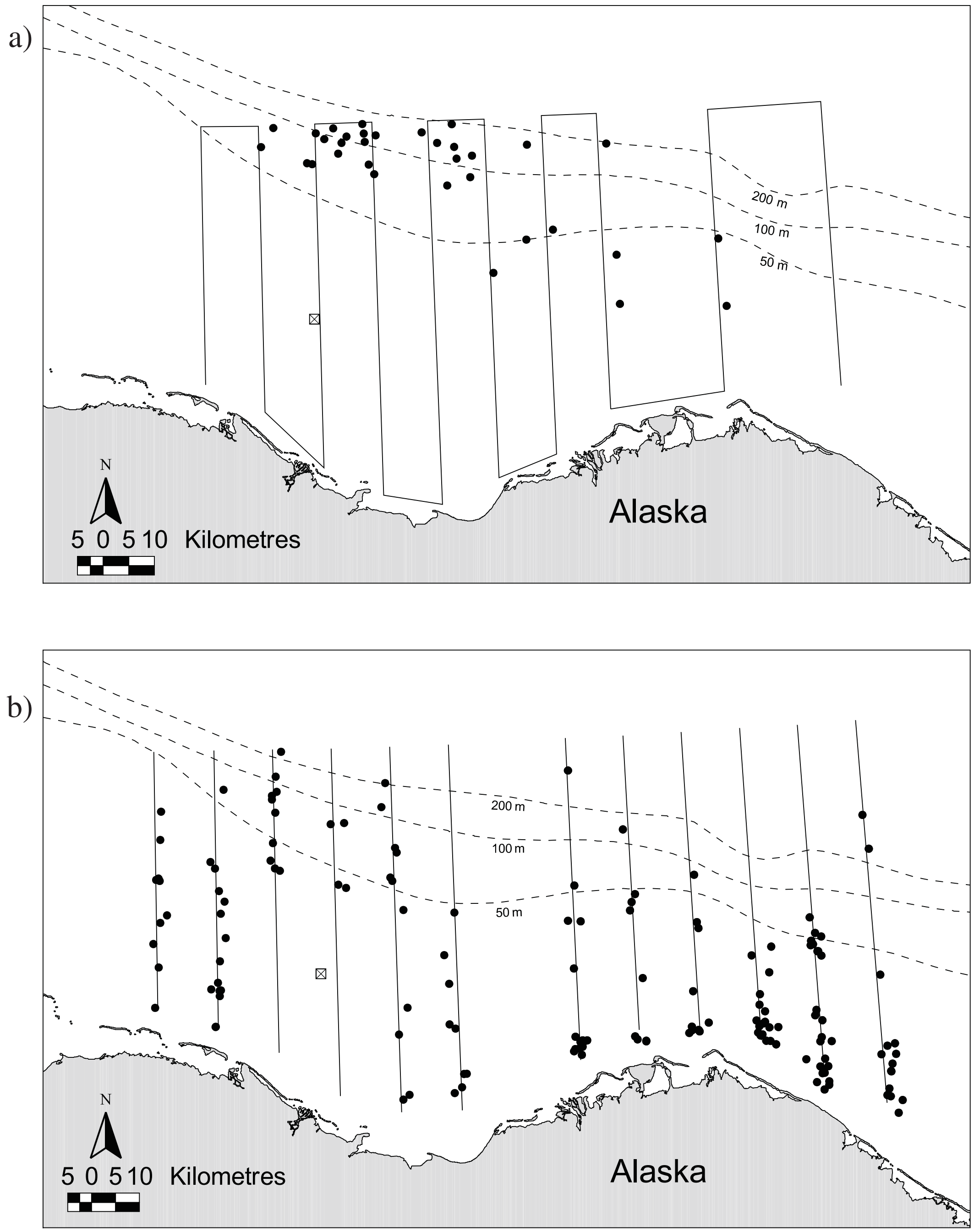


Fig. 2. Maps of flightlines, rig location, and pod locations: (*a*) 1992 Kuvlum No. 1 prospect (n = 33); (*b*) 1993 Kuvlum No. 3 prospect (n = 56). Isobaths are indicated by broken lines, flightlines by solid lines, drilling rig location by the cross-hatched square, and pod locations by circles.

Survey's GEODAS and ETOPO-5 databases, which provided both nearshore and offshore bathymetry readings. A triangulated irregular network using both data sets as inputs was developed to create a depth layer with 1-km resolution. The distance to shore and distance to rig layers were created using a Euclidean distance function to compute shortest distance to shore and distance to the drilling rig, respectively.

Whale sighting locations were used to sample the GIS coverages, extracting for each whale sighting the (x,y) location (in projected map coordinates), ocean depth (metres), distance from shore (kilometres), and distance from the drilling rig (kilometres).

Data analysis

A series of random resampling tests were used to assess the observed distribution of whales within the proximal grid (Manly 1991). We tested the hypothesis that whales were a random subset of the surveyed locations, that is, that where whales were observed was a random subset of where they might have been observed. The resampling test compared the three measured variables (depth, distance to shore, and distance to the drilling rig) for random sites with the values derived from observed sites. Using a custom-written resampling program, we compared mean values of the environmental variables for 56 random locations against the mean values of

Table 1. Values of p from the randomization tests for the effect of the three variables on whale distribution in 1993.

	Depth (m)	Distance to shore (km)	Distance to rig (km)
All points	0.928	0.91	0.191
Points <50 km from rig[a]	0.822	0.736	0.033
Points <40 km from rig	0.182	0.084	0.001
Points <30 km from rig	0.04	0.002	0.001

[a]The resampling was constrained on subsequent trials to look at the effect of the drilling rig at ranges where industrial noise progressively increased.

the environmental variables of the 56 actual pod locations. We repeated this procedure 1000 times and recorded the number of times that the mean value for the random locations was greater than the observed value. All the tests were one-tailed tests because preliminary analysis of the sightings showed that whales near the drilling rig were in deeper water, farther from shore, and farther from the drilling rig than would be expected under a random scenario.

To ensure that we were testing within a range where whales could distinguish industrial sounds from ambient sounds, we repeated these analyses with observations constrained to distances within 50 km from the rig (Richardson et al. 1995). With three separate runs of the resampling program, the 1993 data were constrained by distance from the rig only, starting with 50 km and proceeding downward in increments of 10 km.

Resampling tests, while informative about the pattern of whale distribution, do not address the fact that the three environmental variables exhibit a degree of intercorrelation with one another. For example, as distance from shore increases, depth also increases. Using a series of Mantel tests, we then assessed which of these three variables had the highest degree of correlation with the observed whale distribution. The Mantel test assesses the degree of correlation between whale location and environmental variables while at the same time taking into account the autocorrelation of these variables and the intercorrelation among other variables.

The Mantel test differs from standard parametric regression techniques in that the dependent variables are dissimilarity matrices, and the test measures the degree of pairwise similarity between two sampled plots. This test asks whether samples that are similar in terms of the predictor (environmental) variables are also similar in terms of the dependent variable (whale occurrence). A Mantel test also considers space (geographic location) as a predictor variable, asking whether samples that are close together in space have similar values for other variables. Mantel's statistic is based on a simple cross-product term:

$$(1) \qquad z = \sum_{i=1}^{n}\sum_{j=1}^{n} x_{ij}\ y_{ij}$$

and is normalized:

$$(2) \qquad r = \frac{1}{(n-1)}\sum_{i=1}^{n}\sum_{j=1}^{n}\frac{(x_{ij}-\bar{x})}{S_x}\cdot\frac{(y_{ij}-\bar{y})}{S_y}$$

where x and y are variables (or sets of variables) measured at locations i and j, n is the number of elements in the distance matrices ($= m(m-1)/2$ for m sample locations), and S_x and S_y are the standard deviations for variables x and y, respectively. This normalized equation allows one to consider variables of different measurement units within the same framework, rescaling the statistic to the range of a conventional correlation coefficient bounded on [–1,1]. In practice, a negative Mantel correlation is rare and the magnitude of correlation is often comparatively small, even when highly significant statistically. Because the elements of a distance matrix are not independent, the Mantel test of significance is evaluated via permutation procedures. In this, the rows and columns of the distance matrices are randomly rearranged. Mantel statistics are recomputed for these permuted matrices, and the distribution of values for the statistic is generated via many iterations (~1000 for $\alpha = 0.05$, ~5000 for $\alpha = 0.01$, ~10 000 for greater precision; Manly 1991).

The data were prepared and tested using simple and partial Mantel tests (Legendre and Fortin 1989; S.C. Goslee and D.L. Urban, Nicholas School of the Environment, Duke University, Durham, NC 27708, U.S.A., unpublished data). Seven distance matrices were constructed: one for whales, space, depth, and distance to shore and three for distance to rig (raw, log-transformed, and threshold distance). We summarized whale distance as a group contrast matrix, whereby the input variable from the raw data array was scored as 0 if whales were absent from the sample location and 1 if they were present. Thus, similar sites had a contrast of 0, and dissimilar sites had a contrast value of 1. Geographic distance (space) was computed as Euclidean from spatial coordinates. We computed distance matrices for distance to shore and depth as absolute difference. We tested distance to rig in three alternate ways. First, we considered linear distance as absolute distance from the rig. Second, we considered that noise levels decline in a strongly nonlinear way, and so log-transformed distance to rig. This variable emphasizes the shorter distances while deemphasizing longer distances (H. Whitehead, Department of Biology, Dalhousie University, Halifax, NS B3H 4J1, Canada, personal communication). Finally, we considered that whale response to the rig might be a threshold behavior (Richardson et al. 1995), in that the difference between 0 and 10 km is not the same as between 50 and 60 km. We used CART (Breiman et al. 1984) to identify an appropriate threshold distance that maximized the contrast between whale presence and absence. This threshold distance was set at 18.6 km from the drilling rig. This third distance measure thus collapses distance to rig into a binary measure, either close or far. From this, we computed a distance matrix that coded points as similar (0) if they were either both close or both far or else dissimilar (1).

Simple Mantel tests look at the effect of one variable on whale distribution (for example, the effect of depth on whale location). A simple Mantel test was used to test both data sets for the effect of each ecological variable on whale distribution and the effect of space on each variable. A partial Mantel test answers a more limiting question: that of the effect of the drilling rig on whale distribution given that distance to the rig has spatial structure (autocorrelation) and is correlated with the other variables. In the case of depth, a partial Mantel test controlling for the effect of space and distance to shore explains the effect that depth has on species location given that depth is spatially autocorrelated and intercorrelated with the distance from shore variable. Using partial Mantel tests, the data sets were tested for the effect of each variable given that each has spatial structure and given that there may be intercorrelation between variables. When using the partial Mantel test to explore the effect of the drilling rig on whale pattern, we only used one of the three distance to rig variables at a time.

Results

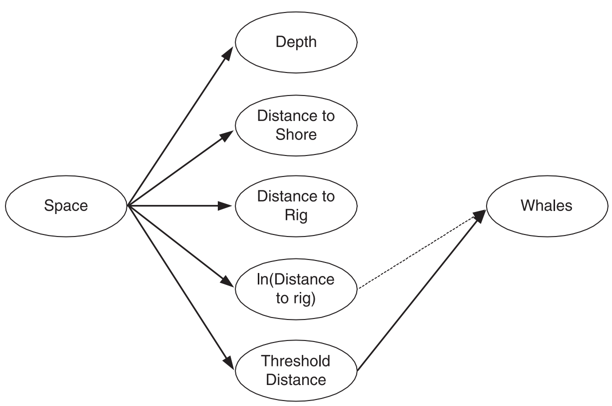
The resampling results for 1993 are significant for values <50 km from the drilling rig, while the other two variables were only significant under 30 km, indicating that within audible ranges of the drilling rig (<50 km), whales were farther away than expected randomly ($p < 0.033$) (Table 1). The Mantel test results indicate that the most important patterning variable is threshold distance once spatial autocorrelation

Table 2. Mantel *r* coefficients and *p* values (ns, nonsignificant) for results of simple and partial Mantel tests for the 1993 data set (n = 56 sightings).

	r_{we}[a]	$r_{(w\ or\ e)s}$	$r_{we \cdot s}$	$r_{we \cdot se}$[b]
Whales		ns		ns
Depth	ns	0.347 ($p < 0.001$)	ns	ns
Distance to shore	ns	0.497 ($p < 0.001$)	ns	ns
Distance to rig	ns	0.205 ($p < 0.001$)	ns	ns
Ln(distance to rig)	ns	0.036 ($p < 0.007$)	ns	ns[c]
Threshold distance	0.062 ($p < 0.0007$)	–0.075 ($p < 0.0001$)	0.064 ($p < 0.0004$)	0.064 ($p < 0.0002$)

Note: Threshold distance is the most important variable once its autocorrelation is taken into account.
[a]The notation implies a regression of an environmental variable (e), e.g., depth, distance to shore, ln(distance to rig), on whale presence (w). The third column represents a regression of an environmental variable on whale presence controlling for spatial autocorrelation (s). The fourth column extends the regression to control for both spatial autocorrelation (s) and the correlation with other environmental variables (e).
[b]The first entry in this column is the effect of space on whale distribution controlling for all environmental variables. For the distance to rig partials, we only tested one of the three distance to rig variables at a time.
[c]This result is marginally nonsignificant (Mantel r = 0.027, p = 0.097).

Fig. 3. Results from Mantel test for 1993 presented as a path diagram, whereby arrows indicate a significant effect. The arrows to the left of the ecological variables indicate simple correlations, while the arrows to the right indicate both simple and partial correlations. The marginal result between whales and the log-transformed distance to rig variable is represented with a broken line.



and intercorrelation are accounted for (Mantel r = 0.060, $p <$ 0.0002). The partial Mantel result for the log-transformed distance to rig variable was marginally nonsignificant (Mantel r = 0.027, $p < 0.098$) (Table 2). The threshold distance variable was the only variable with a significant Mantel r coefficient for both the simple and partial Mantel test (Fig. 3). The first column in Table 2 represents the pure simple results between whales and each environmental variable, which suggest that the pattern of whales is being influenced by the presence of the drilling rig. Mantel tests for spatial autocorrelation (column 2) show that with the exception of the whales, each environmental variable is highly spatially structured. Partial Mantel results for the relationship between the environment and whales, controlling for spatial autocorrelation (column 3), show that the presence of the rig is influencing spatial pattern. Pure partial results controlling for spatial autocorrelation and correlation with other environmental variables (column 4) also show that the presence of the drilling rig is altering the spatial pattern of bowheads. A comparison between the three different measures of distance to rig indicates that threshold distance had the strongest Mantel correlation with the spatial pattern of the whales.

Discussion

Results from the randomization tests indicated that observed whale distribution in 1993 is nonrandom across the study area; specifically, distance to the drilling rig in 1993 is the most strongly significant variable. It is clear that within a 50-km radius from the drilling rig, whales are staying farther away from the rig than under a random scenario.

However, the resampling tests do not provide clean inferences about these variables because of the problems with autocorrelation and intercorrelation discussed previously, which led us to use the family of Mantel tests. In 1993, the results from the Mantel tests suggest that the spatial pattern of bowhead whales is highly influenced by the presence of the drilling rig. Only the threshold distance from the rig variable had significant simple and partial results, while depth, distance to shore, and distance to the rig had no significant partial Mantel correlation with whale distribution. Plots that are similar in terms of whale distribution are significantly similar in their distance to the rig. Thus, we can infer that the area of whale density surrounding the drilling rig in 1993 was significantly low. And once the spatial structure of the threshold distance to the rig variable is taken into account, along with its potentially confounding correlation with depth and distance to shore, we can conclude that this is the most important variable in the patterning of whale distribution around the rig. We found it interesting that the straight linear distance to the rig variable was not significant given the initial exploration of the data. However, using a linear variable, such as distance to the rig, does not differentiate in differences between 0 and 20 km from the rig and between 30 and 50 km. Thus, representing the presence of the rig using a threshold variable makes more sense given that between 0 and 20 km, the noise from the rig is much louder than between 30 and 50 km. Indeed, Richardson et al. (1995) suggested that there may be different noise thresholds to which marine mammals respond. The results for the three different distance to rig models suggest that there is much to be learned about how whales perceive noise underwater, and that it is most likely a more complex behavioral model than we have posed here.

Since we do not have data on actual noise levels, we cannot conclude that noise from the drilling rig causes the low density near the rig; however, the results do indicate that the presence of the rig has a highly significant effect on distribution. Were we to obtain information about the actual sound level at each whale sighting, we would be able to make additional claims about what is actually causing the distribution. In addition to the drilling rig, there are numerous supply ships, transport helicopters, and icebreakers that operate in the vicinity of the rig and represent additional sources of noise disturbance. These ships are in constant support of the drilling rig, such that even when the rig may be idle, there is industrial activity that may have as much influence on the whale distribution as the rig itself. Richardson and Malme (1993) mentioned the increased response of a bowhead whale to a varying sound source, such as that coming from a moving ship, and Richardson et al. (1995) mentioned the strong and varied source produced by active icebreakers caused by the ahead and astern motion of the ships as they break ice. Icebreakers were present throughout the Kuvlum exploration and represent a significant source of acoustic disturbance for bowheads. A more complete test of the effects of oil exploration on spatial pattern would include actual noise levels received from all sources in relation to ambient levels, not just the drilling rig.

As mentioned in the Methods section, data from 1992 were analyzed along with the 1993 data; however, they were not included in the results due to a lack of metadata. Yet the results from these data bear mentioning in the context of the biological interaction studied here as well as the techniques used to study that interaction. In 1992, the randomization tests indicated that whales were avoiding the rig ($p < 0.05$) and staying farther offshore than would be expected by chance ($p < 0.001$). The Mantel results yielded only one significant pure partial result, geographic distance (Mantel $r = 0.066$, $p < 0.024$), although partials controlling for space only were significant for distance to shore (Mantel $r = 0.066$, $p < 0.033$) and depth (Mantel $r = 0.071$, $p < 0.018$). The space result, which tested the effect of geographic position on whale distribution once all environmental correlation is taken into account, reveals spatial pattern unaccounted for by the model that we tested. This result is of special interest given that 1992 was a particularly heavy ice year (S.D. Treacy, U.S. Department of the Interior, Mineral Management Service, Anchorage, Alaska, personal communication). It seems clear that an important variable, ice, is missing from this model, yet because metadata were not available for this year in terms of when each whale was sighted, ice was not used. Because ice may be an important patterning variable for bowheads, we are precluded from drawing strong inference from the 1992 results with reference to the interaction between the whales and the drilling rig.

Moore and DeMaster (1998) proposed that migrating bowheads are often found farther offshore in heavy ice years because of an apparent lack of feeding opportunities. Ultimately, the pattern in the 1992 data may be explained by ice presence rather than by the presence of the drilling rig. Rather than draw inference from an incomplete data set, we wish to return to the flexibility of the analysis techniques proposed and suggest that with additional environmental data, the model can only be made stronger. The analytical framework allows us to pose more complicated patterning agents as well. As was noted earlier, we are not testing whale–noise interaction specifically; rather, we are testing spatial pattern and are using distance from the rig as an explanatory variable. We acknowledge that the variable that we are using (distance to the drilling rig) is not an exact measure of the sound received by each whale. Sound transmission and loss underwater is extremely complex and can be affected by environmental variables such as wind, ice cover, and ocean depth among others. Microclimate patterns can change transmisssion properties hourly if not daily. In addition, the threshold distance variable is most likely too simple as an explanatory variable for bowhead whale response to noise. If we had detailed sound loss models, or better still, actual received levels at each whale sighting, these could be easily accommodated into the structure of this spatial test.

Rather than make strong claims about the observed interaction based on 2 years worth of data, we wish to highlight the power and flexibility of the techniques while at the same time acknowledging the limits of our data. While we have not made the link between noise and whale pattern explicitly, using resampling tests and Mantel tests, we have noted a significant result of the presence of the rig on the pattern of whales. Although we may lack the data to make definitive claims about the interaction between bowhead whales and oil exploration, we now have an analytic technique to powerfully test the linkage between exploration noise and bowhead behavior as data become available in the future.

What these results actually mean to bowhead whales remains to be determined, as the long-term effect of short-term exposure to industrial sounds is not clear. Additional research should consider the possible deleterious effects of long-term exposure and should include sound–environment interaction models. For example, if ice cover is heavy and sound levels are loud, whales may respond differently to the noise than if no ice is present, which our 1992 results suggest. In addition, as other sources of noise are introduced into a marine environment, scientists may consider testing spatial pattern, if accurate sound levels prove too difficult to obtain at each location. The techniques proposed can also be used in a variety of other marine applications where the role of spatial pattern is of interest, whether as a response to disturbance or to natural patterning agents.

In conclusion, it should be noted that this paper serves two purposes: (*i*) to assess the critical factors essential to observed whale distribution and (*ii*) to propose a new suite of analytical techniques for marine ecological research. Previous research into habitat usage by bowhead whales has relied on parametric analysis, even with highly autocorrelated data. The methods proposed here allow one to effectively test observed distributions in the face of potentially confounding variables and offer a statistically rigorous way to help understand the pattern–process paradigm in a given biological system, whether marine or terrestrial.

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