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Ringed Seal (*Phoca hispida*) Use of Subnivean Structures in the Alaskan Beaufort Sea During Development of an Oil Production Facility

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Abstract

We investigated whether ringed seal (*Phoca hispida*) use of breathing holes and lairs (structures) during winter and spring was affected by construction and drilling on Northstar Island, built in the nearshore Alaskan Beaufort Sea. Trained dogs searched the sea ice for structures within 3.5 km of Northstar during each of three survey periods: November/December 2000, March 2001, and May 2001. Temperature sensors were placed in 54 different ringed seal structures to determine dates of abandonment. Ringed seals created and used sea ice structures within 11 to 3,500 m of Northstar activities. Of the 35 structures located in November and December 2000, 68% had been abandoned by late May 2001. Of the 60 structures located in March 2001, 42% had been abandoned by late May 2001. During all surveys combined, 181 structures were located, and 118 (65%) were actively used by late May 2001. We used Cox regression to determine three primary factors influencing the abandonment of these structures: (1) structures found during later searches were significantly less likely to be abandoned; (2) structures in areas of higher ice deformation were significantly more likely to be abandoned; and (3) structures farther from the ice road to Northstar were more likely to be abandoned, though marginally significant. We would have predicted structures closer to Northstar would have been abandoned at higher rates if Northstar activities negatively affected seal use of structures. Ringed seals in the Alaskan Beaufort Sea appear to create and abandon structures throughout the winter and spring at rates higher than previously documented.

Key Words: ringed seal, *Phoca hispida*, sea ice use, subnivean structures, noise exposure, offshore oil development, Alaska

Introduction

Landfast sea ice is an important overwintering and spring breeding habitat for the ringed seal (*Phoca hispida*) (McLaren, 1958; Burns, 1970; Smith, 1973). Within the landfast ice zone, ringed seals create and maintain breathing holes and lairs (snow caves) in which they haulout and give birth (Smith & Stirling, 1975). Structures are "subnivean" because lairs are by definition below the snow surface, and holes frequently are covered by snow. The length of time that ringed seals maintain breathing holes and lairs, and the persistence of these structures after natural and human-induced disturbances, have not been studied quantitatively. Most research on ringed seals, including studies in the Alaskan Beaufort Sea, has been conducted during late winter and early spring (e.g., Smith & Stirling, 1975; Smith & Hammill, 1981; Kelly et al., 1986; Frost & Burns, 1989; Kelly & Quakenbush, 1990; Kelly & Wartzok, 1996). Little is known about ringed seal ecology from November through January.

Ringed seals start to construct and maintain a series of breathing holes as soon as ice begins to form in late autumn or early winter (Smith & Stirling, 1975; Frost & Burns, 1989). Individual seals maintain many breathing holes (Smith & Hammill, 1981; Hammill, 1987; Frost & Burns, 1989; Kelly & Quakenbush, 1990; Belikov & Boltunov, 1998). As sufficient snow accumulates around these breathing holes, some are developed into lairs that afford protection from predators and weather (Smith & Stirling, 1975; Kelly et al., 1986). Ringed seal pups are born in lairs from mid-March through April, and mothers nurse their pups in the lairs for 5 to 8 weeks (Smith, 1973; Hammill et al., 1991; Lydersen & Hammill, 1993).

From mid-May through early June, ringed seals frequently haulout on the exposed ice surface.

Ringed seals are thought to maintain many of the same breathing holes and lairs throughout the ice-covered period, although seals appear to naturally abandon some structures during the winter (Hammill, 1987; Kelly et al., 1988; Frost & Burns, 1989; Williams et al., 2001). Several factors confound evaluation of the abandonment of seal structures: (1) multiple ringed seals can use a single structure (Smith & Stirling, 1975; Kelly & Quakenbush, 1990), (2) different age classes and sexes of seals may maintain different densities of structures in overlapping areas (Hammill, 1987; Hammill & Smith, 1989), (3) abandoned structures can be reopened (Williams et al., 2001), (4) new structures can be created through at least 34 cm of ice (Hammill, 1987), and (5) new cracks in sea ice provide opportunities for creating new structures (Frost & Burns, 1989; Hammill & Smith, 1989).

The relatively stable landfast ice that provides habitat for ringed seals in winter and spring also provides a platform on which some oil-industry activities occur in the central Alaskan Beaufort Sea. BP's Northstar Development Project is the first offshore oil and gas production facility seaward of the barrier islands in the Alaskan Beaufort Sea (Figure 1). Northstar is located 9.5 km from the mainland on a manmade gravel island in 12 m of water; this region is covered by landfast ice from November to early July. Landfast sea ice in this region extends from 25 to 40 km offshore, where water is 18 to 27 m deep (Kovacs & Mellor, 1974; Stringer, 1974; Wadhams, 2000). The construction of Northstar occurred primarily during the ice-covered season of 1999-2000, beginning one year before this seal investigation was initiated. Construction in early 2000 involved hauling 18,300 truckloads of gravel from the mainland over the ice to the island, along with constructing pipelines to shore. Drilling commenced in late 2000, and less-intensive construction of on-island facilities continued in early 2001, concurrent with this study. Other activities in the winter of 2000-2001 included creating a 12-km artificially thickened ice road from the mainland to the island, and maintaining a tracked vehicle trail on the sea ice above the pipelines.

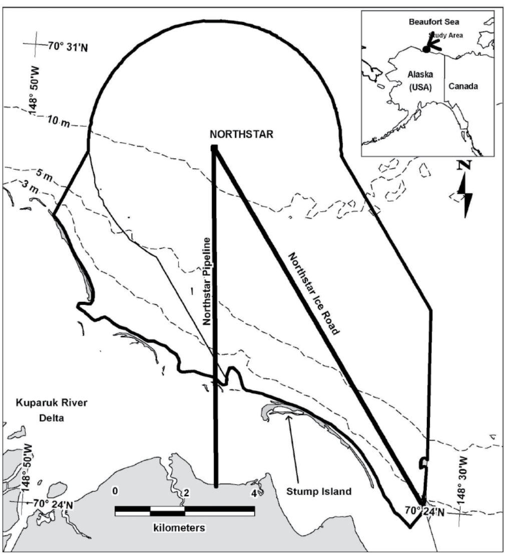

Figure 1. Study area in the central Alaskan Beaufort Sea near Prudhoe Bay showing the ice road, Northstar Island, and pipeline trail; the entire ice road, perimeter of Northstar, and some sections of the pipeline trail were artificially thickened by flooding with seawater and regularly cleared of snow.

Richardson et al. (1995) summarized evidence suggesting ringed seals may be displaced from active artificial islands. Intensive aerial surveys showed no significant reduction in seal densities near Northstar Island in the spring during 2000, 2001 or 2002, however (Moulton et al., 2003, 2005). Nonetheless, peer reviewers for the Northstar Development Project hypothesized that seal use of breathing holes and lairs near the industrial development might have been affected in ways not detectable from spring aerial survey data.

The primary objective of this study was to characterize the effects of offshore oil development on the use of breathing holes and lairs by ringed seals in the Alaskan Beaufort Sea. Relevant stimuli of the development included noise, vibration and visual cues, and physical alteration of the floating sea ice. A secondary objective of this study was to investigate ringed seal use of structures relative to natural factors in order to provide a comparative baseline to assess the influences of industrial activities on the sea ice. We hypothesized that, after allowance for the effects of natural environmental factors on structure density and persistence, fewer seal structures would be found or maintained near Northstar and the associated ice roads than farther away.

Materials and Methods

Study Area

In late 2000 and early 2001, sea ice in areas near Northstar Island where summer water depth was > 1.5 m was searched for ringed seal structures. By March, waters < 1.5 m deep have generally frozen to the bottom and are thought to be unsuitable for basking ringed seals (Moulton et al., 2002). The study area totaled 84.5 km^2 and included all of the area where BP planned to physically alter the ice, as well as a zone extending 3 km beyond the planned edge of the primary ice road and 3.5 km around Northstar (Figure 1). The sea ice considered to be physically altered covered about 2.7 km^2 and included the artificially thickened ice road, the ice that was cleared of snow and ice ridges, and the adjacent areas where removed snow and ice were deposited. Northstar was a source of continuous noise in the air and in the water, and of vibrations in the ice, beginning in late 1999 and for the duration of the study (Blackwell et al., 2004a). There was continuous noise from diesel generators and living facilities beginning in early September 2000 and continual noise from well drilling starting 14 December 2000. (Thereafter, drilling occurred every day until 13 June 2001, except for a few days in January.) There were also several intermittent noise sources on the island and sea ice.

On 18 November 2000, BP began surveying the centerline of an ice road from the mainland to Northstar (Figure 1). Artificial flooding along the 12-km long ice road began on 27 November 2000 and was completed in March 2001. The ice road was created by drilling through the sea ice with power augers, pumping seawater to the surface and flooding the ice surface until adequate thickness was achieved. The road was subsequently used until 3 June 2001 for transporting personnel, supplies, and equipment to Northstar. In addition, in January 2001, a trail on the sea ice was cleared of snow along the pipeline alignment. At seven locations along this trail, an area was thickened to support heavy equipment. Workers used heavy equipment to cut openings in the ice surface, haul gravel in dump trucks, and place the gravel over the pipeline in select locations to meet permit and design requirements. The ice at these seven locations along the pipeline was flooded during the third week of February 2001, cut for access to the sea floor, and gravel placed during a 30-day period beginning 13 March 2001.

Search Methodology Using Trained Dogs

Biologists using trained Labrador retrievers searched the sea ice for subnivean seal structures during three field periods: (1) 24 November-8 December 2000, (2) 2-13 March 2001, and (3) 4-19 May 2001. The dog-based searches were performed using methods similar to those of previous investigators (Smith & Stirling, 1975; Kelly et al., 1986, 1988; Kelly & Quakenbush, 1990; Lydersen & Ryg, 1991; Furgal et al., 1996).

We used a repeatable transect design to systematically search the daily survey area. The experienced 6-year-old female dog ran 10 to 20 m in front of the handler who followed on a snow machine (small snowmobile). The experienced dog was accompanied by an inexperienced young dog during nearly all of the searches. Each transect was oriented on a quartering headwind or crosswind, and the dog searched an area upwind of that transect. When the dog detected a structure, she departed from the transect line in an upwind direction until she located it. The structure was marked and investigated, and the survey then resumed from the point of departure from the transect line. The area searched daily was estimated, assuming that experienced dogs detected a consistent proportion of seal structures up to 1-km upwind (T. G. Smith, pers. obs.). Transect locations were logged at 2-s intervals using Garmin® 12 XL or 2 Plus global positioning system (GPS) receivers. We downloaded transect coordinates from the GPS every evening to estimate survey coverage.

Occasionally, the experienced dog located structures at distances greater than 1 km. Based on the results of similar work in 1999-2000 and the 2000-2001 work described here, we assumed that two searches along transects through the same area would detect a high proportion of the seal structures present (Hammill & Smith, 1990). Assuming a standard detection distance of ~1 km, the entire study area was estimated to be surveyed twice during each of the three search periods.

Structure Recording and Marking

All seal structures found during the first two field periods were marked with wooden stakes placed < 1 m from the structure, and locations were recorded using a GPS receiver. During the third field period in May, we marked structures as previously, but we also encountered seals outside of structures basking on the surface of the snow and ice. We used carved snow blocks to mark these basking sites to minimize any response by basking seals to a wooden stake.

When a structure was first located, we carefully excavated through the snow into the structure to determine its type and status. We subsequently replaced the snow cover to minimize our disturbance. We recorded the following data for each location when first found: (1) type of structure (i.e., resting lair, birth lair, breathing hole, basking site), (2) status of structure (open or frozen), (3) visual estimate of % ice surface deformation (i.e., broken, cracked, or buckled ice) within a ~10 m^2 area centered on the structure, (4) snow depth at seal hole, (5) evidence of predator presence, (6) indication (smell) of a reproductively active male (*tiggak*; McLaren, 1958; Smith & Stirling, 1975; Hardy et al., 1991), and (7) local wind speed (km/h) and direction (degrees true).

We characterized ringed seal structures based on their general function as in (1) above. Resting lairs showed no sign of pup occupation or birth. Birth lairs contained the remains of a dead pup, blood, or placenta. Lairs with lateral excavations smaller than the main chamber or white hair from the lanugal coat were categorized as suspected birth lairs. Basking sites were defined as lairs with collapsed, excavated, or melted ceilings, or breathing holes excavated to allow access to the surface of the snow and ice. The status of a seal structure was defined based on whether the structure was recently used (breathing hole open) or abandoned (frozen).

Assessing Fate of Seal Structures

Forty data loggers with internal and external temperature sensors were used to obtain the dates of abandonment of a subsample of ringed seal structures located during the course of the study. Data loggers (Onset Computers; HOBO® H8 Pro) were placed at the structure to record air temperature inside and outside. Each 2-channel data logger was equipped with a built-in temperature sensor and an external plug-in sensor at the end of a 1.2-m cable. The cabled sensor was placed within a structure, and the built-in sensor sensed ambient air temperature outside the structure. Ideal placement of the sensor within the lair was ~16 cm above the breathing hole. Ambient temperature could then be compared to temperature within the seal structure to identify times when a seal was present. The data loggers were programmed to record both temperature values at 5-min intervals.

During searches for new structures in March and May, data were transferred in the field to a remote device ("shuttle") and later uploaded to a laptop computer. Data loggers were restarted automatically by the shuttle and continued collecting temperature data for the remainder of the season. When a revisit to an instrumented structure showed that it had been abandoned by seals, the data logger was moved to an active structure.

In March and May 2001, we also used 1.5-m steel rods to physically check the status of previously located structures. If status could not be determined with the rod, we excavated the structure, but this excavation was typically less invasive than the initial examination.

Placement of the sensor was checked visually during subsequent status checks at some structures where physical disturbance could be minimized. Upon subsequent review in the field, if the temperature data showed obvious errors, erroneous temperatures, or did not correspond to the physical check of structure status with the steel rod, the structure was revisited, visually examined, and the temperature sensor was repositioned. We could not determine the actual date of abandonment in frozen structures when the temperature sensor was found encased in ice during a recheck. There was no way to determine if the sensor was encased in ice before or after the hole froze. If a structure was frozen, we removed the data logger. During 16-22 May 2001, the final status of all structures was checked, and the data loggers were removed from the remaining active structures.

Temperature data were inspected visually to determine the date when the breathing hole in an instrumented structure was frozen (i.e., abandoned). Temperatures within the structure were compared to ambient conditions measured simultaneously. Any whole number increase in temperature within the structure that was not associated with a simultaneous increase in ambient temperature was assumed to indicate the presence of a seal. Date of abandonment was estimated to be 24 h after the last indication that a seal was present (i.e., we assumed it would take ~24 h for a structure to freeze without maintenance by a seal).

Statistical Analyses

Instrumentation of structures provided continuous records of structure status (i.e., active or abandoned). If an instrumented structure was abandoned during the study, the day of abandonment could be identified reliably. We examined ringed seal use of structures using two statistical approaches: (1) Cox proportional hazards regression and (2) logistic regression. For both approaches, we combined all structure data regardless of structure type, as all structures originate as breathing holes (Smith & Stirling, 1975); this was necessary to provide an adequate sample size. The response variables considered in the Cox and logistic regressions, respectively, were the number of days that each structure was used and whether the structure was frozen or open at the end of a given period. These analyses allowed evaluation of the influence of covariates on structure use. The influences of all covariates were assumed to be consistent over the duration of the study period (i.e., we did not consider interactions of time and other covariates).

Cox Proportional Hazards Regression for Instrumented Structures—This technique was developed to analyze data for which the dependent variable is the time associated with a given event, in our case, structure abandonment, and for which the influences of factors potentially affecting that event are to be evaluated (Cox, 1972). Cox regression was used to model the "survival" of the instrumented structures in relation to the following potential covariates: water depth, distance to Northstar Island, distance to ice road, distance to pipeline trail, presence/absence of excavation by predators, number of excavations by investigators prior to abandonment or end of field season, % ice deformation, and date of entry into the study (i.e., date found).

A total of 54 structures were instrumented with temperature sensors, but only 50 cases were available for the analysis because of immediate equipment failure ($n = 3$) or re-opening of a frozen structure ($n = 1$) (see below). Right censoring of the data occurred for two reasons: (1) equipment failed before the end of the field season while the structure was still active ($n = 6$) or (2) the field season ended with the structure still active ($n = 22$). In the remaining 22 cases, the structure's abandonment was recorded via temperature monitoring.

True age of the structures was unknown because they were discovered at an unknown interval after creation. For purposes of this analysis, we ignored this aspect of the data and instead treated all structures as having originated when they were discovered. This approach necessarily introduced "noise" due to the variable age of structures at discovery and resulted in greater variances for estimated coefficients. We assumed that this "noise" did not bias the coefficients. That assumption would be violated if date of structure origin were somehow related to one or more covariates, or if covariate effects were not constant for the duration of the study. Analysis of structure survival is complicated by the fact that seals sometimes re-open frozen structures (Williams et al., 2001; see also "Results"). Even so, we excluded this infrequent event from the analysis (1 of 54 instrumented structures and 3 of 181 structures overall), and we treated the structure as frozen for the duration of the study.

Structures were found throughout the field season, though entries were clustered because of our intermittent visits in late November/early December, March, and May. To account for the staggered entries, we constructed another covariate, "Entry," representing the number of days from the beginning of the study to the date of entry.

The Cox regression model was

$$\log[h(t \mid Z) / h_0(t)] = Z\beta$$

where Z was a matrix representing covariate observations, β was the vector of effects parameters to be estimated, $h(t|Z)$ was the hazard rate for an individual with covariate vector Z, and $h_0(t)$ was the baseline hazard rate. Model selection was based on Akaike's Information Criterion (AIC). All possible models were fitted using *SAS Proc Phreg* (SAS Institute, 1999) and then ranked by their AIC values.

Logistic Regression for All New Structures by Period—Non-instrumented structures did not have a continuous time record and, thus, were not suitable for analysis via Cox regression. The fates of most of these structures were known within broad intervals because survival or abandonment was determined by physical rechecks. Thus, a dataset was constructed for all structures using status

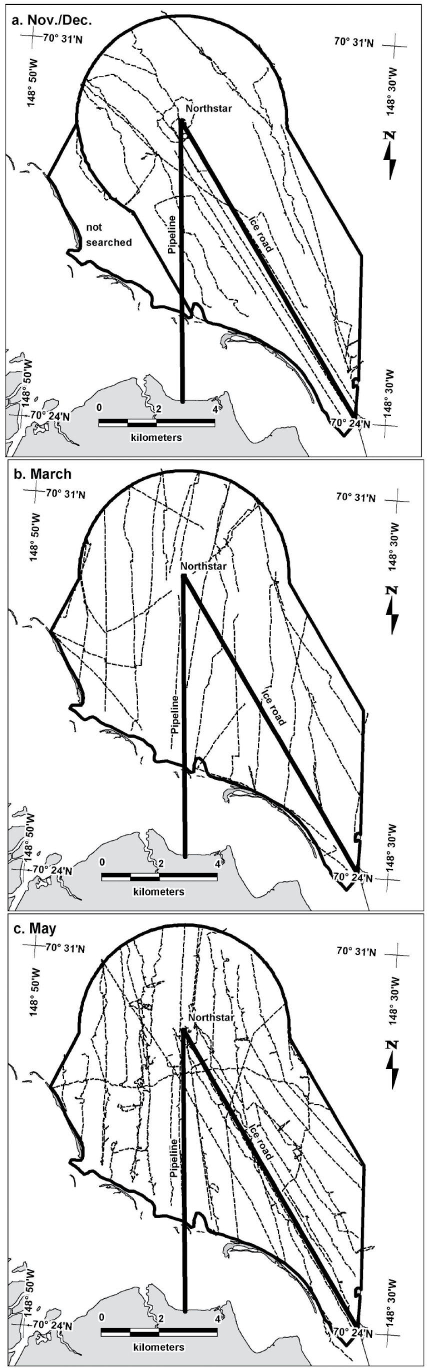

Figure 2. Transect lines searched by dogs during (A) November/December 2000, (B) March 2001, and (C) May 2001; the ice road and pipeline trail were built subsequent to our searches in November/December, and the study area was extended to the southwest during the latter two periods.

based on physical rechecks during the following search period or end of the study. For these data, logistic regression was used to assess the relationship between structure abandonment during each search period and the same covariates examined in the Cox regression. The logistic regression did not identify any significant covariate effects or models and is not discussed further.

Results

Locating Seal Structures

First Survey Period—During 11 days from 24 November through 8 December 2000, ~158.5 km of transects were searched (i.e., 14.4 km/day) (Figure 2a). A total of 35 ringed seal structures were found during that period (Figure 3a). Overall, 32 of these 35 structures were open and in active

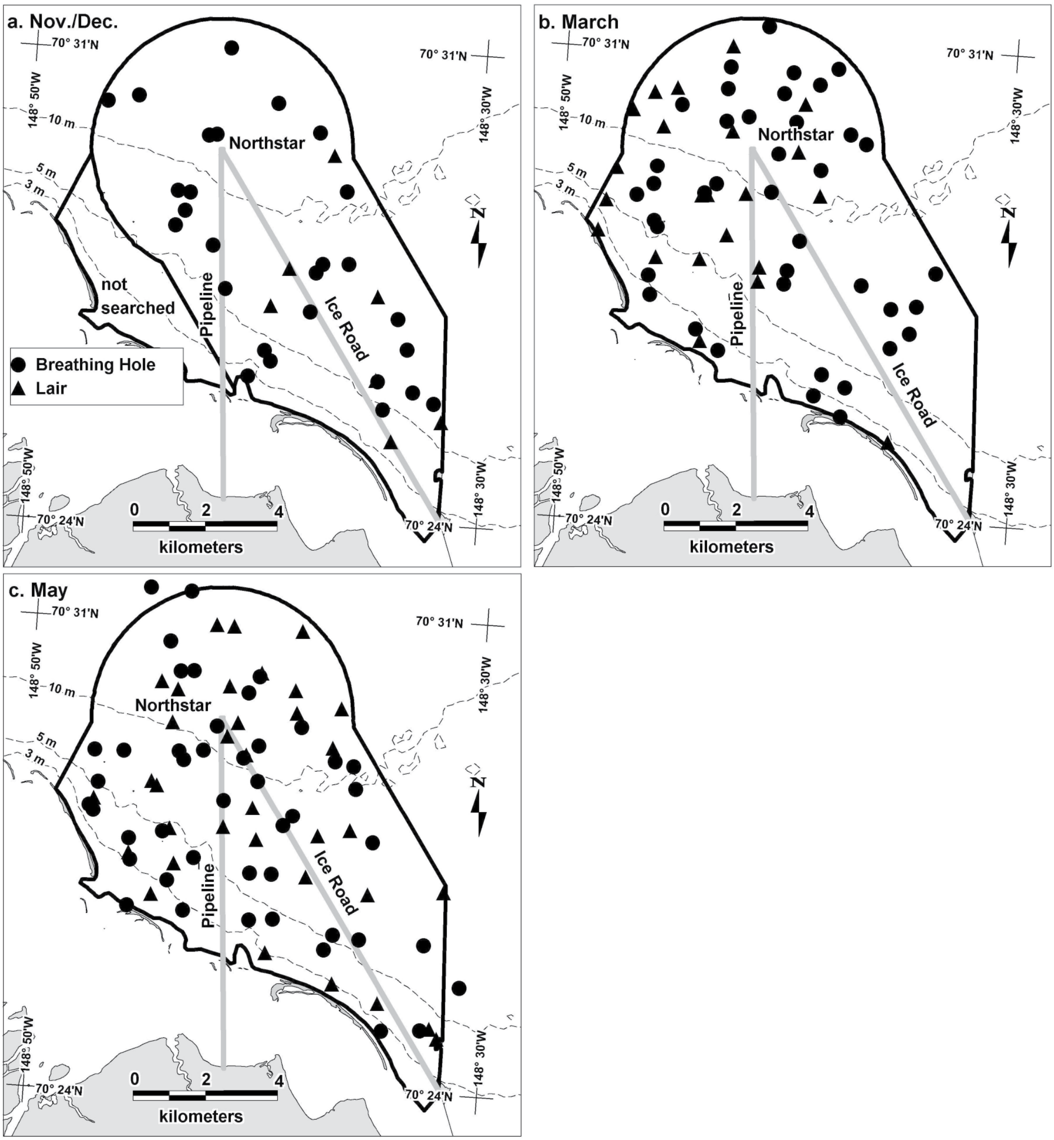

Figure 3. Structures newly found by dogs during (A) November/December 2000, (B) March 2001, and (C) May 2001; the ice road and pipeline trail were built subsequent to our searches in November/December, and the study area was extended to the southwest during the latter two periods. One, two, and one structures are not shown due to the extremely close (< 1 m) proximity to other structures on the maps for November/December, March, and May, respectively.

Table 1. Number of newly found seal structures of each type located during each of the three survey periods in both the original 75.3-km² study area and the enlarged 84.5-km² study area. In November/December, only the 75.3-km² area was searched.

	November/December 2000				March 2001				May 2001[a]			
	Breathing hole		Lair		Breathing hole		Lair		Breathing hole		Lair	
	Open	Frozen	Open	Frozen	Open	Frozen	Open	Frozen	Open	Frozen	Open	Frozen
75.3 km² study area	27	1	5	2	35	2	18	0	33	0	30	1
84.5 km² study area	--	--	--	--	39	2	23	0	45	0	35	1

[a]One additional structure of unknown type and status was found in May within the original 75.3-km² study area and is not included in the table.

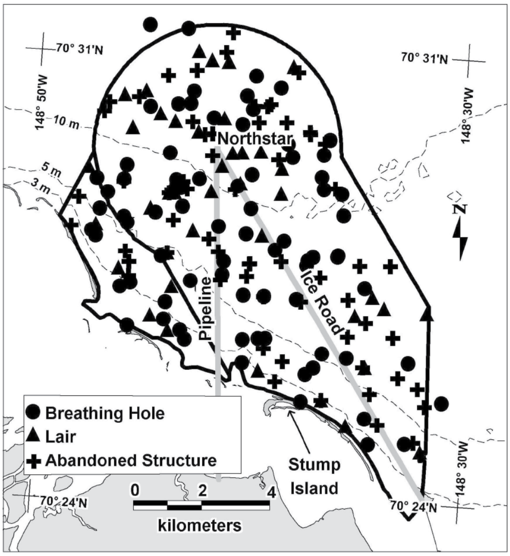

Figure 4. Status and distribution as of 22 May 2001 of structures found during all search periods

use by seals (Table 1). There were no signs of active predation (i.e., excavation of structures) by polar bears (*Ursus maritimus*) or by arctic foxes (*Alopex lagopus*) in the study area up to the end of this period. Foxes had marked three structures with urine or feces, however. Of the 35 structures found in the study area in November/December, 28 (80%) were breathing holes and 7 (20%) were lairs (Table 1).

Second Survey Period—During 10 days from 2 to 13 March 2001, ~164.2 km of transects were searched (i.e., 16.4 km/day) (Figure 2b). Of the 35 structures located in November/December 2000, 12 or 34% were open and active and 23 or 66% were frozen and presumed abandoned when rechecked in March 2001. In addition, during March, we found 64 previously undiscovered structures, 62 of which were open (Figure 3b; Table 1). Including the 35 structures found in November/December, at least 99 structures had been used within the study area by 13 March. Of these, 74 were open and active during March 2001. Forty-one (64%) of the newly found structures were breathing holes and 23 (36%) were lairs. Ringed seals were actively using all 23 lairs and 39 of the 41 breathing holes found in March.

Final Survey Period—During 14 days from 4 to 19 May 2001, ~282.0 km of transects were searched (i.e., 20.1 km/day) (Figure 2c). Of the 99 structures found during previous searches, 47 (47%) were still open in May. An additional 82 previously undiscovered structures were found during May (Figure 3c). One unknown structure was found by dogs underneath a large slab of angled ice, and its type and status could not be determined. Of the confirmed structures found in May, 45 (56%) were breathing holes and 36 (44%) were lairs (Table 1). None of the newly found breathing holes was frozen, but one lair was frozen (Table 1).

In summary, of the 181 verifiable structures found during the three search periods, 118 or 65% were still open during late May. Active seal structures appeared to be evenly distributed across the study area in relation to Northstar facilities (Figure 4) at the end of the study.

Persistence of Instrumented Structures

Twenty-five structures were equipped with temperature sensors in November/December 2000. One structure was frozen when instrumented on 1 December, reopened by a seal on 9 December, and used for the remainder of the study period. This structure was excluded from subsequent statistical analyses, but it is described below. By the March recheck, 23 (66%) of 35 structures found previously had frozen, including 15 (63%) of the 24 instrumented structures. We removed the temperature sensors from these frozen structures. Twelve of the 15 frozen structures had been abandoned by 17 January. The remaining nine sensors whose structures were open in March continued to log data until 21 May 2001, when seven (78%) of those nine instrumented structures were still open.

Eighty-three percent of the November/December structures that were still open in March were open at the end of the study.

In March 2001, 28 instruments were deployed in addition to the nine restarted from the first period. Initially, those sensors were installed in seven breathing holes and 21 lairs. The sensors were easier to install in lairs, however, where less manipulation of snow was required to support the sensor; hence, three sensors were removed from breathing holes and re-deployed in lairs found during searches later in March. Twenty-six of 28 sensors logged useful data from March to May, and 20 (71%) of the 28 instrumented structures were still active when the final status checks were made at the end of the study. Sixty percent of all structures found active in March were still open at the end of the study. On 8 May 2001, two unused temperature sensors were re-deployed in lairs. These sensors logged useful data until 21 May.

Overall, 31 (57%) of 54 instrumented structures remained open until late May compared to 69% of all structures found (Table 2). Eight of those 31 instrumented structures had remained open for at least 163 days. One of the eight instrumented structures used for 163 days was frozen when we first instrumented the structure (see above). We were not able to use this structure in the Cox regression analysis due to unreliable data as a result of fox interactions with the sensor and the sensor freezing into the ice, but the structure remained open for the rest of the study. Twenty-three (43%) of 54 structures equipped with temperature sensors at some point between November and May were abandoned and eventually froze during the study. The exact abandonment dates for six of the 23 abandoned structures were unknown due to sensor malfunction or sensor destruction by seals or foxes.

Factors Affecting Structure Use

Cox Regression for Instrumented Structures—The top five models (i.e., those with the lowest AIC values) are summarized in Table 3. Note that the variables' entry date into study, ice deformation, and number of investigator excavations appear in all five models, while distance to road is included in four of the five models. Detailed results for the best model (i.e., the one with the lowest AIC) are shown in Table 4.

The estimated coefficient for entry date into the study is negative (Table 4). This indicates the probability of abandonment (hazard) decreased and days of use increased for structures that entered the study later in the season (Figure 5a). Similarly, the negative coefficient for number of investigator excavations indicates that the number of days of use was higher at structures that were excavated by investigators a greater number of times (Figure 5b). This was undoubtedly related to the fact that the number of opportunities to check a structure was a function of its continued use. Higher levels of ice deformation were associated with greater hazard (i.e., fewer days of use by ringed seals) (Figure 5c). The positive coefficient for distance to road was contrary to the expectation that hazard would be higher near the ice road (i.e., that seals would use structures near the ice road for fewer days). Instead, results indicate structures nearer the road were marginally significantly ($p = 0.056$) used by seals for more days (Figure 5d).

Preliminary investigations of pair-wise associations among the four covariates in the final model indicated that multicollinearity was not severe; all Pearson correlation coefficients were < 0.4. Not surprisingly, entry date into study and number of investigator excavations were negatively associated; structures that entered the study later were inevitably excavated less frequently by investigators. Also, entry date into study and distance to road were positively associated; structures discovered later in the study tended to be farther from the ice road. This was at least partly an artifact of the southwestward expansion of the study area in March (Figures 1 & 2). The mean distance (± SD) between instrumented structures and the ice road was 2,099 m (± 1,199 m), and the closest instrumented structure was 144 m away.

Table 2. Status of seal structures at the end of the study (May 2001) in relation to period when first found (November/December 2000, March 2001, and May 2001); unknown structures are those that could not be found during the final check of structure status and were likely frozen.

Survey period	Open	Frozen	Unknown
November/December 2000	10	24	1
March 2001	37	25	2
May 2001	70	6	5

Location of Birthing Lairs

Some structures found during the study were categorized as birth lairs. These structures were included in all of the analyses; however, we suspected that these structures might be more sensitive to disturbance than others. Confirmed or suspected birth lairs (n = 7) were found during searches in March and May 2001. Three of the birth lairs were confirmed based on the presence of either a dead pup or the remains of a fox kill. The remaining four suspected birth lairs were assessed as such based on the presence of blood on the floor, placental remains, size of chamber, or small diameter tunnels off the main chamber (Smith & Stirling, 1975). Of the seven cases, the

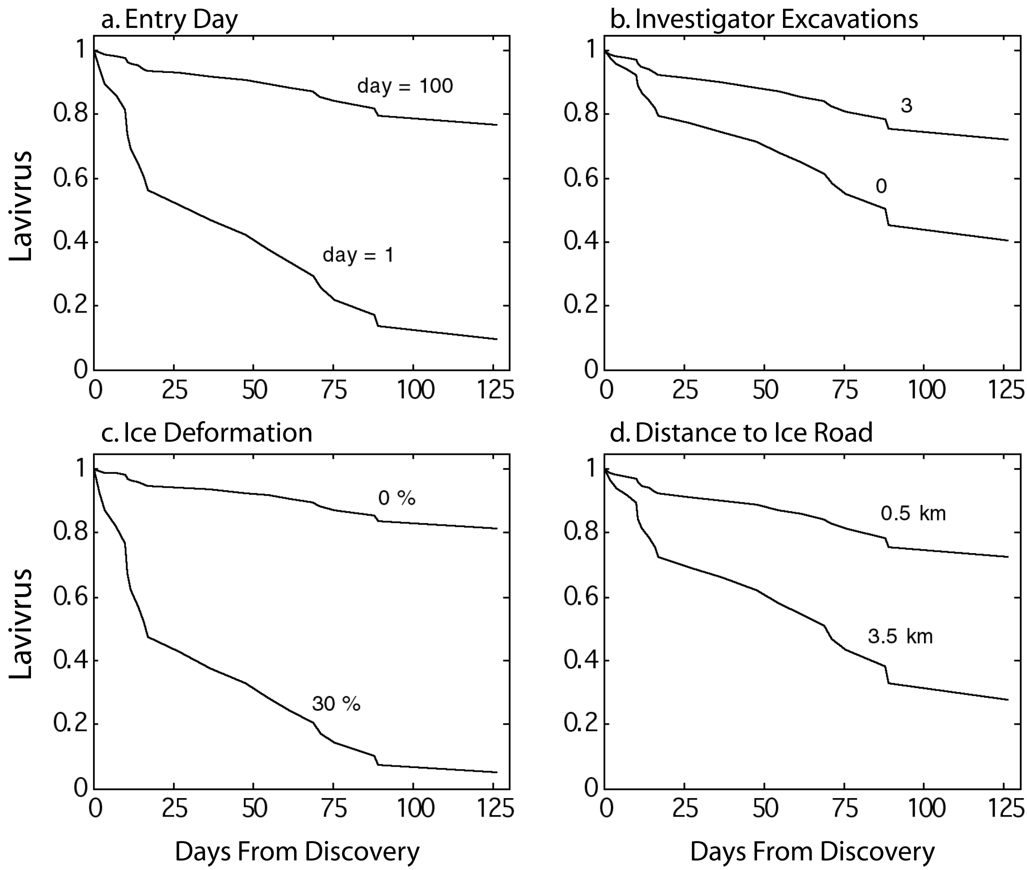

Figure 5. Estimated structure survival based on the final Cox regression model at two fixed values of each explanatory variable in the model, with the remaining variables held at their mean values; (a) entry day = 1 vs. 100, (b) number of investigator excavations = 0 vs. 3, (c) ice deformation = 0% vs. 30%, and (d) distance to ice road = 0.5 km vs. 3.5 km.

Table 3. The top five Cox proportional hazards regression models for structure abandonment, showing the covariates included in each; lowest AIC value indicates best fit.

Model	Covariates included	AIC
1	Distance to road, # investigator excavations, ice deformation, entry date into study	137.1
2	Distance to road, distance to pipeline, # investigator excavations, ice deformation, entry date into study	138.0
3	# investigator excavations, ice deformation, entry date into study	138.8
4	Distance to road, predator excavation[a], # investigator excavations, ice deformation, entry date into study	138.9
5	Distance to Northstar, distance to road, distance to pipeline, # investigator excavations, ice deformation, entry date into study	139.0

[a]Presence or absence of an excavation of the structure by a predator

birth lairs nearest to the Northstar infrastructure were 882 m and 144 m from the island and ice road, respectively. Those two closest birth lairs remained open at the end of the study on 21 May. Two (29%) of the seven birth lairs were frozen by the end of the study; both of these were > 1.8 km from the nearest Northstar activities on the sea ice and were found in March with dead pups inside.

Discussion

Was There a Northstar Effect on Sea Ice Use or Structure Abandonment?

Our data show no widespread evidence that ringed seal use of the landfast ice < 2 km from Northstar Island or the ice roads was different than their use of the ice 2 to 3.5 km away. Structure

Table 4. Covariates included in the "best" Cox regression model for structure abandonment

Covariate	Estimate (± SE)	Chi-square	*p*-value	Hazard ratio
Entry date into study	-0.0219 (0.0064)	11.660	<0.001	0.978
No. investigator excavations	-0.8050 (0.3416)	5.552	0.018	0.447
Ice deformation	0.0427 (0.0195)	4.802	0.028	1.044
Distance to road	0.4624 (0.2415)	3.667	0.056	1.588

abandonment was more strongly related to the time of year when found and ice deformation than to distance from Northstar activities. The analysis of abandonment suggested that structures farther from the ice road were more likely to be abandoned than those closer—contrary to what would be expected if there were a negative "Northstar effect."

Is it possible that impacts from Northstar extended far enough (at least 3 or 3.5 km) to affect the full study area? An examination of two factors indicates otherwise. First, if the full study area were affected, one would expect a stronger effect at distances close to the sources of noise and vibrations within the monitored area than near the periphery of the study area. The structure use data showed no such trend. Also, if seal numbers in the area during spring were reduced appreciably out to ≥ 3 km, this should have been detected during the intensive systematic aerial surveys done in June 2000, 2001, and 2002 (Moulton et al., 2005). No such effect was found. Second, extensive acoustic measurements made during the ice-covered seasons of 2000, 2001, and 2002 indicate that sounds from Northstar were detectable under water to ≥ 3 km only a small fraction of the time (Blackwell et al., 2004a, 2004b). The acoustic data showed that these sounds are predominantly at low frequencies and noted that ringed seal hearing sensitivity at those frequencies is probably not very acute. As a result, the maximum detection distance for these underwater sounds would be less for seals than for acoustic recording equipment. Similar considerations apply to in-air sounds. Also, in-air sounds from industrial activities on and above the surface would, for a seal occupying a lair, be attenuated by the strong dampening effect of snow (Cummings & Holliday, 1983; Blix & Lentfer, 1992). Thus, there was no evidence that noise-related impacts extended far enough to affect the full study area.

Ringed seals abandoned structures as a result of physical alteration of the ice surface due to scraping or flooding. If we conservatively assume that the eight unknown-status structures had been abandoned by 22 May, then 63 structures froze during the course of the study. Of the 63 frozen structures, as many as four structures were abandoned due to Northstar ice road flooding and thickening. All four of these structures were found within 450 m of the planned centerline before ice road construction began and were frozen by 22 May 2001.

Also, flooding of the sea ice may have excluded some ringed seals from using about 2.7 km^2 of thickened sea ice from December through March. We estimated the farthest perpendicular distance from the centerline of the ice road that was physically altered due to flooding or snow removal was ~450 m. We found only two new structures within 450 m of the ice road in early March. One of two structures found within 450 m of the ice road during March searches was frozen by late May. The potential for exclusion of ringed seals from this area by 22 May 2001 seems unlikely; in fact, 13 active structures were found within 450 m of the ice road during the searches in May. All 13 structures found in May were still open at the end of the study.

Spring vehicle traffic on the ice road did not influence ringed seal use of the sea ice. The two closest structures to the ice road were only 11 and 15 m from the nominal centerline of the ice road and were both open at the end of the study. Both of these open structures were basking holes found in May for the first time. We suspect they were created as a result of new cracks forming in and adjacent to the ice road as solar heating increased in the spring and the predominant northeast wind during winter and spring became more variable (Kovacs & Mellor, 1974; Wadhams, 2000).

Dynamics of Ringed Seal Use of Sea Ice

Ringed seals inhabit a dynamic environment, and their distribution and abundance are driven by a variety of factors, some of which are difficult to measure accurately. This complicates any assessment of the effects of localized human activity. In particular, rigorous analysis of habitat use is confounded by constantly changing sea ice and snow conditions. We estimate the fast ice edge was ~22 km north of Northstar Island in June 2001, but its location can vary by 20% or more annually. Within the study area, ice and snow conditions were expected to vary with time and location. Overwintering seals are known to move as temperatures increase in May and ice breakup begins (Kelly & Quakenbush, 1990). By 22 May 2001, no meltwater pools had developed, most lairs were still covered with snow, and seals were intermittently basking. In addition, we expected some parts of this area to be exposed to varying levels of noise, vibrations, and surface disturbance due to oil development (and our investigations), while the remaining area was exposed only to our investigations. The Cox regression confirmed the importance of characterizing seasonal (i.e., date of entry) and habitat (i.e., ice deformation) factors when trying to assess abandonment of seal structures.

Ringed seals abandon breathing holes and lairs naturally in response to predation, lack of snow, or changing ice conditions (Kelly et al., 1988; Frost & Burns, 1989; Hammill & Smith, 1989). Kelly et al. (1988) estimated the natural abandonment rate of seal structures in shorefast ice to be 4% over the late February or March to June interval. That estimate was based on studies from 1983 through 1987 done east of and including a portion of our study area. The number of frozen structures located by dogs during the first search over a given area of sea ice was used to calculate the 4% natural abandonment rate (Kelly et al., 1988; Frost & Burns, 1989). Using a similar approach, our estimate of "natural" abandonment might have been about 8% (1/35), 3% (2/64), and 1% (1/81) of the structures found frozen during the November/December, March, and May search periods, respectively. The dogs' ability to detect frozen structures may decrease as seal scent dissipates over time, resulting in an underestimate of the abandonment rate by this method.

We found the variability in ringed seal structure abandonment was best described by the season and ice deformation, and 2000-2001 abandonment rates were higher than reported by Kelly et al. (1988) and Frost & Burns (1989). Our study extended from late November to late May, whereas the earlier work lasted ~3 mo less from late February to June. Both our different approaches to assessing use of structures and longer study duration accounted for the higher proportion of abandoned structures. Based on the instrumented structures, the seasonal effect was statistically significant, with a lower rate of abandonment later (dashed line) than earlier (solid line) in the study. Abandonment rate also depended on ice deformation, with a significantly higher rate of abandonment as ice deformation increased. The abandonment rate was, if anything, lower close to the Northstar infrastructure as compared with farther away.

Ringed seals apparently do not rely exclusively on structures created early in the winter; they can create new breathing holes throughout the winter and spring. The number of new structures detected increased as the season progressed, supporting the concept of non-exclusive reliance on early winter structures. As the winter progresses, ringed seals reopen some previously frozen structures (see below) and likely create new structures through the thinner ice in cracks caused by changes in pack ice pressure and wind. Little is known about the ability of seals to create new structures through thick ice, but some evidence indicates that it might occur (Hammill & Smith, 1989).

We have documented that a frozen structure is not necessarily a permanently abandoned structure. Two frozen structures that had been created prior to the November/December 2000 searches were open again in March and May 2001. Another seal structure that was frozen in March 2001 was open in May 2001. In the same area during the previous year, a structure that was frozen when first located in December 1999 was open in May 2000 (Williams et al., 2001). These results show that some abandoned structures can be re-occupied, and that abandoned structures are not necessarily unavailable for the remainder of the winter. Given the turnover and creation of new structures during the ice-covered season, it is unlikely that the loss of a breathing hole or resting structure over the course of the winter, either from natural or anthropogenic causes, would significantly impact an individual seal.

Structures used by ringed seals are not distributed randomly and are usually concentrated along pressure ridges, cracks, leads, or other surface deformations (Smith & Stirling, 1975; Hammill & Smith, 1989; Furgal et al., 1996; Nichols, 1999). Our analysis suggested that ringed seals tend to use structures for shorter periods in areas of higher ice deformation. Also, during the spring, the density of observed seals in the general Northstar region was related to ice deformation: higher densities occurred in areas with lower ice deformation (Moulton et al., 2002, 2005). Adult ringed seals must balance the need to use habitats with some ice deformation (which promotes the snow accumulation needed for lairs) against the possible instability of deformed ice and its possible use as cover by approaching polar bears. Sea ice features (e.g., cracks or pressure ridges) no doubt are discerned by seals, and they presumably have a large influence on the distribution of structures on the sea ice. It is likely that ringed seals use these features depending on biological and feeding constraints during a particular season. For example, ringed seals were found to travel under water along "simulated" cracks to search for new holes (Wartzok et al., 1992).

The significant relationship between date of entry and structure abandonment rate likely resulted from a combination of two phenomena: (1) seasonal changes in seal behavior (related to reproduction or the presence of pups) and (2) changes in the rate of sea ice freezing.

Seasonal variation in snow cover and temperature over the course of the winter strongly influences the rate of sea ice freezing (Wadhams, 2000). This is likely related to structure abandonment, given the reduced number of structures that a seal could maintain when freezing is rapid. During late winter and spring, it may be easier for seals to maintain more structures because they do not refreeze as fast as in the winter.

Study Limitations

The limitations to the methodology include (1) verification of the proportion of structures detected by dogs during a search period, (2) safety considerations for working on new sea ice, and (3) analytical considerations due to sample size and multiple covariates. The major limitation of the present methodology is that it cannot verify what proportion of the structures present is found by dogs during single or multiple searches over a specific area in each study period. Previous studies have shown that, even with multiple surveys using trained dogs, one cannot confirm that every structure present has been located (Hammill & Smith, 1990). We believed that two searches with dogs would find a consistently high proportion of structures present, assuming a standard detection distance. Four or more surveys with dogs were needed to obtain an accurate estimate of the number of seal structures (Hammill & Smith, 1990); the size of our study area prohibited such intensive searches within each period. Ultimately, we searched the entire study area six times from November to May and are confident that most structures were detected. Structures doubtless have varying probabilities of detection by dogs, depending on seasonal factors such as reproductive status (Furgal et al., 1996), elapsed time since last used by a seal, and structure characteristics (breathing hole vs. lair, exposed vs. snow covered, etc.). Although seal scent is no doubt an important cue used by the dogs when detecting structures, the way in which dogs find structures is not fully understood.

Our search effort was limited due to safety and logistical concerns in newly formed unstable ice east of the island and north of the northern end of the ice road during November/December. In March and May, that area was thicker, consolidated ice, with small hummocks and ridges, allowing relatively more survey coverage. In March, this habitat was of a type often used by seals to construct lairs (T. G. Smith, pers. obs.). We may have missed structures within this area in November/December that were subsequently found in March. Other searches were altered due to highly deformed ice, and the handler following the dogs on foot. It is not known how areas obscured by ridging or the slower search pace may have influenced detection.

Our evaluation of investigator effects on structure survival was likely confounded because structures that survived longer were rechecked more often and subsequently maintained in the Cox regression. Further investigation of this potentially confounding factor is necessary to evaluate the role of multiple excavations on continued use of structures by ringed seals. Investigator-induced abandonment of structures has been reported (Kelly et al., 1988; Frost & Burns, 1989; Hammill & Smith, 1990). Conversely, researchers often capture ringed seals repeatedly at breathing holes during the spring breeding period (T. G. Smith, pers. obs.). Thus, the sensitivity of a structure to investigator disturbance may be more strongly related to the season and type of structure involved.

Locating and excavating structures in a sense mimics natural predation, however, and, therefore, should influence the continued use of structures by ringed seals. Interestingly, we did not detect an effect of the presence of predator excavations on structure abandonment. Frost & Burns (1989) found such a relationship, and the work of others has shown the strong influence of predators on ringed seals (Smith, 1976, 1980; Hammill & Smith, 1989; Furgal et al., 1996). One of the instrumented structures contained evidence of a fox kill, but the structure was open at the end of the study. Ten of 181 (5%) structures were excavated by predators in our study, compared to 18% entered by foxes (Frost & Burns, 1989), and the small sample may account for the lack of a detectable effect.

Conclusions

Based on our results, three main conclusions can be made: (1) ringed seals used sea ice exposed to noise, vibration, and surface alteration related to Northstar activities in late 2000 and early 2001; (2) ringed seals showed a strong seasonal and habitat component to structure use; and (3) repeated dog searches are necessary to detect sea ice selected by ringed seals. These conclusions are further discussed below. Ringed seal breathing holes and lairs were established in the landfast ice before and during activities within a few meters of the Northstar offshore oil development, and many of these structures were maintained by seals for extended periods (up to 163 d). This occurred despite the presence of low-frequency industrial noise and vibration, construction and use of an ice road, and other occasional industrial activities on the sea ice. Construction activity on the sea ice was largely completed by late March 2001. Subsequent activities were primarily vehicle traffic on ice roads, snow removal, and numerous activities and drilling on the island. New structures were apparently created throughout the ice-covered season. This indicates that ringed seals are capable of adapting to highly variable habitat availability. The abandonment rate was not significantly different closer to the Northstar Island and ice roads versus farther away. This, plus associated aerial survey results (Moulton et al., 2005), showed that if there was altered habitat use near Northstar it was not detectable. We detected higher structure abandonment rates than previous work, and we determined that the higher ringed seal structure abandonment was due mainly to the season and ice deformation and does not seem to be related to the proximity of Northstar.

The influence of season on the creation and persistence of ringed seal structures must be considered for future studies and impact assessments. Simply detecting some unknown proportion of structures at a single time during winter, and then following the persistence of these structures, does not adequately consider the adaptations of ringed seals to sea ice dynamics and snow accumulation. We suspect there may be seasonal variation in ringed seal sensitivity to activities on the sea ice. This seasonality is an important consideration when assessing project impacts different than those studied here.

Repeated dog searches are useful and appropriate to detect ringed seal use of floating sea ice. This approach can reliably identify usable habits and minimize potential impacts to pregnant or lactating females and their dependent young. Studies of seal structures and the factors influencing their use are complicated by methodological difficulties and confounding influences of numerous natural and anthropogenic factors. This situation requires analysis procedures that take multiple factors into account. Even with those procedures, clear interpretations of the causes of abandonment remain elusive. Although ringed seals may abandon structures due to an anthropogenic activity (e.g., habitat alteration or disturbance), it is clear that structure abandonment often occurs for natural reasons related to seasonal changes in sea ice freezing, prey abundance, or other ecological factors difficult to measure.

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