Detecting Denning Polar Bears with Forward-Looking Infrared (FLIR) Imagery

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Polar bears give birth in snow dens in midwinter and remain in dens until early spring. The survival and development of cubs is dependent on a stable environment within the maternal den. To mitigate potential disruption of polar bear denning by existing and proposed petroleum activities, we used forward-looking infrared (FLIR) viewing to try to detect heat rising from dens. We flew transects over dens of radio-collared females with FLIR imager–equipped aircraft, recorded weather conditions at each observation, and noted whether the den was detected. We surveyed 23 dens on 67 occasions (1 to 7 times each). Nine dens were always detected, and 10 dens visited more than once were detected on some flights but not on others. Four dens were never detected (17 percent), but three of those were visited only under marginal conditions. The odds of detecting a den were 4.8 times greater when airborne moisture (snow, blowing snow, fog, etc.) was absent than when it was present, and they increased 3-fold for every 1°C increase in temperature–dew point spread. The estimated probability of detecting dens in sunlight was 0. Data suggested that FLIR surveys conducted during optimal conditions for detection can produce detection rates approaching 90 percent and thus can be an important management and mitigation tool.

Keywords: polar bear, infrared imagery, maternal denning, human impacts, management

Petroleum developments span approximately 200 kilometers (km) of the Alaskan Beaufort Sea coastal area and are proposed for dramatic expansion. Such operations are a potential threat to denning polar bears (Stirling 1990, Stirling and Andriashek 1992), which construct maternal dens in snowbanks in autumn (Amstrup and DeMaster 1988), give birth to altricial young in midwinter, and emerge from dens by early April (Blix and Lentfer 1979, Amstrup 1993, Amstrup and Gardner 1994). In Alaska, dens are not concentrated in mountains, as they are in most other locations (Uspenski and Chernyavski 1965, Uspenski and Kistchinski 1972, Larsen 1985, Ovsyanikov 1998). Nor are they associated with particular vegetation types (Ramsay and Andriashek 1986). Rather, snow accumulation sufficient for denning in northern Alaska occurs mainly in narrow linear patches of coastal and riverbank habitats that are widely scattered across broad reaches of flat terrain (Benson 1982, Amstrup 1993, Amstrup and Gardner 1994, Durner et al. 2001, 2003). These banks are largely invisible under the snow in winter, and their scattered distribution confounds efforts to locate dens with visual techniques (Ramsay and Stirling 1990, Amstrup and Gardner 1994, Clark et al. 1997).

We have mapped suitable habitats for polar bears (Amstrup 1993, Durner et al. 2001, 2003) and shown that much more denning habitat is available than is used in any one year. These maps allow developers to avoid many areas suitable for denning. Nonetheless, because it can be very expensive to reroute roads and so on to avoid mapped habitats, managers regularly ask whether banks or bluffs that are "in the way" of particular industrial activities actually hold dens. Until now, radio telemetry has been the only method allowing identification of dens in early winter, when most industrial land uses are planned. Collaring and following all females in the population, however, is prohibitively expensive and unacceptable as a routine management practice.

Watts (1983) reported that polar bears emit approximately 200 watts of heat energy while denning. He also reported that den temperatures were as much as 30°C higher than ambient levels, and that surface temperatures over a den averaged 10°C warmer than in snowbanks adjacent to the den. We hypothesized that modern forward-looking infrared (FLIR) imagers might detect that heat and thereby provide another method for detecting which banks actually hold dens. The term *FLIR* refers to fast-framing thermal imaging systems, as distinguished from downward-looking thermal mapping systems or single-framing thermographic cameras (FLIR

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Systems undated [a]). FLIR imagers can be mounted on aircraft or other fast-moving platforms, their field of view can be adjusted independent of the platform carrying them, and they can write images to television-compatible recorders. Older FLIR instruments have already shown promise in both marine mammal and terrestrial wildlife applications (Wyatt et al. 1980, Trivedi et al. 1982, Kingsley et al. 1990, Naugle et al. 1996). In this article, we describe efforts to test the effectiveness of newer FLIR imagers in another application: the detection of denning polar bears along Alaska's North Slope.

Locating dens

We captured polar bears by injecting immobilizing drugs (tiletamine hydrochloride plus zolazepam hydrochloride) with projectile syringes fired from helicopters (Larsen 1971, Schweinsburg et al. 1982, Stirling et al. 1989). Capture protocols were approved by independent animal care and welfare committees. Polar bears were captured in coastal areas of the Beaufort Sea between Barrow, Alaska, and the Canadian border, from March through May and from October and November in the years 1996 through 2001. Satellite and VHF radio transmitters were attached to solitary adult female polar bears with neck collars (Amstrup et al. 2000). Using a combination of satellite and aerial radiotelemetry, we tracked pregnant, radio-collared females to their dens. During the course of FLIR surveys we detected additional, previously unknown dens.

Surveying dens

We assessed the effectiveness of the FLIR Safire II, AN/AAQ-22 (see *www.flir.com*), by flying transects over known denning locations during the winters from 1999 to 2001. The Safire, which operates in the 8- to 14-micron wavelength range, can detect differences in temperature down to 0.1°C under ideal circumstances, according to the operations manual (FLIR Systems undated [b]). The Safire was gimbal mounted under the nose of a Bell 212 helicopter. This mounting system allowed the imager to be directed independent of the attitude of the aircraft and in any direction below the horizontal plane of the aircraft.

We evaluated the FLIR imager in transect and hovering flight modes. We flew transects along bank features (Durner et al. 2001, 2003) holding known dens. We oriented the aircraft, as much as possible, so that the prominent snowdrifts likely to hold dens were below and to the side of the aircraft. This oblique view allowed us to focus the FLIR imager approximately perpendicu-

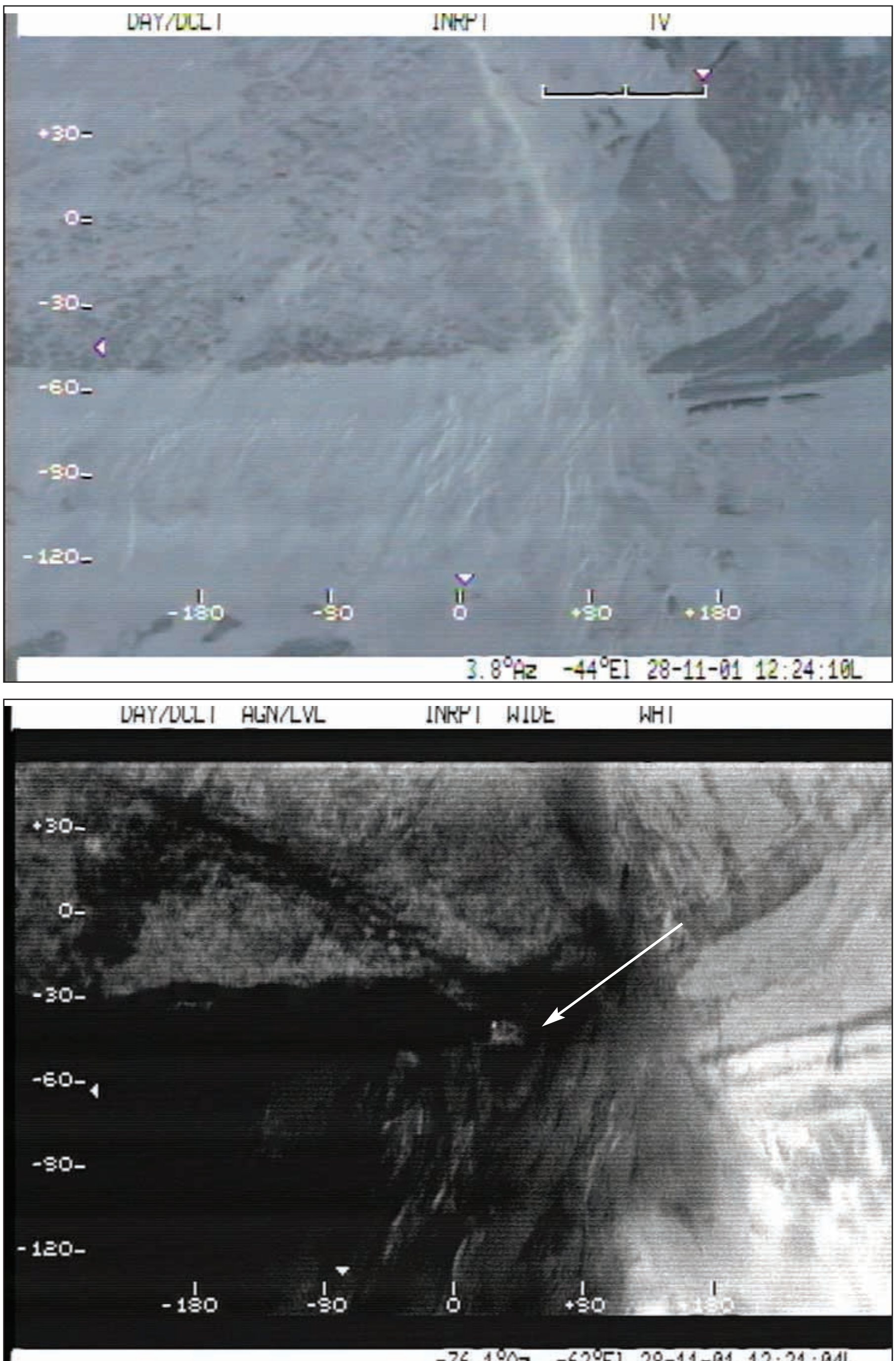

Figure 1. Video image of the snowdrift along the south shore of a coastal island (top) and forward-looking infrared (FLIR) image of the same location (bottom). The FLIR image reveals the heat emitted by a polar bear maternal den, and the arrow indicates the relative "hot spot" created by the body heat of the bear. The distance between reticule marks is approximately 18 meters.

lar to the face of the drifts we were searching. To prevent FLIR operators from easily keying in on den locations and to simulate searches for unknown dens, we surveyed portions of bank habitats at least 1.6 km on either side of known dens. Also, during November 2001, we surveyed bank habitats along more than 175 km of coastline where no collared bears were known to be denning. The 2001 surveys and the transect sections adjacent to known dens allowed us to detect dens of noncollared bears.

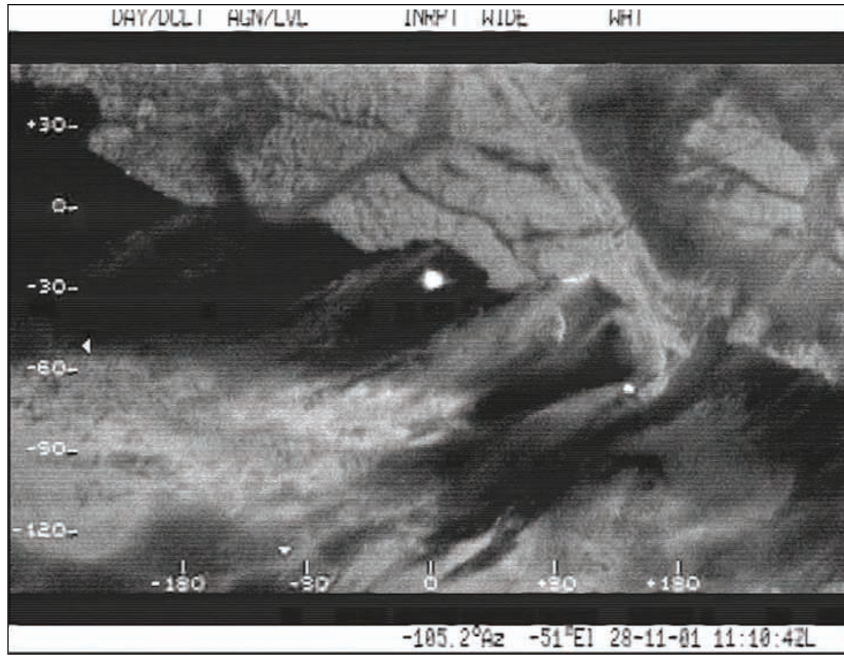

Figure 2. Forward-looking infrared image of two polar bear dens in the snow bank on the south shore of an Alaskan coastal island. The bright den in the center of the image is open, and the den at the right tip of the island is partially or completely covered by snow. Note the detail of polygon tundra, the dark drift of snow along the tundra bank, and the relative brightness or warmth of the sea ice at the bottom edge of the figure. The distance between reticule marks is approximately 18 meters.

When a thermal signature, or "hot spot," was seen on a transect, we hovered over the spot at a variety of altitudes and angles to adjust the image and determine whether we were seeing a den or some other source of heat differential. Tape segments were recorded and labeled for both flight modes. Known dens were recorded as "detected" or "not detected" on the basis of flight notes and subsequent tape review. Hot spots not known to be dens also were recorded on tape. We recorded weather conditions during each survey occasion. The records we compiled from the weather reporting station geographically closest to each survey flight included ambient temperature, wind speed, wind direction, visibility, percentage of cloud cover, cloud ceiling elevation, relative humidity, and dew point. Dew point, the temperature to which a given parcel of air must be cooled for saturation to occur, incorporates the effect of pressure and temperature on relative humidity. We recorded the presence of moisture in the form of blowing or falling snow, airborne ice crystals, or fog at the site of each transect. If any of these conditions, either singly or in combination, was detectable, airborne moisture was recorded as present. Similarly, if the sun was above the horizon and shining on the snow surface (even with cloud cover present), the variable "sun" was recorded as present.

After the bears left their dens in spring, we attempted to visit each den and hot spot located the preceding winter. At that time, we recorded the amount of snow overlying the lair. We also attempted to visit many of the dens in the summer after snowmelt. During those visits, we were able to record additional characteristics of the den location and also to check the soil and vegetation for evidence of denning activity (Durner et al. 2003).

Polar bears in the Beaufort Sea region of Alaska and Canada frequently den on the sea ice as well as on land (Amstrup and Gardner 1994). Early in the study we abandoned attempts to detect dens in the ice environment because of the array of competing heat signatures. FLIR systems detect a difference in temperature between adjacent sites in the field of view. In winter, the ocean is relatively hot; and cracks, holes, and pressure ridges in the sea-ice surface created an infinitely variable mosaic of hot, warm, and cold spots in the FLIR screen. We once captured a clear image of the den of a collared bear high in a pressure ridge of landfast ice. Extremely cold weather and tight ice, along with ideal atmospheric conditions, must have contributed to that successful detection, because during later visits we were unable to distinguish the den from major heat sources throughout the pressure ridge and surrounding area. We also failed to differentiate the heat signatures of other dens that had been visually observed on landfast ice. Similarly, we consistently failed to detect the dens of two radio-collared bears denning on drifting pack ice. The heat signatures from these dens may have appeared on the FLIR screen. Because of the abundance of competing hot spots, however, we were unable to determine whether or not we were seeing them. These early experiences mandated that we limit our FLIR testing to dens on land.

Data analyses

Analyses were performed using S-Plus (ver. 2000; *www.insightful.com*) and SAS (ver. 8; *www.sas.com*). We first calculated descriptive statistics and examined our data in a univariate context. Differences in values of individual continuous variables (e.g., cloud cover or ceiling) were tested with the Student's *t*-test. We tested for frequency differences in individual categorical variables (e.g., presence or absence of airborne moisture or sunlight) between occasions when dens were detected and when they were not with Fisher's exact test

(Zar 1984). All variables were then cast in a Pearson correlation matrix to search for collinearity. One member of each pair of variables with correlation coefficients of at least 0.70 was deleted from consideration for additional multivariate analyses.

We modeled detection of dens in a multivariate context with logistic regression (McCullagh and Nelder 1989). Although most FLIR images were acquired during darkness, eight attempts to detect dens were made after sunlight had begun to light up the snow surface, and no dens were detected during these attempts. Logistic regression is not possible when responses associated with a single level of a categorical variable are either all successes or all failures. Failure to detect any dens when the sun was shining on the snow meant that our logistic regression models applied only to nonsunny periods.

We assessed the probability of detecting a polar bear den during nonsunny times, with a stepwise selection procedure (Neter et al. 1996, Ramsey and Schafer 1997). This modeling procedure considered environmental covariates for each recorded video segment. In other words, our sampling units were the video segments from each flight over each den. Covariates considered during the modeling process included *air_moist* (the presence or absence of airborne moisture); *spread* (the temperature–dew point spread); *visibility* (reported visibility); and *wind* (reported wind speed). Cloud ceiling data were missing in 23 cases and thus were not considered. Cloud cover data were found to be highly correlated ($P = 0.71$) with *air_moist* and were therefore not considered in modeling. Temperature and dew point individually were not considered because *spread* was a function of both. We did not include snow depth because only one measurement (made at the end of each field season) was available for each den, and we had no way to assess possible differences among survey flights. At each step in the variable selection process, the most significant variable (not already included) entered the model if its significance level was less than $\alpha = 0.10$. Additionally, at each step any variable in the model was eliminated if its significance became greater than $\alpha = 0.10$. The stepwise variable selection procedure was carried out using the SAS routine *Proc Logistic*.

Because the coefficients in logistic regression do not affect responses linearly (as they do in linear normal theory regression, for example), we assessed the importance of each covariate in the final model by calculating odds and odds ratios. In logistic regression the outcomes are either 0 (no detection) or 1 (detection). The term *odds* means simply the probability of obtaining a 1 divided by the probability of obtaining a 0. In this FLIR application, the odds of detecting a den were computed (probability of detection [Pr(detection)] divided by [1 – Pr(detection)]). Then, to help explain the role of covariates in the final model, we calculated the odds ratio of seeing a den at one level of a covariate to the odds of seeing it at the next incremental level of the covariate (e.g., odds of seeing a den when *spread* = 2 divided by the odds of seeing a den when *spread* = 1).

Sunlight seemed to have a profound effect on FLIR performance. Because we could not evaluate the effect of sun in a multivariate context and therefore could not assess its added contribution to odds of detection, we wanted to provide some measure of the precision of our estimated probability of detection in sunny times. We did this by inverting a one-sided binomial hypothesis test (Lehmann 1986, p. 93) to estimate a 95 percent confidence interval for the probability of detecting a den during sunny times. The lower value of our confidence interval was 0, our point estimate. We computed the upper value of the confidence interval, by iteratively guessing at the value of an upper bound, p_u, until the hypothesis H_0 ($p \geq p_u$) was rejected at the $\alpha = 0.05$ level of significance in favor of the hypothesis H_1 ($p < p_u$). For example, assume n (here, $n = 8$) FLIR video segments were recorded during sunny times, and we identified a_0-occupied polar bear dens on those n videos (here, $a_0 = 0$). The upper $(1 - \alpha)$ percent confidence limit was the smallest value of p_u that satisfied the condition for rejection of H_0; that is,

$$\sum_{x=0}^{a_0} b(x,n,p_u) \leq \alpha,$$

where the probability of observing x successes in n trials from a binomial distribution with probability p_u was:

$$b(x,n,p_u) = \frac{n!}{x!(n-x)!}\, p_u^{\,x}(1-p_u)^{n-x}.$$

Den observations recorded

During this study we located 19 polar bear maternal dens on land by radio telemetry. Bad weather, poor-quality radio fixes, difficult terrain, and a malfunctioning tape player prevented us from securing FLIR images at four dens of radio-collared polar bears. During attempts to view the 15 remaining dens, we observed 12 previously unknown hot spots that we concluded, either in flight or upon subsequent review of FLIR tapes, were polar bear dens. Dens (and targets presumed to be dens) appeared as small bright (hot) spots, usually with fuzzy boundaries, within a normally dark (cold) band of drifted snow (figures 1, 2). We attempted to visit all of the hot spots at least twice with FLIR imager–equipped aircraft. Such revisits eliminated most hot spots from our list or increased our confidence in calling a hot spot a den.

Spring and summer surveys confirmed that only three unknown hot spots were not polar bear dens. Because of weather and other logistical limitations, each of these three had been visited only once with FLIR. The thermal differentials at those three sites turned out to be the result of, respectively, an empty steel barrel, a large boulder partially embedded in an unstable permafrost bank, and a piece of sloughed tundra lying partway down a permafrost bank. We failed to obtain evidence confirming whether a fourth previously unknown hot spot was a den. We flew over that fourth hot spot twice, with the FLIR imager, en route to a known den. We simply missed this hot spot during tape reviews conducted in the field, and did not notice it until final review of both tapes at the end of the field season. At that time,

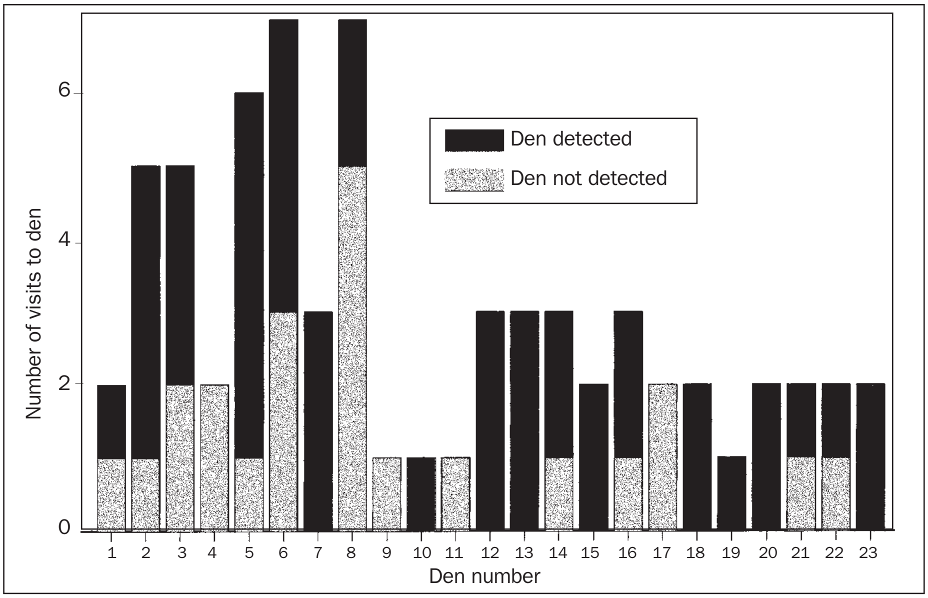

Figure 3. Summary of detections and detection failures for 23 polar bear dens along Alaska's northern coast surveyed with forward-looking infrared imagery during the winters of 1999 and 2001.

revisiting and reexamining it in hover flight mode were not possible. This hot spot was viewed in transect flight mode only, but it appeared to have had all the earmarks of a den. Because we did not hover over it, as we had over other hot spots, however, and because we were unable to return to the site in either spring or summer to search for evidence of polar bear use, we could not conclude whether or not it was an occupied den.

We surveyed the other 23 dens on 67 occasions (1 to 7 times each). Six of these dens were occupied by unknown bears and the remaining 17 dens by 15 radio-collared bears. Collared bears occupied one den each, except for bear 20330, which denned three times during the study. The number of viewing occasions at each den was inversely proportional to the distance of the den from the home base of the helicopter used for the FLIR missions. Reaching more distant dens resulted in increased difficulties with weather and other logistics. Figure 3 summarizes the frequency of detection for the 23 dens surveyed. Four dens (17 percent) were never detected with FLIR. Two of these were visited on two occasions, the other two only once. Two dens visited one time each were detected on those single visits. Four dens visited twice were detected both times. Three dens visited three times were detected on each visit. Detection success of the other 10 dens was mixed. Bear 20330, the known individual tracked to multiple dens, was detected on at least one visit to each of her three dens and also not detected on at least one visit to each.

Analyses of individual covariates

When evaluated singly, in the two-sample t context, only wind speed and temperature–dew point spread differed significantly between detection and nondetection events. The mean wind speed (11 knots per hour [kts/hr]) on occasions when we did not see dens was significantly higher than on occasions when we did see dens (6 kts/hr) ($t = 2.897$, degrees of freedom [df] = 65, $P = 0.0051$). Similarly, the mean spread between temperature and dew point on occasions when dens were not seen (2.56°C) was significantly narrower than the mean spread (3.01°C) when dens were seen ($t = 2.891$, df = 65, $P = 0.0052$). It stands to reason that there should be an inverse relationship between depth of snow over the bear and heat transmission to the snow surface. The range of depths recorded, however, was apparently below any threshold that, by itself, prevents detection by FLIR imaging. Mean snow depth over detected dens was 40 centimeters (cm) and only 31 cm over undetected dens; the greatest depth (96 cm) was recorded over a detected den. Depth differences between detected and undetected dens were not significant ($t = -1.001$, df = 18, $P = 0.383$).

Airborne moisture was detectable on 12 of 23 (52 percent) occasions when dens were not seen and on only 15 of 44 (34 percent) occasions when they were seen. The two-sided Fisher's exact test, however, suggested this difference was not significant ($P = 0.1931$), indicating that the absence of air moisture alone did not explain the detection of known dens. Sunlight was present on 8 of 23 (35 percent) occasions when dens were not seen, and on none of the occasions when dens were seen. According to Fisher's exact test, this difference was highly significant ($P = 0.00008$). The probability of seeing an occupied polar bear den on FLIR video that was recorded in sunlight was estimated to be 0. The upper 95 percent confidence bound on the probability of detecting a den when sun was shining on the snow was 0.313 (see table 1).

Modeling den detection with multiple covariates

Some insights regarding the ability of our measured covariates to explain detection by FLIR imaging were obtained from the above individual comparisons. Recognition of possible interactions among our covariates, however, mandated modeling approaches in which all covariates were eligible to be considered. After removing the 8 observations associated with sunny conditions, 59 observations were available for this model fitting. The final logistic regression model for the probability that an occupied polar bear den was seen on the FLIR video recorded during nonsunny times was

$$\hat{p} = \frac{\exp[-2.8576 + 1.1237(spread) + 1.5692(air\_moist = 0)]}{1 + \exp[-2.8576 + 1.1237(spread) + 1.5692(air\_moist = 0)]}$$

(eq. 1).

Standard errors for coefficients in the final model were 0.5401 for *spread* and 0.6846 for *air_moist.* Table 2 summarizes descriptive statistics for the covariates appearing in this model. The odds ratio point estimate for *spread* was 3.08, indicating that for every 1 degree (°C) increase in the difference between temperature and dew point, the odds of detecting a den increased 3.08 times. Calculation of this odds ratio can be illustrated in three steps. First, the probability of detecting a den when *spread* = 1 was estimated, according to equation 1, as

$$\hat{p} = \frac{0.848}{1.848} = 0.459.$$

The odds of an event is the ratio of the probability that the event occurs to the probability that the event does not occur, so the odds of detecting a den when *spread* = 1 is

$$\frac{0.459}{1 - 0.459} = 0.848.$$

Second, when *spread* increases to 2°C, the probability of detecting a den was estimated, according to equation 1, as

$$\hat{p} = \frac{2.609}{3.609} = 0.7229.$$

The odds of detecting a den when *spread* = 2 is

$$\hat{p} = \frac{0.723}{1 - 0.723} = 2.61.$$

Finally, the odds ratio for a one-unit increase in spread from 1°C to 2°C is

$$\frac{2.61}{0.845} = 3.08.$$

Some algebra reveals that odds ratios are easily calculated for a one-unit increase in a predictor variable by simply exponentiating the coefficient value of that predictor variable (raising *e* to the value of the coefficient); for example, $e^{1.1237} = 3.08$. The odds ratio for smaller changes in temperature–dew point spread also can be calculated as above. For example, the odds ratio for a 0.5°C increase in *spread* (the difference between the mean temperature–dew point spread of detected and undetected dens) was estimated as 1.75. Therefore, the odds of a trained biologist detecting a den increased 75 percent for every 0.5°C increase in *spread*.

Similarly, the odds ratio for *air_moist* was $e^{1.5692} = 4.803$, indicating that the odds of a trained biologist detecting a den were approximately 4.8 times higher when there was no visible moisture in the air at the time the video was recorded than when there was moisture in the air. Confidence intervals (95 percent) on odds ratios were 1.067–8.867 for *spread* and 1.255–18.375 for *air_moist*.

Interpretations and conclusions

Although they showed some promise, early infrared sensors did not reliably detect either white-tailed deer *(Odocoileus virginianus)* or mule deer *(Odocoileus hemionus)* (Wyatt et al. 1980, Trivedi et al. 1982). Naugle and colleagues (1996) and Wiggers and Beckerman (1993), however, demonstrated that newer FLIR scanners were more reliable in detecting heat signatures of deer. Similarly, Kingsley and colleagues (1990) demonstrated that an older FLIR imager mounted on a helicopter did detect some under-snow lairs of ringed seals *(Phoca hispida)*; they also reported that the thickness of snow over the lair, ambient temperature, wind, and sunlight prevented seal lairs from being detected consistently enough to allow census by FLIR surveys. Ringed seal lairs occur exclusively in the sea-ice environment. Our preliminary testing with a newer FLIR imager indicated that there were too many competing heat signatures in that environment to consistently detect denning polar bears. Hence, failure to consistently detect lairs of the much smaller ringed seal in sea-ice habitats is not surprising. In the assortment of hot spots detectable on the sea ice, observers cannot be certain they are seeing a lair, even if it is visible on the monitor.

Whereas even modern FLIR devices may not be satisfactory for distinguishing dens of either seals or polar bears on the sea ice, we found that FLIR imaging was effective in detecting dens on land. Bears denning on land generally are surrounded by colder and more uniform substrates than seals or bears occupying subnivian lairs at sea. Polar bears also are larger and presumably emit more heat than ringed seals. The potentially greater thermal contrast of denned bears, the more uniform backdrop of land, and the more advanced equipment used in this study combined to create a useful tool for detecting polar bears in land dens in early winter, before construction projects and seismic surveys typically occur. Fortunately, it is the dens on land that are the greatest management concern related to industrial development in the north. Sea-ice dens are, by virtue of their location, relatively insulated from human activities.

We recognize that our FLIR surveys were not 100 percent effective in detecting dens even when we knew they were there, and we do not expect that current FLIR technologies could ever detect all dens regardless of ambient conditions. However, we believe FLIR imaging has an important place in

Table 1. Upper confidence limit (shaded line), calculated with the inversion of hypothesis method, for the probability of detecting a denning polar bear with forward-looking infrared imagery during sunny conditions (n = 8 and x = 0).

p_u	$n!/[x!(n-x)!]$	p_u^x	$(1 - p_u)^{n-x}$	Probability
0.1	1	1	0.43047	0.430467
0.2	1	1	0.16777	0.167772
0.3	1	1	0.05765	0.057648
0.31	1	1	0.05138	0.05138
0.312	1	1	0.0502	0.0502
0.313	1	1	0.04962	0.04962
0.314	1	1	0.04904	0.049045
0.32	1	1	0.04572	0.045716
0.35	1	1	0.03186	0.031864

the management of human activities that could adversely affect polar bears denning on land.

The four dens (17 percent) that we failed to detect during our study were visited a total of six times. The first of these dens was initially visited immediately after a blizzard with extensive blowing and falling snow. Surface snow temperatures apparently had not stabilized, and the ground surface was extensively mottled with a windrow pattern of alternate bands of newer warm snow and older colder snow. This windrow effect on the snow surface often was apparent on the FLIR monitor even when wind speeds were below those that result in obvious blowing snow, and it seemed to persist for hours after wind speeds subsided. That may partially explain why our *t*-test suggested that dens were less detectable under elevated wind conditions. Additionally, this survey was conducted despite a cloud ceiling of only 400 feet and a temperature–dew point spread of only 2.2°C. The only other time we were able to get to this den, the sun was shining. Clearly, neither of these visits maximized our odds of detecting the den.

Table 2. Descriptive statistics for variables in a final logistic regression model.

Variable	Set	Number		
		Den seen	Den not seen	Total
air_moist	Yes	15	10	25
	No	29	5	34
Total		44	15	59

Variable	Statistic	Value of statistic		
		Den seen	Den not seen	All observations
spread	Minimum	1.67	1.67	1.67
	Median	3.33	2.22	3.00
	Mean	3.00	2.64	2.91
	Maximum	3.89	3.89	3.89

Note: Eight dens that were undetected when visited while the sun was shining are not included.

The second and third dens that went undetected were visited only once each. Both of those flights occurred despite airborne moisture visible in the FLIR monitor. Our detection model verifies that the odds of seeing these dens were nearly five times lower than would have been the case had we visited them on days without airborne moisture. The fourth den that escaped detection was visited twice. On the first visit, the temperature–dew point spread was only 2.2°C, less than the mean value for dens that were not detected. The second visit, however, occurred under conditions that should have been favorable for detection, yet we did not see the den.

Five of these six den visits were during weather conditions we have shown to compromise the effectiveness of FLIR imaging, and only one of these four dens was ever visited when conditions were deemed favorable. Although additional visits might not have allowed us to detect the den that was visited once during good conditions, the odds of detecting the other three dens visited only in poor conditions would have been more than three times greater had we been able to visit them under better weather conditions. With detection of some or all of those, our overall den detection rate would have increased to a value between the 83 percent we observed and the 96 percent that would have resulted from three added detections. We cannot be sure that added visits under conditions maximizing the odds of detection would have resulted in successful detections of those three dens. However, the great expense of rerouting roads and other development projects around potential denning habitat suggests that developers would make the investments necessary to visit potential den sites under ideal conditions rather than be required to change development plans. Therefore, in real-world applications where big money is at stake, an increase in the overall detection rate to at least 90 percent seems highly probable. That level of detectability clearly would be significant in efforts to minimize disruptions of denning polar bears.

Logistical constraints prevented acquisition of sufficient data to quantify the probabilities of false positives—that is, calling a thermal signature a den when it is not. It is reassuring, however, to recognize that in conducting hundreds of kilometers of FLIR surveys, we misidentified only three such thermal signatures. During this study, nearly all of the hot spots initially identified as suspected dens were confirmed not to be dens after additional visits. The three misidentified hot spots remained on our list of possible dens because we were unable to revisit them. Our experiences at other sites, however, make us confident that repeated visits to the misidentified sites would have resulted in their removal from the list of suspected dens. Had such hot spots occurred in habitats that were proposed for disturbance, the great costs required to reroute projects around them assure that repeated surveys would have been done to reveal whether or not they were dens. Likewise, we are confident that the fourth unknown hot spot would have been revisited in a real management situation before avoidance measures were taken. Hence, our experiences in this study suggest that the risks of false positives are low.

Because polar bears roam over large areas at low densities, general surveys for bears or their dens would not be practical even with new FLIR technologies. Polar bears, however, den primarily in steep bank faces (along streams, lakeshores, and coastlines of the mainland and some offshore islands) that have been identified and mapped across a large section of Alaska's North Slope (Durner et al. 2001). Therefore, high-sensitivity FLIR imagery applied to those mapped habitats provides the first real tool for detecting polar bears in dens early enough in winter to alter the paths of human activities and thereby protect denning bears. With denning habitats either mapped or clearly described, many human activities that might affect denning bears would be routed around those preferred habitats, thereby avoiding the possibility of negative impact. If plans for a road or other development project include traversing such habitat, FLIR surveys of the development corridor can help show which of the pieces of that habitat must be avoided because of known dens. Such efforts can assure that the effect of human activities on denning polar bears is minimal.

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