CONTRIBUTED PAPER

Effects of environmental conditions on the use of forward-looking infrared for bear den detection in the Alaska Arctic

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Abstract

Industrial off-road activity in winter overlaps denning habitat of polar bear (*Ursus maritimus*) and grizzly bear (*Ursus arctos*) in the North Slope oilfields of Alaska (United States). To prevent disturbance of dens, managers have used forward-looking infrared (FLIR) cameras to detect dens, but the effectiveness of FLIR under different environmental conditions is unresolved. Our objective was to evaluate the effects of environmental variables on FLIR-based techniques for arctic bear den detection. Using a FLIR-equipped unmanned aircraft system (UAS), we conducted observations of artificial polar bear (APD) and grizzly bear (AGD) dens from horizontal and vertical perspectives between December 2016 and April 2017. We recorded physical characteristics of artificial dens and weather conditions present during each observation. We captured 291 images and classified each as detection or nondetection based on the number of pixels representative of a den "hot spot." We used logistic regression to model the effects of four weather variables on the odds of detection (detection). We found that UAS-FLIR detects APDs two times better than AGDs, and that for both species detections are four times more likely from the vertical than horizontal perspective. Lower air temperature and wind speed, and the absence of precipitation and sunlight increased detection for APDs. A 1°C increase in air temperature lowered detection by 12% for APDs and by 8% for AGDs. We recommend that UAS-FLIR surveys be conducted early in the denning season, on cold, clear days, with calm winds, in the absence of sunlight (e.g., civil twilight). Our study further refines the application of FLIR techniques for arctic bear den detection and offers practical recommendations for optimizing detection. Putative den locations should be confirmed by a secondary method to minimize disturbance as anthropogenic activity continues in the Arctic.

KEYWORDS
FLIR, grizzly bear, human-bear conflict, polar bear, remote sensing, unmanned aircraft system

1 | INTRODUCTION

Winter denning by grizzly bear (*Ursus arctos*) and polar bear (*Ursus maritimus*) in the North Slope oilfields of Alaska (United States) is a complex ecological strategy to reduce energy expenditures during periods of unfavorable environmental conditions (Watts, 1990). Grizzly bears of both sexes and all age classes use winter dens (Manchi & Swenson, 2005), but only pregnant female polar bears exhibit denning behavior (Ferguson, Taylor, Rosing-Asvid, Born, & Messier, 2000; Watts, 1990). Pregnant female polar bears in Alaska establish maternal dens predominantly within large drifts of snow (Amstrup, York, McDonald, Nielsen, & Simac, 2004). They enter the den in November and exit in March or April (Amstrup & Gardner, 1994; Smith, Partridge, Amstrup, & Schliebe, 2007). Grizzly bears dig earthen dens between late September and early November and exit between March and May, with males and nonpregnant females entering and exiting dens earlier and later, respectively, than pregnant females (Shideler & Hechtel, 2000). Both species give birth in the den during the winter to protect their young from the harsh winter conditions during their most vulnerable stage of life (Linnell, Swenson, Anderson, & Barnes, 2000). If disturbed, a bear may abandon its den resulting in higher bear mortality, family dissolution, and subsequent cub mortality due to exposure, starvation, or predation (Amstrup, Stirling, Smith, Perham, & Thiemann, 2006; Linnell et al., 2000; Swenson, Sandegren, Brunberg, & Wabakken, 1997).

Losses in critical arctic sea ice habitat have placed the long-term viability of the polar bear in question, resulting in "threatened" status under the U.S. Endangered Species Act since 2008 (Federal Registrar, 2008). Reduced access to sea ice may be contributing to increased selection of land-based dens, raising the chances of adverse human-bear interactions with residents of coastal villages and personnel associated with industrial activity on the North Slope (Amstrup & Gardner, 1994; Fischbach, Amstrup, & Douglas, 2007; Rode, Robbins, Nelson, & Amstrup, 2015). Since the 1970s, extensive petroleum exploration and extraction on the North Slope has occurred and may further overlap with denning habitat for both polar bears (Wilson & Durner, 2020) and grizzly bears. It is crucial for bear conservation that the oil industry has reliable methods for locating and avoiding occupied dens during development activities in the Arctic. The U.S. Fish and Wildlife Service (USFWS) manages the southern Beaufort Sea polar bear stock on the Alaska North Slope and has a federally codified regulation (50 CFR § 18.128 1(b)(2)) requiring minimal industrial activity ≤1.6 km from known polar bear dens. Likewise, the Alaska Department of Natural Resources and the U.S. Bureau of Land Management have specific permit stipulations on off-road

exploration and construction projects during winter to minimize industrial activity ≤0.8 km from an occupied grizzly bear den (Reed, 2018). These buffer zones around occupied bear dens are established for bear conservation and human safety purposes (Löe & Röskaft, 2004; Naughton-Treves, Grossberg, & Treves, 2003; Voorhees, Sparks, Huntington, & Rode, 2014). In order to reduce negative human-bear interactions and threats to worker safety, it is critical that managers are able to accurately identify the location of active bear dens for avoidance.

Polar bear denning habitat in the North Slope of Alaska oilfields is associated with landscape features that allow drifting snow to accumulate deep enough for excavation (Liston, Perham, Shideler, & Cheuvront, 2016). These features are widely dispersed and difficult to differentiate from the surrounding environment (Amstrup & Gardner, 1994; Durner, Amstrup, & Ambrosius, 2001; Durner, Amstrup, & Fischbach, 2003). Grizzly bear denning habitat can be even more difficult to identify, as it constitutes a variety of landscape features (e.g., riverbanks, pingos, and terraces) that provide relief in the landscape (Shideler & Hechtel, 2000). Den entrances are discrete, and they are quickly covered by drifting snow, which can impede visual den detection techniques (Amstrup & Gardner, 1994; Clark, Stirling, & Calvert, 1997; Ramsay & Stirling, 1990). For this reason, it is preferable to identify and map suitable den habitat to facilitate knowledge of where occupied dens are more likely to occur (Durner et al., 2001, 2003; Liston et al., 2016).

Polar bear den interiors can be 30°C higher than outside air temperatures and the snow surface temperature above the den can be 10°C warmer than surrounding snow (Watts, 1983). A denning grizzly bear can emit heat signatures less than or equal to polar bears (Watts, 1990). Forward-looking infrared (FLIR) cameras can detect minor heat differences in the landscape by measuring *emissivity*: the ability of a substance to release thermal energy (Hyll, 2012). The USFWS has used FLIR techniques to detect polar bear dens in advance of industrial operations on the North Slope of Alaska since 2004. Sensors on the airborne FLIR imager used in these surveys can measure 0.1°C differences in surface temperature (Amstrup et al., 2004) and produce an image that represents relative temperature differentials. Body heat of a denning bear is emitted through the snow surface creating a "hot spot" in a FLIR image. This is represented by a discrete cluster of image pixels on the snow surface above the den, or den entrance that can be differentiated from the surrounding surface (Figure 1). Previous studies on the effectiveness of FLIR imagery have documented both false positives (hot spots are detected at unoccupied dens) and false negatives (hot spots are not detected at occupied den). False positives occur because landscape structures
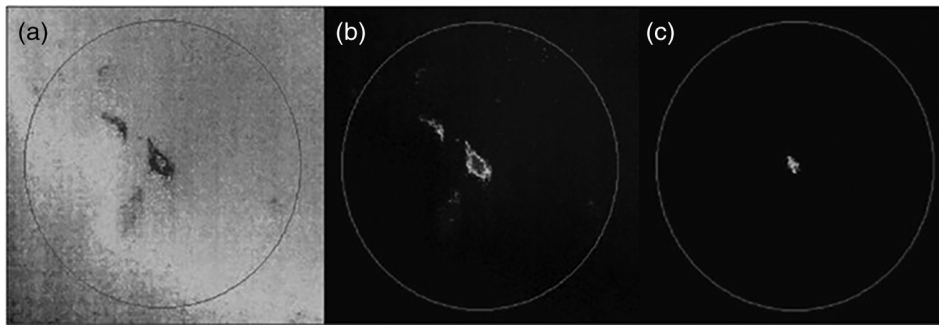
FIGURE 1 From left to right: forward-looking infrared image of an artificial polar bear den at a distance of 50 m vertical above the den, post-processed using a "segment" feature to eliminate colder pixels from image (a), to partially segmented image (b), and leave only the warmer pixels associated with the den "hot spot" in image (c) to be counted using a "region of interest" (circle) as a means to evaluate the quality of the detection in comparison to other detections at this distance

(e.g., human-made infrastructure, exposed soil) can absorb and re-emit solar radiation, or have substantially different emissivity that can be confused with the infrared (IR) signature of an occupied den (Amstrup et al., 2004; Shideler & Perham, 2013). Weather conditions and den physical characteristics (i.e., den snow wall ceiling thickness) can inhibit the ability of FLIR sensors to differentiate temperatures on the snow surface, causing a false negative. False negatives are a much greater conservation and safety concern than false positives because occupied bear dens are not detected.

Aerial and handheld FLIR camera platforms have been evaluated to detect occupied and human-made artificial polar bear and grizzly bear dens (Amstrup et al., 2004; Robinson, Smith, Larsen, & Kirschhoffer, 2014; Shideler & Perham, 2013). Each of these previous studies revealed limitations on the effectiveness of FLIR cameras under varying ambient conditions that may influence odds of detection (detection). However, each of these previous studies was limited in scope, leaving ample room for testing and optimization of the FLIR-based technique. For example, either logistics hindered sufficient data collection for precise and conclusive results (Amstrup et al., 2004; Shideler & Perham, 2013), or data collection occurred over short observation period (19 days) when polar bears begin exiting the den (March) using images that were only captured from a horizontal perspective (Robinson et al., 2014). Den detection using ground-based horizontal images are more likely to be influenced by convection and blowing snow. Previous studies indicated that a more meaningful evaluation of FLIR techniques could be obtained by overcoming logistical issues to collect a robust sample size of FLIR observations from the horizontal and vertical perspective, across the denning season, using dens with known physical characteristics and known weather conditions for comparison (Amstrup et al., 2004; Robinson et al., 2014; Shideler & Perham, 2013).

To overcome technical and logistical problems, we employed an Unmanned Aircraft System (UAS) platform equipped with a FLIR camera to obtain a greater sample of images of artificial polar bear (APD) and grizzly bear (AGD) dens under different environmental conditions that may affect detection. Our objectives were to capture images of artificial dens throughout most of bear denning season (December to April) to (a) estimate differences in detection from horizontal and vertical perspectives; (b) model the relative influence of environmental variables on detection, and (c) opportunistically collect imagery of occupied bear dens for comparison with artificial dens and to demonstrate the ability of UAS-FLIR to survey and monitor bear dens in arctic winter conditions. Drawing from previous research, we hypothesized that detection would be optimized using vertical perspectives under certain environmental conditions, which includes low wind speed and relative humidity, along with the absence of direct solar radiation and precipitation.

2 | METHODS

We constructed six artificial bear dens during October and December 2016 within the North Slope oilfields of Alaska (Figure 2). We used the same methods and similar dimensions specified in an earlier study (Shideler, 2014). AGDs were excavated in the soil in late October, and the entrances were covered with slabs of snow to allow for additional drifted snow to form a snow wall over the entrance and soil wall (Supporting Information). Internal den dimensions were measured upon excavation of the dens and verified at the end of the winter monitoring period (Table 1). We created APDs in prominent snowdrifts in December and covered entrances with slabs of snow to allow the entrance to fill in with drifted snow to form a wall (Table 1). Two artificial dens were
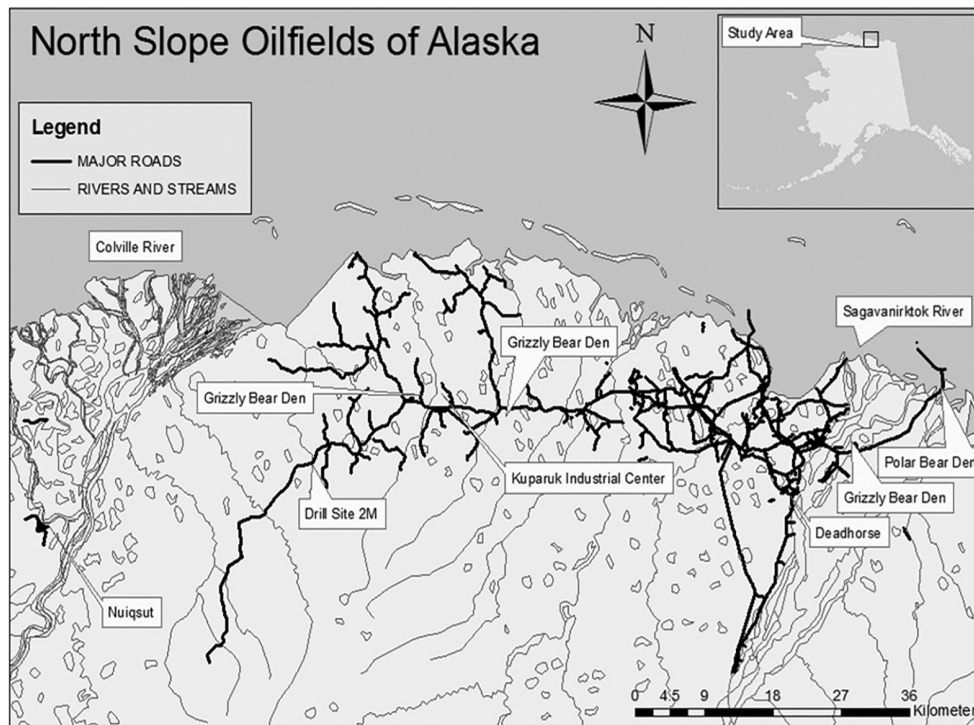
FIGURE 2 Study area: North Slope oilfields of Alaska (United States). One artificial grizzly bear and one artificial polar bear den located at Drill Site 2M and two artificial grizzly bear and two artificial polar bear dens located at the Kuparuk Industrial Center. The location of the one occupied polar bear den and three grizzly bear dens are labeled

		Polar bear	Grizzly bear
Den dimensions (cm)	Depth	136.7 (SD 40.9)	94.3 (SD 21.2)
	Width	152.7 (SD 45.5)	126 (SD 41.2)
	Height	94.2 (SD 41.8)	86.7 (SD 23.6)
Den wall thickness (cm)	Mean	30.9 (SD 16.7)	51.6 (SD 45.8)
	Minimum	1	15
	Maximum	57	150
Temperature (°C)	Den interior	−2.5 (SD 1.9)	−4.4 (SD 4.5)
	Den surface	−10.1 (SD 6.9)	−11.9 (SD 8.4)
	Snow surface	−18.1 (SD 8.3)	−18.1 (SD 8.3)
Air temperature (°C)	Mean	−18.3 (SD 7.7)	−18.3 (SD 7.7)
	Maximum	−9	
	Minimum	−29	
Solar radiation	Present	9	
	Absent	32	
Wind speed (kph)	Mean	25.9 (SD 8.8)	
	Maximum	36.6	
	Minimum	5.6	
Precipitation	Present	20	
	Absent	21	

TABLE 1 A comparison of means with *SD* for artificial den dimensions, wall thickness (cm), and temperature characteristics (°C) of den interior, snow surface above the den, and ambient snow surface near the den, as well as predictor variables: air temperature (°C), wind speed (kph), and presence or absence of solar radiation and precipitation during the forward-looking infrared-based bear den detection study period in the North Slope oilfields of Alaska (United States)

established at drill site 2M (DS2M; 1 AGD and 1 APD) and four artificial dens were established at the Kuparuk Industrial Center (KIC; 2 AGDs and 2 APDs; Figure 2). We monitored snow wall thickness (cm) throughout the denning season by inserting a measuring stick through the den entrance wall of AGDs and through the ceiling wall of APDs. We measured snow wall thickness of artificial dens at the beginning and end of the denning season and during each observation period. Each AGD had a 60 W silicone heating unit, and each APD had a 120 W

silicone heating unit, placed on the den floor to mimic temperatures commensurate with the conservatively estimated heat generated by a single grizzly bear or polar bear (Shideler, 2014). A HOBO Water Temperature Pro v2 Data Logger, or "thermistor" (Onset Computer Corporation, Bourne, MA) was placed securely inside each of the six artificial dens to measure interior temperatures once every 12 hours for the duration of the study.

To capture IR spectrum imagery from a vertical perspective above artificial dens, we used a Ptarmigan Hexacopter UAS (Northern Embedded Solutions, LLC, Fairbanks, AK) fitted with a FLIR Vue Pro (FLIR Systems, Inc., Wilsonville, OR) camera. We used the same camera for horizontal images from handheld level. We used Mission Planner (ArduPilot Development Team, 2016) to program the Ptarmigan for a repeat flight pattern at artificial den sites. We collected vertical and horizontal images of each den from 20, 50, and 100 m distances to obtain imagery from comparable distances without exceeding an altitude of 122 m AGL (Federal Aviation Administration restriction; Dorr, 2018). We measured outside air temperature, ambient snow surface temperature 10 m from the den, and the snow temperature directly above each artificial den using a digital thermometer. At the time of each flight, we measured average wind speed and direction with a Kestrel 1000 (Nielsen-Kellerman, Boothyn, PA) to obtain average wind speed and direction. We categorized direct sunlight (solar radiation) as either present or absent. Humidity, dew point, and precipitation were recorded from the nearest airport (i.e., Kuparuk Airport). We categorized precipitation as either present or absent. We collected UAS-FLIR imagery during 1–3 day trips each month, between mid-December 2016 and mid-April 2017, to capture sufficient seasonal variation throughout the den season. We collected imagery during civil twilight and daylight hours.

We were able to opportunistically sample occupied bear dens to compare with, and ensure that, artificial den imagery was representative of occupied dens. We collected vertical imagery of one occupied polar bear den on December 21, 2016 and February 15, 2017, and horizontal imagery on 11 January and March 8, 2017. We collected vertical imagery of three occupied grizzly bear dens, two on February 15, 2017 and one on 17 and April 18, 2019, and collected horizontal imagery on March 8, 2017. The presence of a polar bear within the den was confirmed by oilfield worker observations, UAS-FLIR detection, and camera trap imagery when the female and two cubs emerged in the spring. The presence of grizzly bears within these dens was confirmed by radio and GPS-collar information, indication from a scent-trained dog, camera trap imagery, and oilfield personnel observation of den excavation and emergence. All activities involving occupied bear dens were approved by the Institutional Animal Care and Use Committee (Approval Number 716202-1, April 24, 2015).

We conducted 30 UAS-FLIR missions at the KIC and 11 at the DS2M (Figure 2), for a total of 41 UAS-FLIR missions (Supporting Information). At the KIC site, we sampled four artificial dens from the horizontal and vertical perspective ([4 dens × 30 observation periods] × 3 distances: 20, 50, and 100 m) for a total of 360 possible samples (Supporting Information). At the DS2M, we sampled two artificial dens from the horizontal and vertical perspective ([2 dens × 11 observation periods] × 3 distances: 20, 50, 100 m) for a total of 66 possible samples. Thus, we had 426 (KIC: 360 + DS2M: 66) opportunities to collect samples of artificial dens. The imagery that we included in the analysis consisted of two possible outcomes: nondetections (correct UAS-FLIR position but no artificial den visible: false negative) and detections (correct UAS-FLIR position with artificial den visible: true positive). We used Research IR (FLIR Systems, Inc., Wilsonville, OR) software for analysis of the radiometric properties recorded in each image. The software applied a color code for the average IR intensity (heat) of each pixel in the image. We uniformly applied the "segment" feature to all images to remove colder pixels from the image until a discrete cluster of the warmest pixels (hot spot) remained that was approximately the size of a bear den footprint or smaller: 1.5 m long by 1.3 m wide (Durner et al., 2003). We summed the pixel count for each hot spot (Figure 1). This allowed us to highlight the size of clustered hot spot pixels and classify them as either a detection (1) or a nondetection (0). We estimated median hot spot pixel counts of true positives within each subcategory (e.g., APD, vertical, 20 m; see Supporting Information) to account for effects of distances, species, and perspectives on pixel count. We expected pixel count within the hot spot to decrease with distance because the camera resolution remained constant. We classified false negatives and imagery with hot spot pixel counts at or below the median within each subcategory as nondetections prior to estimating the effects of environmental variables.

We used a logistic regression model (Hosmer & Lemeshow, 2000) to predict den detection (dependent variable: 0 or 1 categorized using size of den hot spot) based on environmental variables recorded at the time of observation. We considered the following environmental variables as predictors in the logistic regression models: air temperature, humidity, dew point, temperature dew point spread, solar radiation, wind speed, cloud cover, and precipitation. We excluded variables that would be unmeasurable in the field when attempting to detect an occupied bear den, such as den snow wall thickness and snow surface temperature directly above the den. We

TABLE 2 Logistic regression model estimates of strength of influence (exponential beta coefficient, Exp (B)) of ambient weather predictor variables on odds of detection (odds of outcome "detection" instead of reference "nondetection") in forward-looking infrared images ($n = 291$) of artificial grizzly bear and polar bear dens observed from the vertical and horizontal perspective

Species	Perspective	Variable	Coefficients		95% CI	
			p-value	Exp (B)	Lower	Upper
Grizzly bear ($n = 130$)	Horizontal ($n = 78$)	Constant	.03	0.00		
		Air temperature	.05	0.92	0.85	1.00
		Wind	.08	1.18	0.98	1.42
		Precipitation[a]	.47	3.51	0.12	105.40
		Solar[a]	(insufficient sample variation)			
	Vertical ($n = 52$)	Constant	.47	0.37		
		Air temperature	.77	0.99	0.91	1.07
		Wind	.17	1.05	0.98	1.13
		Precipitation[a]	.68	0.66	0.21	11.00
		Solar[a]	.43	0.45	0.30	16.76
Polar bear ($n = 161$)	Horizontal ($n = 80$)	Constant	.79	0.64		
		Air temperature	.01	0.90	0.84	0.97
		Wind	.53	0.97	0.86	1.08
		Precipitation[a]	.06	0.10	0.01	1.05
		Solar[a]	.88	0.89	0.18	4.32
	Vertical ($n = 81$)	Constant	.93	1.10		
		Air temperature	.00	0.88	0.82	0.95
		Wind	.10	0.95	0.90	1.01
		Precipitation[a]	.03	0.18	0.04	0.87
		Solar[a]	.05	0.23	0.05	1.01

[a]Categorical variables (odds of detection outcome instead of nondetection with one category change: presence instead of absence of precipitation or solar).

used variance inflation factor (VIF) and Spearman's rank (r_s) correlation matrix (Supporting Information) to reduce our starting set ($n = 8$) of environmental variables, and avoid multicollinearity (VIF score ≥ 4.0; $r_s > 0.6$; Zar, 1971; O'Brien, 2007). We selected one predictor variable from a set of highly correlated predictor variables for inclusion in our model based on importance in previous research (Amstrup et al., 2004; Robinson et al., 2014) and ability for future researchers to readily measure and account for. We excluded predictors from the model if there was insufficient variation within the sample for our model to converge. We conducted a logistic regression on all imagery within our four UAS-FLIR observation categories (Table 2). All statistical analyses were performed using IBM SPSS (IBM Corporation, 2015, V23). We interpreted the results of the logistic regression model by considering any continuous or categorical predictor variable with $p \leq .1$ as significant and used the beta coefficients to obtain the odds ratio. Using the odds ratio, we estimated the effect that a 1-unit change in a continuous variable or

a categorical change in predictor variable would have on the odds that a detection (1) occurred. We evaluated the relationship between month of the denning season with ambient air temperature and den wall thickness for AGD and APD using a Kruskal–Wallis test to provide insight on the best time of year to locate dens.

3 | RESULTS

Out of 426 sample collection opportunities, we successfully captured 291 images (68%) of the artificial dens for inclusion in our analysis. The images were distributed as follows: AGD vertical ($n = 52$), AGD horizontal ($n = 78$), APD vertical ($n = 81$), and APD horizontal ($n = 80$). We classified 41% as detections ($n = 119$) and 59% as nondetection ($n = 172$; Supporting Information). The APD images comprised 55% of observations ($n = 161$), and AGD comprised 45% of observations ($n = 130$); 54% of images were taken from the horizontal perspective

FIGURE 3 True positive "hot spot" pixel counts for artificial polar bear (a) and grizzly bear (b) den imagery captured with forward-looking infrared (FLIR) camera from a distance of 20, 50, and 100 m, at a vertical and horizontal perspective, in the North Slope oilfields of Alaska (United States). "Hot spot" pixel count represents the quality of detections relative to the distance and perspective of the FLIR image

(a) Median and inter-quartile range of true positive hot spot pixel counts for artificial polar bear den FLIR imagery

(b) Median and inter-quartile range of true positive hot spot pixel counts for artificial grizzly bear den FLIR imagery
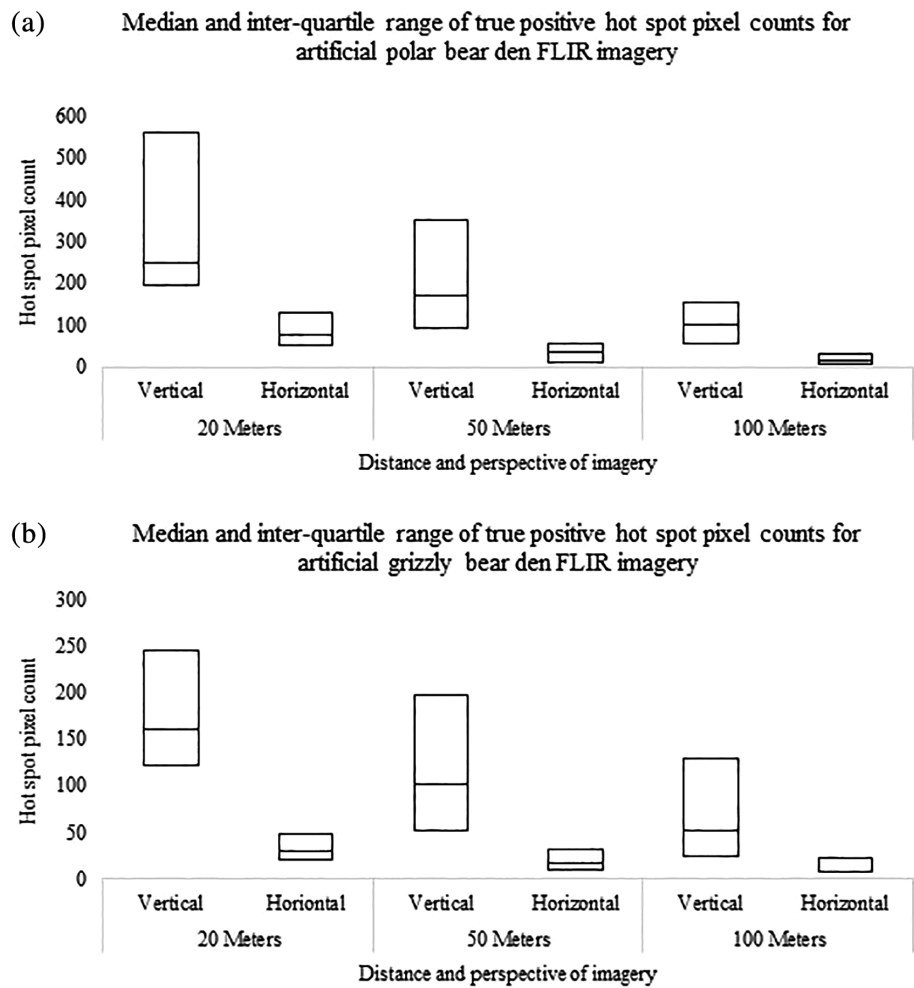
($n = 158$) and 46% were taken from the vertical perspective ($n = 133$). Median pixel counts of true positive hot spots from the vertical perspective were four times greater than that of hot spots from the horizontal perspective. Median APD hot spot pixel counts were approximately two times greater than that of AGD hot spots at both the horizontal and vertical perspectives (Figure 3; Supporting Information).

Our factor reduction analysis indicated that 4 of 8 environmental predictor variables (air temperature, wind speed, precipitation, and solar radiation) explained 81% of the variation in our dataset. Air temperature was a significant predictor of detection in three (vertical and horizontal APDs, and horizontal AGD) out of four models (Table 2). For the AGD horizontal model, an increase of 1°C ambient air temperature lowered detection by 8% ($p = .05$). For APD horizontal and vertical models, an increase of 1°C in ambient air temperature lowered detection by 10% ($p < .01$) and 12% ($p < .01$), respectively. Precipitation was a significant predictor in both APD models, and the presence of precipitation from the horizontal and vertical perspectives lowered detection by 10 times ($p = .06$) and 5.6 times ($p = .03$), respectively. Solar radiation was a

significant predictor for the vertical APD model, presence of solar radiation lowered detection by 4.3 times ($p = .05$). Wind was a significant predictor in the vertical APD model. An increase of 1 kph in wind speed lowered detection by 5% ($p = .1$). Wind was a significant predictor of the horizontal AGD model ($p = .08$). An increase of 1 kph in wind speed increased detection by 18% ($p = .08$), however, we suggest that this finding should be viewed with caution as it may indicate a failure of our technique. The Kruskal–Wallis test indicated that ambient air temperature increased each month ($p = .09$) and that den wall thickness increased each month for both AGDs and APDs ($p < .01$). The temperature differentials between inside and outside air increased as ambient outside air temperatures decreased. The average air temperature inside of the artificial dens was warmer than ambient outside air by 13.8 and 15.7°C for AGD and APD, respectively (Table 1).

4 | DISCUSSION

Warmer air temperatures resulted in lower UAS-FLIR den detection for three out of four models because of

(a) colder ambient air temperatures causing an increased contrast between den snow wall surface temperature and surrounding ambient snow temperature, (b) the tendency for colder temperatures to be associated with clear, dry conditions, and (c) warming outside air temperatures that occurred later in the winter season when den walls are thickest and most insulating. As FLIR imagers measure relative differences in surface temperatures, colder ambient air temperatures increase the differential between exterior and interior den air temperature. This draws internal warm air through the snow wall over the top (APDs), or through the den entrance (AGDs), which increases the contrast between ambient snow surface temperatures and den snow surface temperatures.

A lower air temperature was highly correlated with lower humidity and greater temperature dew point spread which may also explain the influence that air temperature had on detection. A previous study observed that a 1°C increase in temperature dew point spread increased detection, and that the presence of airborne moisture reduced detection for occupied polar bear dens from airborne FLIR, suggesting that this was due to the FLIR sensor measuring the temperature of suspended particulate in the air between the sensor and the den rather than den snow surface temperature differentials (Amstrup et al., 2004). The presence of precipitation (falling or suspended moisture) decreased detection for APDs in our study more than previously reported, and this effect is expected to have an even greater influence on detection as distance increases for UAS-FLIR imagery.

In previous studies, solar radiation has been shown to have a negative effect on detection for both occupied and artificial polar bear dens (Amstrup et al., 2004; Robinson et al., 2014). In our study, the presence of solar radiation decreased detection for APDs at the vertical perspective, but was not significant in any other models. Solar radiation is expected to reduce detection due to solar reflectance from the snow surface interfering with the FLIR sensor's ability to distinguish fine-scale temperature differentials. We collected samples during daylight hours and hours of morning and evening civil twilight but our sample size of observation periods with solar radiation present was low ($n = 9$) due to the presence of clouds. Even with a low sample size, our findings (APD vertical) agree with earlier studies.

High wind speed was a slightly significant predictor and reduced detection for vertical APDs, supporting previous findings of FLIR detection of APDs from the horizontal perspective (Robinson et al., 2014). Wind speeds ≥20 kph were considered to have a negative effect on detection due to the effect of rolling and suspended snow particles on the FLIR sensor's ability to measure snow

surface temperature differentials (Amstrup et al., 2004). Considering that 73% ($n = 30$) of our observation periods took place in wind speeds ≥20 kph, a condition normal for the North Slope, it is possible that we did not sample sufficiently low wind speeds to measure a threshold at which wind speed affects detection. Increased wind speed raised detection for AGDs from the horizontal perspective, but this may be misleading because the hot spot in AGD imagery was associated with exposed soil on top of two AGDs. We believe that these hot spots were the result of a difference between snow and soil emissivity rather than a positive relationship between increased wind speed and the strength of AGD IR signal (Hyll, 2012). For example, clumps of exposed soil away from the den surface were also warmer pixels within our imagery as compared to the snow surface. This suggests patchy snow conditions may cause problems (i.e., false positives) when applying the FLIR technique. It is unlikely that wind friction would generate a measurable heat difference on exposed soil features, but this warrants further study.

The positive relationship that air temperature and the advancing winter months had with den snow wall thickness is intuitive, and its significance is representative of two things: (a) contrast between ambient snow temperature and den snow wall temperature decreased as den snow wall thickness increased, and (b) one AGD accumulated a 125 cm snow wall over the den entrance by March 6, 2017, after which there was no measurable temperature contrast between ambient snow and den snow wall surface; it was no longer visible with the UAS-FLIR. A previous study found that a 1 cm increase in den snow wall thickness decreased detection by a 1.49% for artificial polar bear dens from the horizontal perspective, with a mean den snow wall thickness of 90 cm (Robinson et al., 2014). In our study, we observed that a threshold occurred between 80 and 125 cm for AGD. The positive relationship between an increase in snow wall thickness and month implies that it is best to conduct UAS-FLIR surveys early in the winter when snow walls are at their thinnest levels, before large-scale snow events and subsequent drifting snow.

Part of the reason that AGD detections had fewer pixels in their hot spot than APD detections is explained by the difference in denning strategies by each species. Soil and other materials that grizzly bears excavate for a den are more permanent than snow and provide additional insulation to snow accumulation over the top of each den. We speculate that this causes heat to absorb into the ground or mainly escape through the snow wall over the grizzly bear den entrance rather than through the snow wall ceiling of a polar bear den. The APDs were also 1.9 times larger than AGDs and were equipped with

twice the heating elements for an approximately equal heat output (0.006 W/m^3). Interior temperatures of APDs and AGDs remained within the range of occupied bear dens (Watts, 1983, 1990), but APD interiors averaged 1.8°C warmer than AGD interior temperatures. The APD snow wall surface temperatures also averaged 1.8°C warmer than that of AGDs. The larger, less insulated, and warmer APDs losing heat through their snow wall ceilings contributed to better detections with greater median hot spot pixel counts and surface temperature contrast than the smaller, more insulated, and less warm AGDs.

This result was not surprising but the real-world implications are significant to understanding the efficacy of using UAS-FLIR for detecting grizzly bear dens. If our AGDs accurately represented the variation in grizzly bear den morphology, the size and shape of visible AGD hot spots imply that UAS-FLIR grizzly bear den detection surveys will be difficult to perform effectively because (a) if grizzly bear dens produce small hot spots, they may not be readily visible to the observer, resulting in false negatives, and (b) the small size and variable shape of the grizzly bear den hot spot will make grizzly bear dens more difficult to distinguish from other landscape features with different emissivity (i.e., exposed soil), increasing the chances of both false negatives and false positives. The known variation in physical den characteristics introduces uncertainty whether grizzly bear dens, or polar bear dens established within the earth surface (Clark et al., 1997), are possible to reliably detect using UAS-FLIR.

We collected UAS-FLIR images of the occupied polar bear den from the vertical and handheld perspective monthly between December 2016 and March 2017 (Supporting Information). The den was possible to detect with the UAS-FLIR until March, at which point a substantial (>1 m) accumulation of drifted snow had formed over the den and an IR signal was no longer visible. We also collected observations of three occupied grizzly bear dens on three separate occasions in February and March 2017, and April 2019. Two dens were detectable with UAS-FLIR from the vertical perspective (Supporting Information), but one was difficult to discern when viewed from the horizontal perspective. The other den was not detected from either perspective, on either of the two sampling occasions. The fact that two grizzly bear dens were possible to detect with such certainty from the UAS-FLIR was a significant accomplishment of our study, but the inability to detect the other grizzly bear den under similar conditions calls into question the effectiveness of this technique for broad application when searching for the location of occupied grizzly bear dens that are not known in advance. The occupied grizzly bear

dens were known based on radio-collar triangulation, GPS collar fix, trained scent dog indication, and observed emergence. Den site selection appeared similar in that each bear had excavated a den within a small 1.5–2 m tall bank.

Our study found that air temperature, wind speed (vertical, APD), and presence or absence of precipitation and solar radiation can be used to predict detection for artificial dens from both the vertical and horizontal perspectives, especially early in the winter season when den wall thickness is at its minimum. We found that vertical imagery produced better detection qualities than that of horizontal imagery. We were unable to capture and test UAS-FLIR imagery of artificial dens from an oblique (45–60°) perspective due to the difficulty of maintaining the den location in field of view at a constant angle and distance in the presence of wind. Den surveys in mountainous terrain with steeper slopes may need to be able to adjust the angle of view to maintain a perpendicular perspective to the surface of the ground. However, our vertical perspective directly above the den was ideal for the relatively flat terrain on the North Slope of Alaska, and our vertical perspective was representative of manned aircraft surveys conducted in the area. Given that our artificial dens were representative of the physical characteristics of occupied polar bear and grizzly bear dens, and that we sampled our artificial dens in environmental conditions representative of those present in bear den habitat of arctic Alaska, we expect that our results will also apply to UAS-FLIR surveys of occupied bear dens. We recommend UAS-FLIR surveys be conducted vertically in cold, clear conditions with calm winds (≤20 kph) at night or during civil twilight, at a distance of 100 m (46 × 35 m swath coverage per image), in December (grizzly bear) and January (polar bear) before den wall thickness accumulates to its maximum extent.

We also recommend the use of FLIR cameras with simultaneous visual and IR spectrum image collection to help distinguish true positives from false positives. The visual spectrum may help confirm if other landscape characteristics are creating hotspots. Some training and experience with FLIR-imagery is necessary. Because the false negatives present the greatest management concern for bear conservation and worker safety we recommend that UAS-FLIR surveys be coupled with reliable secondary methods, such as repeat surveys or confirmation with trained scent dogs, to reduce the occurrence of false negatives. UAS-based FLIR imagery is a useful tool for arctic bear den detection that may enhance worker safety and bear conservation on the North Slope oilfields of Alaska, with broad application throughout the north.

CONFLICT OF INTEREST

The authors have no conflict of interest to declare.

AUTHOR CONTRIBUTIONS

Nils J. Pedersen was the lead author of this paper and helped to conceptualize the study with Todd J. Brinkman and major input from Richard T. Shideler and Craig J. Perham. Nils J. Pedersen and Todd J. Brinkman led data collection, management, and analysis. Nils J. Pedersen led the writing with major input from all authors. All authors contributed to the revision and preparation of the final manuscript.

DATA AVAILABILITY STATEMENT

The list of weather conditions present during each sampling period and the Spearman's rho correlation matrix are available as Appendixes S7 and S8, respectively. Artificial den detection data requests can be made to NP. Location of occupied bear dens is considered sensitive.

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SUPPORTING INFORMATION

Additional supporting information may be found online in the Supporting Information section at the end of this article.