ARCTIC
VOL. 66, NO. 2 (JUNE 2013) P. 197–206

Mapping Polar Bear Maternal Denning Habitat in the National Petroleum Reserve – Alaska with an IfSAR Digital Terrain Model

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(*Received 20 July 2012; accepted in revised form 26 November 2012*)

ABSTRACT. The National Petroleum Reserve–Alaska (NPR-A) in northeastern Alaska provides winter maternal denning habitat for polar bears (*Ursus maritimus*) and also has high potential for recoverable hydrocarbons. Denning polar bears exposed to human activities may abandon their dens before their young are able to survive the severity of Arctic winter weather. To ensure that wintertime petroleum activities do not threaten polar bears, managers need to know the distribution of landscape features in which maternal dens are likely to occur. Here, we present a map of potential denning habitat within the NPR-A. We used a fine-grain digital elevation model derived from Interferometric Synthetic Aperture Radar (IfSAR) to generate a map of putative denning habitat. We then tested the map's ability to identify polar bear denning habitat on the landscape. Our final map correctly identified 82% of denning habitat estimated to be within the NPR-A. Mapped denning habitat comprised 19.7 km^2 (0.1% of the study area) and was widely dispersed. Though mapping denning habitat with IfSAR data was as effective as mapping with the photogrammetric methods used for other regions of the Alaskan Arctic coastal plain, the use of GIS to analyze IfSAR data allowed greater objectivity and flexibility with less manual labor. Analytical advantages and performance equivalent to that of manual cartographic methods suggest that the use of IfSAR data to identify polar bear maternal denning habitat is a better management tool in the NPR-A and wherever such data may be available.

Key words: Arctic Coastal Plain, denning habitat, digital terrain model, DTM, IfSAR, maternal den, National Petroleum Reserve–Alaska, NPR-A, polar bear, *Ursus maritimus*

RÉSUMÉ. La réserve pétrolière nationale–Alaska (NPR-A), située dans le nord-est de l'Alaska (NPR-A), constitue un habitat hivernal de tanières de mise bas pour l'ours polaire (*Ursus maritimus*) et présente de grandes possibilités du point de vue des hydrocarbures récupérables. Les ours polaires des tanières qui sont exposés aux activités de l'être humain peuvent abandonner leur tanière avant que leurs petits ne soient prêts à survivre les rigueurs de l'hiver de l'Arctique. Afin de faire en sorte que les activités d'exploitation pétrolière hivernales ne posent pas de menaces aux ours polaires, les gestionnaires doivent connaître la répartition des caractéristiques du paysage où les tanières de mise bas sont susceptibles de se trouver. Ici, nous présentons une carte sur laquelle sont indiqués des habitats de tanières possibles au sein de la NPR-A. Nous avons utilisé un système de modélisation numérique des hauteurs à haute définition dérivé du radar interférométrique à synthèse d'ouverture (IfSAR) pour produire une carte putative de l'habitat de tanières. Ensuite, nous avons mis la carte à l'épreuve pour déterminer son aptitude à repérer l'habitat de tanières de mise bas au sein du paysage. Notre carte finale a repéré avec exactitude 82 % de l'habitat de tanières qui se trouverait à l'intérieur de la NPR-A. L'habitat de tanières cartographié s'étendait sur 19,7 km^2 (0,1 % de l'aire étudiée) et était largement dispersé. Même si la cartographie de l'habitat de tanières au moyen des données de l'IfSAR était aussi efficace que la cartographie des méthodes photogrammétriques employées dans d'autres régions de la plaine côtière arctique de l'Alaska, l'utilisation du SIG pour analyser les données de l'IfSAR a donné lieu à une plus grande objectivité et flexibilité, avec moins de main-d'œuvre. Les avantages analytiques et l'exécution équivalant à celles des méthodes de cartographie manuelles suggèrent que le recours aux données de l'IfSAR pour repérer l'habitat de tanières de mise bas d'ours polaires constitue un outil de gestion supérieur au sein de la NPR-A et de n'importe quel autre endroit où ces données sont disponibles.

Mots clés : plaine côtière arctique, habitat de tanières, modèle numérique de terrain, MNT, IfSAR, tanière de mise bas, réserve pétrolière nationale–Alaska, NPR-A, ours polaire, *Ursus maritimus*

Traduit pour la revue *Arctic* par Nicole Giguère.

INTRODUCTION

Polar bears (*Ursus maritimus*) in Alaska give birth to their young during winter in dens that are dug into snowbanks on land and on sea ice (Amstrup and Gardner, 1994; Fischbach et al., 2007). The relatively warm and stable environment within the den is necessary for the development of newborn cubs (Blix and Lentfer, 1979; Watts, 1983). Disturbance of

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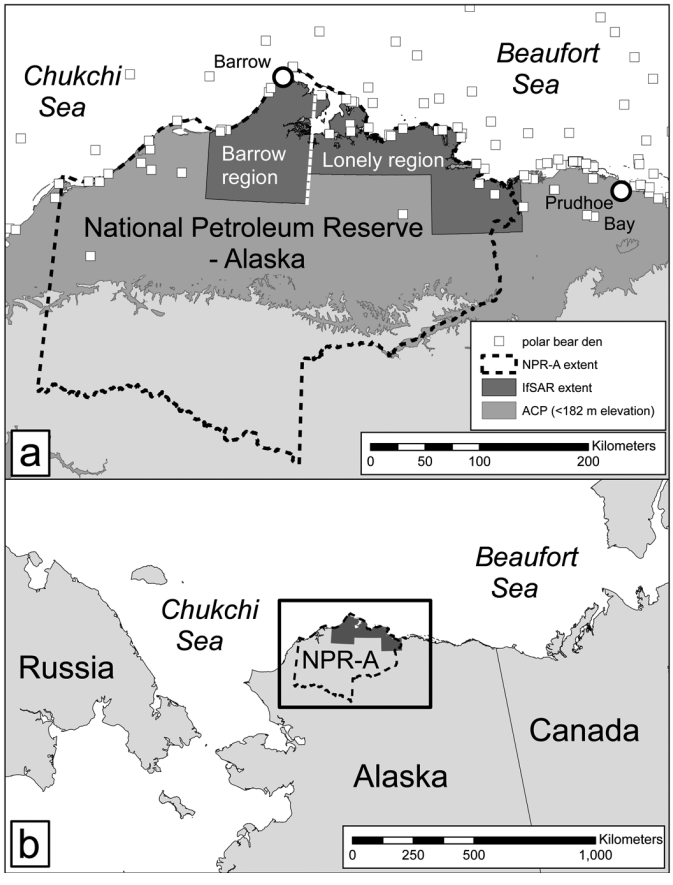

FIG. 1. (a) Extent of IfSAR tiles, the National Petroleum Reserve – Alaska (NPR-A), the Arctic Coastal Plain (ACP; as defined by Wahrhaftig, 1965), and the distribution of polar bear maternal dens (Durner et al., 2010) located within and near the NPR-A from 1910 to 2010. (b) Location of the study area in relation to Russia, Alaska, and Canada.

maternal dens can result in premature den abandonment, which may negatively affect cub survival (Amstrup, 1993). Polar bears have been listed as threatened under the United States Endangered Species Act (USFWS, 2008) because of concerns over the observed and projected loss of their sea ice habitat. To mitigate the effects of sea ice loss, the U.S. Fish and Wildlife Service has designated maternal denning habitat as "critical" (USFWS, 2010). The Arctic Coastal Plain (ACP) in northern Alaska and adjacent sea ice (Fig. 1) provide denning habitat for polar bears and occur within a region judged to have one of the highest potentials for undiscovered oil and gas reserves in the Arctic (Gautier et al., 2009), with several oil and gas fields in the central plain in development or extraction phases. To ensure that wintertime oil and gas exploration and development activities do not disrupt denning and threaten survival of cubs, managers require knowledge of the distribution of the landscape features that are capable of accumulating snow deep enough for pregnant polar bears to dig maternal dens. Photogrammatic techniques have been used to map polar bear denning habitat in the eastern and central portions of the ACP (Durner et al., 2001, 2006), but the necessary photography has not been available for the western ACP. Here, we present a new method—the automated interpretation of fine-grain digital elevation data—for mapping potential polar bear maternal denning habitat in the coastal regions of the National Petroleum Reserve – Alaska (NPR-A) in the northwest ACP. This new method provides a tool that could be used in other regions where polar bear maternal denning habitat (Harington, 1968) overlaps with potential hydrocarbon extraction areas (Gautier et al., 2009).

Polar bears that use the Alaska ACP for denning are from the Southern Beaufort Sea (SB) subpopulation (Amstrup et al., 2004a). The SB subpopulation includes approximately 1500 individuals (Regehr et al., 2006) and is one of 19 subpopulations in a total worldwide population of 20 000 – 25 000 polar bears (Obbard et al., 2010). Winter snow depths on the ACP, which generally range from 10 to 40 cm (Benson, 1982), are insufficient for maternal denning. However, surface deformation of the landscape permits enough snow accumulation (Sturm et al., 2006) for polar bears to den (Durner et al., 2003). Denning habitats include coastal banks, riverbanks, lakeshores, and even some human-made features (Durner et al., 2001, 2003). On the coastal plain of northern Alaska east of the Colville River, suitable denning habitat comprises less than 1% of the total area (Durner et al., 2001, 2006), yet approximately 63% of pregnant polar bears in the SB subpopulation rely on terrestrial habitat for maternal denning each winter, and the proportion of on-land denning is increasing (Amstrup and Gardner, 1994; Fischbach et al., 2007). Though most terrestrial denning has occurred within 2 km of the coast (Durner et al., 2003), some polar bear dens have been observed 61 km inland of the Beaufort Sea coast (Fig. 1; Amstrup and Gardner, 1994). Coastal denning habitats are susceptible to erosion (Jones et al., 2009), so the loss or inland retreat of some present coastal habitat may place greater importance on inland denning habitat for pregnant polar bears.

Although land provides a more stable denning substrate than sea ice, the spatial overlap of potential denning habitat with areas of current and anticipated industrial activity raises concerns about polar bear welfare. Although exploration for hydrocarbons during winter minimizes impacts to most Arctic habitats and wildlife, the potential impacts on polar bears are greatest during this season, as maternal denning is the only time in their life-cycle when bears cannot simply move away from a disturbance without negative consequences. Disruption of a den may result in den abandonment before the young are able to withstand the rigors of the Arctic winter (Amstrup, 1993; Lunn et al., 2004). To minimize potential negative effects of industrial exploration and development on denning polar bears, information on the distribution of potential denning habitats is needed. Incidental take regulations (USFWS, 2011), designation of critical habitat (USFWS, 2010), and aerial surveys for polar bear dens (Amstrup et al., 2004b) all depend on knowing how landscape features suitable for maternal dens are distributed.

The NPR-A holds an estimated 502 million barrels of economically recoverable oil (Attanasi and Freeman, 2011).

As of 2012, there were 186 petroleum exploration leases within its borders (Bureau of Land Management, 2013). Although polar bears are known to den in the NPR-A (Fig. 1; Amstrup and Gardner, 1994; Durner et al., 2003, 2010; Fischbach et al., 2007), potential maternal denning habitat has not yet been mapped. To develop such a map, the U.S. Geological Survey (USGS) and the U.S. Bureau of Land Management (BLM) obtained very high-resolution Interferometric Synthetic Radar (IfSAR) elevation data for the NPR-A (Intermap, 2012) in standard geographic information system (GIS) format. IfSAR imagery has been used effectively to map fine-grain features on Arctic landscapes (Nolan and Prokein, 2003; Jones et al., 2012; Wang et al., 2012). Because of its greater vertical and horizontal resolution and accuracy, IfSAR provides a superior alternative to traditional photogrammetric methods (Nolan and Prokein, 2003). Here, we assess the applicability of an IfSAR-derived digital terrain model (DTM) for identifying and mapping polar bear maternal denning habitat in the NPR-A. In a GIS format, a map of potential polar bear denning habitat may easily be used by resource managers to increase protection of polar bears in maternal dens.

METHODS

A Description of IfSAR DTM Data

IfSAR data for the coastal portions of the NPR-A (area: 18 918 km^2; Fig. 1) were collected by Intermap Technologies during July 2002 with the Intermap STAR-3i airborne IfSAR system (Intermap, 2012). Richards (2007) provides an in-depth presentation of IfSAR theory and applications. IfSAR data were analyzed to calculate a geometrically correct Digital Surface Model (DSM) of elevation. The DSM had a horizontal cell dimension of 5 × 5 m (1.25 m root mean square error, or RMSE) and a vertical cell resolution of 0.01 m (1.0 m RMSE; Intermap, 2010; Nolan and Prokein, 2003). Independent testing of STAR-3i IfSAR imagery has shown that the vertical accuracy is greater on low-relief terrain (i.e., 0.46 m RMSE; Mercuri et al., 2006), which is the typical landscape of the NPR-A. The DSM was composed of overlapping 7.5 × 18 minute (latitude × longitude) tiles in UTM projection (zones 4 and 5, datum NAD83), which corresponded to USGS 1:63 360 topographic quadrangle maps. Intermap Technologies converted the DSM into a digital terrain model (DTM) by removing buildings and vegetation so that the final elevation data represented the closest approximation to the true surface of the earth.

A Provisional Polar Bear Denning Habitat Map for the NPR-A

Durner et al. (2001) found that the minimal bank height that accommodated a polar bear den was 1.3 m. Therefore, we created a provisional polar bear denning habitat map from the DTM by extracting each 5 × 5 m cell with an elevation difference of 1.3 m or more between it and at least one of the eight adjacent cells. We used a moving-window analysis implemented through commands from the GRID module of ARC/INFO (ver. 9.2, ESRI, Redlands, California) to interrogate DTM tiles for cells that met our criterion of maternal denning habitat (Durner et al., 2003). When this initial map was compared to GPS locations of eight previously identified maternal den sites in the NPR-A, we found that the denning habitat at one den site was not detected. To ensure that our provisional map included known polar bear den sites, we performed a second extraction of the DTM by identifying each cell with an elevation difference of 1.0 m or more between it and at least one of the eight adjacent cells. This 1.0 m selection criterion ensured that our provisional map identified denning habitat at all known den sites. We used this provisional map to field test against actual landscape features so that we could further refine the polar bear denning habitat map.

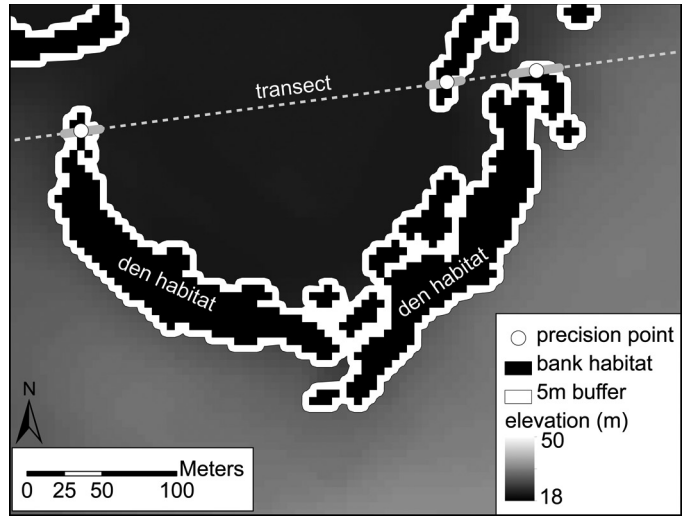

FIG. 2. Method for creating sample points for a polar bear denning habitat map in the National Petroleum Reserve – Alaska. Mid-points (white dots) of transect intersections (bold grey line) with mapped denning habitat and 5 m buffer were selected as precision points (sampling points for ground-truthing).

DTM cells identified as potential denning habitat were converted to an ARC/INFO vector coverage of polygons. To smooth the border across adjoining cells and to connect cells that were separated from the main group of identified cells, we applied a 5 m buffer to the outside margin of all clusters of adjoining cells and non-adjacent cells (see Fig. 2). This buffer allowed us to recognize landscape features composed of cells that were near but not directly adjacent to each other and to group them into a single polygon of denning habitat.

Field Evaluation of the Provisional Polar Bear Denning Habitat Map

We ground-truthed the final denning habitat map by examining ground-level characteristics encountered along 16 survey transects. Ten transects originated from the town

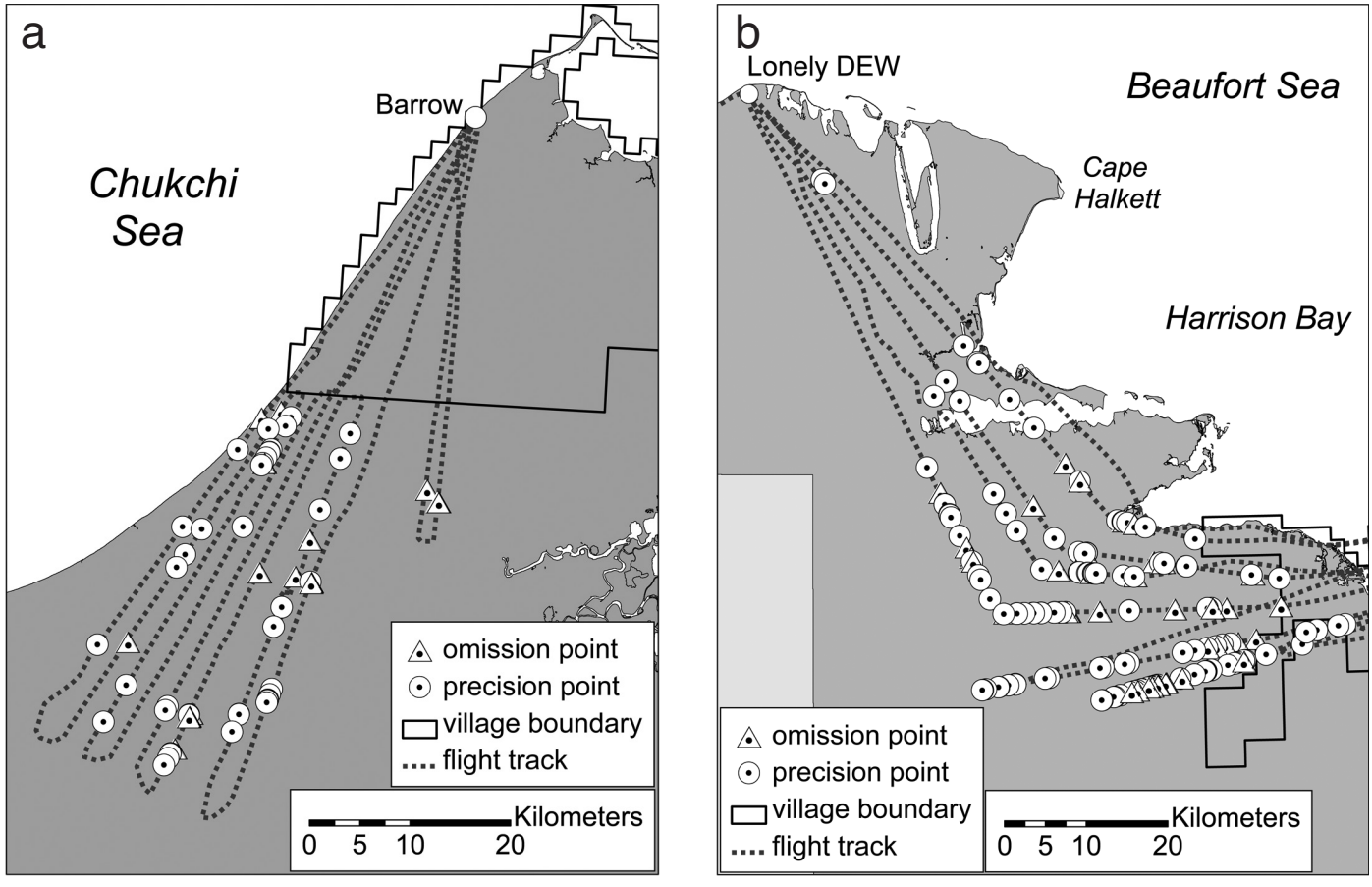

FIG. 3. Distribution of helicopter flight tracks, precision points, and omission points for ground-truthing a polar bear maternal denning habitat map in (a) the Barrow region and (b) the Lonely region of the National Petroleum Reserve – Alaska, in July 2004 (Lonely region only) and September 2010 (Lonely and Barrow regions).

of Barrow, and six originated from the eastern border of the NPR-A and extended to the Lonely Distant Early Warning (DEW) Station (Fig. 3). These transects were chosen from a total of 62 potential transects through a "1 in k" systematic sample (Scheaffer et al., 1986). Average minimum spacing between transects was 3173 m, average maximum spacing was 3685 m, and average transect length was 49.0 km (STD = 23.9; range 12.5 – 95.2 km). The resulting distribution of transects was a compromise that allowed us to achieve an adequate and unbiased sample effort while remaining within the logistical constraints imposed by limited helicopter flight time. We flew transects with a Raven R-44 helicopter (speed: 80 – 100 km/hr; altitude: 30 – 50 m above ground level) and used a dual on-board/handheld GPS receiver to navigate along transects and to sample points.

We measured ground features of two types of sample points encountered along transects: 1) precision points – points where GIS-generated denning habitat intersected transects, and 2) omission points – points encountered along transects that met the minimum on-the-ground requirements for denning habitat but were not identified by the GIS-generated map (for details, see Durner et al., 2001, 2006). At each precision point, we used a fiberglass measuring tape to measure the straight-line distance (i.e., the hypotenuse) from the top of the bank to the bottom of the bank. We then measured the angle (i.e., the slope) of the hypotenuse with an inclinometer. We also measured distance from the precision point to the actual habitat feature with a fiberglass measuring tape or with the GPS receiver. Bank hypotenuse and slope were used to calculate bank height (Durner et al., 2003). From these measurements we determined whether the habitat met the minimum required slope ($\geq 8^{\circ}$; Durner et al., 2003) and height (≥ 1.3 m; Durner et al., 2001) to be considered denning habitat. Precision points that failed to meet slope or height minimums were classified as non-denning habitat and were used to estimate precision error.

We visually identified all suspected omission points encountered along flight transects (Fig. 3). We recorded the same data at suspected omission points as we did for precision points in order to determine whether the location met our criteria as denning habitat. Suspected omission points that met our criteria for denning habitat and were later identified to be within 15 m of mapped habitat (based on the estimated GPS position accuracy; Garmin, 2007) were reclassified as precision points. The percent omission error was calculated as the number of omission points divided by the total number of omission and precision points × 100.

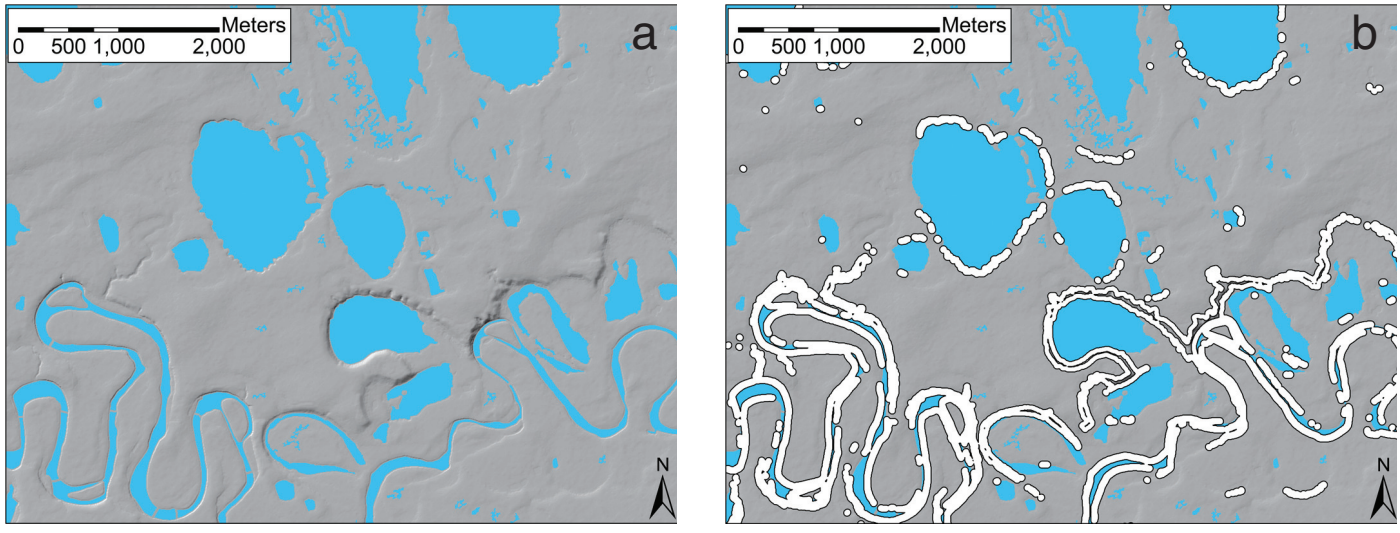

FIG. 4. Examples of IfSAR DTM data in the National Petroleum Reserve – Alaska. (a) Hill shading is used to increase the visibility of terrain changes. Abrupt changes in landscape are indicated by extreme dark or extreme light shading. (b) Polar bear denning habitat, identified by white lines highlighted with a black border, occurred mostly along stream banks and lakeshores.

RESULTS

We analyzed 149 IfSAR tiles for polar bear denning habitat in the NPR-A. Tiles were distributed from the coast south to 70˚15′ north latitude (N) between 155˚50′ and 158˚26′ west longitude (W) (Barrow region; Fig. 1) and from the coast to 70˚0′ N between 150˚53′ and 155˚59′ W (Lonely region; Fig. 1). The total area of the two regions was 18 918 km^2. Our provisional map suggested that denning habitat occurred along coastal banks, streams, and lakeshores (Fig. 4) but also that it was dispersed throughout the region of IfSAR coverage in the NPR-A (Fig. 5).

Ground-truthing was conducted on 29–30 July 2004 (Lonely region) and 12–18 September 2010 (Barrow and Lonely regions). For the provisional map (i.e., the map created with selection criterion ≥ 1.0 m), 142 of 185 precision points (76.8%) met the minimum requirements for slope (≥ 8˚) and height (≥ 1.3 m) of denning habitat. An additional 28 omission points (i.e., denning habitat that we failed to map with IfSAR) were encountered along transects. This brought the omission error rate to 13.1% (i.e., 28 ÷ (28 + 185) × 100).

Though precision points that we visited were often abrupt landscape features (Fig. 6), most of these had relatively small changes in elevation. Approximately 76% of measured denning habitat was 4 m or less in height (Fig. 7). However, omission points (denning habitats the GIS mapping process failed to detect) sometimes had relatively abrupt and large changes in elevation (Fig. 8).

Modifying the selection criteria of elevation change with standard GIS software showed how the omission and precision errors of IfSAR data can be adjusted with little effort. A liberal selection criterion (i.e., using a small elevation change between adjacent cells to identify denning habitat) ensured that most of the actual denning habitat on the landscape was included in our map (Fig. 9), but it also increased the chance that landscape could be incorrectly identified as denning habitat. For example, with a stringent selection criterion (≥ 1.3 m difference in elevation), the mapping process did not identify 61 of 182 sample points (i.e., 33.3% omission error; Fig. 9). All but 12 of 121 mapped points, however, met slope and height minimums (9.9% precision error; Fig. 9). Conversely, with a liberal selection criterion (0.5 m difference in elevation), only 4 of 220 sample points were not mapped (1.8% omission error), but the precision error rate was projected to be very high (Fig. 9).

By using Figure 9 as a guide, we determined that a selection criterion of 1.08 m was a useful compromise between omission and precision errors. This criterion resulted in an error rate of approximately 18% for both omission and precision. Using a selection criterion of 1.08 m and a 5 m buffer around selected cells, we identified the total area of maternal denning habitat as 19.7 km^2, or 0.1% of the entire region of IfSAR imagery in the NPR-A.

DISCUSSION

Terrain features suitable as polar bear maternal denning habitat within the region of the NPR-A predictably occurred along coasts, streams, and lakeshores (Figs. 4, 5). The polar bear maternal denning habitat in the NPR-A (as estimated by IfSAR) was only 0.1% of the total area. The amount of denning habitat and its distribution relative to coasts, streams, and lakeshores were similar to those determined for the Prudhoe Bay region (0.2% of the total area; Durner et al., 2001) and the Arctic National Wildlife Refuge (ANWR) coastal plain (0.3% of the total area; Durner et al., 2006). Both the oil field and the ANWR were mapped through cartographic (manual) interpretation of high-resolution aerial photography. However, NPR-A mapping was performed solely through computer interrogation of a digital

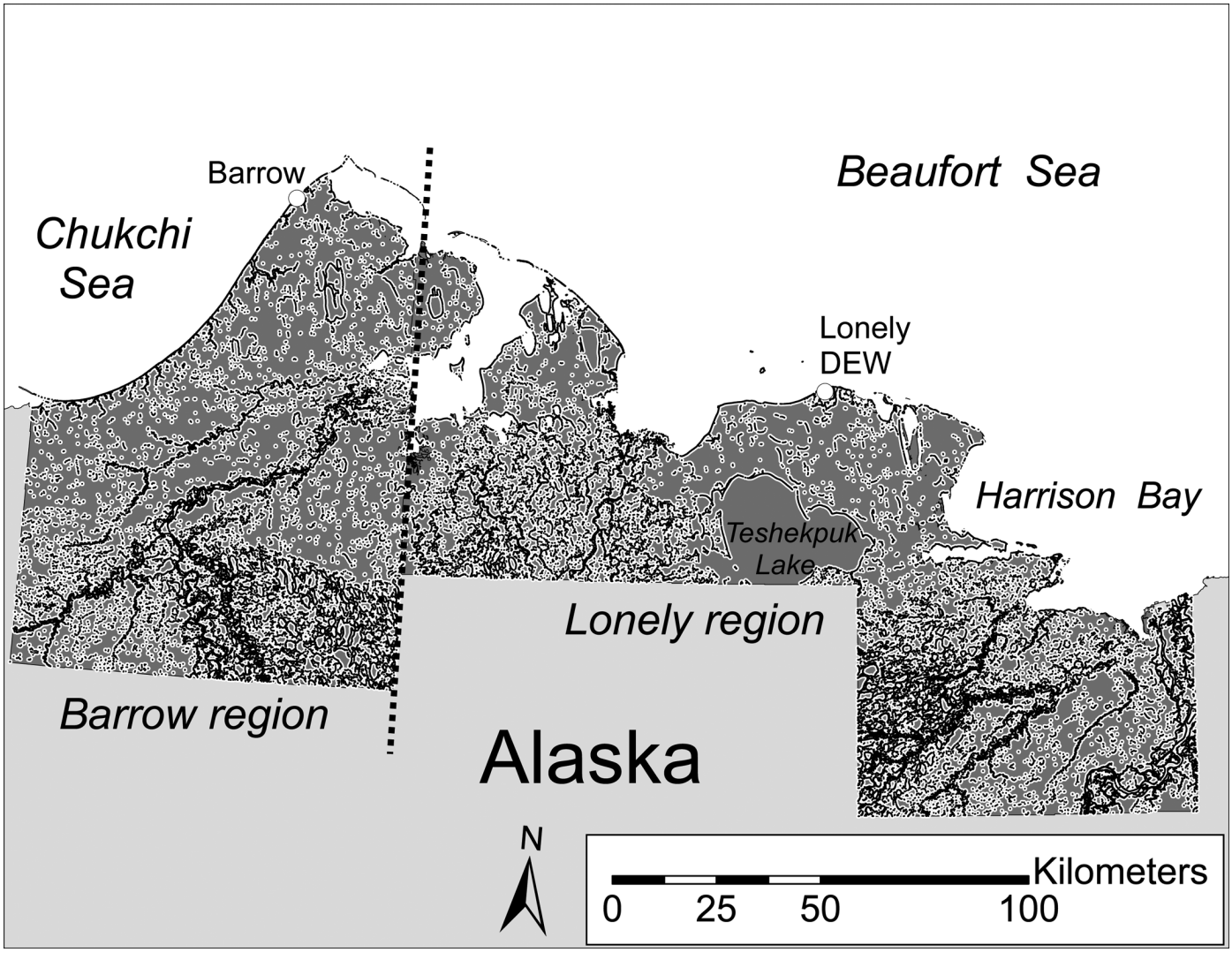

FIG. 5. Distribution of polar bear denning habitat, black lines highlighted with a white border, mapped with IfSAR in the coastal regions of the National Petroleum Reserve – Alaska for Barrow and Lonely regions (separated by dashed line).

terrain model. Despite the difference in method, our map of denning habitat for the NPR-A consistently predicted denning habitat similar to that predicted by photogrammetric methods, which bolstered our confidence in the applicability of IfSAR for mapping polar bear denning habitat.

Digital data, such as the IfSAR imagery used in this report, have analytical advantages over manually inspected photomaps. Though earlier maps (i.e., Durner et al., 2001, 2006) performed well, the initial effort of one study required several months of labor by a cartographer to inspect 1655 photos (6786 km^2; Durner et al., 2006). Therefore, it was not possible, without a great deal of additional labor, to adjust the denning habitat maps on the basis of ground-truthing data, nor was it possible to "bracket" estimates of denning habitat distribution with more or less restrictive criteria.

In contrast, the time required to process the IfSAR DTM (18 918 km^2) using standard GIS tools was less than 1 hour. Hence, we were able to calibrate the selection criteria to maximize our ability to identify ground locations that had topography typical of polar bear den sites. Raster data, such as the digital terrain model used in this report, allow the user to decide the level of noise to information (i.e., habitat incorrectly identified as denning habitat versus correctly identified denning habitat) that best serves to identify polar bear denning habitat, as well as providing a range of values that can be useful for planning on-the-ground exploration activities. With selection criteria of 1.08 m, our estimated precision error was 18% in the NPR-A, which was lower than those estimated in the Prudhoe Bay region (35.5%; Durner et al., 2001) and in the ANWR (22.0%; Durner et al., 2006). Our estimated omission error was also 18%, which is higher than those estimated for denning habitat maps in the Prudhoe Bay region (12.3%; Durner et al., 2001) and the ANWR (8.5%; Durner et al., 2006). These comparisons of precision error rates suggest that, when denning habitat is identified, interpretation of fine-grain (i.e., 5 × 5 m) DTMs with computer GIS tools is more effective than manual photogrammetric methods. However, interpretation of a DTM has a greater omission

FIG. 6. Photograph of lakeshore polar bear denning habitat identified with IfSAR data in the National Petroleum Reserve – Alaska.

FIG. 8. A stream approximately 5 m wide, with an elevation difference of more than 1.3 m between water level and the top of a bank. Although this site is suitable as polar bear denning habitat, it was not detected by the GIS mapping process of IfSAR data in the National Petroleum Reserve – Alaska.

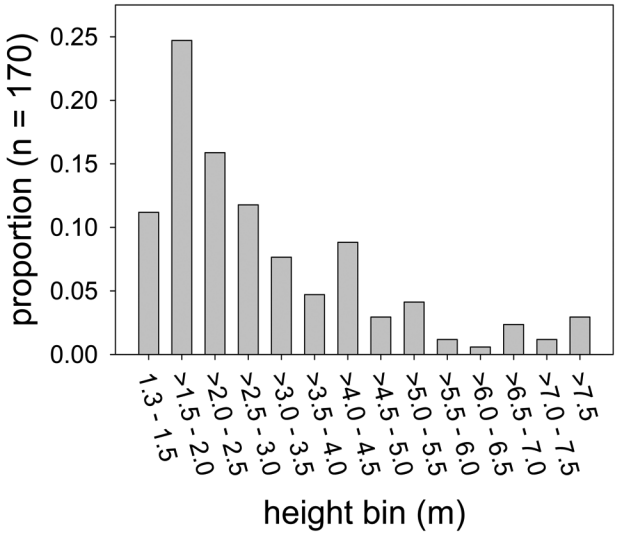

FIG. 7. Distribution by height bins of polar bear denning habitat at 170 sample points in the National Petroleum Reserve – Alaska.

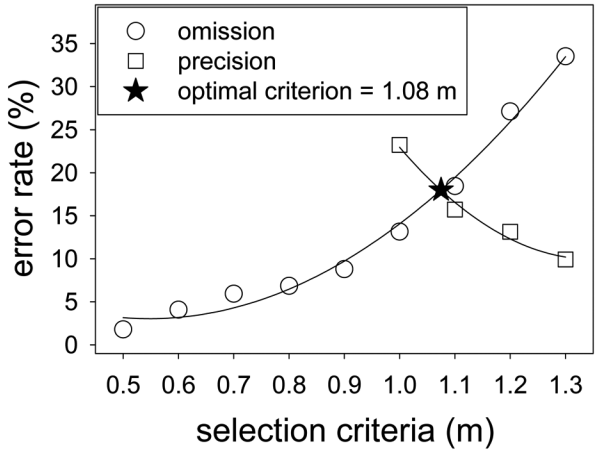

FIG. 9. Comparison of omission error rate (circles) and precision error rate (squares) relative to the selection criteria (maximum elevation difference between a 5 × 5 m cell and its eight neighboring cells) used to identify polar bear denning habitat on the National Petroleum Reserve – Alaska. The star represents the selection criterion that minimizes both omission and precision errors. No precision estimations were possible for selection criteria below 1.0 m. Trend lines were estimated with a second-order polynomial.

error rate and thus is slightly inferior to manual techniques in the ability to locate denning habitat.

The precision and omission error rates that we observed may be explained at least partly by the vertical accuracy of the IfSAR data. The estimated vertical RMSE of an STAR-3i IfSAR DTM ranged from 0.46 m or more (Mercuri et al., 2006) to 1.0 m or more (Intermap, 2010). Because the vertical resolution of the DTM was 0.01 m, an error as small as 1 cm had the potential to cause a precision error (exaggerate true elevation difference) or an omission error (mask true elevation difference). For example, if the true maximum elevation difference between a target cell and its neighboring cells was 99 cm (non-denning habitat) but the IfSAR DTM indicated a difference of 100 cm because of a +1 cm error in one of the neighboring cells, our GIS routine would have identified the target cell as denning habitat.

Another potential explanation for the omission error rate that we estimated may be the nature of IfSAR data. The IfSAR 5 × 5 m cell includes an area that is larger than the "footprint" of polar bear dens (Durner et al., 2003). Cell values are an average elevation within a 5 × 5 m area. Hence, the maximum and minimum elevation values within the bounds of a cell are not available within the respective IfSAR DTM cell. Elevation differences that we calculated are the difference in mean elevations and not the difference between elevation extremes (i.e., the maximum elevation in one cell with the minimum elevation in the adjacent cell). Hence, small landscape features that are otherwise suitable for maternal denning could be invisible to the sensors used to generate IfSAR data. For example, a stream with deep

banks but with a narrow width (< 5 m) identified as denning habitat during a field visit was not identified as polar bear denning habitat in the IfSAR data (Fig. 8). Finer grain DTMs (e.g., to 2 m horizontal spacing) are possible from Light Detection and Ranging technology (i.e., Lidar; Chow and Hodgson, 2009) and could reduce the omissions and improve the precision of polar bear denning habitat maps. Although it could be acquired, Lidar imagery is not currently available for most of the Alaska Beaufort Sea coastal plain.

Most of the NPR-A coastline consists of permafrost bluffs that range in height from 2 to 6 m (Mars and Houseknecht, 2007). We did not ground-truth these coastal habitats, however, because rapid and ongoing coastal erosion (Mars and Houseknecht, 2007; Jones et al., 2009; Wobus et al., 2011) has likely placed the shoreline mapped with IfSAR in 2002 more than 50 m offshore of the actual coastline in 2010, when most of our ground-truthing took place. As an estimated 69% of maternal dens in Alaska are located on coastal banks (Durner et al., 2003), high rates of erosion can move or eliminate some denning habitat. Loss of barrier islands with tundra banks will require bears to select den locations farther inland. Though some polar bears in Alaska have denned 61 km inland (Fig. 1; Amstrup and Gardner, 1994), the average distance of terrestrial dens from the coast was found to be 1.7 km (Durner et al., 2003). An increased frequency of inland denning by Southern Beaufort Sea polar bears would not necessarily have a negative impact on this subpopulation; in fact, most polar bear maternal dens in some subpopulations (e.g., Southern Hudson Bay and Western Hudson Bay) are found 13 – 118 km from the coast (Kolenosky and Prevett, 1983; Richardson et al., 2005). However, the loss of coastal denning habitat, combined with reduced suitability of sea ice as a maternal den substrate (Fischbach et al., 2007), would place a greater importance on all inland regions of the Alaska ACP, including the NPR-A, for polar bear maternal denning.

We found that by interrogating an IfSAR-derived digital terrain model we could identify most landscape features in the NPR-A that are capable of accumulating wind-borne snow to a depth sufficient for polar bear maternal dens. Meeting the prerequisites of slope and height, however, does not necessarily mean that all of the mapped denning habitat will ever be used by a polar bear, and we have made no attempt to weight a particular mapped habitat, on the basis of its likelihood to be used by a bear, relative to other mapped habitat. During any particular year, some of the denning habitat that we mapped could actually be devoid of snow because of prevailing winds or recent storm events (Evans et al., 1989). Also, patches of shrubs above 1.3 m in height can accumulate snow to a depth (Sturm et al., 2001) that would be sufficient for polar bears to dig maternal dens, but our map does not account for vegetation. However, because there is a close association of tall shrubs with riparian areas (Sturm et al., 2001), and because much of the denning habitat that we mapped occurred along rivers and streams, it is likely that our map included some potential denning habitat (i.e., snow > 1.3 m deep) that could result from tall shrubs.

Much of the denning habitat that we describe occurs far from the coast, where the probability it will be used for denning is lower than near the coast. However, the U.S. Fish and Wildlife Service included an area on the Alaska ACP within 25 miles (40.2 km) of the coast for managing industrial activities in relation to polar bear maternal denning (USFWS, 2011). Hence, although our map includes regions that were seldom used by polar bears in recent years, it also includes the entire terrestrial region of concern to the primary agency responsible for polar bear management in the United States.

We have shown that fine-grain digital elevation data, such as the IfSAR DTM used in this paper, could provide a flexible tool for managing human activities in regions where polar bears may occupy maternal dens. Likewise, similar fine-grain elevation data can be useful in other regions where polar bear maternal denning and mineral extraction overlap. Cost of IfSAR DTM data (with an accuracy of 1.0 m RMSE) was approximately $40/km^2 (U.S. dollars; 2004 estimate; Mercer, 2004). Thus funding limitations may limit the availability of IfSAR data to some agencies. Our map of polar bear maternal denning habitat for the NPR-A is available in vector GIS format to all potential users at http://alaska.usgs.gov/science/biology/polar_bears/pubs.html. We suggest that a denning habitat map, derived from elevation data of similar or better spatial resolution and created with selection criteria of 1.08 m, may satisfactorily balance omission and precision errors in the NPR-A. A great strength of IfSAR imagery is that managers with access to such data may adjust the selection criteria to bracket estimates of potential denning habitat that have the desired level of omission and precision for their management objectives.

ACKNOWLEDGEMENTS

Principal funding for IfSAR data acquisition and fieldwork was provided by the U.S. Geological Survey, Alaska Science Center, and the U.S. Bureau of Land Management. Additional funding for IfSAR data was provided by the National Science Foundation. The U.S. Geological Survey Climate and Land Use Change Research and Development Program provided funding for some of the radio collar data used to identify polar bear den sites. The instrumentation of polar bears with radio collars was permitted under the U.S. Marine Mammal Protection Act and the U.S. Endangered Species Act by U.S. Fish and Wildlife Service permit MA 690038 and by the U.S. Geological Survey Alaska Science Center Institutional Care and Use Committee (assurance no. 2010-3). We thank Anthony Fischbach for assistance in the field. The following individuals provided constructive suggestions on earlier versions of this report: Todd Atwood, Martyn Obbard, Karen Oakley, David Yokel, and two anonymous reviewers. Use of trade names is for descriptive purposes only and does not imply endorsement by the U.S. government.

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