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The Effect of Traffic Levels on the Distribution and Behaviour of Calving Caribou in an Arctic Oilfield

Alexander K. Prichard,[1,2] Joseph H. Welch[1] and Brian E. Lawhead[1]

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ABSTRACT. Caribou are the most abundant large terrestrial mammals in Arctic Alaska, providing important cultural and subsistence resource values for local communities. As oil and gas development expands across the Arctic Coastal Plain of northern Alaska, understanding the potential impacts on caribou and improving associated mitigation measures are a crucial focus of applied research. One consistently observed impact in northern Alaska is displacement of maternal caribou within 2–5 km of active oilfield roads and gravel pads for a period of 2–3 weeks during and immediately after calving. A potential mitigation measure to address calving displacement is convoying of traffic to reduce traffic frequency and vehicle-related disturbance on roads in calving areas. We conducted frequent road and aerial surveys of caribou near two oilfield roads, one with convoying and one without, over a 3-year period during the precalving, calving, and postcalving periods to evaluate the effectiveness of traffic convoying. Road surveys indicated that caribou closer to the roads and groups with calves exhibited more frequent and stronger behavioural reactions in response to traffic, and that moderate or strong reactions to traffic, such as standing up and walking or running away, were more frequent near the road with convoying than near the road with unlimited traffic. Aerial survey results indicated some avoidance of areas up to at least 2 km from the road with convoying and 4 km from the road without convoying by caribou groups with calves. This relationship was present even after adjusting for other factors affecting distribution. This avoidance of roads by maternal caribou was limited to the calving period and was not evident during the precalving or postcalving periods. In addition, an inactive elevated terrestrial drilling platform was present on the calving grounds during one year, but we found no evidence of caribou avoidance of that structure during calving at our scale of analysis.

Key words: Alaska; calving; caribou; Central Arctic herd; development; disturbance; mitigation; oil and gas; *Rangifer tarandus*; traffic

RÉSUMÉ. Le caribou est le plus abondant des grands mammifères terrestres de l’Arctique alaskien, ce qui signifie qu’il représente d’importantes valeurs sur le plan des ressources culturelles et de subsistance des communautés locales. Au moment où la mise en valeur du pétrole et du gaz s’intensifie dans la plaine côtière arctique du nord de l’Alaska, la compréhension des incidences potentielles de ces activités sur le caribou et l’amélioration des mesures d’atténuation connexes représentent un aspect crucial de la recherche appliquée. Une incidence couramment observée dans le nord de l’Alaska prend la forme du déplacement du caribou maternel dans un rayon de deux à cinq kilomètres des routes actives des champs de pétrole et des assises en gravier pendant une période de deux à trois semaines, durant le vêlage et juste après celui-ci. Une mesure d’atténuation potentielle pour contrer le déplacement dû au vêlage consiste à faire des convois afin de réduire la circulation et la perturbation causée par les véhicules sur les routes situées dans les aires de vêlage. Nous avons effectué de nombreux relevés routiers et aériens du caribou près de deux routes de champs pétroliers, une avec convois et l’autre sans convois, sur une période de trois ans durant la période de vêlage ainsi qu’avant et après celle-ci afin d’évaluer l’efficacité des convois. Selon les relevés routiers, les caribous évoluant plus près des routes et les groupes accompagnés de veaux affichaient des réactions comportementales plus fréquentes et plus fortes en présence de circulation. Ces relevés ont également permis de constater que des réactions allant de modérées à forte en présence de circulation, comme le fait de se lever, de marcher ou de s’enfuir, étaient plus fréquentes près de la route avec convois que près de la route avec circulation illimitée. Quant aux relevés aériens, ils ont indiqué un certain évitement des zones se situant jusqu’à deux kilomètres de la route en situation de convois, et jusqu’à quatre kilomètres de la route en l’absence de convois, par les groupes de caribous accompagnés de veaux. Cette relation était présente même après avoir fait des redressements en raison d’autres facteurs concernant la distribution. Cet évitement des routes par le caribou maternel se limitait à la période du vêlage, et n’était pas évident au cours des périodes précédant ou suivant le vêlage. Par ailleurs, une plateforme de forage terrestre élevée et inactive était présente sur les lieux de vêlage pendant un an, mais à l’échelle de notre analyse, aucune preuve n’a permis de croire que les caribous évitaient cette structure durant le vêlage.

Mots clés : Alaska; vêlage; caribou; troupeau de l’Arctique central; développement; perturbation; atténuation; pétrole et gaz; *Rangifer tarandus*; circulation

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[1] ABR, Inc.—Environmental Research and Services, PO Box 80410, Fairbanks, Alaska 99708, USA
[2] Corresponding author: aprichard@abrinc.com

INTRODUCTION

As oil and gas development expands across Arctic Alaska, understanding and mitigating the associated impacts on wildlife movements, distribution, and behavior are of paramount importance for sustaining wildlife populations. The Arctic Coastal Plain of northern Alaska is used by four herds of barren-ground caribou (*Rangifer tarandus granti*): the Western Arctic herd, Teshekpuk herd, Central Arctic herd (CAH), and the Porcupine herd (Prichard et al., 2020b). Caribou are the most abundant large terrestrial mammals in the region, currently totaling approximately 500,000 animals among all four herds, providing culturally and economically important subsistence resource values for local communities. The range of the CAH has included oil and gas development for more than four decades (Murphy and Lawhead, 2000; NRC, 2003; Prichard et al., 2020a), but only limited development currently exists on the ranges of the other three herds (Person et al., 2007). With oil development expanding into the range of the Teshekpuk herd and recent lease sales on portions of the summer range of the Porcupine herd, applying the knowledge gained from analysis of historical data collected on the CAH has become increasingly important for impact prediction, planning, and mitigation of development.

Although the population of the CAH has generally increased since oilfield development, populations of migratory caribou and wild reindeer have declined by 56% across the Arctic over the last two decades (Russell et al., 2019), possibly due to climate change. Climate change is having multiple, sometimes countervailing, effects on caribou, including increased frequency of rain-on-snow events (Bieniek et al., 2018), changes in vegetation composition (Fauchald et al., 2017), a longer snow-free season (Tveraa et al., 2013), and more severe insect harassment (Weladji et al., 2003). If development causes fragmentation of seasonal ranges, loss of preferred habitat, or hindrance of movements, it could interact with climate change by limiting options for caribou to adapt to these changing conditions near development.

Habitat fragmentation and loss resulting from extensive areas of development, human activity, and forest harvesting, and associated increases in predation or changes in parasites are issues of concern for woodland caribou (*Rangifer tarandus caribou*) (Frenette et al., 2020). These factors may have resulted in a northward range retraction by woodland caribou populations (Schaefer, 2003), and multiple herds are in danger of extirpation (Johnson et al., 2015). Development has been more limited and dispersed in Arctic areas of North America, but some studies have reported notable effects on barren-ground caribou from industrial development and roads (Boulanger et al., 2012; Johnson and Russell, 2014; Plante et al., 2018; Johnson et al., 2020; Prichard et al., 2020a).

Most of the CAH winters in or near the Brooks Range in Alaska. Pregnant females typically arrive in the calving range in mid to late May, and peak calving occurs during the first week of June (Arthur and Del Vecchio, 2009). Before calving, some caribou feed along gravel roads, where dust deposition can lead to early snowmelt (e.g., the dust-shadow effect; Murphy and Lawhead, 2000). Caribou bulls typically arrive in the area of the northern Alaska oilfields by mid-June.

Concentrated calving activity by the CAH tends to occur in two areas of the central Arctic Coastal Plain, one located between the Kuparuk and Colville Rivers and the other east of the Sagavanirktok River (Wolfe, 2000; Arthur and Del Vecchio, 2009; Nicholson et al., 2016). Parturient females are sensitive to disturbance and most avoid gravel roads and pads with human activity for 2–3 weeks after birth, resulting in a zone of localized displacement reported to range from 2 to 5 km (Dau and Cameron, 1986; Lawhead, 1988; Cameron et al., 1992; Johnson et al., 2020; Prichard et al. 2020a). Following construction of the Kuparuk and Milne Point oilfields in the western calving area, high-density calving gradually shifted south and southwest of the Kuparuk oilfield (Murphy and Lawhead, 2000; Wolfe, 2000; Noel et al., 2004; Joly et al., 2006). This shift in calving distribution may have been a result of development, resulting in regional displacement from a previously used calving area (NRC, 2003; Cameron et al., 2005; Prichard et al., 2020a), although the calving distribution in the eastern area, where there is limited development, also shifted to the west and southwest in the last two decades (Arthur and Del Vecchio, 2009; Lenart, 2015).

After calving ends and calves become more mobile, CAH caribou form large nursery bands and drift northward before the seasonal emergence of mosquitoes. During this postcalving period, avoidance of roads declines (Murphy and Lawhead, 2000; Haskell et al., 2006; Johnson et al., 2020; Prichard et al., 2020a). After mosquito harassment begins, the western segment of the CAH moves rapidly to the coast, often crossing back and forth through oilfield infrastructure multiple times throughout the midsummer insect season (Murphy and Lawhead, 2000; Prichard et al., 2020a).

Four main concerns have been identified regarding development impacts on the CAH: (1) potential displacement of maternal caribou around roads and pads during the calving period; (2) delays or impediments during summer movements to and from mosquito-relief habitat along the Beaufort Sea coast; (3) disturbance effects on caribou activity budgets resulting from exposure to industrial activities and infrastructure; and (4) impacts on subsistence harvest levels or harvest effort (NRC, 2003).

Various mitigation measures have been implemented or proposed to ameliorate the impacts of oil and gas development on caribou, including elevating pipelines to allow caribou passage underneath, separating pipelines from adjacent roads, minimizing the surface area of roads and pads, reducing vehicle speeds, and reducing or eliminating traffic and other human activity during critical periods (Cronin et al., 1994; Murphy and Lawhead, 2000; Lawhead et al., 2006). Cronin et al. (1994) recognized

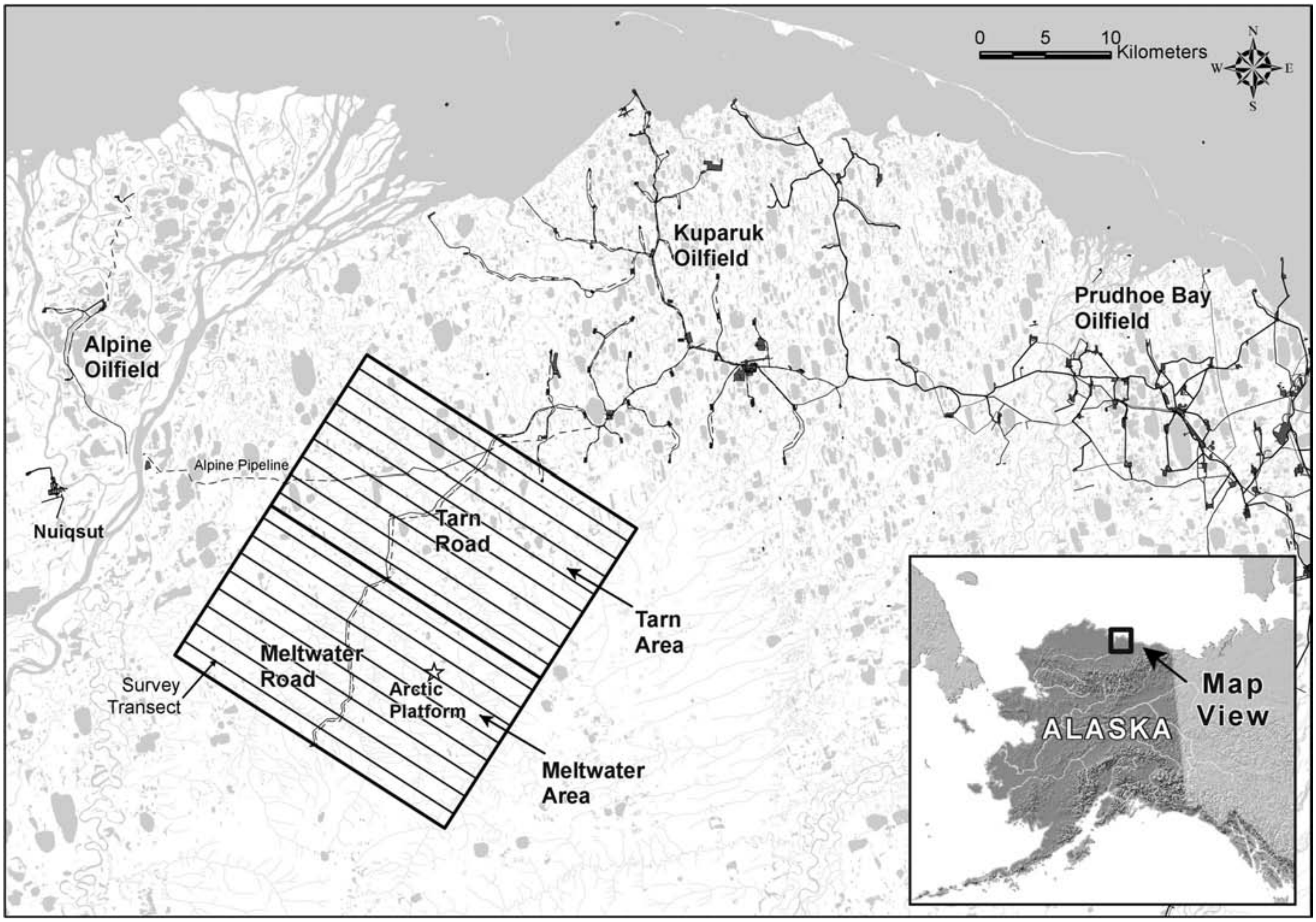

FIG. 1. Study area boundary for aerial strip-transect surveys of caribou distribution conducted in the Tarn and Meltwater survey areas in northern Alaska, 2001–03.

vehicle traffic as a major cause of caribou disturbance and suggested convoying as one measure to decrease the frequency of traffic-related disturbance. For this study, convoying refers to limiting vehicle traffic to a fixed number of periods per day and requiring all vehicles to travel the road together during those periods. While lowering the amount of human activity is likely to lower the degree of caribou disturbance (Skarin, 2006; Nellemann et al., 2010; Leblond et al., 2013), limited information is available on the effectiveness of traffic reduction and convoying on caribou or on the response of maternal caribou to inactive infrastructure during calving.

The Tarn (Kuparuk drill sites 2L and 2N) and Meltwater (Kuparuk drill site 2P) projects analyzed herein were constructed at the western edge of the western calving area of the CAH (Figs. 1, 2). To address the concerns of local residents from the nearby community of Nuiqsut, permit stipulations for the Meltwater project required a study of caribou movements and the efficacy of mitigation measures. Of primary interest was evaluation of the effectiveness of vehicle convoying as a potential technique to reduce displacement of caribou during and immediately after the calving period. Accordingly, during 2001–03, traffic convoying was implemented on the Meltwater Road while normal traffic patterns continued on the Tarn Road.

In addition, during the winter of 2002–03, Anadarko Petroleum Corporation's "Arctic Platform" drill site was erected in the eastern half of the Meltwater study block (Fig. 1). The Arctic platform, which consisted of an elevated terrestrial drilling platform constructed on pilings entirely above ground level (thus not using any gravel fill), was present but was not occupied or operated during the 2003 precalving, calving, and postcalving periods. Although the platform was inactive, the raised structure was easily visible for over 5 km in all directions (Fig. 3). The presence of this structure on the CAH calving ground and within our study area provided a unique opportunity to assess the level of displacement of caribou near an inactive drilling structure during calving.

We used road and aerial surveys to compare caribou behavior and distribution along these two roads during 2001–03 and aerial surveys near the inactive elevated drilling platform during 2003. These results were first presented in unpublished reports for mitigation plan monitoring (e.g., Lawhead et al., 2004), but we reanalyzed the data using different statistical techniques in response

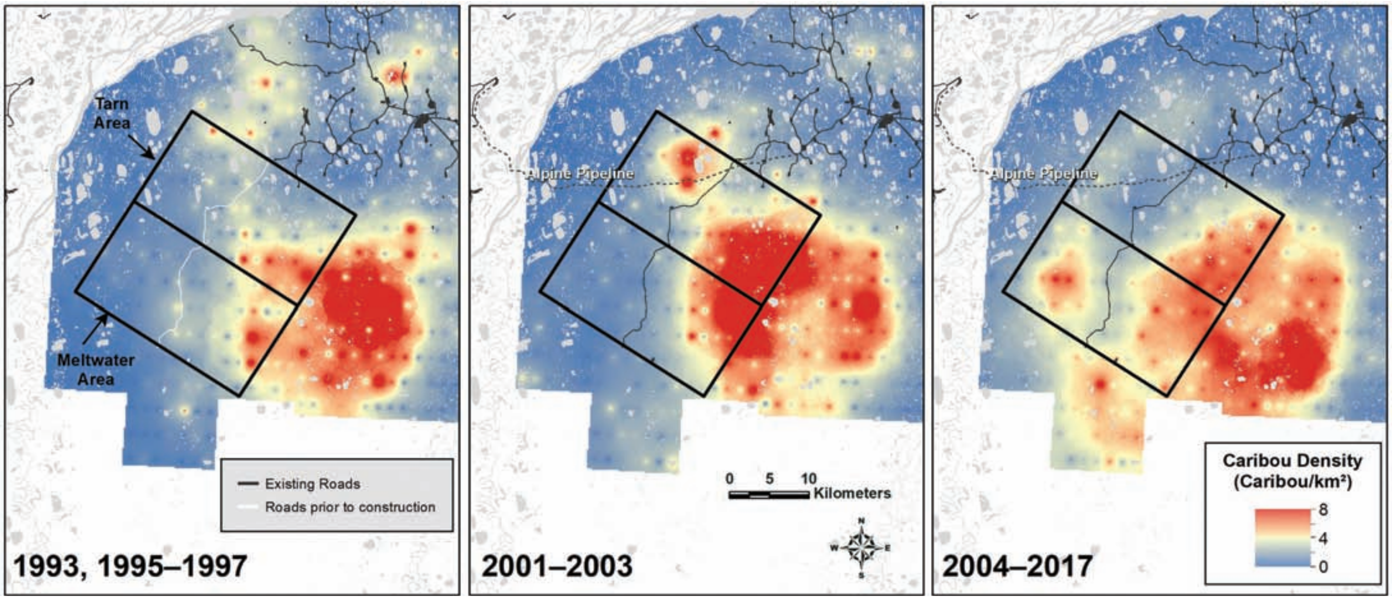

FIG. 2. Estimated caribou density during calving (6–16 June) calculated from annual aerial strip-transect surveys conducted in the Kuparuk oilfield area during the years prior to construction of the Tarn and Meltwater Roads (1993, 1995–97), the years of this study (2001–03), and the years after this study was completed (2004–17).

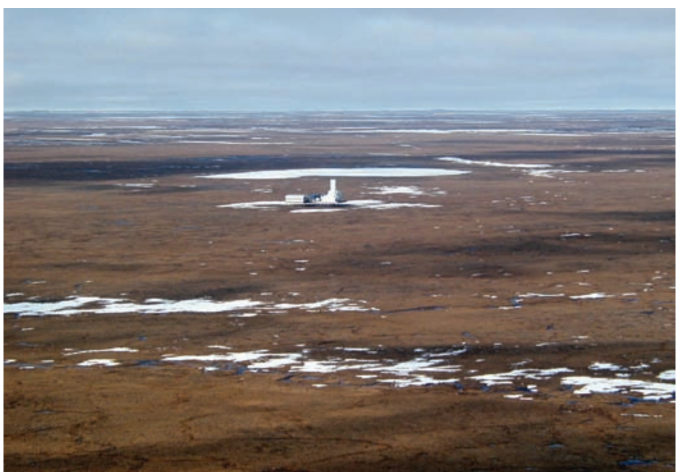

FIG. 3. Photograph of the inactive elevated drilling platform on the calving range of the Central Arctic Herd, June 2003.

to increasing interest in traffic convoying as a possible mitigation method to limit human activity for new development. We also used regional aerial strip-transect surveys conducted during 1993 and 1995–2017 to provide a long-term context for calving distribution when interpreting our results.

We identified the following objectives: (1) compare the behavioral reactions of caribou to traffic with and without convoying; (2) compare the level of displacement of maternal caribou between road types, between all groups and groups with calves, and among periods (precalving, calving, and postcalving); (3) compare the distribution of caribou groups in our study (2001–03) with long-term (1993, 1995–2017) calving survey data from a larger area; and (4) examine whether maternal caribou were displaced from an inactive drilling platform in 2003.

STUDY AREA

The principal summer range of the CAH is located between the Colville and Canning Rivers on the central Arctic Coastal Plain (Murphy and Lawhead, 2000; Cameron et al., 2005; Nicholson et al., 2016), a region that includes the Kuparuk, Milne Point, Prudhoe Bay, Endicott, Badami, and Point Thomson oilfields. Major construction activities began in the mid-1970s, when the CAH was estimated at 5000 caribou. With the exception of a short-lived decline in the early 1990s, the herd grew steadily to 68,000 animals by 2010 (Lenart, 2021), and the most recent survey conducted in 2019 indicated the population has declined to 30,000 animals (ADFG, 2020). Herd size was estimated at approximately 34,000 caribou in July 2002 and was growing at the time of our study (Lenart, 2021).

The Meltwater study area is located in the southwestern Kuparuk oilfield on the Arctic Coastal Plain of Alaska and approximately 30 km east of the community of Nuiqsut (Fig. 1). The landscape in the region slopes down gently from upland, moist tussock tundra in the south to moist and wet coastal tundra communities closer to the coast. The region is characterized by permafrost-related features such as oriented thaw lakes, beaded streams, and pingos. The physiography, vegetation, and climate of the central Arctic Coastal Plain were described by Walker et al. (1980).

During the winter of 1997–98, a 16.2 km gravel road and associated pipelines were constructed between two gravel drill sites (Kuparuk DS-2L and DS-2N) for the Tarn project (Tarn Road), extending south from existing infrastructure in the southwestern Kuparuk oilfield (Fig. 1). Gravel roads and pads are typically built 2 m thick with sloping sides. During the winter of 2000–01, the road and pipelines were extended south by an additional 16.3 km to Kuparuk DS-2P for the Meltwater project (Meltwater Road). The Meltwater and Tarn projects consist of a gravel access road and adjacent pipelines oriented generally parallel to the roads, elevated to minimum heights of 1.5 m (Tarn) and 2.1 m (Meltwater) above ground level. The road and pipelines were separated (mean distance of 188 m for the Meltwater Road) to facilitate caribou passage, following recommended mitigation measures (Curatolo and Murphy, 1986; Cronin et al., 1994).

The study area was subdivided into two contiguous survey blocks (~313 km² each) for aerial surveys conducted during May and June: the Tarn block, encompassing the Tarn Road (without convoying), and the Meltwater block, encompassing the Meltwater Road (with convoying; Figs. 1, 2). The survey areas extended approximately 12 km east and west of the roads, three times the caribou displacement distance (4 km) reported by studies in the 1980s along the Milne Point Road, which is located immediately east of the Kuparuk oilfield (Dau and Cameron, 1986; Cameron et al., 1992).

METHODS

As a part of the mitigation plan to minimize potential traffic impacts, vehicle speeds were reduced to 25–30 mph (40–48 km/h) on the Meltwater Road starting on 15 May, and convoying was implemented from 25 May to 30 June. This seasonal timing was selected to encompass the period from when caribou arrive in the area following spring migration to when they move to the coast for relief from mosquito harassment. During the convoying period, traffic was restricted to four scheduled convoy round trips (8 one-way trips) every 24 h. Vehicles on the roads included pickup trucks, maintenance vehicles, and larger trucks. These convoys included two round trips for gravel maintenance lasting approximately 2 h each (departing 0300 and 1500 local time) and two general traffic round trips (departing 0800 and 2000), consisting of approximately 30 min of travel to the Meltwater pad, approximately 2 h at the Meltwater pad, and approximately 30 min of travel back to the southern Tarn pad (Kuparuk DS-2L). Travel along the Tarn Road did not include convoys or other limitations on traffic frequency and the speed limit was 45 mph (72 km/h), which was the norm throughout most of the oilfield during the study years.

In 2001, the condition of the newly constructed Meltwater Road quickly deteriorated following the spring thaw, so all traffic except maintenance crews was halted on 4 June before large numbers of caribou were present in the area. Road maintenance work was conducted during 5–8 June, but the road was closed after that point to all traffic except for limited repair equipment, so no road survey data could be collected after 4 June. In 2002, traffic convoying proceeded as planned. In 2003, the completion of development drilling on the Meltwater pad resulted in a large reduction in the amount of convoy traffic needing to travel to the pad, so routine traffic consisted primarily of a single vehicle for the drill-site operator to perform routine operational tasks (Table 1).

TABLE 1. Mean traffic levels on the Tarn and Meltwater Roads during 25 May–30 June 2001–03.

	Tarn		Meltwater			
Year	Vehicles/d	SD	Vehicles/d	SD	Convoys/d	SD
2001[1]	214.8	143.0	59.4	14.1	7.3	1.8
2002	197.6	109.8	7.8	5.2	4.7	1.5
2003	160.4	201.2	3.8	3.4	2.4	0.8

[1] In 2001, Meltwater traffic convoys ended on 4 June and maintenance convoys ended on 8 June.

The study periods were designated based on the typical peak of calving (Arthur and Del Vecchio, 2009) and the timing of postcalving behavior (formation of large nursery bands). Surveys were grouped into the precalving period (17 May–29 May), the calving period (30 May–13 June), and the postcalving period (14–29 June), with the exception of 2002 when the start of the postcalving period was designated as 13 June because of early snowmelt.

Road Surveys and Behavioral Reactions

The study plan called for two road surveys of caribou within 1 km of the road per day per road, with a survey defined as one-way travel along a single road, although the actual number of surveys varied daily (from 0 to 4), based on logistical constraints. A single observer drove the Tarn Road at ~25–30 mph (40–48 km/h) or rode on a convoy vehicle to survey the Meltwater Road. The observer recorded the number, location, estimated distance from the road, behavior, and, when possible, the sex and age composition for all caribou groups within 1 km of the roads. The distance to the road was estimated with a laser rangefinder or by mapping the location on large-scale maps. Because surveys were conducted frequently, some caribou were likely observed on multiple surveys, although there was adequate time between surveys for caribou to move to different areas.

The behavioral reactions of caribou groups to the vehicles were classified as none, mild, moderate, or strong. No reaction was assigned when caribou did not exhibit a visible response; a mild reaction involved at least one caribou looking at a vehicle but with no change in activity state; a moderate reaction involved a change in activity state such as standing up or walking away; and a strong reaction involved trotting or running away. The group was assigned the strongest reaction by any individual caribou in the group, although in most cases all individuals in the group exhibited similar reactions. We combined these categories for analysis and compared groups exhibiting moderate or strong reactions with groups exhibiting no or mild reactions.

Traffic rates were estimated by tallying the number of vehicles traveling the Tarn Road in half-hour sampling periods and by tallying the total number of vehicles traveling the Meltwater Road during convoys. We used logistic regression to evaluate which factors influenced the occurrence of no/mild versus moderate/strong reactions by caribou groups. Four factors were examined: period (precalving, calving, and postcalving); area (Tarn Road, Meltwater Road); distance from road (0 – 100 m, 101 – 250 m, 251 – 500 m, 501 – 1000 m); and presence of calves (yes, no). We ran models with all combinations of main factors and two-way interactions, but included interaction terms only when both terms in the interaction also were included as main effects. We also excluded interaction terms with the presence of calves variable because of the low sample sizes of some of these combinations. This analysis resulted in a total of 26 models in the candidate model set.

We calculated Akaike information criteria adjusted for small sample size (AICc) for each model and used Akaike weights (Burnham and Anderson, 1998; Anderson et al., 2000) to estimate the relative probability of each model being the best model in the candidate set. We calculated the probability of a variable being in the best model set as the sum of the Akaike weights for all models containing that variable. We then calculated the model-averaged parameter estimates and standard errors (SE) by calculating the mean value of the estimated parameter values for each model containing the variable of interest while weighting the parameter values by the Akaike weight (Burnham and Anderson, 2002). We used the Hosmer-Lemeshow goodness of fit test in the R package ResourceSelection, using 10 categories to test how well the top model fit the data (Lele et al., 2019; Hosmer and Lemeshow, 2000).

Aerial Surveys and Resource Selection

We began aerial strip-transect surveys for caribou distribution as early as 15 May and conducted them approximately every four days until as late as 29 June in all three years. Survey methods were similar to those used by Prichard et al. (2019). Two observers looked out opposite sides of a fixed-wing Cessna 206 airplane, which followed transect lines oriented across the survey area, roughly perpendicular to the Tarn and Meltwater Roads and pipeline alignments (Fig. 1). A third observer recorded data. The pilot maintained the aircraft speed at ~150 km/h and the altitude at ~90 m above ground level, using a radar altimeter for the latter. Transect lines were spaced systematically at intervals of 1.6 km. Observers counted caribou within a 400 m wide strip on each side of the flight line, for a sampling intensity of 50% (0.8 km of each 1.6 km). The strip width was estimated visually with tape markers on the struts and windows of the aircraft, following the method of Pennycuick and Western (1972). For each caribou group observed within the strip, the airplane location was recorded using a GPS receiver, the number of adults and calves were recorded, and the group was assigned to a distance category (one of four 100 m wide zones) northeast or southwest of the airplane. Because we recorded distance in 100 m categories, the maximal error in perpendicular distance from the plane was 50 m.

The CAH is exposed to frequent air traffic and most caribou exhibited no overt response to the survey aircraft. A small percentage (< 5%) would walk or run away as the aircraft passed. These groups were recorded in the location where they were first observed. Although adult caribou have high sightability on open tundra, young calves can be difficult to observe, especially if they are behind their dams or lying down. We acknowledge that our method may have underestimated the total number of caribou, especially calves during some surveys, but we placed particular emphasis on assessing calf presence in each group.

We also used data from regional calving surveys using the same aerial strip-transect methods to provide context on caribou distribution over a longer time frame and across a larger portion of the western CAH calving range. These surveys were conducted along north-south transects in a larger area that included the Meltwater and Tarn survey areas during the calving period (6 – 16 June) annually during 1993 and 1995 – 2017. The Tarn and Meltwater Roads were constructed on the western edge of the CAH calving distribution and, based on these regional aerial surveys before construction, a west-to-east gradient of increasing calving density was expected to be present, independent of the presence of the roads (Fig. 2). To summarize and account for this predevelopment distribution data, we used the inverse-distance-weighted (IDW) interpolation technique using the gstat package in R (Pebesma, 2004) to map average preconstruction caribou densities in the study area using data collected during calving in 1993 and 1995 – 97. This IDW analysis used the total number of caribou observed during the calving period pooled in 3.2 km segments of the transect strips and assigned to the segment centroids. IDW interpolation was then used to create a density surface as the distance-weighted density of the centroids. To select the parameters giving the best fit, the power (between 1 and 1.4) and number of adjacent centroids (between 8 and 36) used in calculations were selected based on the values that minimized the residual mean square error. This analysis produces surface models of the estimated density of all caribou in the study area based on the calving distribution observed during the years before construction of the Tarn and Meltwater Roads (hereafter referred to as IDW). For comparison, we also calculated IDW surfaces from regional calving surveys for the years of this study (2001 – 03) and the years afterward (2004 – 17; Fig. 2).

We then used resource selection function (RSF) models (Boyce and McDonald, 1999; Manly et al., 2002) to assess the distribution of caribou group locations from aerial surveys with respect to multiple factors that could influence caribou distribution in the study area. We used group locations from our aerial surveys conducted in 2001 – 03 in the Tarn and Meltwater areas, but excluded a small number of group locations (~1.5%) located in waterbodies based on a landcover map.

To conduct the RSF analysis, we ran logistic regressions (Manly et al., 2002) in R (R Core Team, 2020) and compared actual caribou locations to random locations. For each caribou group location, we generated 25 random locations in non-water landcover classes from anywhere within the study area. These random locations were assigned to the same period and year as the actual location so that each period and year combination had 25 random locations per actual location. For this analysis, we use the terms "selection" and "avoidance" to refer to attributes that are used more or less than expected by caribou, when compared with random points. Because weather conditions, caribou density, and vehicle traffic along the Meltwater Road varied by year, we ran the analyses both separately by year and for all years combined. We focus on the results of the analysis of all years combined, but results of the analyses of individual years are included as supplemental material (Supplemental Tables S1–S8).

To assess impacts of development, we ran the model with variables thought to affect caribou distribution in the area. Variables included in the model were landcover class, elevation, landscape ruggedness (Sappington et al., 2007; calculated over a 150 × 150 m box centered at each 30 m pixel), estimated predevelopment caribou densities (IDW), distance to the coast, distance to the roads, and distance to the inactive elevated drilling platform (2003 analysis only). The inclusion of the IDW variable was necessary to account for the east-west gradient in calving densities present prior to the construction of the Tarn or Meltwater Roads. Landcover classes were derived from the North Slope Science Initiative (NSSI, 2021) landcover layer and were merged into seven categories. We merged the tussock tundra, tussock shrub tundra, and mesic sedge (*Carex* spp.)–dwarf shrub tundra classes into a single landcover type: sedge–shrub tundra. We grouped the open water, ice and snow, and pendant grass (*Arctophila fulva*) classes together as water. We lumped bare ground, sparsely vegetated, birch (*Betula* spp.)–ericaceous low shrub, low and tall willow, and coastal willow as riparian/other because most of those spatially limited cover classes occurred along streams and rivers (Prichard et al., 2020a). These groupings resulted in seven landcover classes: water, aquatic sedge (*Carex aquatilis*), mesic herbaceous, wet sedge, sedge–shrub tundra, dwarf shrub–*Dryas*, and riparian/other.

To account for the lack of precision in caribou group locations from aerial surveys, we modified the original landcover map (30 m pixels) by calculating the most frequent landcover class occurring in a moving window of size 7 × 7 pixels. Using this process, we created a map of the most common landcover class within a 210 × 210 m block centered on each original 30 m pixel. We used the natural logarithm of the landscape ruggedness variable to account for a skewed distribution.

To test for caribou group avoidance from the two roads, we added a variable for different distance zones for both roads (distance categories: 0–2 km, 2–4 km and > 4 km). We chose these distance categories (0–2 km and 2–4 km) based on previous research indicating that maternal caribou avoided the nearby Milne Point Road by 4 km (Dau and Cameron, 1986; Cameron et al., 1992) and to keep the number of categories small, avoid correlation among variables, and maximize the power to detect an effect. To test for potential caribou avoidance of the inactive elevated drilling platform, we added a variable for different distance zones (0–2 km, 2–4 km, > 4 km from the platform), but because the platform was only present in 2003, we included this variable in the RSF model of 2003 data only (Supplemental Tables S5–S8).

All locations were tested for collinearity between explanatory variables by calculating variance inflation factors (VIF) for the full model using the DescTools library in R (Signorell et al., 2019). In addition, we scaled continuous variables (subtracted the mean and divided by the standard deviation) to aid in model convergence and parameter interpretation (Zuur et al., 2009).

For each period, we tested all combinations of the variables (no interactions were included) using the glmulti package in R (Calcagno and de Mazancourt, 2010) using AICc values to compare models. We calculated the model-weighted coefficients and SE of each parameter as described above.

We tested the fit of the best RSF models for each period using *k*-fold cross-validation (Boyce et al., 2002). At each step, we withheld one-fifth of the caribou locations and calculated relative probabilities of use for locations used by those caribou (testing data) based on the remaining data (training data). We repeated this process five times; that is, for each one-fifth of the caribou locations. We used the mean Pearson's rank correlation coefficient for the five testing data sets as a measure of model fit.

Because we expected that groups with calves were likely to exhibit stronger avoidance of infrastructure, we ran the models both for all groups and separately for just groups containing at least one calf (during the calving and postcalving periods). We also calculated the mean density of total caribou and caribou calves, as well as the proportion of calves, by distance to the Tarn and Meltwater Roads for each year and time period.

RESULTS

Weather conditions were highly variable among years, with snowmelt occurring later than average in 2001, earlier than average in 2002, and near the long-term average in 2003. Snow melted at the Kuparuk airstrip on 4 June 2001, 12 May 2002, and 28 May 2003 (although trace amounts were present until 6 June 2003). Snow generally persisted longer in the study area than at the Kuparuk airstrip; however, snow melted in the study area by mid-May 2002, whereas it persisted through most of the calving period in 2001.

ROAD SURVEYS AND BEHAVIORAL REACTIONS

As expected, the Meltwater Road where convoying was instituted had both a lower number of vehicles and a lower frequency of traffic events than did the Tarn Road with unrestricted traffic. The traffic rate along the Tarn Road ranged from 214.8 vehicles/d in 2001 to 160.4 vehicles/d in 2003, while the number of convoys (one way) along the Meltwater Road ranged from 7.3 convoys/d in 2001 to 2.4 convoys/d in 2003 (Table 1). In 2001, however, most Meltwater Road convoys ended on 4 June because of the need for road repairs, so road surveys ceased on that date. Although overall traffic rates were higher on the Tarn Road, the annual variability in traffic rates was greater on the Meltwater Road.

We conducted 102 road surveys on the Tarn Road and 109 surveys on the Meltwater Road. Before the end of convoying in 2001, we conducted 10 Tarn Road surveys and 28 Meltwater Road surveys. We only observed four caribou groups in 2001 because of the shortened survey period (Table 2), so we excluded those observations from the analysis of caribou reactions to traffic.

We recorded the behavioral reactions of 1348 caribou groups across all 3 years (Table 2), comprising 744 groups along the Tarn Road (7808 caribou) and 604 groups along the Meltwater Road (6257 caribou). The mean distance (weighted by group size) of caribou groups observed within 1 km of roads was 329 m for the Tarn Road and 333 m for the Meltwater Road. In 2002, only three calves (0.6% of caribou) were observed during the calving period along the Meltwater Road. In 2003, no calves were observed along the Meltwater Road during calving, and 46 calves (10.1% of caribou) were observed along the Tarn Road during calving, all on 11 and 13 June.

Reaction strength did not vary significantly ($p > 0.05$) between 2002 and 2003, so we lumped those years together for analysis. The top model included all four variables as main factors as well as the distance*area interaction (Supplemental Table S1). Results of the goodness-of-fit test for the best model showed no evidence of poor model fit ($p = 0.80$). The probability of a moderate or strong response was significantly higher near the road, when the caribou group contained a calf, during the calving period than the precalving or postcalving period, and in the Meltwater area than in the Tarn area (Table 3, Fig. 4). While the distance*area term was included in the top model (Supplemental Table S1), the model-weighted parameter estimates for all interactions had 95% confidence intervals that included zero (Table 3).

Aerial Surveys and Resource Selection

IDW maps created using densities of caribou observed on regional aerial surveys conducted in 1993 and 1995–2017 demonstrated that the highest density of calving activity occurred east of the Meltwater and Tarn Roads before construction, during our study, and after our study (Fig. 2). Before construction of the Tarn Road and pads, caribou primarily calved in the northeastern portion of the study area and lower densities occurred near and west of the future Tarn and Meltwater Roads (Fig. 2). The highest density calving shifted farther west during the years of this study (2001–03; Fig 2). In the years after our study (2004–17), the location of the high-density calving area was more variable, shifting west toward the Meltwater and Tarn Roads during some years, but calving densities remained relatively low in the area adjacent to the roads (Fig. 2). We do not have data on traffic levels after 2003 but, because the wells on the Tarn and Meltwater pads were in production, traffic levels likely were low during most of those years.

During aerial surveys of the Tarn and Meltwater areas in 2001–03, the density of caribou, the number of groups, and the percentage of calves generally increased from precalving to calving to postcalving (Figs. 5, 6; Table 4). Densities were higher in 2002, the year of early snowmelt, than in the other 2 years (Figs. 5, 6). As expected, an increasing west-to-east gradient in densities of calves and total caribou was noted during both calving and postcalving. The density of calves and the proportion of calves declined in the vicinity of both roads during calving, but a large decrease was not apparent during postcalving (Fig. 6).

The number of caribou groups observed on aerial surveys during different periods ranged from 19 to 834 for the years 2001–03 (Table 4). Results of the *k*-fold cross-validation test indicated that the best RSF models had moderate to high predictive power (Pearson's $r = 0.35–0.92$; Supplemental Table S4) for most year, period, and group type combinations. When analyzing data from all three years combined, all values of Pearson's r were 0.71 or higher.

The IDW variable representing the preconstruction distribution had a 100% probability of being in the best model and had a positive coefficient in all models, suggesting that caribou had broadly similar distributions in the study area during 2001–03 compared with 1993 and 1995–97 (Tables 5, 6). The IDW map indicated that the caribou distribution was broadly similar in 2001–03, but calving density east of the roads appeared to change somewhat more abruptly near the road corridor after construction of the Meltwater Road (Fig. 2). Substantial numbers of caribou also used the area northwest of the Tarn Road in 2001–03.

Distance to roads had a 100% probability of being in the best model for all combinations of periods and group types, with the exception of the precalving period for all groups (Table 5). The other variables had a high probability of being in the best model during some period and group-type combinations (Table 5). Caribou groups were more likely to be closer to the coast and in higher elevations during calving (Table 6). High terrain ruggedness was selected by groups with calves during postcalving but was avoided during calving. The 95% confidence intervals for landcover

TABLE 2. Counts of caribou groups, total number of caribou, number of calves, and mean distance of caribou groups from roads observed during road surveys of the Tarn and Meltwater Roads, Kuparuk oilfield, Alaska, 2001–03.

Area	Year	Period	Surveys	Groups	Total	Calves	% Calves	Mean distance (m)
Tarn	2001	Precalving	4	0	0	0	–	–
	2002	Precalving	4	25	142	0	0	386
	2003	Precalving	11	54	340	0	0	295
	All Years	Precalving	19	79	482	0	0	324
	2001	Calving	6	1	2	0	0	–
	2002	Calving	19	151	783	68	8.7	389
	2003	Calving	20	105	455	46	10.1	324
	All Years	Calving	45	257	1240	114	9.2	364
	2001	Postcalving	0	–	–	–	–	
	2002	Postcalving	13	106	2047	247	12.1	358
	2003	Postcalving	25	302	4039	1135	28.1	290
	All Years	Postcalving	38	408	6086	1382	22.7	307
	Total		102	744	7808	1496	19.2	329
Meltwater	2001	Precalving	14	0	0	0	–	–
	2002	Precalving	4	13	34	0	0	285
	2003	Precalving	8	90	753	0	0	259
	All Years	Precalving	26	103	787	0	0	262
	2001	Calving	14	3	22	0	0	633
	2002	Calving	15	133	475	3	0.6	364
	2003	Calving	11	40	160	0	0	443
	All Years	Calving	40	176	657	3	0.5	387
	2001	Postcalving	0	–	–	–	–	
	2002	Postcalving	17	140	2727	270	9.9	342
	2003	Postcalving	26	185	2086	444	21.3	313
	All Years	Postcalving	43	325	4813	714	14.8	323
	Total		109	604	6257	717	11.5	333

classes included zero, but the wettest classes (aquatic sedge and wet sedge) and the riparian class tended to be avoided by all groups (Table 6).

During calving, the area within 2 km of the Tarn Road (relative to areas > 4 km from roads) was avoided by groups with calves and by all groups combined and the area within 2 km of the Meltwater Road was avoided by groups with calves (Table 6). Additionally, the area within 2–4 km of the Tarn Road was avoided by groups with calves during calving. The areas within 4 km of the Tarn Road and 2–4 km of the Meltwater Road were selected by groups with calves during postcalving.

The results from analyses of individual years also generally showed higher avoidance of areas within 2 km of the Meltwater Road and within 4 km of the Tarn Road by groups with calves during calving, and increased use of the area 2–4 km from the roads during postcalving (Supplemental Table S8). Avoidance of the area within 2–4 km of the Tarn Road during calving tended to be greater than within 2–4 km of the Meltwater Road during calving in all years. Avoidance of the area within 4 km of the Meltwater Road by groups with calves was higher during 2002, when traffic levels were highest, than during 2001 or 2003 (Supplemental Table S8).

We did not find any evidence of substantial avoidance of the inactive elevated drilling platform during 2003, based on examination of caribou group locations from aerial surveys (Fig. 5). The highest densities of caribou were found east of the platform, but caribou did not avoid the area near the platform. A total of 21 caribou, including two calves, were recorded in a circular area within a 2 km radius from the platform during the calving period (9.5% calves, 0.11 calves/km², 1.12 caribou/km²), compared with 123 calves and 669 total caribou (18.4% calves, 0.31 calves/km², 1.81 caribou/km²) in a larger radius of 2–8 km from the platform. The difference in calf proportions between the two areas was not significant ($p = 0.398$; Fisher's Exact Test). The closest cow/calf pair we observed was within 1 km of the platform on 10 June (~600 m). The RSF analysis for 2003 supported this conclusion; the distance-to-platform variable had a low probability of being in the best model during calving (0.15 and 0.13 for all groups and calf groups respectively) and the coefficients for the distance-to-platform variables were close to zero. The distance-to-platform variables had a 0.50 probability of being in the best model for precalving for all groups and a 0.83 probability for postcalving for calf groups (Supplemental Tables S5, S6), but the 95% confidence intervals for those variables included zero (Supplemental Tables S7, S8).

TABLE 3. Model-weighted parameter estimates, standard errors, and the probability that the variable or interaction was included in the top model (sum Akaike weight) for models of the probability of a moderate or strong reaction to traffic along the Tarn and Meltwater Roads, Kuparuk oilfield, Alaska, 2001–03. Coefficients in bold type indicate the 95% confidence interval does not contain zero.

Variable	Coefficient	SE	Sum Akaike Weight
Intercept	**0.68**	**0.24**	**1.00**
Area (Tarn)[1]	**−1.52**	**0.35**	**1.00**
101–250 m[2]	**−1.33**	**0.31**	**1.00**
251–500 m	**−1.95**	**0.32**	**1.00**
501–1000 m	**−2.77**	**0.30**	**1.00**
Calves present	**1.03**	**0.20**	**1.00**
Period(postcalving)[3]	**−0.62**	**0.25**	**1.00**
Period(precalving)	**−1.02**	**0.30**	**1.00**
Area(Tarn)*101–250 m	0.78	0.50	0.81
Area(Tarn)*251–500 m	0.71	0.52	0.81
Area(Tarn)*501–1000 m	0.14	0.49	0.81
Area(Tarn)*Period(postcalving)	−0.25	0.36	0.43
Area(Tarn)*Period(precalving)	−0.02	0.38	0.43
101–250 m*Period(postcalving)	< 0.01	0.03	0.01
101–250 m*Period(precalving)	< 0.01	0.05	0.01
251–500 m*Period(postcalving)	< 0.01	0.04	0.01
251–500 m*Period(precalving)	< 0.01	0.07	0.01
501–1000 m*Period(postcalving)	< 0.01	0.04	0.01
501–1000 m*Period(precalving)	0.01	0.10	0.01

[1] Area was compared with the Meltwater area.
[2] Distance zones were compared with the 0–100 m category.
[3] Periods were compared with the calving period.

DISCUSSION

The results of road surveys indicated that caribou reacted more strongly to traffic in an area with traffic convoying, possibly as a result of differences in traffic frequency. Caribou near the Meltwater Road had less frequent exposure to vehicles and were more likely to exhibit moderate or strong behavioral reactions. It is also possible that large traffic convoys were more disturbing than individual vehicles. Caribou with a low tolerance to disturbance may have avoided areas near the Tarn Road, whereas animals that were sensitive to traffic may have moved closer to the Meltwater Road during long periods without traffic.

Behavioral reactions were stronger closer to roads and declined considerably at greater distances. Similar to previous studies (Stankowich, 2008), we found that groups with calves were more reactive to traffic. Caribou were also more reactive during calving than during the other two periods analyzed. Previous studies have reported that the largest impact of roads on caribou distribution and movements occurred during that period (Johnson et al., 2020; Prichard et al., 2020a).

Previous studies have found that caribou can be delayed in crossing roads by high rates of traffic (Leblond et al., 2013; Panzacchi et al., 2013). Curatolo and Murphy (1986) found that traffic rates of more than 15 vehicles/h (360 vehicles/d) reduced crossing rates for CAH caribou when pipelines were closely adjacent to roads. Although our daily

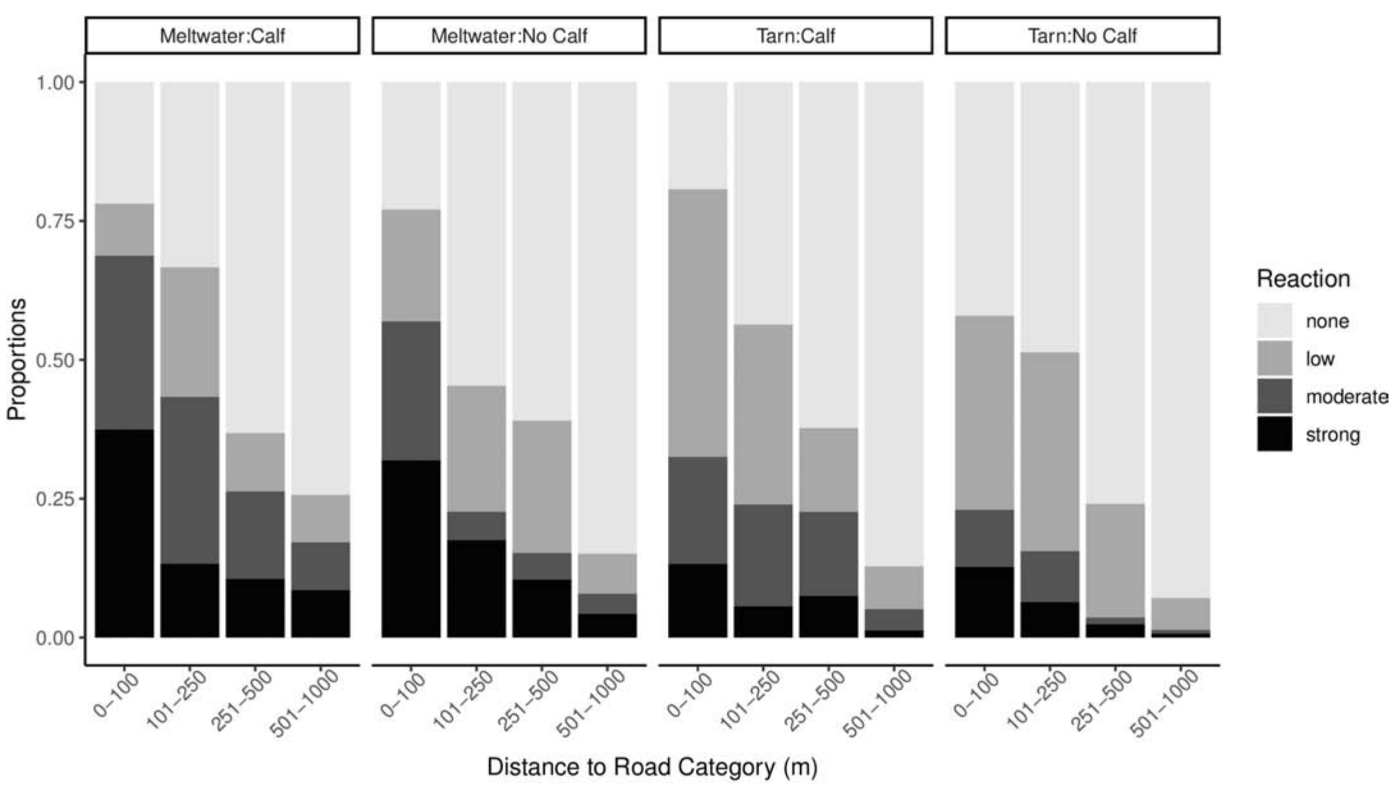

FIG. 4. Rates of different reactions to traffic by caribou observed within 1 km of the Tarn or Meltwater Roads recorded during road surveys conducted 25 May–30 June 2001–03.

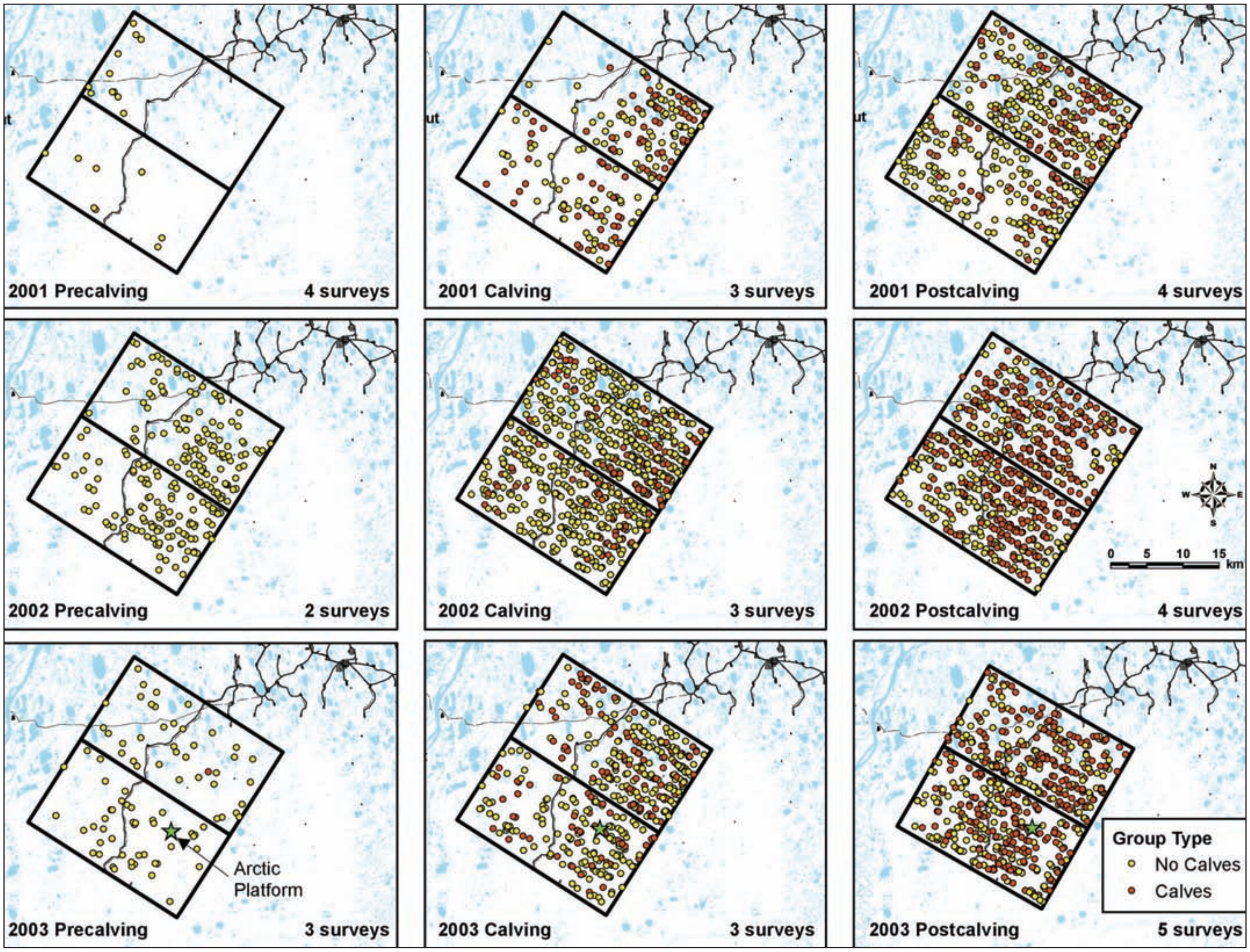

FIG. 5. Locations of caribou groups observed during aerial surveys conducted during the precalving, calving, and postcalving periods in the Tarn and Meltwater survey areas in northern Alaska, 2001–03.

TABLE 4. Number of caribou groups, number of caribou, and percentage of calves observed during aerial surveys in the Tarn and Meltwater survey areas, Kuparuk oilfield, Alaska, 2001–03.

Year	Period	Survey dates	Number of groups	Number of animals	% Calves
2001	Precalving	May 17, 21, 24, 28	19	69	0
2002	Precalving	May 15, 24	229	661	0
2003	Precalving	May 19, 24, 28	82	216	0.5
2001	Calving	June 4, 8, 13	211	1075	17.3
2002	Calving	May 30–31, June 5–6, 9	766	3607	11.9
2003	Calving	June 2, 6–7, 10	442	1295	19.5
2001	Postcalving	June 16, 20, 24, 28	459	3724	21.7
2002	Postcalving	June 13, 18, 22, 26	679	7349	24.8
2003	Postcalving	June 14, 17, 21, 25, 29	834	6206	30.3

traffic rates were lower than this level (Table 1), traffic rates likely exceeded 15 vehicles/h during some short periods along the Tarn Road.

Similar to previous studies, the results of our aerial surveys demonstrated that maternal caribou generally avoided areas within 2–4 km of active roads and pads (Dau and Cameron, 1986; Cameron et al., 1992; Johnson et al., 2020; Prichard et al., 2020a). Analysis of our data was complicated by the presence of a pre-existing gradient of caribou density in the study area. The fact that our study area was on the periphery of the CAH calving area lowered our power to detect calving displacement, but our results did show mixed support for the hypothesis that traffic convoying decreases the disturbance and

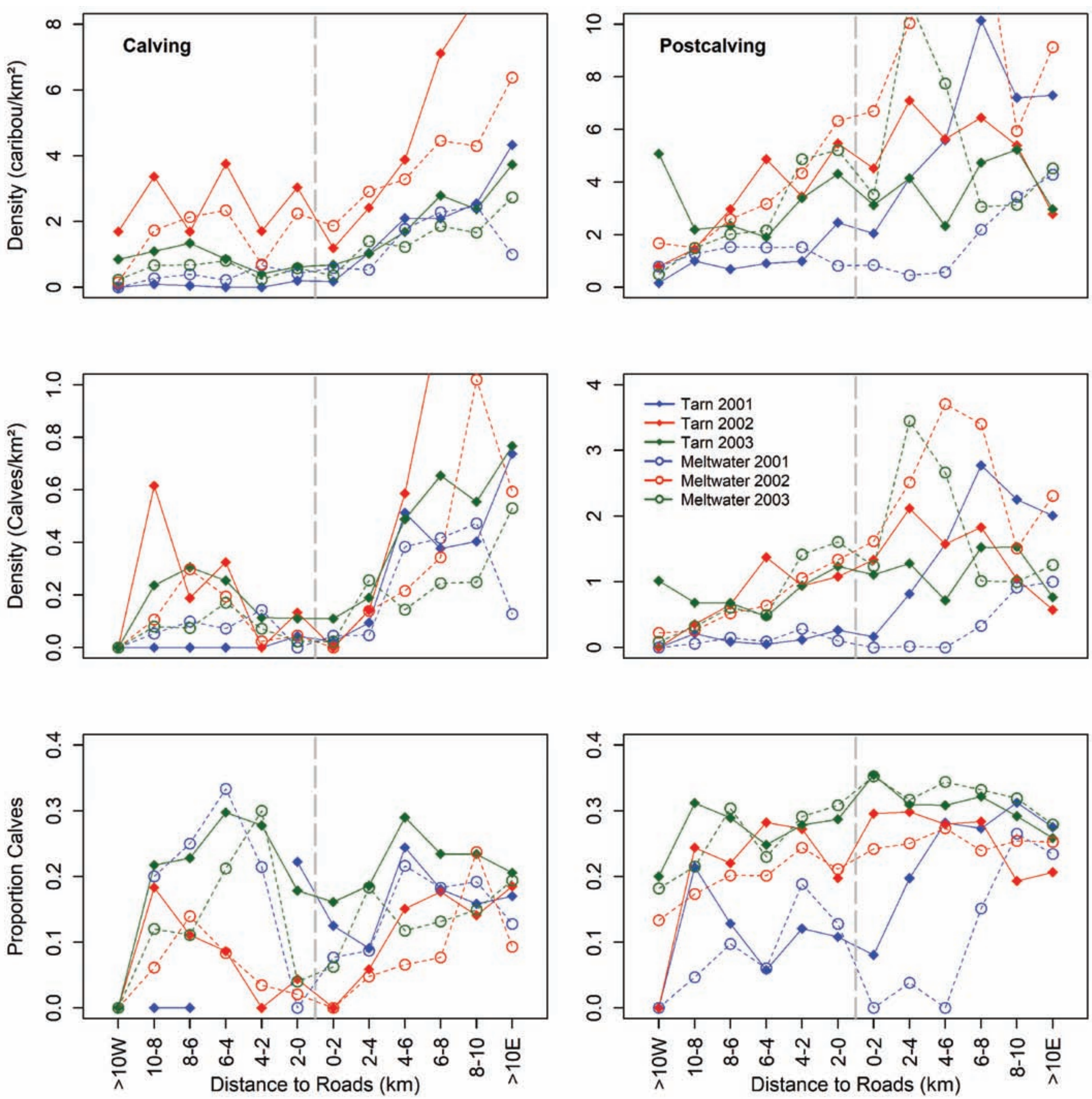

FIG. 6. Estimated densities of total caribou (top row), estimated density of calves (middle row), and estimated proportion of calves (bottom row) observed during aerial surveys conducted along the Tarn and Meltwater Roads during the calving (left column) and postcalving (right column) periods, 2001–03.

displacement of maternal caribou during calving. RSF models indicated that avoidance of the Tarn Road by groups with calves extended at least 4 km from the road, whereas avoidance of the Meltwater Road appeared to extend about 2 km from the road. Some avoidance of the Meltwater Road during calving occurred even at low traffic levels, and caribou near that road showed stronger reactions to traffic than did caribou near the Tarn Road. Few calves were observed within 1 km of either road during road surveys conducted during calving. Despite the avoidance by groups of caribou with calves during the calving period, roads did not appear to strongly influence caribou distribution during pre- and postcalving. Caribou groups without calves also exhibited less avoidance of roads. We did not find evidence that calving caribou avoided a large inactive elevated drilling platform located in an area of moderate calving density in 2003.

Our finding that levels of displacement declined with lower human activity levels is consistent with multiple studies that have reported that caribou responses vary according to the level of human activity. Reindeer used areas near hiking trails more at night and when traffic was

TABLE 5. Independent variables and their probability of being in the best Resource Selection Function model (i.e., the sum of all Akaike weights for all models that included the variable) of locations of all caribou groups and caribou groups with calves observed during aerial surveys, in the Kuparuk oilfield, Alaska, 2001–03.

	All groups			Calf groups	
Variable	Precalving	Calving	Postcalving	Calving	Postcalving
Dist. coast	0.51	1.00	0.31	1.00	0.41
Elevation	0.39	1.00	0.30	1.00	0.32
Previous distribution (IDW)	1.00	1.00	1.00	1.00	1.00
Ruggedness	0.74	0.89	0.90	1.00	0.96
Dist. roads	0.08	1.00	1.00	1.00	1.00
Landcover	0.96	0.97	1.00	0.02	0.52

TABLE 6. Model-weighted parameter estimates for Resource Selection Function models of caribou groups observed during aerial surveys conducted during three periods in the Kuparuk oilfield, Alaska, 2001–03. Coefficients in bold type indicate the 95% confidence interval does not include zero.

	All groups			Calf groups	
Variable	Precalving	Calving	Postcalving	Calving	Postcalving
Dist. coast	−0.06	**−0.38**	0.01	**−0.63**	−0.03
Elevation	−0.03	**0.30**	−0.01	**0.48**	0.01
Previous distribution (IDW)	**0.29**	**0.23**	**0.11**	**0.32**	**0.21**
Ruggedness	0.08	−0.06	0.05	**−0.23**	**0.08**
Dist. Meltwater (0–2 km)[1]	0.02	−0.20	0.20	**−1.76**	0.18
Dist. Tarn (0–2 km)[1]	0.00	**−0.62**	**0.30**	**−1.51**	**0.26**
Dist. Meltwater (2–4 km)[1]	0.03	0.00	0.28	0.05	**0.51**
Dist. Tarn (2–4 km)[1]	0.00	−0.26	0.26	**−1.16**	**0.41**
Aquatic sedge[2]	−0.62	−0.64	−0.24	0.00	−0.13
Dwarf shrub–*Dryas*[2]	0.47	0.02	0.18	0.00	−0.06
Mesic herbaceous[2]	−0.02	−0.32	0.09	−0.01	0.04
Riparian/Other[2]	−0.63	−0.14	−0.55	−0.01	−0.30
Wet sedge[2]	−0.81	−0.25	−0.33	0.00	−0.15

[1] Distance to roads compared with reference category of areas over 4 km from either road.
[2] Landcover classes were compared with the reference class "Sedge–Shrub Tundra."

low (Skarin, 2006). Similarly, caribou of the CAH were closer to oilfield roads at night, when traffic rates were lower than during the workday (Haskell et al., 2006). Eftestøl et al. (2019) found that reindeer avoided the area around a mine more on days when the mine was active than on holidays. Calving reindeer avoided areas near wind turbines, and the displacement was more pronounced during operation of the wind turbines than during construction, but the turbines produced noise and the movement of the turbines was visible far away (Skarin et al., 2018). Hunting from roads also may increase displacement (Ciuti et al., 2012; Paton et al., 2017; Plante et al., 2018).

The reported zones of influence of roads and development on caribou and reindeer distributions have varied widely in different studies. Research on caribou distribution near large open-pit diamond mines (~40 km² total footprint and extensive dust deposition) in northern Canada reported a zone of influence, based on the pattern of caribou density with distance to the mines, varying annually from 6.1 to 18.7 km (Boulanger et al., 2012, 2021). A study of the Porcupine herd in winter reported zones of influence around main roads of 30 km during early years (1985–98) and 18.5 km during late years (1999–2012). The zones of influence for wells, trails, winter roads, and seismic lines were reported to be 11 km and 6 km for the same time periods (Johnson and Russell, 2014). Plante et al. (2018) examined caribou distribution near roads, mines, and human settlements and reported that zones of influence ranged from 0 to 23 km, subject to wide annual variation.

Avoidance of infrastructure in our study area appears to be more spatially and temporally limited. Johnson et al. (2020) reported a decline in use of areas by collared females of the CAH within 5 km, 2 km, and 1 km of infrastructure during the calving, postcalving, and mosquito season, respectively. This range of distances is similar to that reported in a review of regional studies of caribou and reindeer (Vistnes and Nellemann, 2008). Prichard et al. (2020a) also reported partial avoidance of areas near roads and pads during calving but, similar to the current study, found little evidence of avoidance during postcalving. Caribou crossed roads and pads frequently during midsummer and some selected gravel roads and pads during periods of oestrid-fly harassment (Prichard et al., 2020a).

Caribou distribution and reaction to oilfield infrastructure in northern Alaska vary widely by time of year (Murphy and Lawhead, 2000; Haskell and Ballard, 2008; Prichard et al., 2020a) but are likely influenced by snowmelt, forage quality, access to mosquito-relief habitat, and perceived predation threat. The avoidance of areas of human activity and vehicle traffic during the calving period is likely an anti-predator response by parturient caribou at a time when cows and newborn calves are highly susceptible to predation (Bergerud and Page, 1987; Frid and Dill, 2002). Movement by vehicles and humans is likely to trigger an anti-predator response, but the lack of avoidance of an inactive elevated drilling platform and the indications of lower levels of avoidance of the Meltwater Road suggest that this response does not occur near infrastructure in the absence of movement or human activity.

The perceived threat of predation can have a strong effect on caribou behavior and distribution during calving (Bergerud and Page, 1987). Use of the Arctic Coastal Plain for calving by Alaska herds has been postulated as a predator avoidance response (Fancy and Whitten, 1991). Parturient cows from the small Mentasta herd in interior Alaska disperse to high-elevation sites with lower predation risk despite lower forage quality in those areas, while nonparturient cows and cows that lost their calves used lower elevation areas (Barten et al., 2001). Caribou groups without calves exhibited less avoidance of roads than did groups with calves in our study. In 2002, when snowmelt occurred early and caribou densities were high in our survey area, groups with calves exhibited apparent avoidance of areas near roads during the calving period, but numerous groups without calves occurred near the roads (Figs. 5, 6).

Similar to other recent research (Johnson et al., 2020; Prichard et al., 2020a), avoidance of roads appeared to decrease after the calving period when calves were more mobile, which presumably corresponds to a lower perceived threat of predation. Barten et al. (2001) reported that parturient caribou left remote calving sites when their calves were about 10 days old. Adams et al. (1995) reported that 85% of neonatal mortality in a caribou herd in central Alaska occurred within 8 days of birth, indicating that the risk of calf predation declined soon after calving in that herd. Similarly, the higher vulnerability of newborn calves to predation could cause cows to avoid roads with moving vehicles. Unlike Johnson et al. (2020) and Prichard et al. (2020a), our analyses included bull caribou, which typically arrive in the study area during the postcalving period.

Haskell et al. (2006) and Haskell and Ballard (2008) also conducted road surveys of areas within 1 km of roads in the Kuparuk oilfield (excluding the Meltwater Road) in 2000–02, predominantly during our postcalving period (≥ 11 June). Based on their results showing declining distance from roads by date and use of areas near roads occurring later in years of late snowmelt, they hypothesized that caribou rehabituate to oilfield development each year. We found that some caribou used areas along the roads during precalving but apparently moved away during calving and that caribou groups without calves exhibited lower levels of road avoidance than did groups with calves. These results suggest that caribou avoid roads primarily when calves are being born or have limited mobility. Regardless of when caribou arrive in the area during the spring, the western segment of the CAH has to move through the oilfields to reach coastal mosquito-relief habitat as soon as mosquito harassment begins, which has occurred as early as 16 June in recent years (Prichard et al., 2020a).

The distributional shift of maternal females away from roads during calving may also be influenced by the increasing availability of new forage as snowmelt progresses away from the "dust shadow" along roads (Lawhead, 1988). An area of early snowmelt along the roads occurred during the convoy period in 2001, when overall snowmelt was delayed by cold spring weather, and to a lesser extent in 2003 when the timing of snowmelt was near average. In contrast, snow cover in 2002 was mostly gone before the convoy period, so no dust shadow was observed during the convoy period. Caribou in northern Alaska tend to calve farther north in years of early snowmelt (Noel et al., 2004; Carroll et al., 2005; Lenart, 2015), and annual caribou densities in our study fit that pattern, with the highest densities occurring in 2002. Peak calving occurred on 9–10 June in 2001 and about 5–6 June in 2002 and 2003, so peak calving also occurred later in the year of late snowmelt (Arthur and Del Vecchio, 2009).

Based on our aerial surveys, we found that caribou groups used areas of higher elevation during calving, and groups with calves used areas with lower terrain ruggedness during calving. Using similar methods to this study, Prichard et al. (2020a) found no selection for terrain ruggedness during calving, but Nellemann and Cameron (1996) found that caribou selected areas with high terrain ruggedness during calving in an area to the northeast of our study area. The calving distribution in our study was farther inland in an area with higher overall terrain ruggedness, so it is possible that caribou in this context were selecting for intermediate levels of ruggedness. Alternatively, the difference could be due to different scales of selection, as Nellemann and Cameron (1996) calculated terrain ruggedness over large (10.25 km^2) quadrats. Landcover was not a strong predictor of caribou locations, possibly due to the imprecise nature of our locations. Caribou groups tended to avoid wetter landcover types, as was reported by Prichard et al. (2020a).

The potential effects of displacing some maternal caribou from preferred calving areas depend on the availability and quality of alternative calving areas. If caribou are displaced to areas with lower forage quality or higher predator densities, displacement could result in lower calf survival or lower future productivity for cows (Griffith et al., 2002; NRC, 2003; Cameron et al., 2005). The cumulative effects of multiple roads within calving areas potentially could increase calving densities and thus decrease forage availability in alternative areas.

Caribou are known to alter calving distribution depending on the timing of snowmelt and forage growth

(Griffith et al., 2002; Noel et al., 2004; Carroll et al., 2005); therefore, the impacts of displacement may vary by year. Some demographic impacts on the CAH from the gradual shift in the high-density calving distribution to the area south of the oilfields and summer exposure to infrastructure have been postulated based on comparisons between the western and eastern calving segments of the herd (NRC, 2003; Cameron et al., 2005; Arthur and Del Vecchio, 2009), but the herd increased in size until 2010, suggesting that either suitable alternative calving habitat existed or the demographic effects of this shift in calving distribution were not strong enough to halt herd growth.

In recent years, oil development has continued west of the Colville River into the range of the Teshekpuk herd (BLM, 2020), and oil and gas leases have been sold on the coastal plain of the Arctic National Wildlife Refuge (ANWR) in northeastern Alaska (BLM, 2019) within the calving range of the Porcupine herd. Expansion of the areas of caribou range potentially affected by petroleum development heightens the need to understand the impacts of different types of development and the effectiveness of mitigation strategies. Our results indicate that, although the degree of displacement of maternal caribou may be lowered somewhat with traffic convoying, some behavioral disturbance and displacement of maternal caribou during calving still occur with convoying of traffic and low traffic frequency. Convoying may reduce the amount of displacement during periods between convoys, which could improve crossing success. The avoidance of roads was largely limited to caribou groups with calves during the calving period and was not apparent during the precalving or postcalving periods. The limited impact of an inactive elevated drilling platform on calving distribution also suggests that the presence of inactive infrastructure alone does not strongly affect calving distribution, but because this platform was only present in one year, this finding should be reassessed with additional study.

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