Photo: Arctic Canadian Diamond Company Ltd.

Influence of the Ekati Diamond Mine on migratory tundra caribou movements

Prepared for:

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PUBLIC WATCHDOG OF EKATI DIAMOND MINE

Plain Language Summary

Note: this summary can be paired with figures from the body of the report.

Little research has focused on how caribou respond to mines, roads and industrial activity close to mining development and whether rules in place to reduce disturbance to caribou are effective. We began to answer these questions by examining the pathways of individual collared caribou as they approach mine sites. We examined radio-collar data from the Bathurst and Beverly/Ahiak herds around Arctic Canadian Diamond Company Ltd.'s Ekati Diamond Mine (hereafter, Ekati mine) in the NWT from 2010-19. We described annual and seasonal patterns of herd movements near the Ekati mine, and described individual pathways from 232 cow caribou as they encountered and responded to the mine.

During the 2010s, the Ekati mine was on the southern edge of summer range and relatively centrally located in fall range (Fig. 6). Winter range had the greatest annual shifts, with the middle of winter range shifting from southwest to northeast closer to the Ekati mine. Caribou were generally not common around the Ekati mine during winters 2010-16, but were more common during winters 2017-19 because of shifts in Bathurst herd winter range and expansion of the fall and winter range of the Beverly/Ahiak herd. The proportion of Bathurst cow caribou seasonal ranges within 30 km of Ekati infrastructure annually varied, reaching as high as 17–29% during winter, summer and fall.

Changes in seasonal distribution influenced the amount of time caribou spent near the Ekati mine. As expected, caribou did not spend much time near the mine during spring migration when the cows were moving to the calving grounds (Figs. 8 and 9). Highest time spent within 30 km of the mine occurred during summer, fall and winter, with no caribou present during calving and post-calving.

In most year-seasons when caribou were present within 30 km of the mine, caribou spent more time closer to mine infrastructure, declining as distance increased (Fig. 7). Both the sharper turns and slower speeds contributed to why caribou spent more time closer to the mine, especially the roads. Speed (km/h) of caribou movement varied broadly among seasons, being lowest during winter and highest during spring migration and summer (Fig. 10). Speed of movement was generally lowest within 3 km and sometimes within 6 km of the mine and roads (Fig. 14). During fall caribou made more sharp turns closer to the mine, especially when they did not cross the mine or roads, and fewer sharp turns at 21–30 km from the mine (Fig. 15). The pattern was less clear during winter, but still showed more sharp turns close to the mine.

We examined 155 pathways where collared caribou came within 3 km of the mine and major roads. Caribou were delayed on their movements on over half (88/155) of these encounters, and of these, over three-quarters (83%; 73/88) did not cross the mine and its roads (Table 7). Of the 55 caribou which approached but did not cross roads, the mean closest distance to the road was 1,111 m. Only 16% of these non-crossing caribou approached to within 100 m of roads, and for 44% the closest approach was to within 500–2,000 m of roads (Fig. 12). Caribou delayed on average 1.5 days when they eventually crossed the mine/roads and 4.5 days when they did not eventually cross the mine/roads (Fig. 13). The rate of crossing either through the mine site or across the roads was low (25%; 38/155).

Collars that took a location every hour as opposed to less frequently showed more details on the caribou pathways, including showing closer approaches to the mine and faster movements. We were unable to verify whether collared caribou used the crossing ramps built specially to better enable caribou to move across the roads.

Based on similar observations at the Meadowbank mine in Nunavut, we suspect caribou delayed their movements within 3 km of the Ekati mine in part as a response to traffic. More detailed traffic data were not available but in some years an ore haul truck would pass a point on the Misery Road every 13 minutes.

We detected average delays of 4–5 days and low road crossing rates by collared caribou despite the current mines plans, which suggests that better plans to help caribou cross the mine and roads are needed. A key question is whether the delays represent caribou which are used to mine disturbance or the caribou are waiting for a predictable gap in traffic so they can cross the road (assuming that they are motivated to cross the road). It is likely that caribou would cross in the absence of disturbance and the delays are the consequence of caribou waiting to cross. Hourly traffic data are needed to examine this question more carefully.

Our study suggests that the current mine plans to help caribou move through the area are not working well, and that changes to these plans are needed. There is a need to look at collared caribou movement paths along with hourly traffic data to better determine how traffic affects collared caribou movements; hourly collars locations would be very useful. There is also a need to examine collared caribou pathways together with different kinds of monitoring, such as cameras and road surveys, to understand what caribou may or may not be crossing through the mine.

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Introduction

Without clearly understanding how barren-ground caribou (*Rangifer tarandus groenlandicus*) respond to industrial development, we struggle to ensure that mitigation of effects of industrial development on caribou is effective. These concerns are part of a more widespread failure to ensure effective mitigation of the effects of industrial development on caribou in Canada (Collard et al. 2020). Specifically, questions about the effectiveness of mitigation came up during the recent environmental assessment for the proposed Jay Pit expansion of the Arctic Canadian Diamond Company Ltd. (Arctic Diamond) Ekati Diamond Mine (hereafter, Ekati mine) in the NWT (MVEIRB 2016). These concerns led to development of a Caribou Road Mitigation Plan (CRMP) which was applied to all roads at the Ekati mine beginning in mid-2016 (Golder Associates 2017). The CRMP is a three-level hierarchy of an increasing level of road and traffic management relative to thresholds of an increasing caribou presence. The thresholds include numbers of collared caribou within specific distances of the mine and numbers of caribou observed in the vicinity of roads. For this approach to be effective, we need to better understand how caribou behave around the mine site and its roads.

The effectiveness of mitigation can be evaluated through monitoring caribou behavior and movements. Despite on-going mitigation of effects at Ekati, there is a threshold distance around the mine where in most years monitoring using aerial surveys or caribou fitted with satellite or GPS collars has detected a 'zone of influence' (ZOI) where disturbance diminishes habitat selection (Boulanger et al. 2012, 2021). The ZOI around the combined Ekati and adjacent Diavik diamond mines from 2003 to 2017 was detected once both mines were in operation (2003), varied annually in extent at 6–19 km, and was statistically significant in 9 of 15 years (Boulanger et al. 2021).

While the ZOI measures overall change in caribou habitat selection relative to distance from the mine, it is not a zone of avoidance as caribou are found in proximity to the mine. Methods to monitor caribou presence and behavior close to the mine site have changed over the years (Dominion Diamond Mines 2020a). Snow track surveys along the main Misery Road during 2002 to 2010 (Rescan 2011) were replaced in 2011 by cameras (ERM 2014) mostly along the Misery and (after 2017) Sable roads as well as the mine site. Vehicle road surveys were added in 2016 (Golder Associates 2017, Dominion Diamond Mines 2020a). The road surveys reveal a relatively high number of caribou sightings from the roads. For, example in 2020, Arctic Diamond recorded 141 observations involving 5,604 caribou along all roads at site (Arctic Canadian Diamond Company Ltd 2021b.).

Changes in methods to monitor caribou and the methods themselves restrict understanding of how caribou are responding to the mine and whether mitigation is effective. Questions remain as to whether individual caribou delay or avoid passage, or readily cross roads and move through the mine site. Answering those questions is possible through examining the pathways of individual collared caribou as their sequence of movement and duration of encounters with the mine site are measurable.

Our goal was to describe movement patterns of collared cow caribou and explore mitigation effectiveness for caribou from the Bathurst and Beverly/Ahiak herds around the Ekati mine in the NWT from 2010–19. [Note that we use the term 'Beverly/Ahiak' to describe the caribou herd calving in the Queen Maud Gulf area (for further discussion on the history of caribou in this area see Nagy et al. 2011, Campbell et al. 2012, and Adamczewski et al. 2015). During 2010-2019, the frequency, accuracy and sample size of monitoring increased with the transition from satellite collars to GPS collars and deployment of greater numbers of collars. In addition, many of the collars deployed in the latter half of the 2010s were 'geofence' collars which increase fix rates within a programmed distance of industrial development. We first considered the collared caribou overall exposure to the Ekati mine at the annual and seasonal scales. We then examined individual pathways of the collared caribou to characterize how they encountered the mine site:

Our objectives were:

1) Describe annual and seasonal exposure of caribou within 30 km of the Ekati mine site;
2) Estimate individual caribou encounters with and responses to the Ekati mine site;
3) Determine how the individual caribou pathways relate to the effectiveness of monitoring and mitigation of potential impacts to caribou from mining activity.

Study Area

The study area is in the central barrens about 100 km north of tree line and lies within the Southern Arctic ecozone (Ecological Stratification Working Group 1996). The landscape is typical of the Pre-Cambrian Shield with rock barrens, numerous lakes and many glacial features including esker complexes and boulder moraines. Shrub communities of willow (*Salix* spp.), shrub birch (*Betula* spp.), and Labrador tea (*Ledum decumbens*) dominate areas with adequate soil development. Mats of lichens, mosses, and low shrubs are found across exposed rocky and gravel sites.

The Ekati mine (Fig. 1) is an operational open pit and underground mine with the number of active pits varying over time. The Ekati mine was constructed in the mid-1990s with production commencing in 1998. The main site, which lies 15 km north of Lac de Gras, has accommodation complexes, ore-processing buildings and an airstrip. A separate Misery camp and open pit is located near the northeast shore of Lac de Gras and is connected by the all-weather Misery road to the main site. The Misery camp and pit are about 7 km from the Diavik diamond mine, a second operational diamond mine in the area. Diavik mine's footprint is restricted to an island on the north side of Lac de Gras with a footprint of 12 km^2 compared to 38 km^2 for Ekati mine site (2019 figure) which includes extensive roads (totalling 141 km in 2018).

The mine's footprint increased slowly between 2012 and 2018. Lynx Pit, a small pit located about 3 km southwest of the Misery Pit, was under development and production from late 2015 to mid-2019 and the ore was trucked along the 29 km Misery road to the main site. Construction of the Sable haul road was completed in 2016, with pre-stripping of the Sable Pit in 2017 and 2018, and ore production trucking to the main site starting in October 2018. The Jay road northeast of Misery was constructed in 2017 but has had limited subsequent traffic due to re-evaluation of the project.

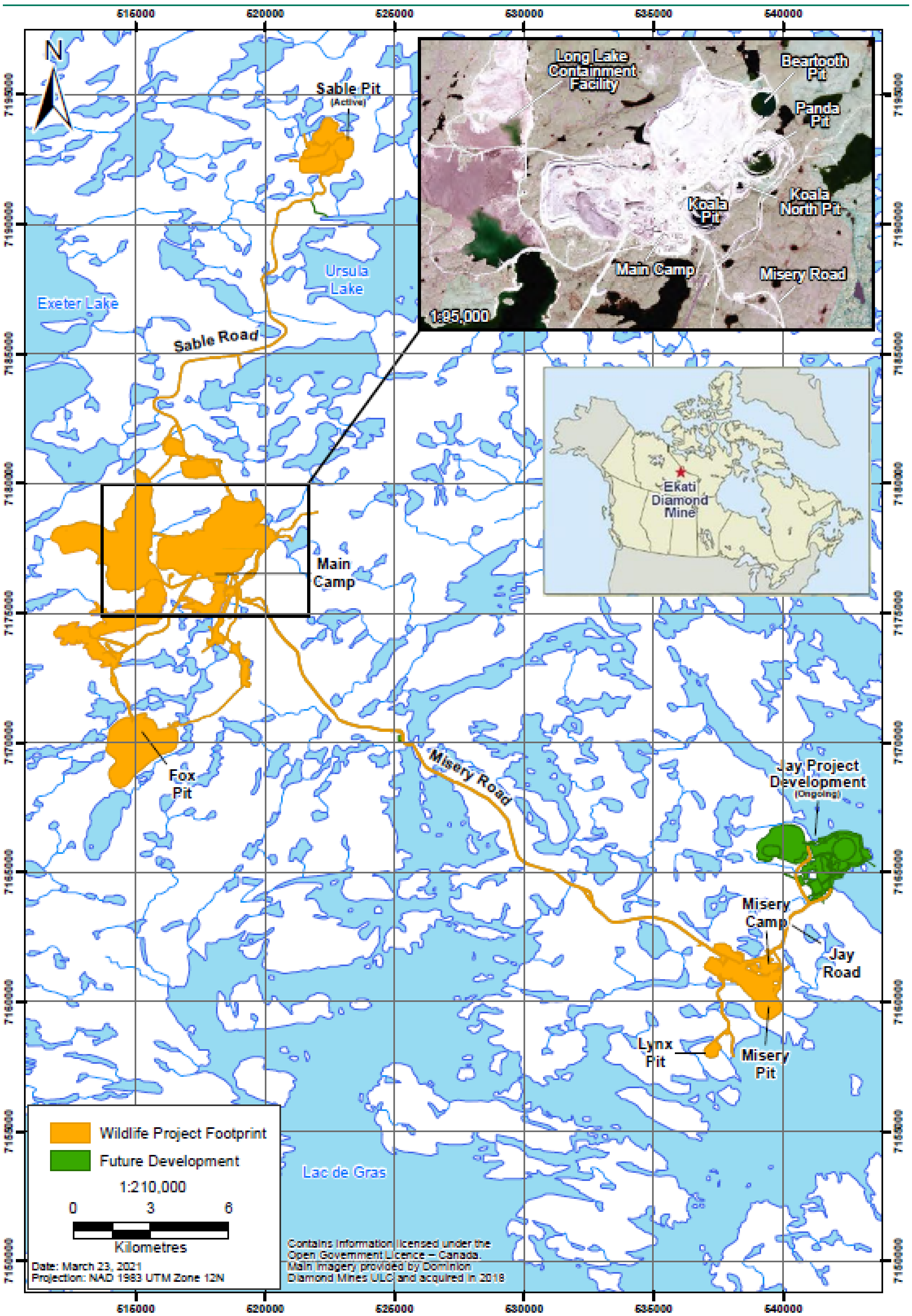


Figure 1. Ekati Diamond Mine site map (Arctic Canadian Diamond Company Ltd. 2021b).

The Ekati mine is immediately north of Lac de Gras and between other large lakes. During summer to early winter, narrow 'bridges' of land (called 'tata' in Tłįchǫ terminology) between large lakes tend to funnel caribou movements (Tłįchǫ Research and Training Institute 2013). Ekati mine lies at the intersection of three main tata (Fig. 2). One tata is between the pair of large lakes (Ursula and Exeter lakes) and funnels caribou toward the Sable area and the road connecting the current Sable Pit to the main Ekati site. A second major tata is formed by Lac du Sauvage and Ursula Lake and funnels caribou toward the Misery Road and Ekati site. The third tata follows the narrows between Lac de Gras and Lac du Sauvage, known as a traditional caribou crossing site, and funnels caribou toward the Misery pit and proposed Jay pit (DDEC 2014:Section 2.2.2.1).

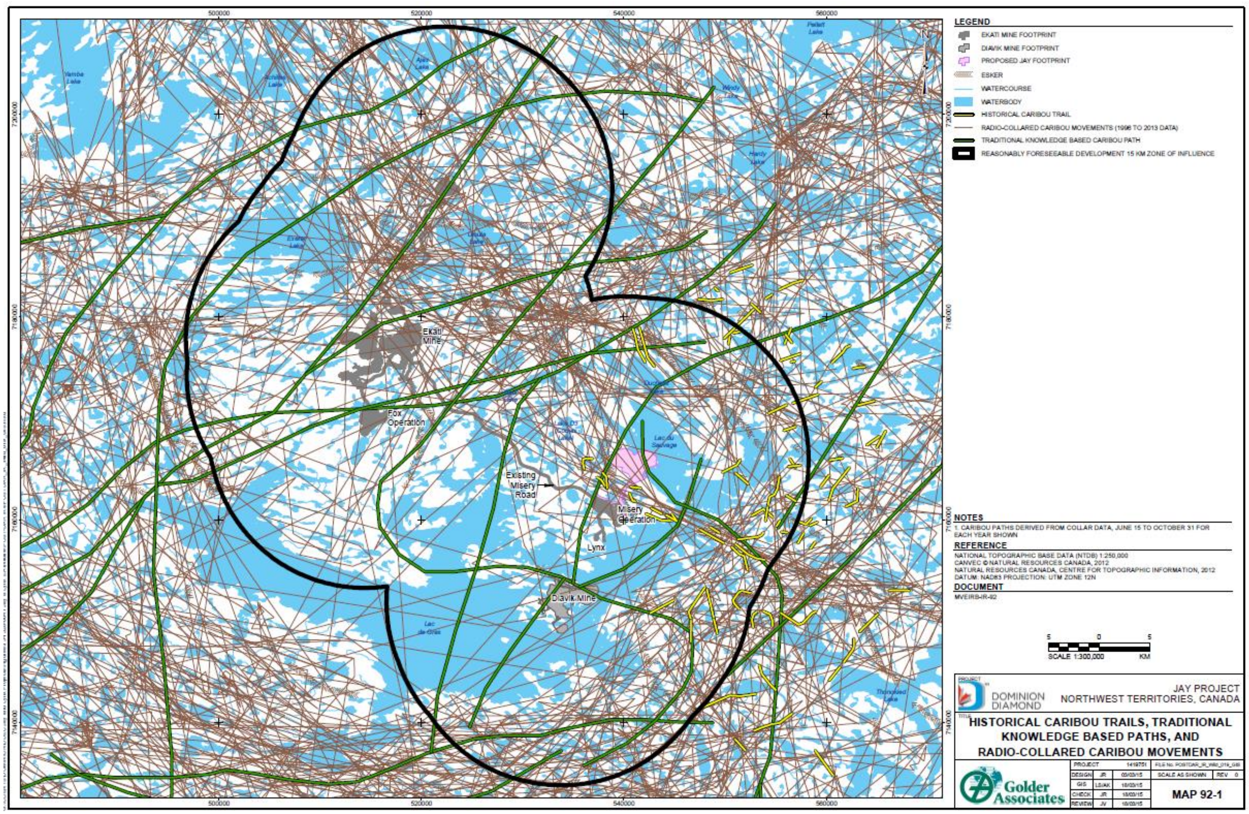


Figure 2. Main caribou paths within the Ekati mine area based on Traditional Knowledge and satellite collar pathways (Map 92-1 from DDEC 2015).

Study Design and Methodology

Spatial data acquisition

Caribou collar data

The Bathurst caribou herd, which has historically been present in the area, has declined from an estimated herd size of 472,000 in 1986 to 8,200 caribou in 2018 (Boulanger et al. 2014, 2017;

Adamczewski et al. 2019). As the abundance of Bathurst caribou sharply declined, the seasonal ranges contracted and shifted north (Virgl et al. 2017, Arctic Canadian Diamond Company Ltd. 2021b, Boulanger et al. 2021). The Beverly/Ahiak herd, which has mainly been observed in the study area since the mid-2010s, likely has been slowly declining since peaking in the mid-1990s (COSEWIC 2016). The most recent trend is a decline from 136,600 in 2011 to 103,400 in 2018 (Campbell et al. 2019). The Bathurst and Beverly/Ahiak herds annually migrate northeast from winter ranges near or below treeline, to calving and summer range on the tundra. The changes in distribution during the decline of the Bathurst herd have markedly contributed to changes in the exposure of caribou to the Ekati mine. During the early 2010s caribou were most likely to be in the vicinity of the mine during the summer through fall seasons (see Table 1 for season dates). However, since 2016, caribou were also present during winter.

Table 1. Caribou seasons (after Bathurst Caribou Range Plan 2017:Fig. 11).

Season	Dates
Calving	2-16 Jun
Post-calving	17-28 Jun
Summer	29 Jun – 6 Sep
Fall	7 Sep - 30 Nov
Winter	1 Dec – 19 Apr
Spring migration	20 Apr – 1 Jun

We obtained caribou collar locations within a 75 km radius of Ekati mine for Bathurst and Beverly/Ahiak herds for January 2010 to September 2019 (Wildlife Management Information System, Environment and Natural Resources (ENR)). Only 8 collared Beverly/Ahiak caribou occurred within 75 km of the Ekati footprint during 2010-15 and none of these occurred within 30 km of the mine, so we only considered Beverly/Ahiak collar data for 2016-19.

Each collar dataset had fields identifying the caribou identification number, herd, sex, date and time of location, latitude, longitude and collar type, and whether the collar was programmed for geofencing. Most GPS collars deployed from 2008 to 2015 used daily and occasionally 8-hour fix intervals which on some collars switched to a fix every 1–3 hours for some seasons. Starting in 2016 most deployed collars used a standard 8-hour fix rate. Geofence collars were programmed to change to a 1-hour fix rate if they came within 30 km of mine infrastructure or 10 km of roads (primarily winter roads; J. Williams, ENR, pers. comm. 19 Aug 2019). Over 140 geofence collars were deployed on Bathurst and Beverly/Ahiak caribou herds within the NWT during 2016–19, with 79 coming within the geofence surrounding development and returning data at the 1 hour fix rate for at least 1 day.

Caribou crossing ramps

As part of on-going mitigation, Arctic Diamond has constructed caribou crossing ramps at sites on the Misery, Sable and Jay roads. These ramps are "*man-made ramps with gradual incline that were created to facilitate caribou crossings at roads, in areas where historical information from Community Members and presence of caribou tracks and trails suggest high use by caribou during annual migrations*" (ERM

Rescan 2014:pg 2-7). Ramps on the Misery Road were in place before our study time period, and were constructed on the Sable and Jay roads during 2017. Over 70% of the Jay Road was constructed with gentle, ramp-like slopes. Arctic Diamond provided the locations of these ramps for our analyses.

Traffic data

Ekati's open pits and underground operations have been developed in sequence since 1997 which has led to high annual variability in the frequency of ore haul trucks needed to truck ore from mining to a centralized ore processing plant. Based on life of mine plan data (Dominion Diamond Mines 2019), we assumed that all road haul traffic during 2010-12 was similar to 2013 levels as Fox Pit was in full production during that period, Misery pit was in development (Misery Pushback), and the Sable road was not yet constructed. Ore hauling from the Fox Pit ceased in 2014, although ore from the rejects pile at Fox Pit was transported to the process plant between June and October 2019 (C. Rock, Arctic Diamond, pers. comm.). Monthly ore haul traffic data to and from the process plant on the three main roads (Misery, Fox and Sable) were obtained from Arctic Diamond for January 2013 to December 2019 and summarized annually (Fig. 3). Haul traffic varied over time and among roads. Averaged over the year, ore truck passages on the Misery Road peaked in 2015 at an ore truck every 13 minutes. Traffic data did not include trucks moving crushed rock, waste rock or waste water, medium or light vehicles, winter ice road traffic, nor ore movements from the Pigeon Pit. For example, non-ore haul truck traffic increased in frequency on the Sable Road in spring 2016 (Arctic Canadian Diamond Company Ltd. 2021b), and roughly 2,000 loads (4,000 passages) were transported on the Tibbitt to Contwoyto winter road during January to March each winter (https://nnsl.wpengine.com/wp-content/uploads/2020/10/2020-Winter-Road-Operating-Summary.pdf).

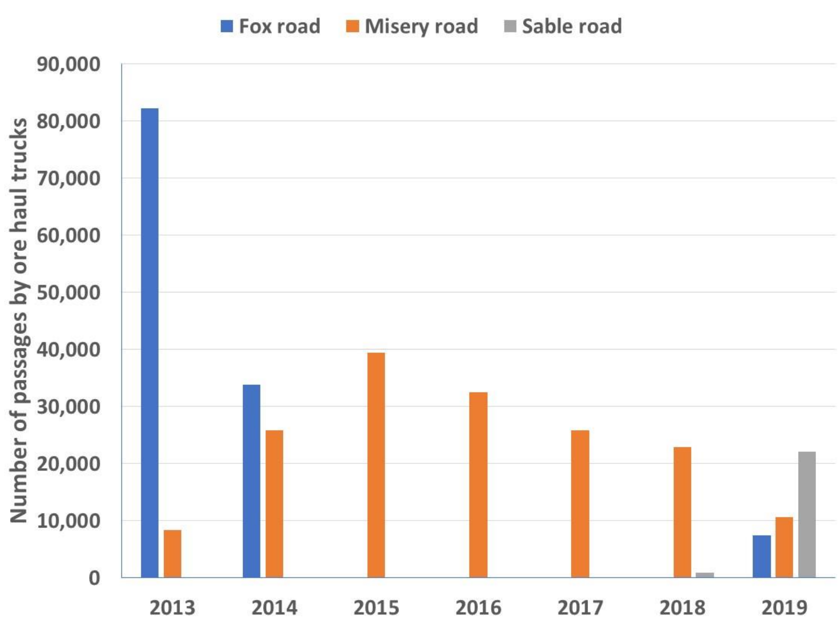


Figure 3. Annual rates of ore haul traffic (one-way passages) along the three main haul roads on the Ekati mine, 2013-19 (courtesy of Arctic Canadian Diamond Company Ltd.).

Data preparation

Caribou collar locations

We screened the collar data prior to estimating the path metrics. Males and Telonics Argos (satellite) collars were filtered from the datasets. Males have different seasonal movement patterns and the sample size of collared males was low. Satellite collars have a lower fix rate and provide locations with much larger potential of location error (up to 350 – 1000 m, depending upon filtering). We deleted 82 Bathurst and 4,188 Beverly/Ahiak caribou locations to remove records with the duplicate datetime stamps for individual caribou. We imported both datasets into a GIS and added x and y coordinate fields based on NAD83/UTM zone 12N (epsg: 26912), with the units for the new coordinate fields in metres. To address duplicate consecutive spatial locations (e.g., consecutive caribou locations at the same spatial location, resulting in issues for spatial analyses) we randomly jittered the x and y coordinates for the entire dataset by 0.5 m in each direction using a uniform distribution. The result of the jitter is that each caribou location was moved a maximum of ±0.5 m in the x and y directions.

The screened dataset was imported into R programing language and movement metrics were estimated using the software adehabitatLT library (Calenge 2020). The adehabitatLT library estimates a variety of movement metrics for each record, referred to as the ***movement metric datasets***. Each dataset was exported from R for further preparation using a GIS (QGIS; QGIS Development Team 2020). For clarity, at this point the path dataset only had the caribou ID field and none of the metrics estimated by the adehabitatLT tool. The movement metric datasets were joined to the path datasets using a spatial join. The output of the data preparation is a ***spatial polyline dataset*** with geometry describing each step between consecutive points. Each line in the spatial dataset included non-spatial fields that estimated the attributes of the spatial record. This spatial dataset was used for all further analysis and summary.

Terminology

Terminology used for describing this dataset is presented in Table 2.

Table 2. Movement terms and definitions.

Term	Definition
Point	A caribou collar location
Step	The line between 2 consecutive points
Path or Pathway	≥2 consecutive steps that represent the route taken by an individual
Residency	Index for **time** spent by individual collared caribou in each of the 3 km buffer zones around the mine site (a series of 10 3-km buffer zones were developed out from the mine footprint; see Data processing, below). Calculated by multiplying the change in time between consecutive locations with the proportion of each path within a buffer zone divided by the area of the buffer zone and expressed as hours per km².
Exposure	Caribou with the potential to interact with the mine, quantified as the likelihood (95% kernel) of the collared cows overlapping with the 30 km buffer around the mine.

Term	Definition
Encounter	A collared caribou pathway within 3 km of mine (a pathway may encounter the mine more than once if the pathway moved away and re-encountered the mine).
Speed	Speed (also termed movement rate) was calculated along the length of a step (distance divided by time) and assigned to the appropriate 3-km buffers. Expressed as km/hr.
Turning angle	The relative change in direction from one step to the next. Calculated in radians which were later translated to degrees. We used the absolute angle of turn to change negative values into positive values. We also calculated the proportion of 'hard turns' which we set at ≥60° angles.
Delay (no delay)	When >2 points are within the 3 km buffer closest to the mine footprint and is measured by the number of 'hard turns' (≥60° turns) (includes reversals, stalls and deflections).
Cross (no cross)	A caribou is considered to have crossed the mine or road when its pathway crosses the mine/road and 2 consecutive points are on opposite sides.

Data processing

We restricted our analysis to only those caribou that came within 30 km of the mine because this is about double the maximum distance reported for the central Canadian barrens that caribou respond to industrial activities (Boulanger et al. 2012, 2021). Geofence collars also activated at approximately 30 km from the mine footprint enabling a consistent rate of caribou locations for many collars. We described the caribou responses to Ekati at the annual, seasonal and daily temporal scales and spatially for seasonal ranges and within 3 km buffers out from infrastructure. The sample units for analyses were an individual cows' movement pathway and turns.

1 Annual and seasonal exposure

We used the entire Bathurst caribou collar dataset (i.e., not clipped to 75 km radius from the mine site) to determine annual trends in seasonal range and centroid during 2010-19 relative to the Ekati mine site. Following Virgl et al. (2017) we conducted 95% kernel density analyses for each year for post-calving through fall and winter seasons (Table 1). The kernel densities were estimated using the bivariate normal kernel method (href) as the smoothing parameter provided in the adehabitatHR package for R (Calenge 2020). Each 95% kernel for each season-year was edited to remove small outlier polygons, leaving a single polygon for each season-year. We calculated seasonal range polygon centroids as the central geographic coordinates of the polygon. Finally, we calculated the proportion of each 95% seasonal range that intersected the 30 km buffer around mine infrastructure.

2 Encounters (pathways)

Encounters relative to distance from Ekati mine

To summarize the differences in caribou movement at various distances from the Ekati mine footprint, we created multi-ring buffers of the annual mine footprints at 3 km intervals out to a maximum of 30 km (Fig. 4). The multi-ring buffers consisted of 10 non-overlapping polygons. Caribou paths were filtered for paths that represented ≤24 hours between locations. The filter was necessary to remove paths that had large temporal gaps between locations – this problem was in part a function of the spatial restrictions (75 km buffer of collar data provided) used when the location data were provided.

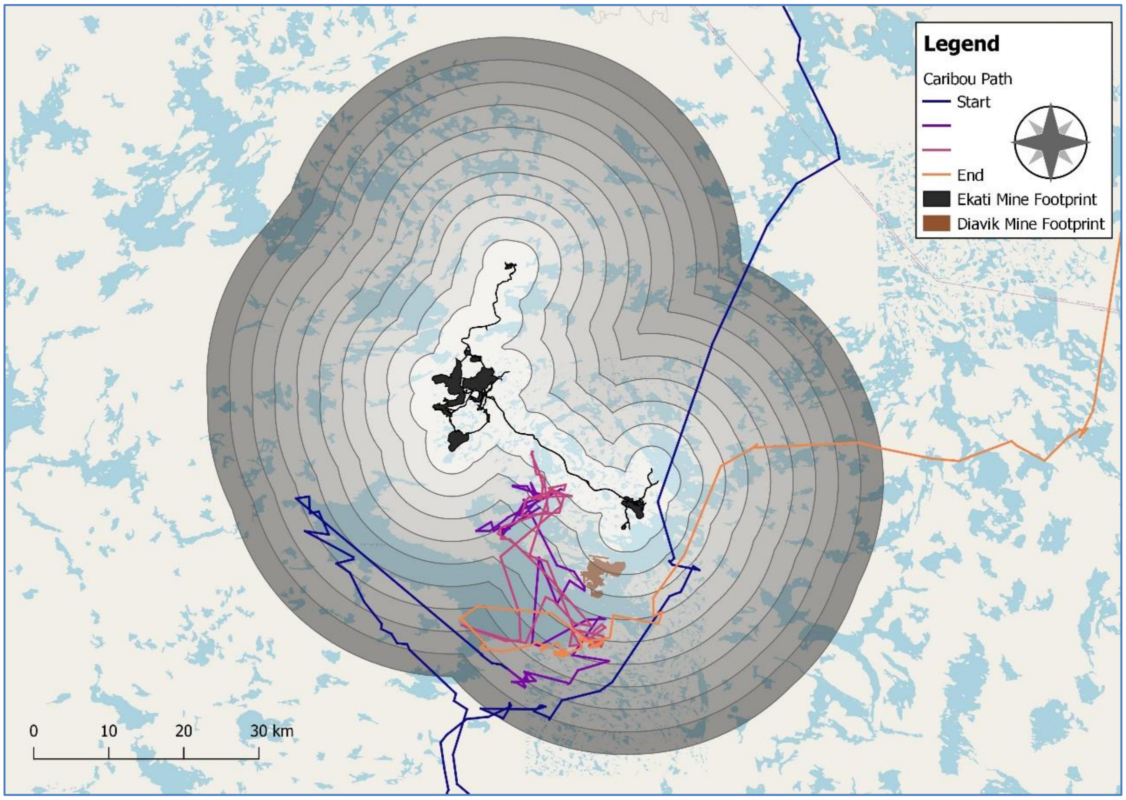


Figure 4. Three-km buffer zones around Ekati mine and an example of a pathway (BEVAH_BGCA14717_Winter_2017).

Residency, speed and turning angle

To estimate the time spent (residency), speed (movement rate) and turning angle by caribou at different distances from the mine site, we overlaid the caribou paths and the multi-3 km ring buffer spatial datasets using the intersection tool. Overlays were completed using the corresponding years where possible; for example, caribou paths during 2012 were intersected with the multi-ring buffer of the 2012 mine footprint. As we only had the mine footprints from 2012 to 2018, we intersected the 2010 and 2011 caribou paths with the 2012 mine footprint and 2019 paths were intersected with the 2018 mine footprint. The intersection resulted in paths that were split where the step intersected a buffer edge which created records for the new objects with new geometry but maintained the same attribute fields. Consequently, the length of the new step was compared to the original length and used to estimate the amount of time that the new line represented by multiplying the proportion of the two lengths by the original time (dt).

To estimate the residency of caribou within each distance buffer, we summed the corrected time a caribou spent within a distance buffer corrected for the size of the buffer providing a residency estimate in hours per km^2. This accounted for the proportion of the path that was within a distance interval divided by the area of the distance interval polygon, so it provided an estimate of time that the caribou was within the buffer zone. We averaged residency among individuals by 3-km buffer annually and by season for each herd. For within seasons, we used only those years with data from ≥5 caribou. Caribou speed was calculated along the length of the step and assigned to the appropriate 3-km buffers, with a similar restriction of sample size. Turning angle was assigned as the relative change in direction from one step to the next. Angles were documented in radians which were later translated to degrees. We used the absolute angle of turn in radians to change negative values into positive values as we were concerned with the degree of deflection from a straight line, not whether the turn was left or right. From these values we calculated the proportion of 'hard turns' which we set at ≥60° angles, with 60° being the approximate median of the absolute value of relative turn angles for both herds (Bathurst 59.3°; Beverley/Ahiak 57.5°).

Response to mine and roads

We classified individual caribou pathways to examine annual and individual variation in exposure to mine infrastructure as a relatively simple scheme to display the variability in caribou responses. We classified the pathways using visual inspection of the movements relative to the mine and main roads to categorize the responses and how they differed among seasons because season likely contributes to variation in exposure and to differences in caribou behaviour (e.g., motivation varies with migratory or non-migratory periods, insect harassment, etc.). For each season and only for pathways within the 30 km buffer (the pathway had to have >2 km distance travelled and ≥2 steps within the 30 km zone), we first classified caribou into whether they moved straight through the 30 km zone >3 km from mine infrastructure or whether the pathway deflected by changing direction of at least 60^{o} between two steps. For the pathways that deflected, we classified them as to whether the deflection was within 3 km of the mine or main roads or was a lake (or some other natural feature).

We took the pathways within 3 km of the mine and its major roads and further classified them as to whether they skimmed past or not – we considered a skim as within 3 km but with no further change in direction. Within the non-skimming pathways, we used at least 2 steps with distinct turns ≥60^{o} as a criterion for a delay or not, relative to the road or mine. Within each of the delay or no-delay categories, we noted whether the caribou crossed the road or mine site (Fig. 5.). In GIS we determined the duration of delays within the 3 km zone.

To provide an indication of how close to the road caribou may approach before turning away we measured in GIS the distance from the closest point on the pathway to the road for those individuals that approached the roads but did not cross.

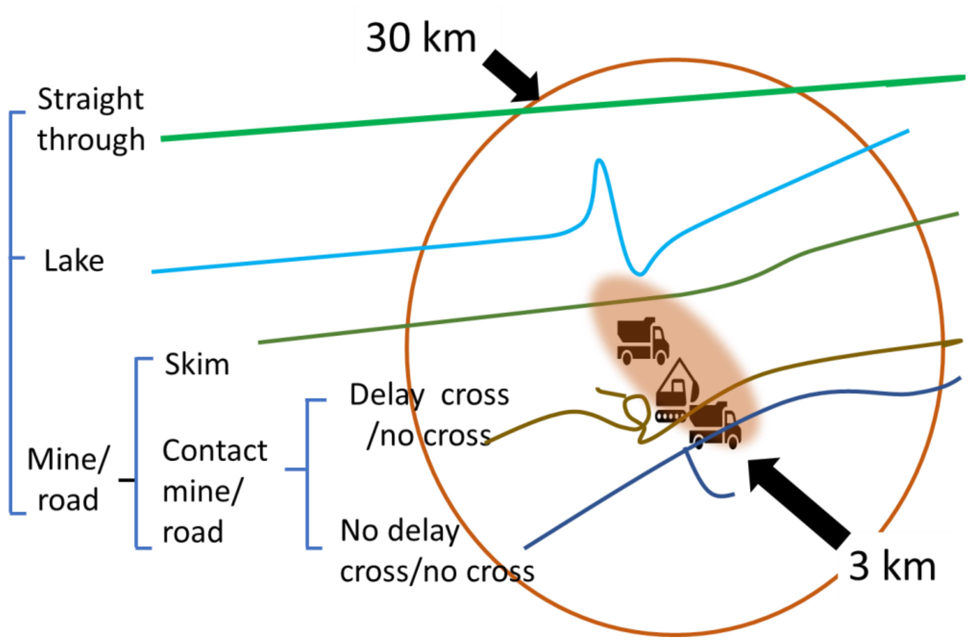


Figure 5. Schematic of caribou pathway classification within 30 km of Ekati. The brown shading represents the 3-km buffer around mine infrastructure.

Geofence collars

We examined the influence of more rapid fix rates (1 hour) characteristic of geofence collars on caribou movements path parameters compared with those derived from a standard 8-hour fix rate. We chose four examples of caribou with 1-hour fix rates that approached mine infrastructure and filtered these collar locations to 8-hour intervals. We mapped both pathways for each caribou and quantified differences in speed, proportion of hard turns, and distance from infrastructure on approaches.

Use of caribou crossing ramps

We recorded all caribou crossings of the Misery and Sable roads to assess whether caribou were using the ramps constructed to facilitate crossing of structures. We restricted our analysis to 2016 to 2019 which had fix rates of 1 hr, since 8 or 24 hr fix rates were too coarse for the resolution required. Given that we do not know the exact path chosen between two telemetry points, we buffered ramp locations by 150 and 300 m and determined the proportion of crossings that were within these distances of ramps.

Results

1 Annual and seasonal exposure

1a Annual ranges

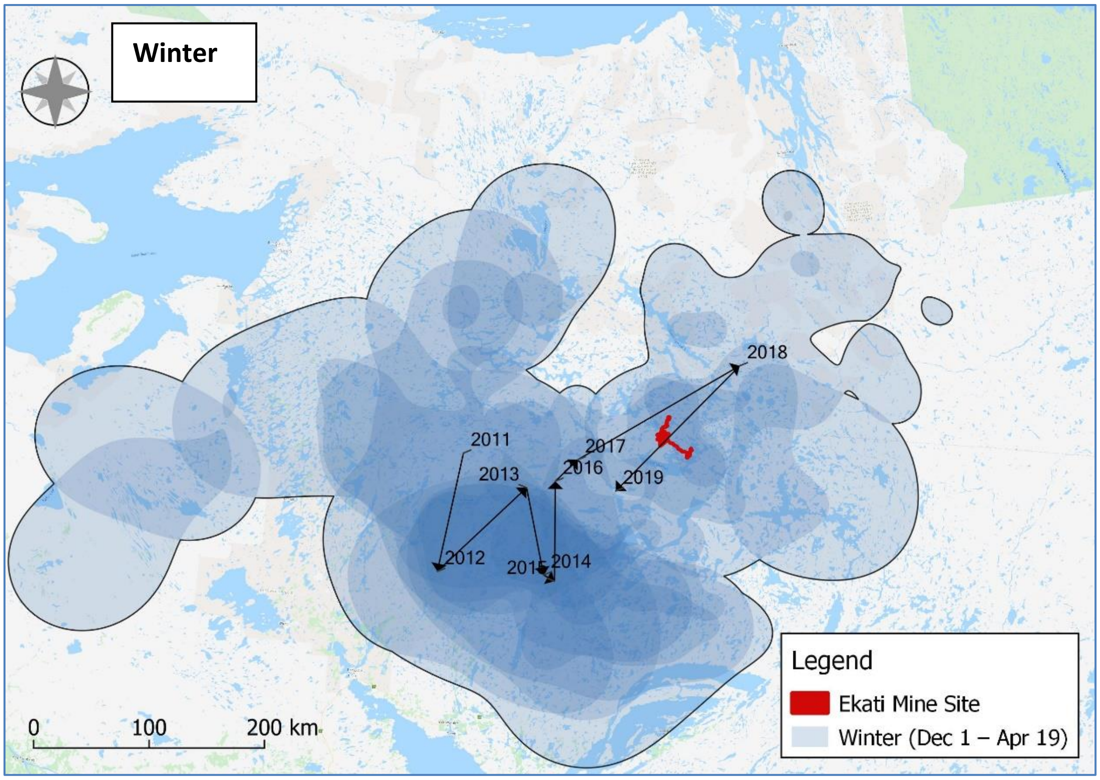
The number of collared cows annually varied within 75 km of Ekati mine (Table 3). An average of 74% and 67% of the collared cows from the Bathurst and Beverly/Ahiak herds, respectively, that occurred within 75 km of the mine reached the 30 km buffer with higher numbers of Bathurst caribou after 2014 and of Beverly/Ahiak caribou from 2016-19. A total of 232 collared cow caribou from both herds entered the 30 km buffer around the mine infrastructure. The annual mean number collars available for analysis within the 30 km buffer for both herds was 16.5 (±1.66 SE; range 7–26) with higher numbers in later years due to the presence of collared Beverly/Ahiak caribou.

Table 3. Presence of individual collared caribou cows from the Bathurst and Beverly/Ahiak herds in the 75 km and 30 km Ekati mine buffers

Herd/year	No. collared cow individuals		
	75 km	30 km	% in 30 km
Bathurst			
2010	19	13	68%
2011	18	7	39%
2012	20	16	80%
2013	13	8	62%
2014	18	14	78%
2015	31	21	68%
2016	25	20	80%
2017	28	26	93%
2018	23	19	83%
2019	26	23	88%
Beverly/Ahiak			
2016	11	7	64%
2017	33	24	73%
2018	27	18	67%
2019	25	16	64%

1b Seasonal ranges

The timing and extent of the caribou's seasonal distribution influenced the changes of caribou exposure to the Ekati mine. During the 2010s, Ekati was on the southern edge of summer range and relatively centrally located in fall range (Fig. 6). Winter range had the greatest annual shifts, with the centroid shifting from southwest to northeast closer to Ekati mine (Table 4), on average 17 km/year closer from 2011 to 2019. The proportion of Bathurst cow caribou seasonal ranges that overlapped with the 30 km buffer around Ekati infrastructure, and hence the probability of exposure, annually varied, reaching as high as 17–29% during winter, summer and fall (Tables 5, 6). Overlap during winter only occurred during 2017-19 and was higher in fall after 2015. Seasonal ranges or centroids were not calculated for Beverly/Ahiak cows but path overlap with the 30 km Ekati buffer occurred during winter 2017-19, summer and fall 2016 and 2017, and fall 2018 (Appendix A).



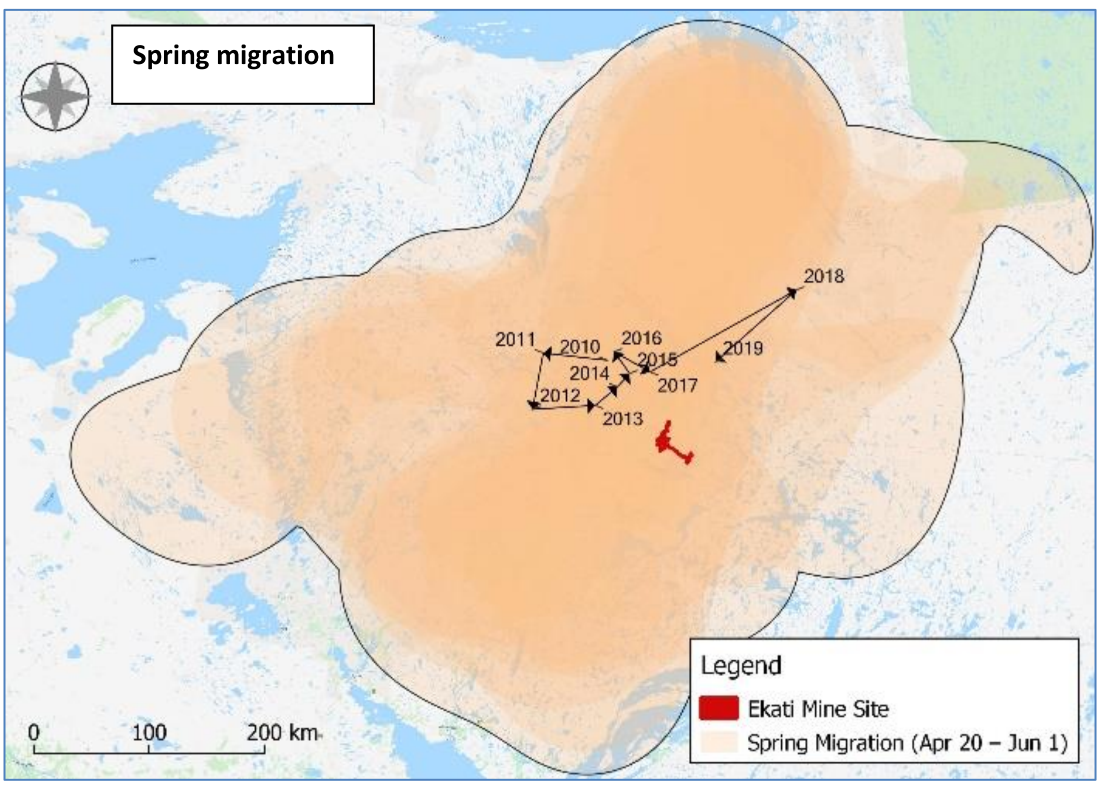
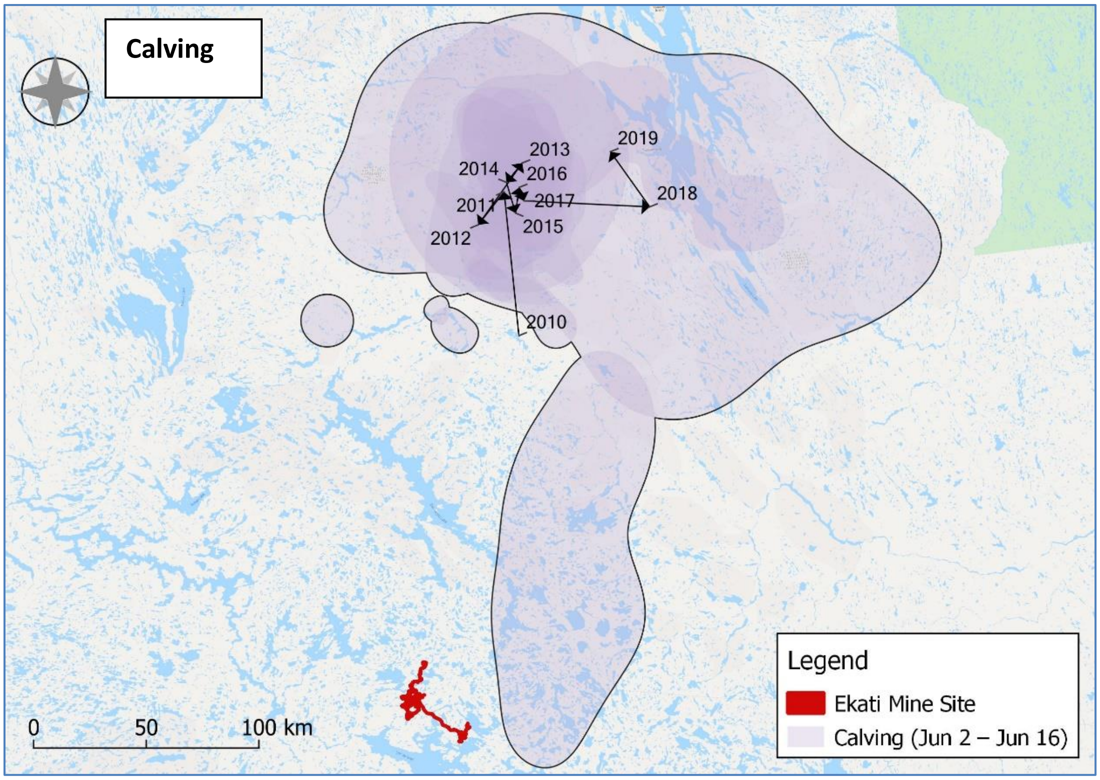


Figure 6. Seasonal ranges (95% kernels) and annual centroids for Bathurst caribou cows, 2010-19.



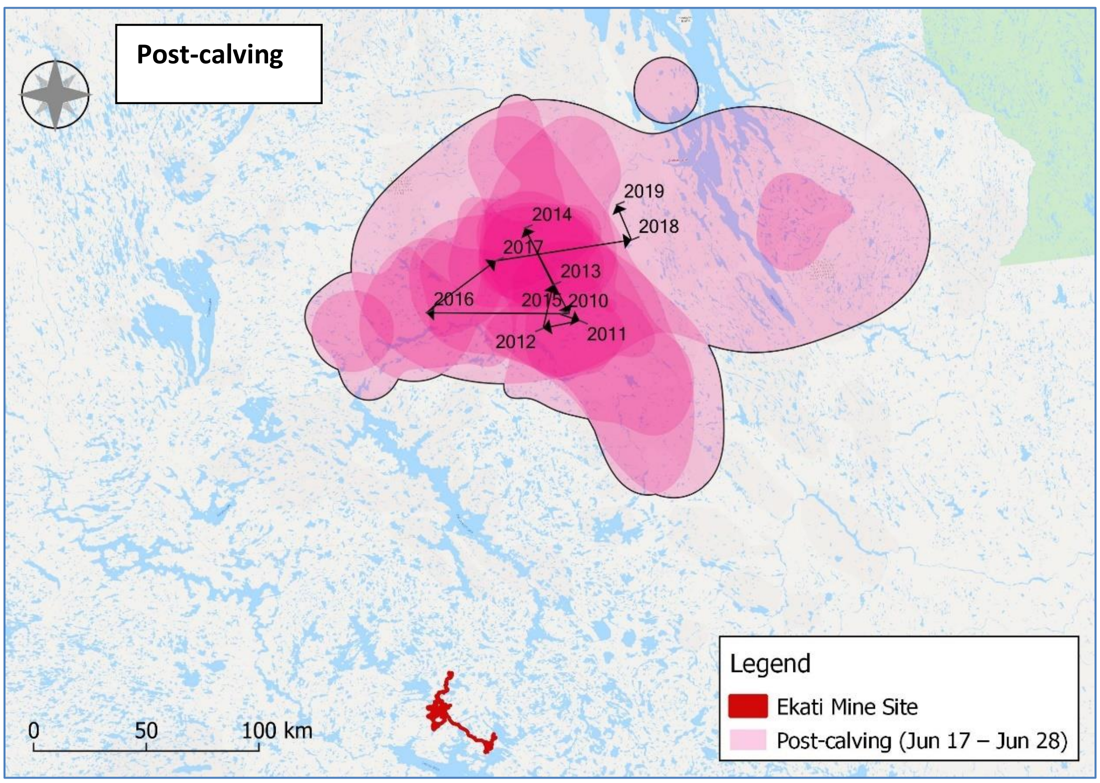


Figure 6 (continued). Seasonal ranges (95% kernels) and annual centroids for Bathurst caribou cows, 2010-19.

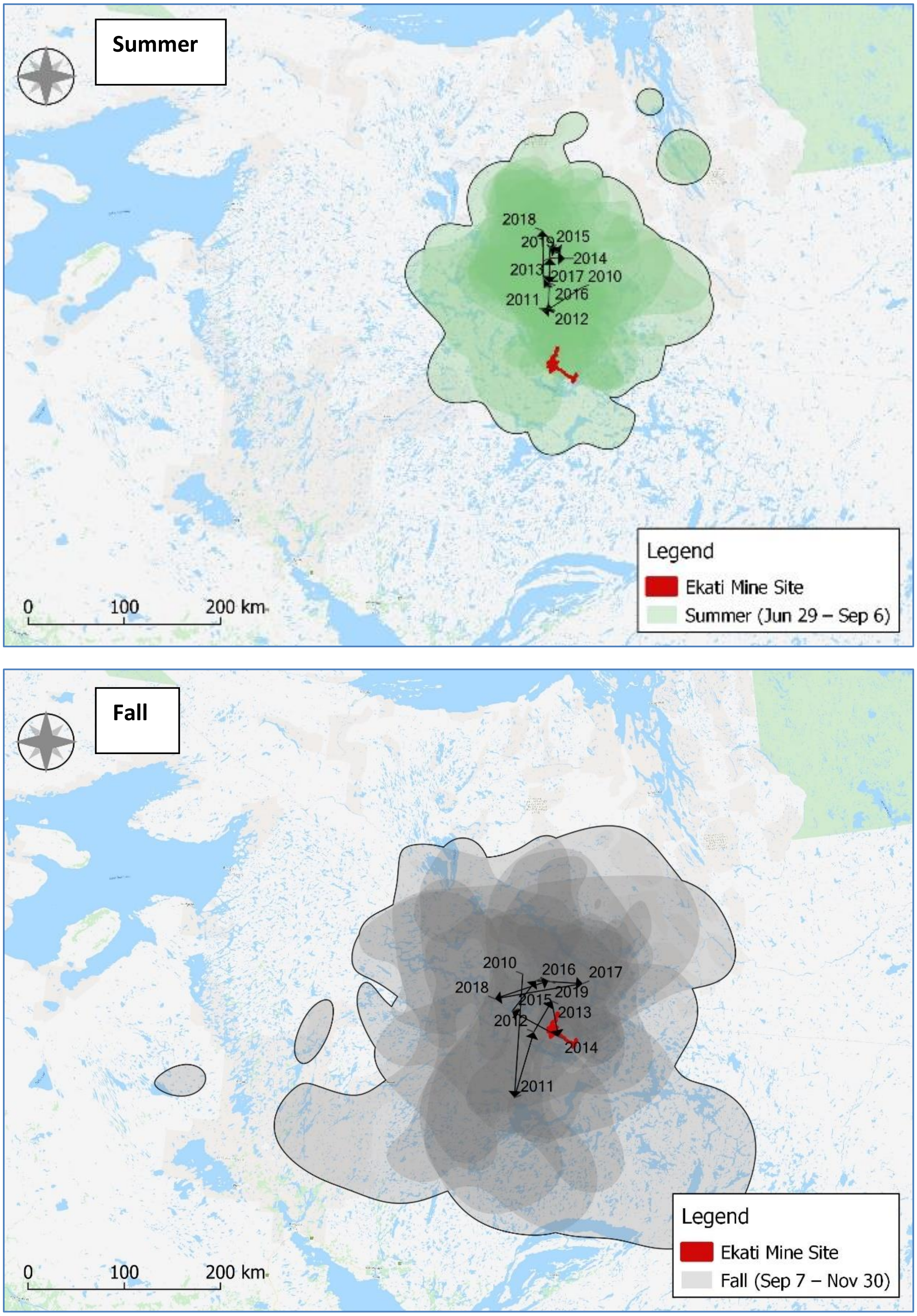


Figure 6 (continued). Seasonal ranges (95% kernels) and annual centroids for Bathurst caribou cows, 2010-19.

Calving and post-calving ranges of Bathurst cows were generally >125 km to the north of Ekati (Fig. 6). (Note that the calving polygon extending south towards Ekati, which occurred in 2010, likely was a result of non-breeders lagging the breeding cow movements). Because of no potential interaction with the Ekati area, we removed calving and post-calving ranges from further analysis.

Table 4. Distance (km) of the Bathurst seasonal range centroids to the Ekati mine site by year, 2010-19. Light to dark green shading represents comparatively closer distances.

Caribou Year	Winter	Spring-Migration	Calving	Post-calving	Summer	Fall
2010		85	167	183	84	65
2011	175	130	228	183	55	83
2012	230	118	212	175	58	21
2013	128	67	242	194	109	29
2014	160	62	232	216	109	10
2015	159	65	220	184	120	47
2016	103	88	231	176	84	53
2017	78	61	226	200	79	55
2018	89	174	242	224	139	69
2019	64	81	257	237	114	50
Mean	132	93	226	197	95	48
SD	50.8	34.9	22.9	20.6	26.1	21.5

Table 5. Percentage of Bathurst caribou cow seasonal ranges that intersect the 30 km buffer of the Ekati mine site by season and year, 2010-19. Light to dark green shading represents comparatively greater overlap.

Caribou year	Winter	Spring migration	Summer	Fall
2010		4%	10%	11%
2011	0	0	7%	5%
2012	0	3%	11%	9%
2013	0	2%	11%	6%
2014	0	4%	7%	7%
2015	0	5%	0	8%
2016	0	4%	18%	18%
2017	9%	4%	21%	29%
2018	14%	8%	2%	3%
2019	17%	6%	11%	20%

Table 6. Number of collared cow caribou paths seasonally within 30 km buffer of Ekati footprint for Bathurst and Beverly/Ahiak (Bev/Ah) herds, 2010-19. Light to dark green shading represents higher overall sample sizes.

Herd	Season	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019
Bathurst	Winter								4	22	8
	Spring migr	3	2	11		4	12	2	2	5	11
	Calving	1									
	Post-calving										
	Summer	5	5	9	5	2		17	22	6	21
	Fall	7	5	11	3	12	19	13	22	1	2
Bev/Ah	Winter								9	25	12
	Spring migr								3	5	5
	Calving										
	Post-calving										
	Summer							2	4	1	
	Fall							4	17	6	

2 Encounters (pathways)

2a Residency

Annual residency 3 km zones

Mean individual residency time near the Ekati mine varied between herds, among years, and across the 10 3-km zones (Fig. 7; Appendix B). In most year-seasons, residency time was highest closer to mine infrastructure, declining as distance increased.

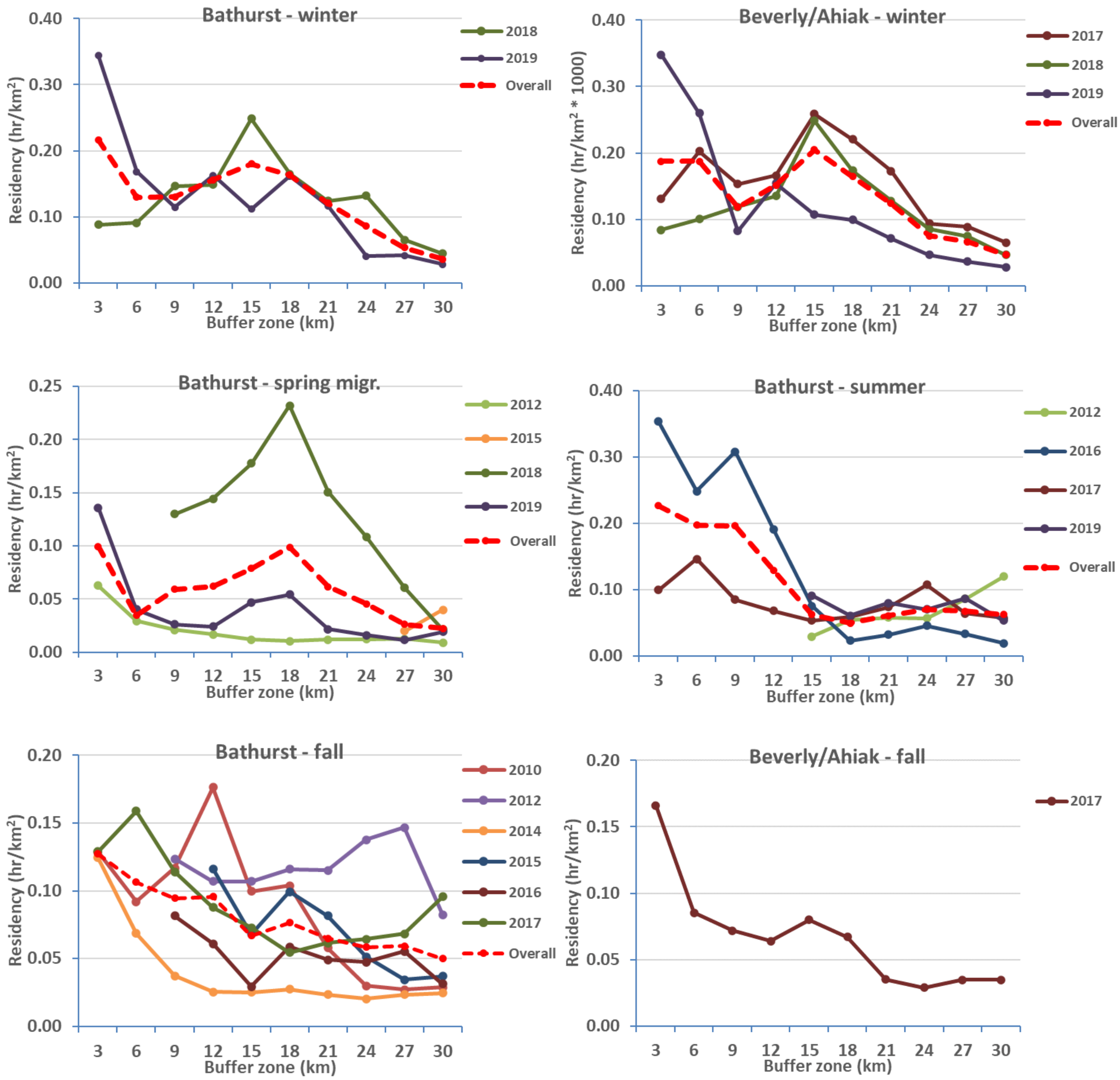


Figure 7. Annual average individual residency by 3 km buffer zones, Bathurst herd, 2010-19 and Beverly/Ahiak herd, 2017-19. Note y-axis scales differ among seasons.

Seasonal residency 3 km zones

Seasonal residency time for Bathurst caribou varied among seasons. It was low during spring migration and was generally higher close to mine infrastructure, although winter residency was highest within 12–18 km buffer zones (Fig. 8; Appendix B). Beverly/Ahiak caribou had a similar pattern of winter residency to Bathurst caribou and a markedly higher residency within 0–3 km buffer zone during summer (Fig. 9).

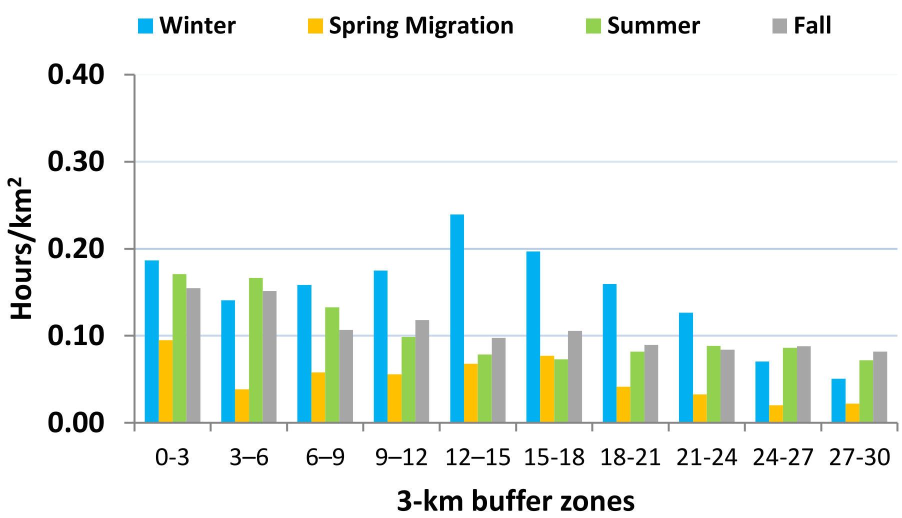


Figure 8. Mean individual residency (hr/km^2) summed among collared caribou within 3 km buffer zones around the Ekati mine footprint for the Bathurst herd by season, 2010-19.

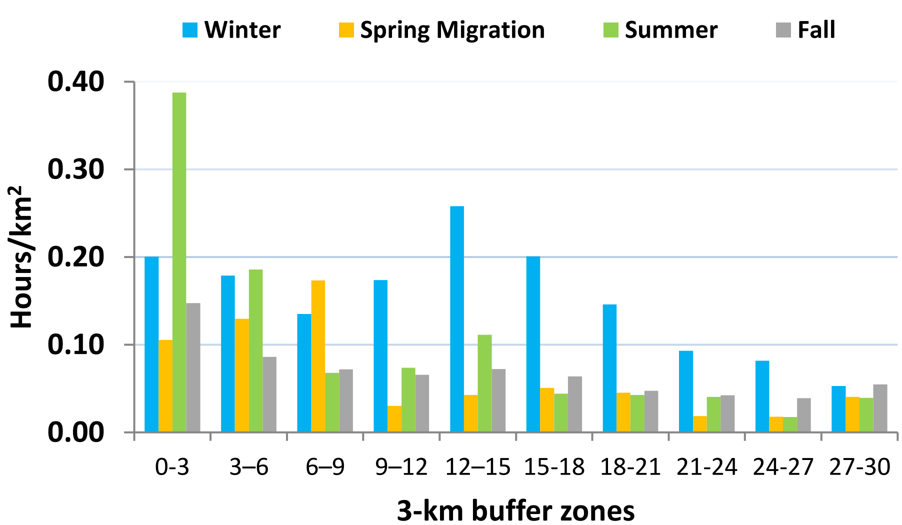


Figure 9. Mean individual residency (hr/km^2) summed among collared caribou within 3 km buffer zones around the Ekati mine footprint for the Beverly/Ahiak herd, 2016-19. Note that individual sample size for summer was ≤4 individuals for buffer areas <18 km.

2b Encounters to roads/footprint

We summarized the encounters relative to landscape features including lakes and the Ekati mine and its major roads. Our sample was 280 pathways within 30 km of the mine: 27% (76/280) passed straight through the 30 km zone, most of which (60%) were during spring migration. Just over one-third (35%; 98/280) changed direction at a lake or other natural landscape feature and 38% were close to the mine (106/280). We have included examples of seasonal pathways in Fig. 4 and Appendix C.

For the 106 pathways within 3 km of the mine, 46 were multiple encounters where the caribou entered the 3 km zone, left and re-entered at least once more, which meant there were 155 encounters within 3 km of Ekati which were 80 and 75 encounters for the mine site and major roads (Sable and Misery), respectively (Table 7).

Table 7. Number of encounters within 3 km Ekati comparing mine site and roads by number of delays and crossing or no crossing.

		Mine				Road			
		Delay		No delay		Delay		No delay	
Season	Skim	Cross	No Cross	Cross	No Cross	Cross	No Cross	Cross	No Cross
Winter	5	7	13	5	4	0	17	2	7
Spring mig.	3	1	7	0	1	3	2	4	1
Summer	4	0	11	0	3	3	7	2	3
Fall	0	0	8	5	15	1	8	5	10
Total		8	39	10	23	7	34	13	21

Of the 155 encounters, 57% (88/155) were delays (≥3 steps and turns). Of the delays, 83% (73/88) did not cross the mine and its roads (Figs. 10 and 11). In comparison, for encounters that did not have delays, 66% (44/67) did not cross mine infrastructure.

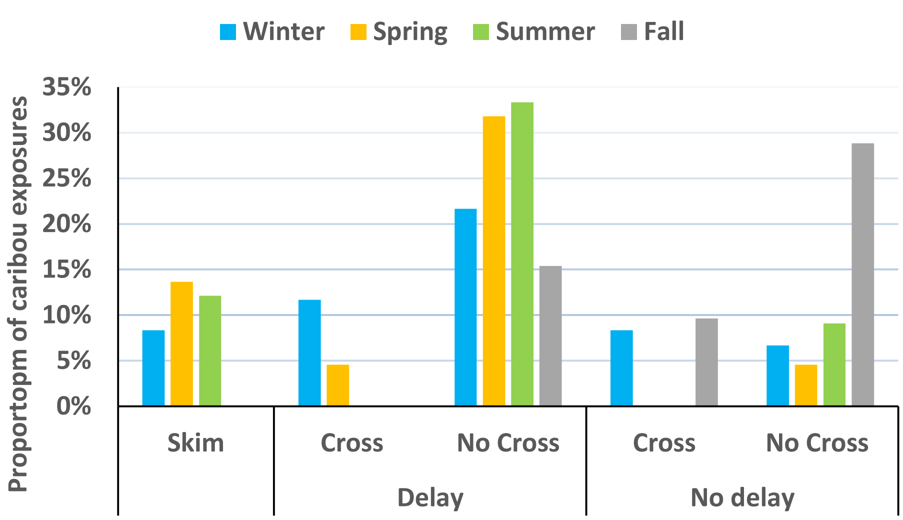


Figure 10. Caribou pathways encountering the main Ekati mine site, 2010-19.

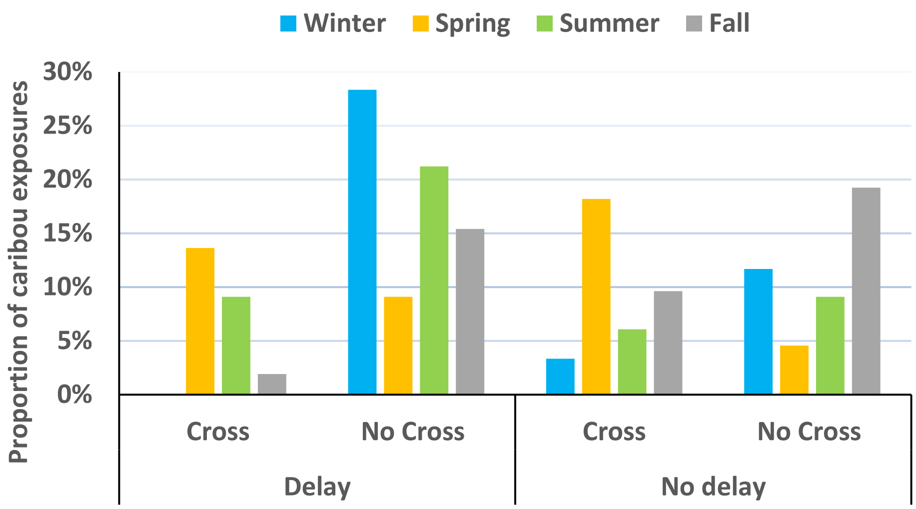


Figure 11. Caribou pathways encountering Ekati roads, 2010-19.

Of the 55 caribou which approached but did not cross roads (Table 7), the mean closest distance to the road was 1,111 m (± 172 m SE). Only 16% of these non-crossing caribou approached to within 100 m of roads, and for 47% the closest approach was to within 500–2,000 m of roads (Fig. 12).

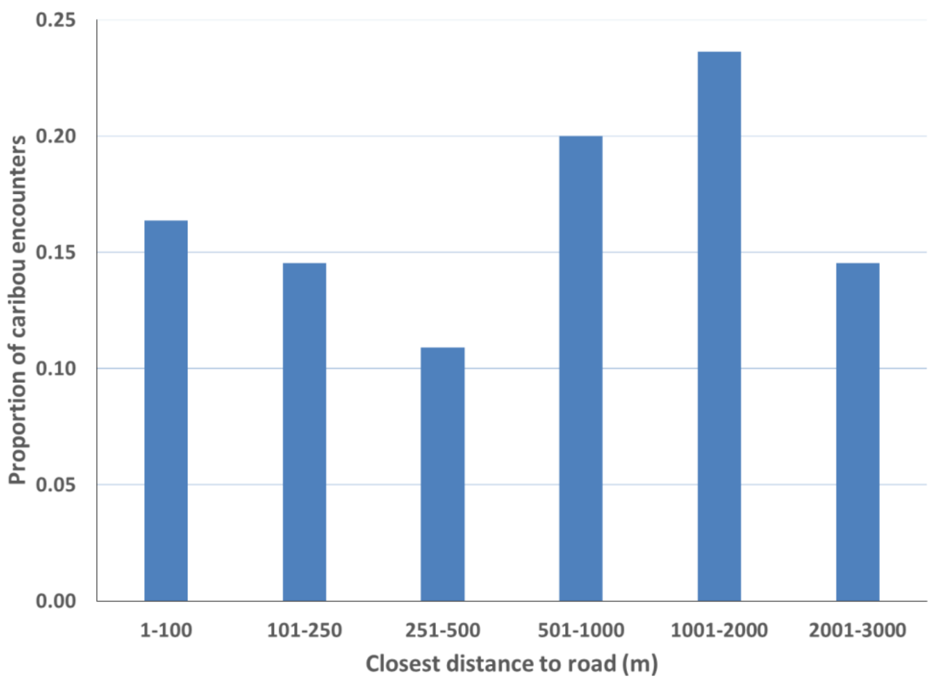


Figure 12. Distribution of closest distance to road from caribou which approached but did not cross roads (*n* = 55).

An example of the movements by caribou as they approached the Misery Road in mid to late March 2019 is provided in this linked animation[1].

The duration of the delays varied seasonally (Fig. 13). Overall, the delay with no crossings averaged 108 hours (± 15 SE; range 3-648 hrs; n = 72 encounters), significantly greater than delays with crossings which averaged 36 hrs (± 10 SE; range 6–144 hrs; n = 14 encounters) (t = 4.1, 70 df, P < 0.0001).

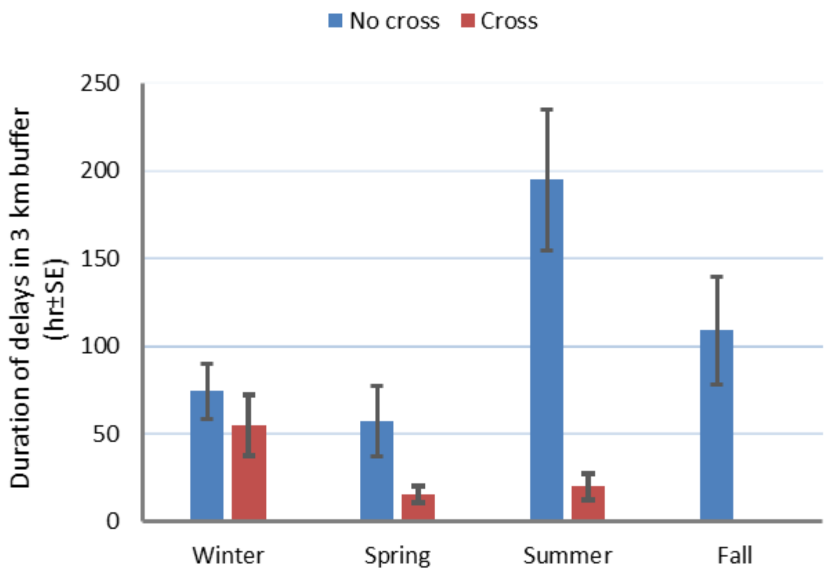


Figure 13. Duration (hours) of delays within 3 km by season.

[1] https://monitoringagency.net/other-agency-documents/

2c Encounters – speed

Speed of caribou movement varied broadly among seasons, being lowest during winter and highest during spring migration and summer (Fig. 14). Speed of movement varied among years, and was generally lowest in the first 3-km buffer and sometimes the 3–6-km buffer from infrastructure. Within fall and winter seasons, caribou moved on average faster in the outer 6 to 9 km from infrastructure.

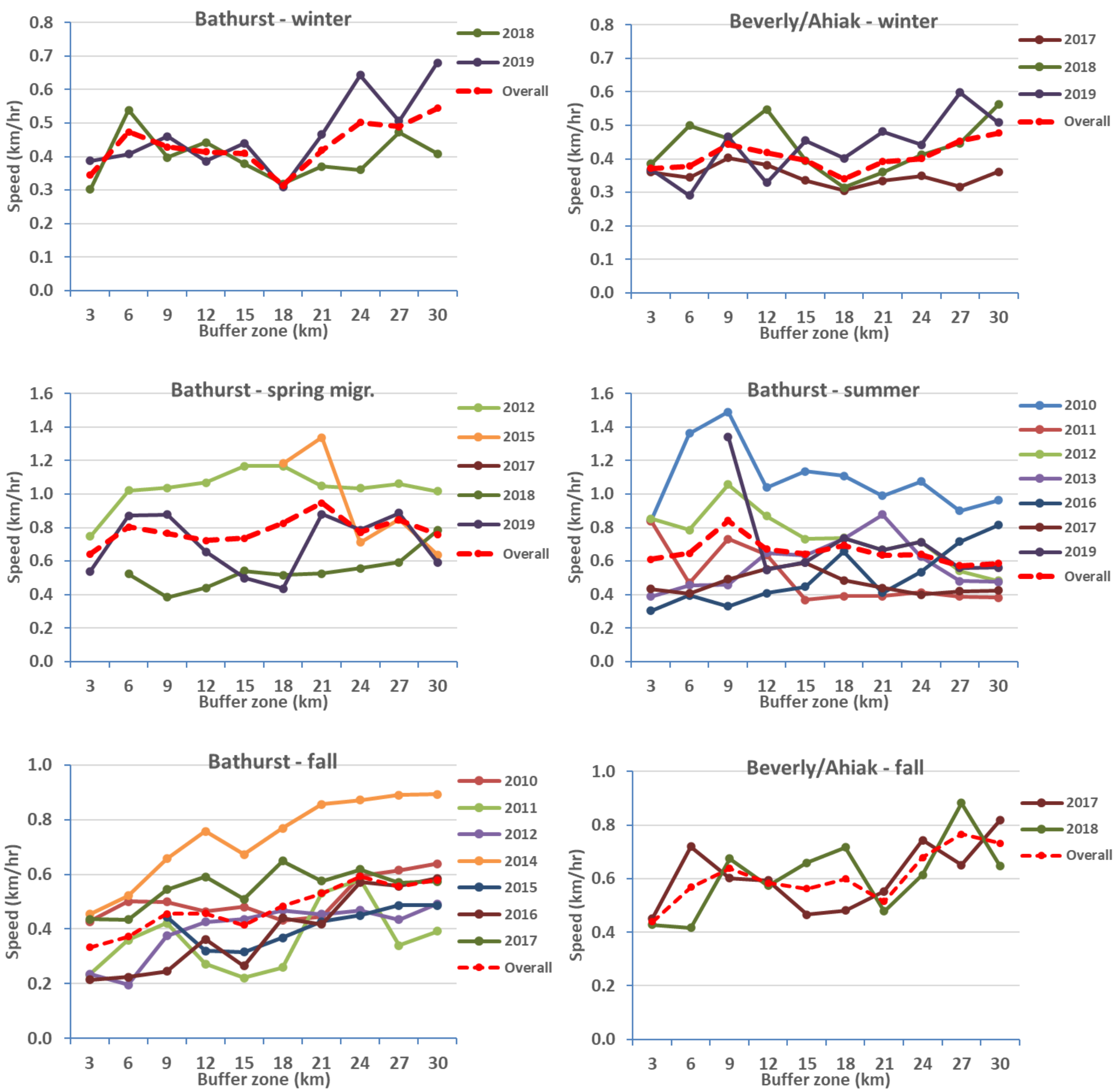


Figure 14. Annual average speed (km/hr) by 3 km buffer zones, Bathurst herd, 2010-19 and Beverly/Ahiak herd, 2017-19. Note y-axis scales differ among seasons.

2d Encounters – turning angles

During fall, caribou showed higher proportions of hard turns (≥60° turns) closer to mine infrastructure, and caribou that did not cross the mine/roads demonstrated an overall higher proportion of hard turns than caribou which did cross (Fig. 15). There was little pattern in buffer zones out from infrastructure to the proportion of hard turns during winter when the mine/roads were not crossed, the pattern when infrastructure was crossed was more variable, with higher proportion of hard turns ≤3 km of the mine, a sharp decrease out to 9 km, and an increase towards the 30 km zone.

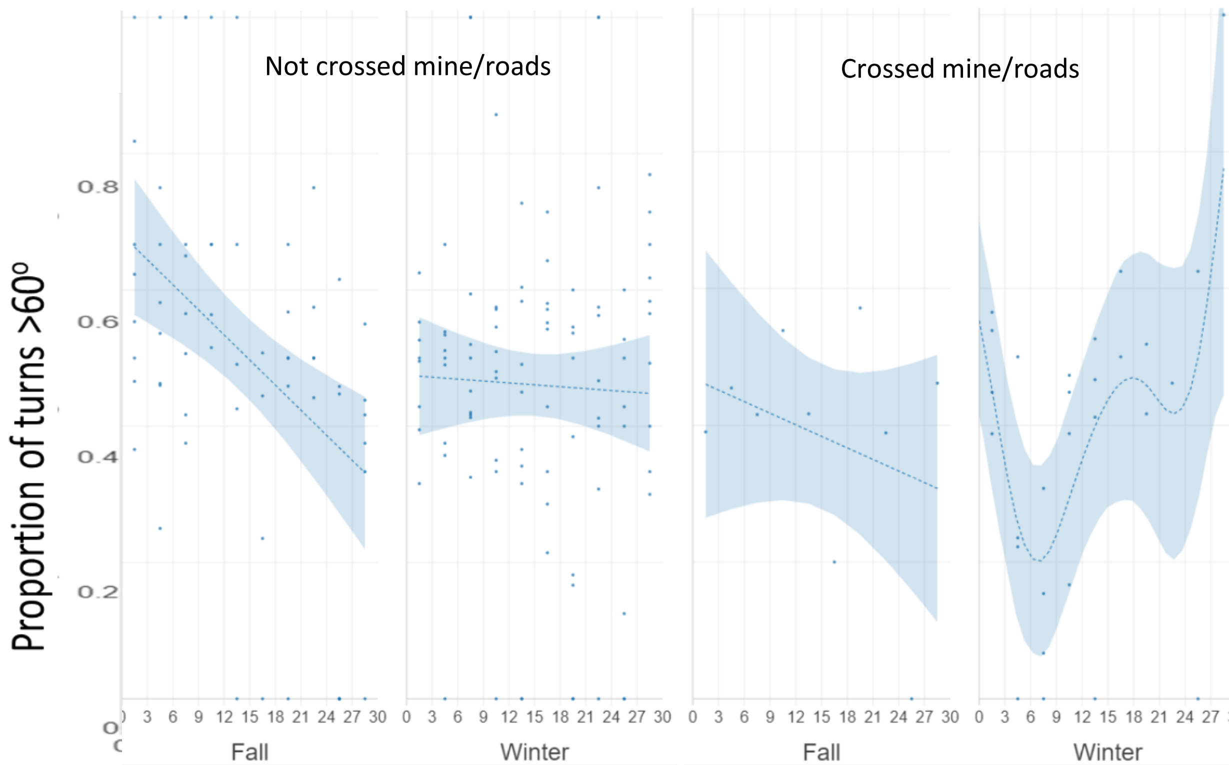


Figure 15. The proportion of hard turns (≥60° turning angle) during fall and winter relative to 3-km buffer zones when the mine/roads were not crossed (left panels) and crossed (right panels), Bathurst caribou herd, 2010-19.

2e Pathways – geofence collars

As would be expected, 1-hr fix rates from geofenced collars gave higher temporal resolution to movement paths, especially where caribou spend a greater duration of time (Figs. 16, 17). We selected the two examples, each with significant delays, to demonstrate how the fix rates make a difference to describing individual pathways. Compared with 8-hr fix rates, 1-hr fix rates documented more frequent and closer approaches to mine infrastructure (t = 8.0, 3 df, P = 0.004), higher mean speeds (t = 4.2, 3 df, P = 0.025), and variable differences in the proportion of hard turns (Table 8). The number of fine-scale approaches detected increased with the 1-hr versus the 8-hr resolution for three of the four caribou.

Table 8. Comparison of movement path metrics between 1-hour and 8-hour fix rates. Approaches were measured at a fine scale and considered unique if the path exited the 3-km buffer. Mean distances (m) provided for matching approaches for each caribou.

	No. approaches		Proportion hard turns		Speed (km/hr)	
Caribou	1-hr ($\bar{x}$ m)	8-hr ($\bar{x}$ m)	1-hr	8-hr	1-hr	8-hr
BEVAH 16116 summer 2016	4 (580)	3 (783)	0.56	0.52	0.64	0.37
BATH 17102 summer 2017	4 (104)	3 (401)	0.50	0.51	0.47	0.40
BEVAH 17105 fall 2017	6 (952)	6 (1,307)	0.40	0.48	0.58	0.39
BATH 18116 winter 2019	5 (965)	4 (1,198)	0.47	0.44	0.46	0.30

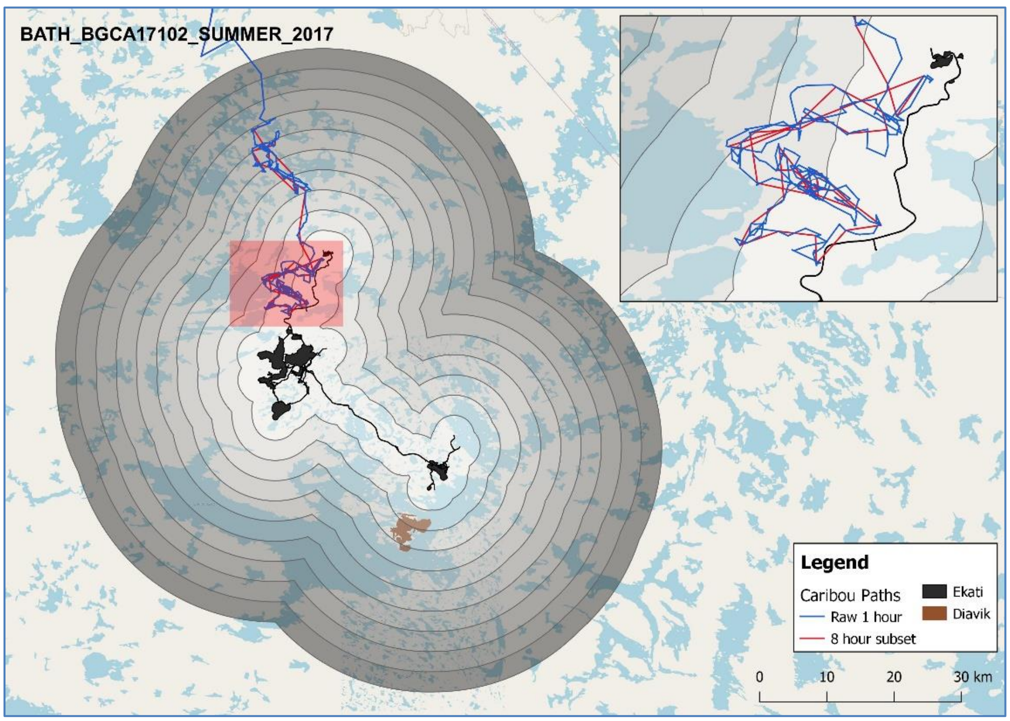


Figure 16. Example of caribou pathways for a collar with 1- and 8-hour fix rates, summer 2017. Area of inset is shown in red shading.

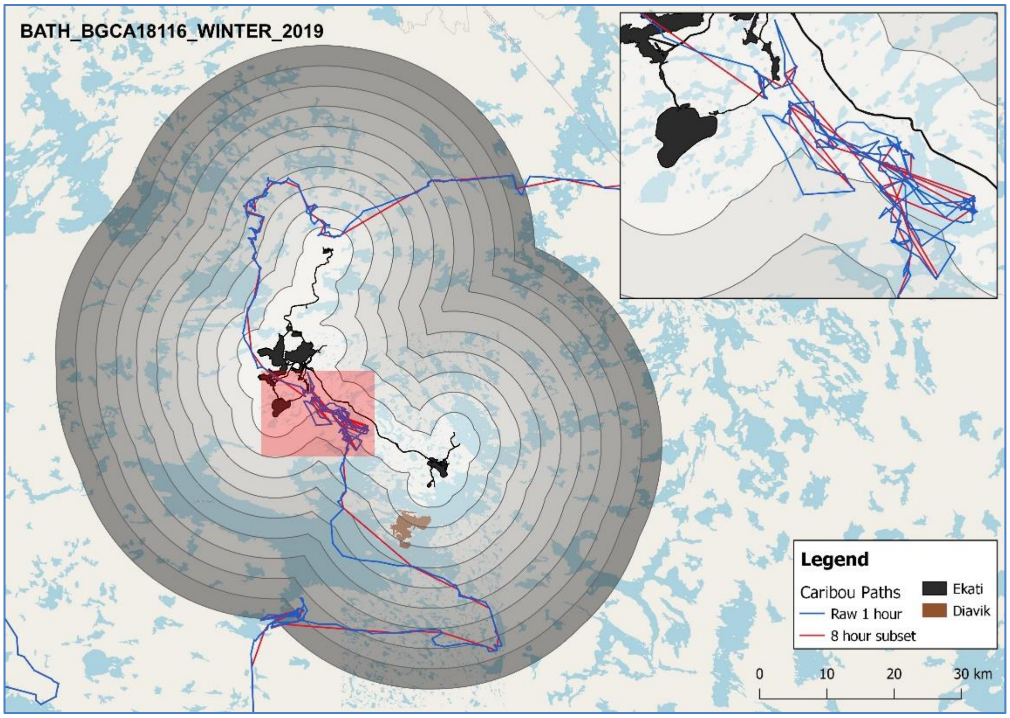


Figure 17. Example of caribou pathways for a collar with 1- and 8-hour fix rates, winter 2019. Area of inset is shown in red shading.

2f Pathways – use of ramps

Few crossings by caribou were recorded on the Misery Road during 2016-19 (*n* = 7), and the apparent use of crossing ramps was low (Table 9). A roughly equal number of pathways (*n* = 6) came within 30 m of ramps but the individuals did not cross. Sample size was too low to correlate ramp use with monthly haul truck traffic on Misery. More crossings of Sable Road were detected, with 78% (14/18) occurring during 2017 during construction but prior to ore hauling. Two-thirds and half of pathways were within 300 m and 150 m of crossing ramps on the Sable Road, respectively. Again, an equal number of caribou were within 300 m of ramps on the Sable Road but did not cross (*n* = 19).

Table 9. Total number of road crossings (No. crossings), and number (proportion) that crossed (Crossed) and did not cross (no crossed) within 300 and 150 m of caribou crossing ramps for the Misery and Sable roads, Ekati, 2016-19. "Crossed" = the caribou crossed the road; "No cross" = the caribou came within 300 or 150 m of a crossing ramp but did not cross the road.

		Crossed		No crossed	
Road	No. crossings	≤300 m (%)	≤150 m (%)	≤300 m	≤150 m
Misery	7	2 (29%)	0	6	3
Sable	18	12 (67%)	9 (50%)	19	6

Discussion

Overall, 38% of the 280 Bathurst and Beverly/Ahiak collar pathways that entered within 30 km of the Ekati mine came to within 3 km (encountered) of the mine footprint during 2010-2019. Of the other pathways, 27% went straight through the 30 km buffer zone and 35% changed direction at a lake or other landscape feature within the 30 km buffer zone. Sequences of individual movement pathways showed low rates of crossing through the mine site or across roads (25%; 38/155) and that caribou were delayed on 57% of the encounters with Ekati. The delays were measured through an increased proportion of hard turns (≥60°) and a reduction in speed within 3 km of mine infrastructure. The delays averaged several days and were twice as long in summer compared with other seasons. These data provide evidence that mitigation applied in the current CRMP may not be effective at facilitating caribou movement through the mine site. Delays to passage may result in additional energetic costs to the caribou.

Based on similar experiences at a mine in Nunavut, we suspect caribou delayed their movements within 3 km of the Ekati mine in part as a response to traffic. During spring migration at the Agnico Eagle Meadowbank mine north of Baker Lake, collared caribou delayed on average 4.3 and 2.5 days during 2018 and 2019 spring migrations, respectively, before crossing the road (Boulanger et al. 2020). However, neither our Ekati study nor Boulanger et al. (2020) could precisely compare the delays or crossings relative to vehicle passages or road closures. Monthly traffic frequency data were available for the Ekati mine but daily or hourly traffic frequency are needed to examine caribou responses using collared caribou. A second limitation to interpreting the delays and low crossing rate based on the individual collared caribou is that we do not know about the collared caribou's neighboring caribou. Caribou are strongly social and group size as well as leadership influence their behavior especially responses to disturbance (Padilla and Kofinas 2014; Appendix D).

Our analysis was exploratory as it was the first time the sequences of individual caribou pathways has been examined close to Ekati mine. While we met our first two objectives (annual and seasonal exposure of caribou to within 30 km and individual caribou encounters with and responses to the Ekati mine site), our results are descriptive and inferences are somewhat limited by low annual sample size for the collared caribou in some years, even though the number of collars increased since 2015. Changes to annual and seasonal distribution also complicated interpreting trends in the exposure of collared caribou to Ekati mine. The Bathurst caribou winter range has annually shifted from southwest to northeast closer to the Ekati mine with higher overlap in fall after 2015 and in winter during 2017-19, increasing the winter exposure of Bathurst caribou within 30 km of the mine in 2017-19. In 2013 and 2015, caribou exposure close to the Ekati mine was minimal (Appendix A). The Beverly/Ahiak herd's overlap with the Ekati mine area was primarily in winters 2017-19, summer and fall 2016 and 2017, and fall 2018.

The description of the use of tata (land-bridges) and depiction of historical caribou routes suggests that the landscape influences caribou movements and partly funnels the caribou toward what is now the Misery and especially Sable roads (Tłı̨chǫ Research and Training Institute 2013; Fig. 2). We do not know what extent the landscape motivates the caribou to cross roads relative to traffic and possible presence of predators. The theoretical framework for describing caribou responses is that caribou respond to anthropogenic disturbance (e.g., people and vehicles) as they do to predators (Frid and Dill 2002). Caribou rely on similar strategies as other prey species which trade-off the risk of predation against forage intake by adjusting the timing of when and how long they forage relative to finer-scale habitat (forage patches) or coarser-scale habitat patches (Morris 2019). We know that, for example, wildebeest (*Connochaetes taurinus*) reduce their speed and increase their turning angles when in a lion's (*Panthera leo*) home-range, because slowing down and turning more gives the wildebeest time to assess the risk from the predators (Droge et al. 2019).

At this stage, we cannot distinguish whether and if the presence of predators intensifies caribou responses to the roads and mine site traffic and activities. Incidental predator sightings are annually variable at Ekati mine but have recently increased. For example, in 2019 there were 212 incidental observations of wolves (*Canus lupus*), 23 of wolverines (*Gulo gulo*), and 252 of grizzly bears (*Ursus arctos*) at the Ekati mine, with an increasing rate of sightings from 2010 to 2019 (Dominion Diamond Mines 2020b). The recent increase has been attributed to more caribou being sighted at the mine (Dominion Diamond Mines 2020b). Whether the presence of wolves, wolverine and grizzly bears are additional aversive stimuli in addition to the noise and activity associated with an operational mine for caribou responses is unknown. Consistently but at a low frequency, wolves have been observed killing caribou adjacent to roads and pits during 11 of 16 years since 2004 (ERM 2019).

Arguments could be made that caribou had little incentive to cross a mine road, especially during non-migratory periods, if preferred habitat were more frequent on the side of the road caribou were on than the other. However, this possible explanation is unlikely. We found that that using the same landcover dataset used in Boulanger et al. (2021), preferred habitats were readily available within close proximity to both sides of the Misery and Sable roads (Fig. 18; see Appendix E for Misery Road figures). Dust from vehicle traffic and mining operations may be influencing caribou residency close to roads and other mine structures (Chen et al. 2017).

A key question is whether the delays represent tolerance of disturbance or that the caribou are waiting for a predictable gap in traffic so they can cross the road (assuming that they are motivated to cross the road). A precautionary interpretation is that caribou would cross in the absence of disturbance and the delays are the consequence of caribou waiting to cross. Social behavior such as group size, leadership and previous experience are likely related to the motivation to cross. Inuit Qaujimajatuqangit (IQ) identifies that caribou's prior experience, including how they are treated (respected), can affect their behaviour and responses and IQ recognizes the role of leadership in caribou movements (Appendix D). Likewise, biologists understand how learning and leadership are important in how caribou respond to roads and traffic (Appendix D).

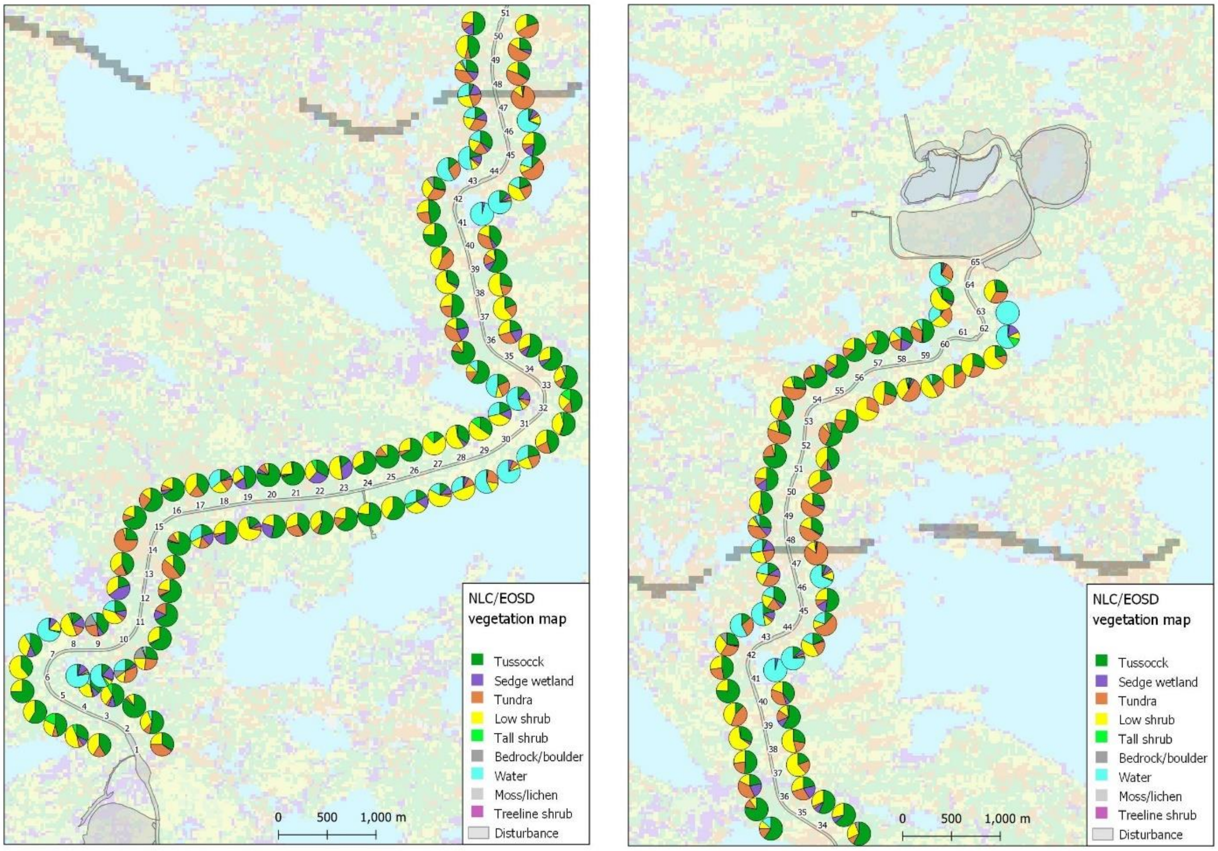


Figure 18. Vegetation classes (see Boulanger et al. 2021) within 100 m radius circles (~50 pixels) spaced 250 m from road edge every 250 m, Sable Road. Linear grey feature is an esker.

We recognize that caribou do stop and turn while they are foraging and depending on the size of habitat patches, those turns can result in clusters of steps with sharp turns. We also recognize that when we identified the clusters inside the inner 3 km zone, we termed them delays based on their proximity to a mine structure such as a road, whereas outside the 3 km zone we did not categorize the clusters. As an example, mean step length (1 hr fix rate) in a cluster of steps close to Sable Road was half as long as a cluster of steps distant from the mine (Table 10). A more detailed analysis using a statistical approach to the segmented pathways would contribute to a better understanding of the underlying caribou's motivation for clusters caused by sharp turns.

Our third objective for this exploratory examination of the collared caribou was how the individual caribou pathways contribute to the efficacy of monitoring. Our findings contribute to Arctic Diamond's Environmental Impact Report Section 8.1.2 on community involvement with roads and caribou (Dominion Diamond Mines 2020a), especially in developing/revising caribou monitoring and mitigation programs. We note that the delays and low rate of mine and road crossings detected coincided with current mitigation practises (CRMP; Golder Associates 2017), which indicates that mitigation could be more effective.

Table 10. A comparison of step length from two sets of pathways within a "cluster" (concentration) of turns in the vicinity of Sable Road and 15–20 km northeast of Misery Road, Ekati mine, September 2017.

	Sable cluster within 3 km		Misery cluster 15–20 km to NE
	Bathurst	**Beverly/Ahiak**	**Mean of 4 BAH and 2 BEV/AH cows**
Mean length ± SE	454 ± 42.8 m	511 ± 45.1 m	1,112 ± 483.1 m
Range	1 – 2,562 m	2 – 2,442 m	473 – 3,503 m
No. steps	144	150	848
Date	7 Sep (12:00 AM) to 13 Sep (12:00 AM)	7 Sep (12:00:00 AM) to 13 Sep (6:59 PM)	7 Sep (12:00 AM) to 28 Sep (13:00 PM)

Geofence collars set to 1-hour fix rate provide higher temporal and spatial resolution data on caribou movements, tortuosity and speed. They documented more approaches to and hard turns from infrastructure, data that could be correlated with finer-scale traffic data. It is not likely that geofence collars will detect crossings that 8-hour fix rate collars would not detect. Finally, geofence collars will provide increased resolution to determine increased likelihood of use of caribou crossing ramps, but even at a 1-hour fix rate the spatial resolution of the caribou pathway may not be adequate – camera studies may be better suited to address this objective (Arctic Canadian Diamond Company Ltd. 2021a). In summary, geofence collars would be appropriate for fine-scale examination of individual pathways close to infrastructure, especially to correlate with changes in mitigation (e.g., closing a road to traffic) and to determine the ultimate 'fate' of a caribou pathway, something that camera monitoring is unable to achieve. The benefits of more rapid fix rates must be weighed against additional power costs and shortened collar battery life.

Caribou crossing ramps have been installed to facilitate the crossing of roads to mitigate the potential barrier effect (ERM Rescan 2014). The locations of these ramps were suggested by Elders and other land users. Mine monitoring indicates a positive association between crossing events and the presence of these ramps, suggesting that caribou will preferentially use these ramps when they are available (ERM Rescan 2014). However, our analysis of pathways indicated caribou turning away from roads at greater distances (mean of about 1,100 m) than would be detected by the current camera design, as well as relatively few crossings of roads and limited likelihood of use of ramps, but we acknowledge that the scale of monitoring to address behaviours at the roads are most likely appropriate for well-designed camera studies.

Unlike camera, road surveys and the behavioural scans, the collar pathways are a sequence of behaviour for the same individual so it is possible to measure the duration of behaviours, such as the duration of delays, and sequences, such as whether delays are followed by the individual caribou crossing the road or not. While this is informative, it is limited by sample size, whether the collared caribou are leading or following other caribou (i.e., the role of social behaviour), and the degree of traffic. Those limitations can be offset by using cameras, road surveys or behavioural scans which generally return large sample sizes, but the results are instantaneous scans of behaviours and numbers of caribou, not sequences of behaviour for individuals. The inescapable conclusion is that for monitoring to be efficient, monitoring methods need to be integrated.

Secondly, how individual pathways could contribute to mitigation is both through fine-tuning timing of mitigation and a precise way of measuring effectiveness. If giving caribou the right-of-way; keeping at least 100 m away; slowing to 10–20 km/hr when caribou are within 200 m of the road or 40 km/h when caribou are within 500 m and finally closing the road are effective, the delays should decrease and the crossings increase. Fine-tuning the timing of mitigation, especially road closures, is necessary as currently the CRMP relies on collars as 'early warning' of the approach of caribou and implementation of mitigation. Even though ENR provided Arctic Diamond with collar information, no retrospective examination of individual collar pathways and traffic management has been conducted. It is unclear how the reported road closures of 0.02 hr to 7.5 hr (total 88.5 hr) in 2019 were related to caribou presence and crossings as the scale of reporting was imprecise (Dominion Diamond Mines 2020b). In 2019, relatively high numbers of caribou were observed during 39 days along Misery Road (3,899 caribou) and during 21 days along Sable Road (2,195 caribou).

Caribou behaviour is complex as the caribou are always integrating information about their surroundings. Our analyses are an attempt to both display and to unpack some of the complexity to refine our understanding of how caribou are responding to the mine site. Our analyses hint at the motivational state of the caribou (migration vs non-migration) but do not take into account memory and how the caribou perceive the landscape and at what scale they make decisions such as about whether to cross a road. Support for understanding the importance of those scales comes from a recent study of how deer (*Odocoileus* sp.) respond to fences (Burkholder et al. 2018). The deer were making their decisions prior to approaching a fence instead of arriving at a fence segment then deciding about whether to cross or not. Our pathways analysis was also intended to allow readers to see the complexity and variability for themselves through the hierarchical classification and the maps with examples.

Our results emphasise the responses of the caribou within 3 km of Ekati mine but several studies have documented larger-scale patterns (tens of kilometres) of responses by migratory caribou herds to industrial development and infrastructure (e.g., Johnson et al. 2005; Boulanger et al. 2012, 2021; Plante et al. 2018). However, these large-scale patterns are based on a composite sample of collared caribou analyzed at seasonal and annual timescales. Few studies have examined the behaviour and movements of individual caribou as they encounter industrial roads or development. For example, the timing, speed and direction of migratory movements by individual caribou can be affected by development (Vistnes et al. 2004, Panzacchi et al. 2013, Wilson et al. 2016, Boulanger et al. 2020). The ZOI measured from the movements of caribou was detected once the mine was in operation (in tandem with Diavik) and was statistically significant in 9 of 15 years from 2003 to 2017 (Boulanger et al. 2021). The opening and closing of the different pits changed the pattern of activity across the mine site as well as changes in overall caribou exposure to the mine and summer weather all contribute to the background variability that caribou are constantly addressing.

Recommendations

Our findings suggest that current mitigation is not yet effective at facilitating caribou movement through the mine site and consequently changes to monitoring and mitigation are required. We have three recommendations from our pathway analyses to contribute to improving adaptive management of caribou at the Ekati mine. Additionally, we have specific technical recommendations about how the caribou collars can contribute to efficient and effective monitoring and mitigation at the Ekati mine:

- Adaptive traffic management: to increase the efficiency and effectiveness of mitigation, we recommend developing a collaborative approach to experimental protocols for testing how to manage traffic flow to create predictable gaps in traffic which would enable caribou, especially the leaders, to cross roads without unnecessarily restricting traffic flow (this is a follow up to an Agency recommendation in 2017[2]).
- Integrated monitoring: Our findings lead us to recommend a collaborative approach to monitoring design using individual pathways from collared caribou to test options for defining deflection and quantifying deflections and delays to caribou passage. Currently, the deflections observed in camera studies are limited to the immediate area within camera view around or on the road (Arctic Canadian Diamond Company Ltd. 2021a). Decisions by many caribou about whether to cross a road appear to occur at greater distances from roads than captured in the current Ekati camera program.
- Cumulative impacts: We recommend that the individual collar caribou pathways should be used to address spatial cumulative impacts. Our finding that caribou are making decisions while approaching but distant from Ekati mine infrastructure raises questions about how future changes to the mine footprint have the potential to constrain free passage of caribou.
- Specific technical recommendations:
  - Our pathway analyses reinforce previous Agency requests (e.g., 2018-2019 annual report) that daily and hourly traffic should be used as covariates in determining impacts on caribou speed, turning angles and success in road crossings.
  - Caribou pathways derived from geofence collars (programmed to obtain 1-hour fix rates within 30 km of development) should correlated with caribou movements and daily/hourly traffic data.
  - Our studies reinforce the need to integrate the monitoring data acquired by geofence collars, road and powerline surveys and cameras, especially because the cameras can increase the spatial resolution beyond which the collars can provide for fine-scale monitoring and measuring gaps in traffic flow.
  - Integrating collar pathway analyses with road and powerline surveys and camera data will strengthen the efficiency of monitoring such as using these monitoring methods to add group sizes to collar data.

[2] Agency letter to Environment and Natural Resources, January 9, 2017; Re: Ekati Wildlife Effects Monitoring Plan (WEMP) and Caribou and Roads Mitigation Plan (CRMP) December 2016 Review.

- Different and updated approaches to analyze sequential movements should be explored, such as visually-explicit and tree-based Sequence Analysis Method (De Groeve et al. 2019)

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APPENDIX A

Annual and seasonal exposure of Bathurst and Beverly/Ahiak collared to Ekati mine site, 2010-2019.

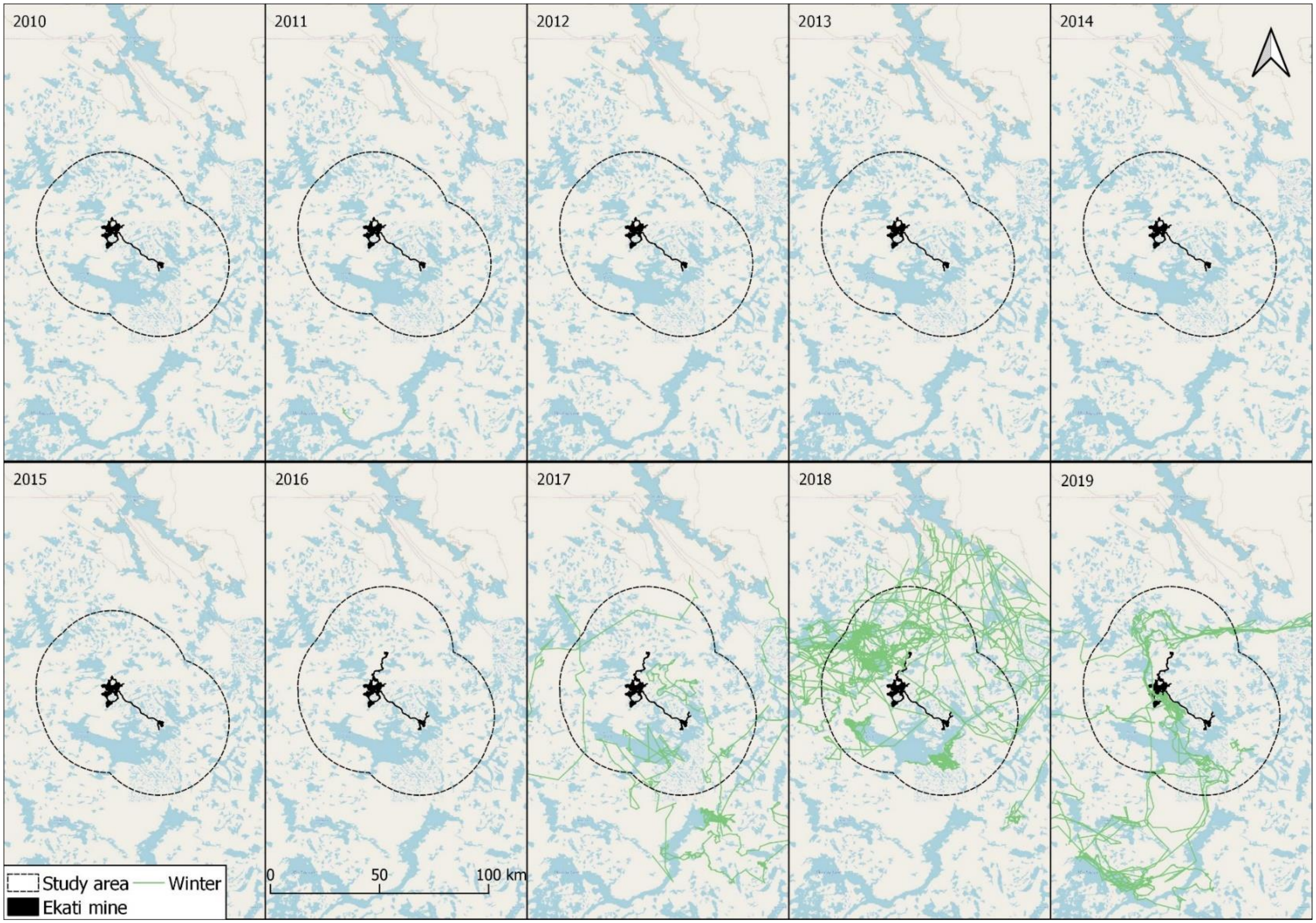


Figure A19. Collared Bathurst caribou cow movement paths during winter, 2010-19.

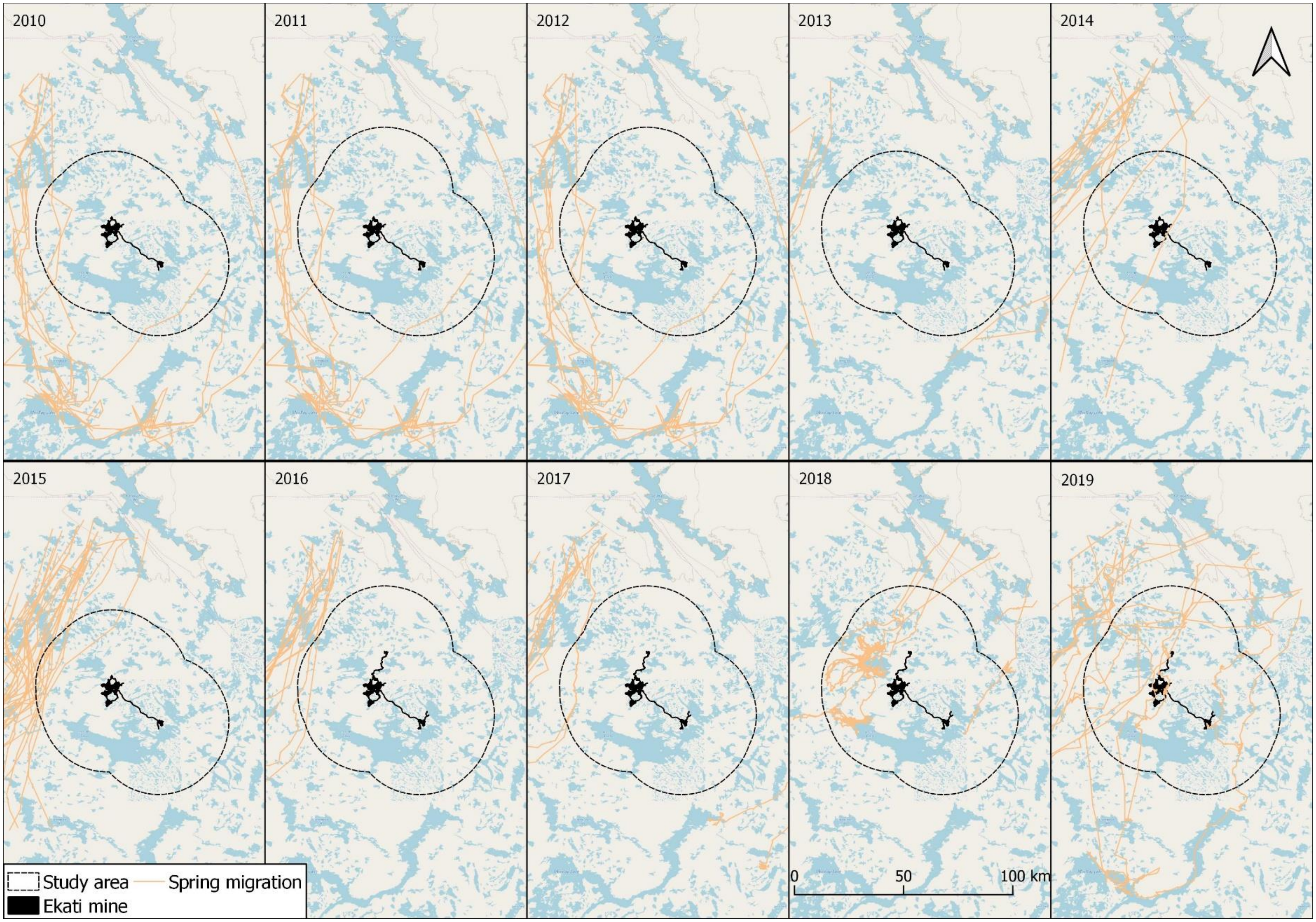


Figure A20. Collared Bathurst caribou cow movement paths during spring migration, 2010-19.

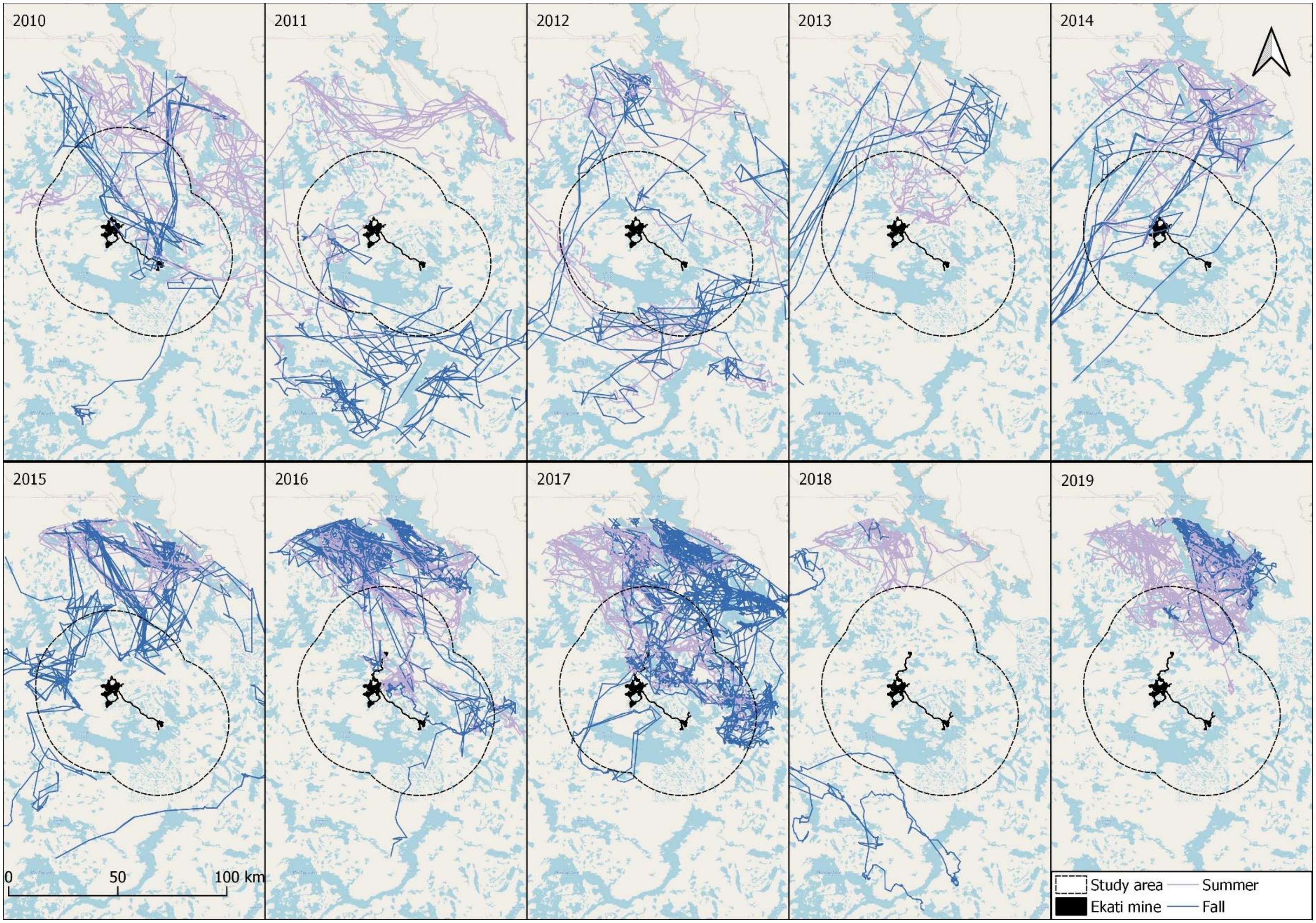


Figure A21. Collared Bathurst caribou cow movement paths during summer and fall, 2010-19.

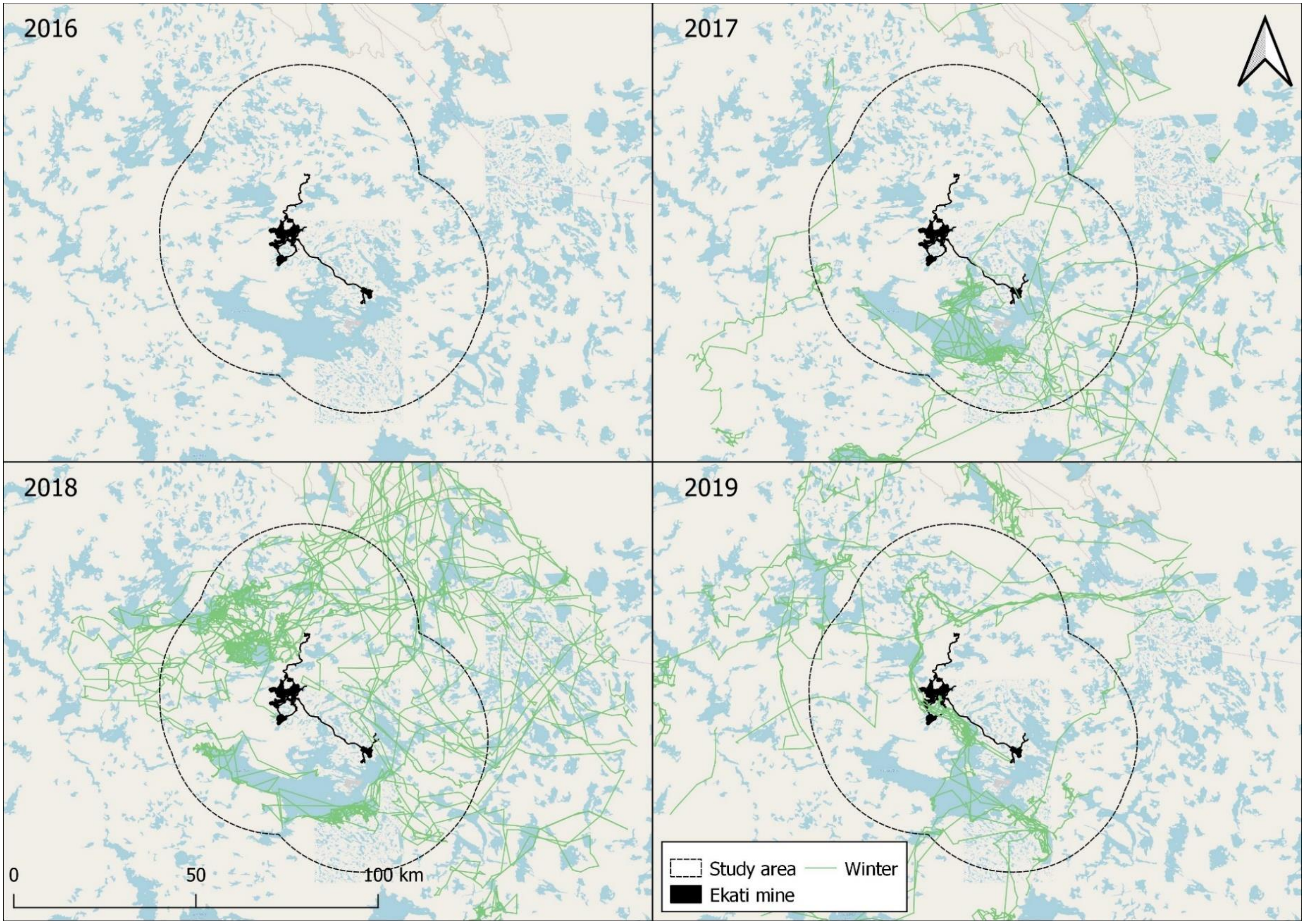


Figure A22. Collared Beverly/Ahiak caribou cow movement paths during winter, 2016-19.

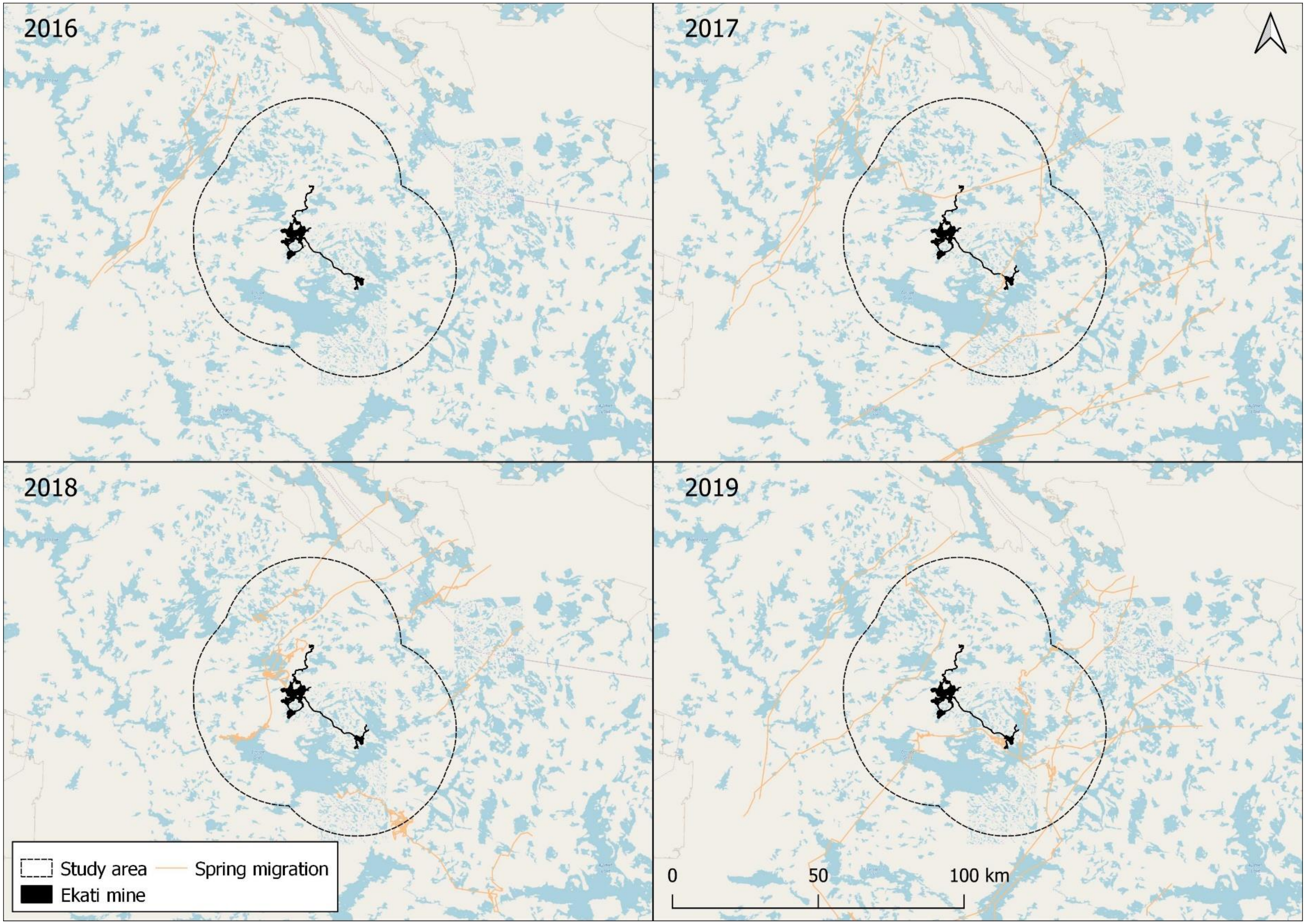


Figure A23. Collared Beverly/Ahiak caribou cow movement paths during spring migration, 2016-19.

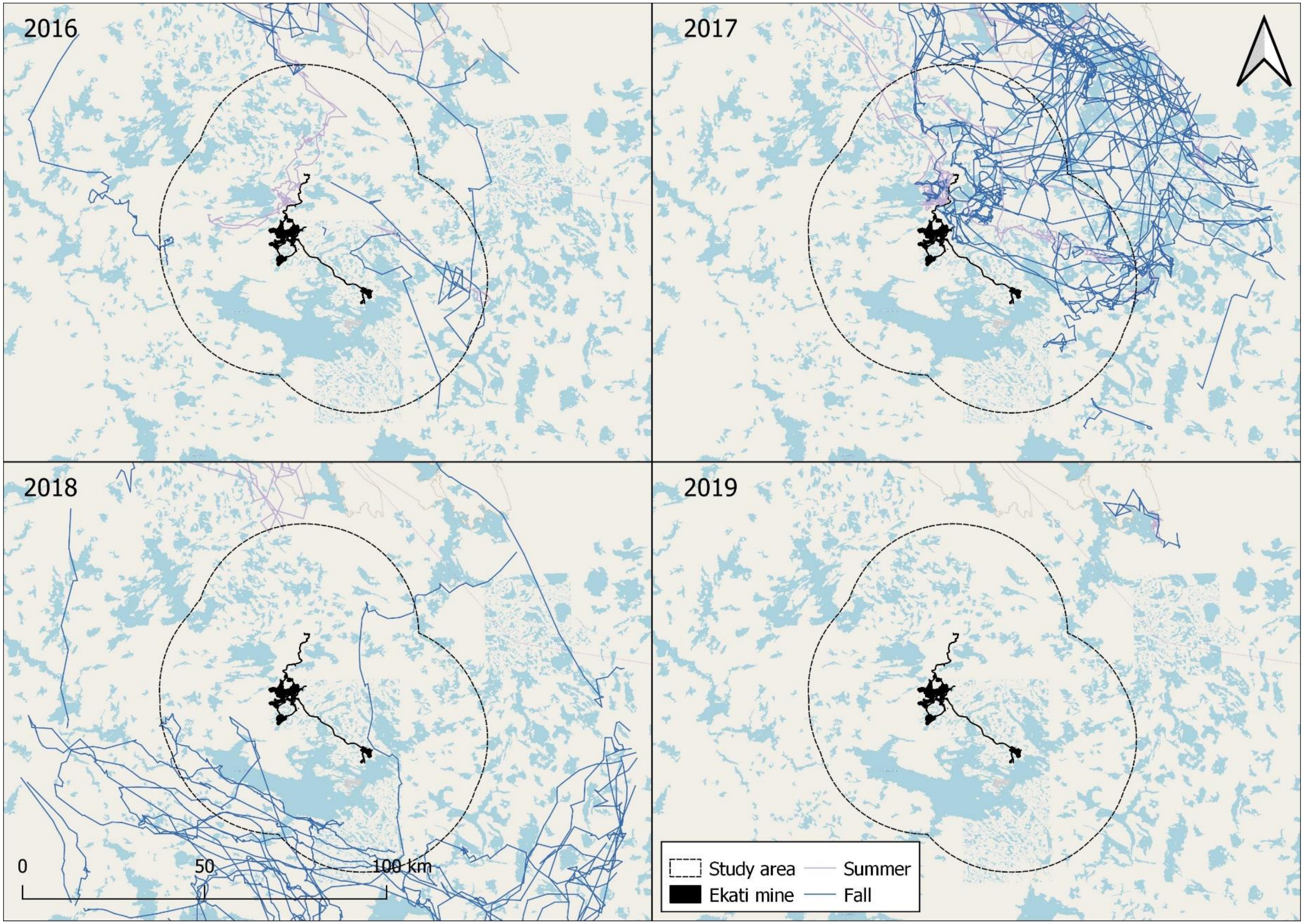


Figure A24. Collared Beverly/Ahiak caribou cow movement paths during summer and fall, 2016-19.

APPENDIX B

Table B11. Mean individual residency (hours/km²) for collared Bathurst caribou within 3-km buffer distances by year. Only year-buffers with ≥5 caribou are shown.

Year	3	6	9	12	15	18	21	24	27	30
2010	0.103	0.084	0.093	0.143	0.085	0.095	0.058	0.032	0.032	0.033
2011				0.095	0.252	0.179	0.061	0.037	0.118	0.097
2012	0.066	0.081	0.062	0.059	0.067	0.091	0.098	0.126	0.158	0.130
2013						0.059	0.044	0.055	0.088	0.060
2014	0.111	0.063	0.032	0.028	0.026	0.040	0.051	0.029	0.032	0.033
2015					0.068	0.101	0.083	0.060	0.038	0.056
2016	0.396	0.312	0.324	0.207	0.086	0.053	0.057	0.067	0.058	0.038
2017	0.161	0.225	0.139	0.126	0.113	0.108	0.131	0.146	0.111	0.129
2018	0.088	0.088	0.160	0.182	0.282	0.226	0.162	0.153	0.071	0.042
2019	0.261	0.115	0.074	0.112	0.118	0.129	0.119	0.089	0.096	0.067
Overall	0.169	0.138	0.126	0.119	0.122	0.108	0.086	0.079	0.080	0.069

Table B12. Mean individual residency (hours/km²) for collared Beverly/Ahiak caribou within 3-km buffer distances by year. Only year-buffers with ≥5 caribou are shown.

Year	3	6	9	12	15	18	21	24	27	30
2016										
2017	0.247	0.189	0.110	0.107	0.182	0.144	0.103	0.073	0.070	0.065
2018	0.082	0.121	0.138	0.131	0.237	0.172	0.139	0.087	0.078	0.065
2019	0.302	0.216	0.097	0.137	0.095	0.095	0.059	0.039	0.029	0.029
Overall	0.210	0.175	0.115	0.125	0.171	0.137	0.100	0.066	0.059	0.053

Table B13. Mean individual residency (hours/km²) for collared Bathurst caribou within 3-km buffer distances by season. Only year-buffers with ≥5 caribou are shown.

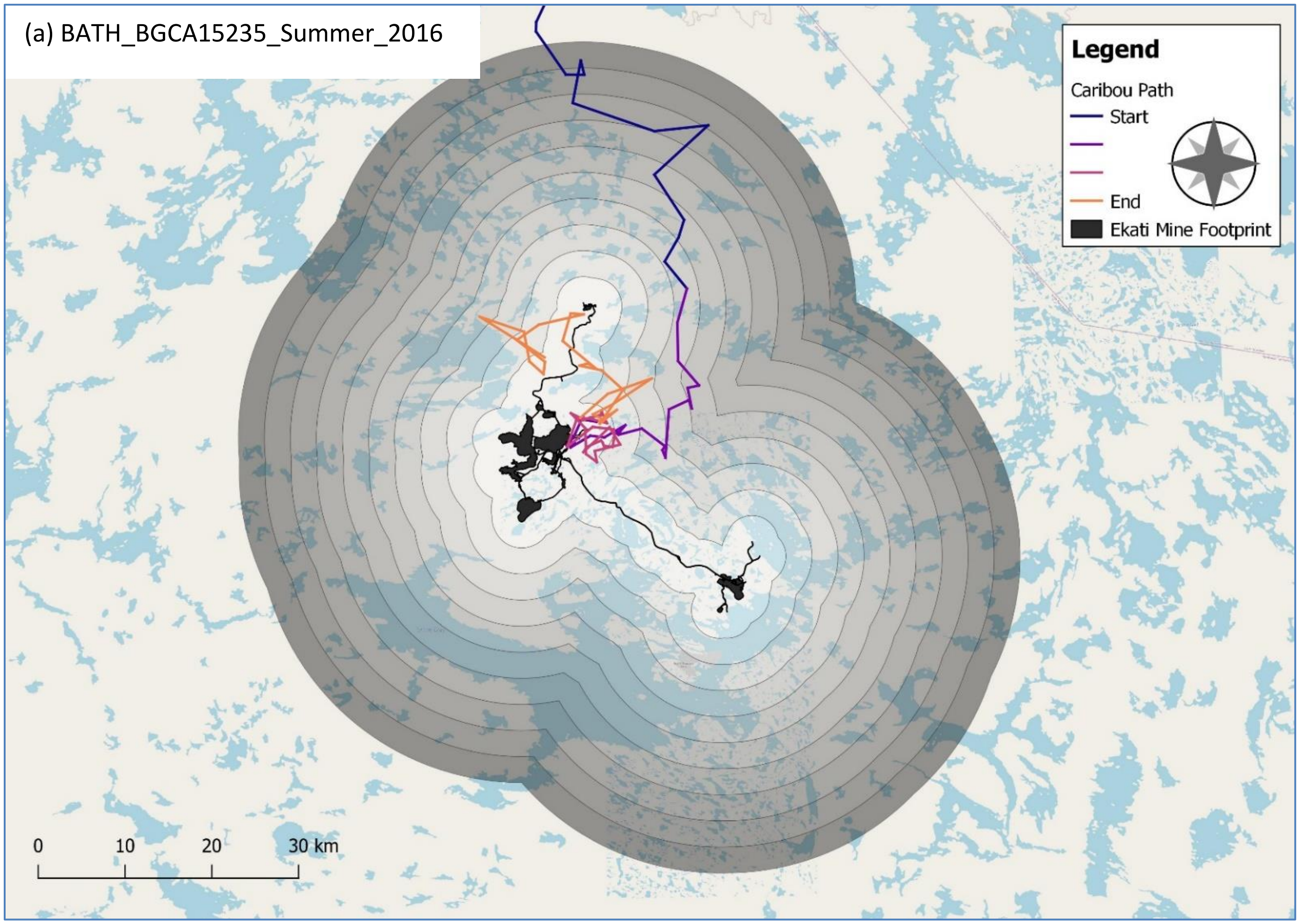
Year	3	6	9	12	15	18	21	24	27	30
Winter	0.187	0.141	0.158	0.175	0.240	0.197	0.160	0.127	0.070	0.051
Spring mig.	0.095	0.039	0.058	0.056	0.068	0.077	0.042	0.033	0.020	0.022
Summer	0.171	0.167	0.133	0.099	0.078	0.073	0.082	0.088	0.086	0.072
Fall	0.155	0.151	0.107	0.118	0.098	0.106	0.089	0.084	0.088	0.082

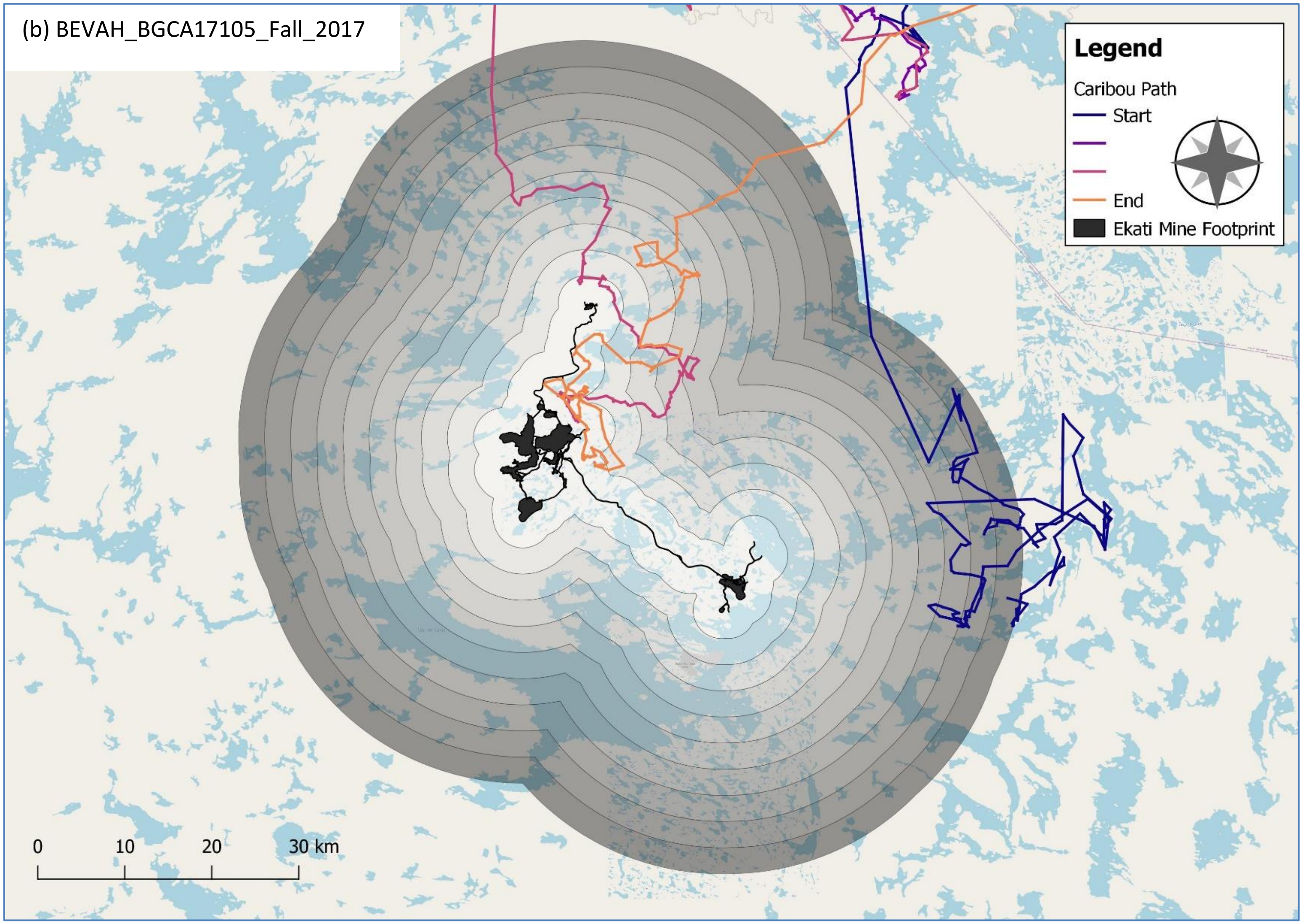
Table B14. Mean individual residency (hours/km^2) for collared Beverly/Ahiak caribou within 3-km buffer distances by season. Only year-buffers with ≥5 caribou are shown.

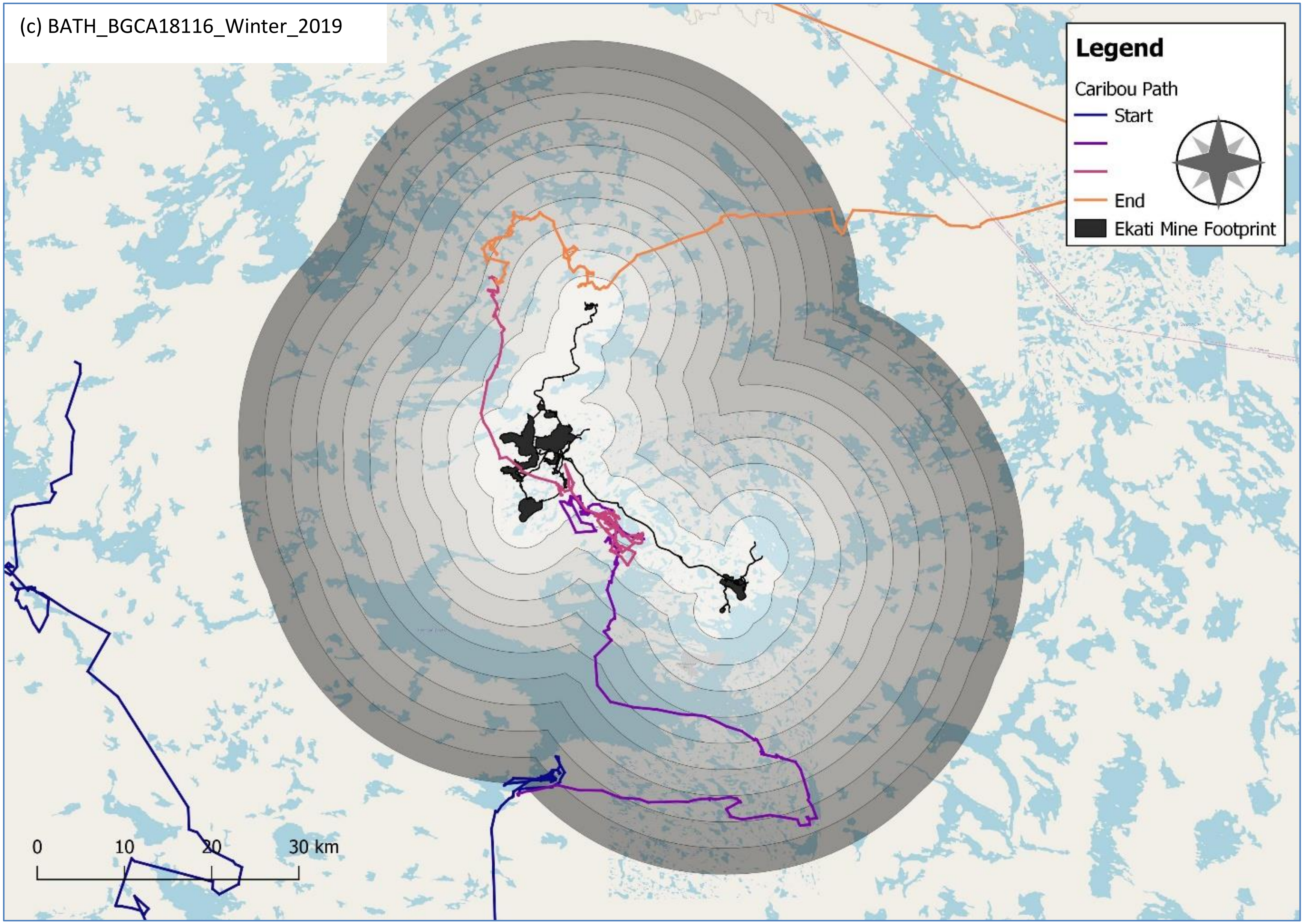
Year	3	6	9	12	15	18	21	24	27	30
Winter	0.200	0.179	0.135	0.174	0.258	0.201	0.146	0.093	0.082	0.053
Spring mig.	0.105	0.130	0.174	0.030	0.043	0.051	0.045	0.019	0.018	0.040
Summer						0.044	0.043	0.040	0.018	0.040
Fall	0.147	0.086	0.072	0.066	0.072	0.064	0.048	0.042	0.039	0.055

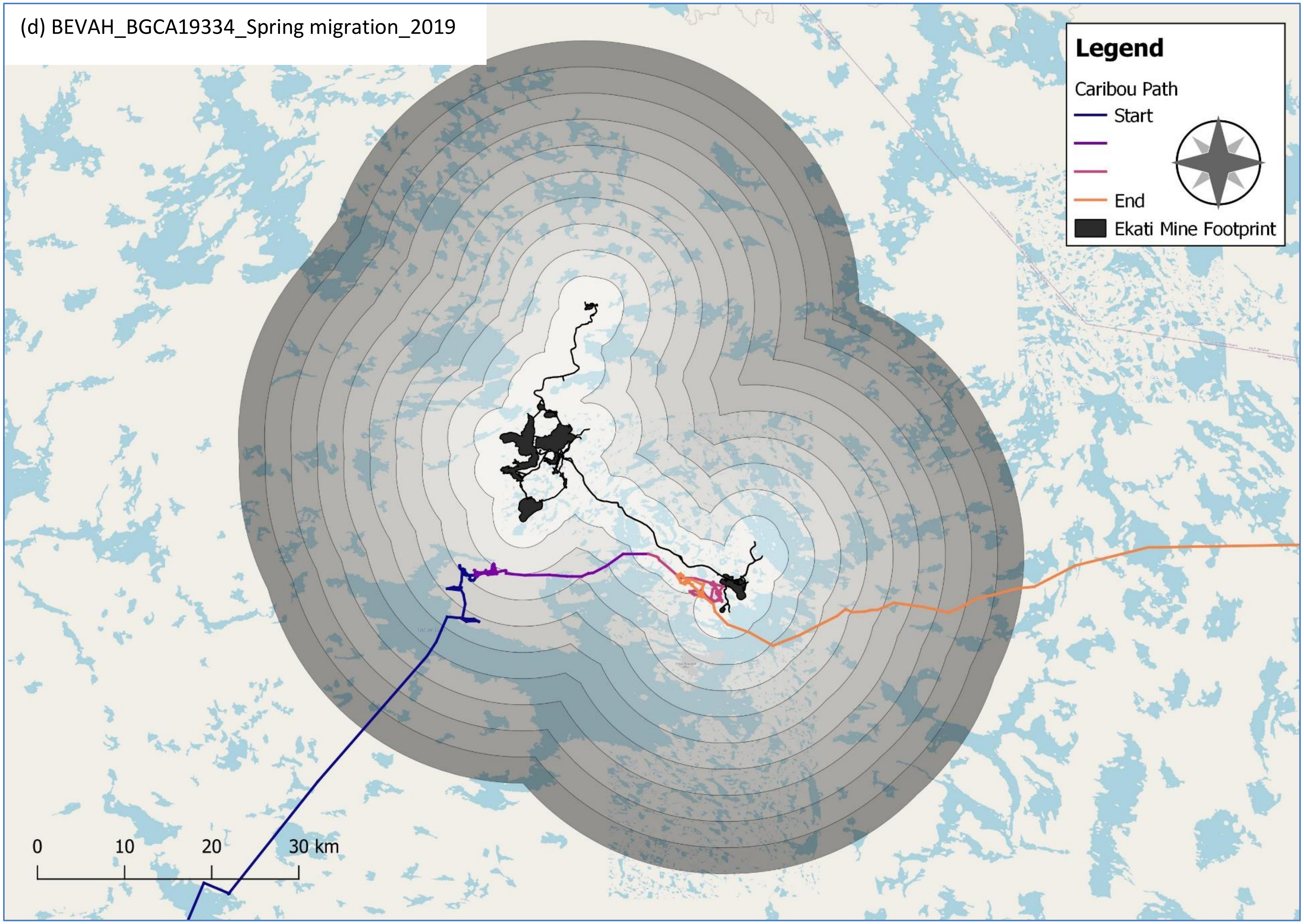
APPENDIX C

Figure C25. Examples of individual collared caribou pathways encountering Ekati mine site and roads with delays and crossings or not crossing (a) BATH_BGCA15235_Summer_2016, (b) BEVAH_BGCA17105_Fall_2017, (c) BATH_BGCA18116_Winter_2019, and (d) BEVAH_BGCA19334_Spring migration_2019.




(b) BEVAH_BGCA17105_Fall_2017
Legend
Caribou Path
Start
End
Ekati Mine Footprint
0
10
20
30 km


(c) BATH_BGCA18116_Winter_2019
Legend
Caribou Path
Start
End
Ekati Mine Footprint
0
10
20
30 km


(d) BEVAH_BGCA19334_Spring migration_2019
Legend
Caribou Path
Start
End
Ekati Mine Footprint
0
10
20
30 km

APPENDIX D

Technical summary of published literature on memory, group behaviour and leadership

Memory is part of an individual's internal state which is the underlying mechanism for why [move] based on Nathan et al.'s (2008) conceptual framework for underlying mechanisms for movements. A starting point was describing how herbivores foraging among habitat patches depends on memory in determining return rates to previously used patches (Van Moorter et al. 2009, Bracis et al. 2015, Avgar et al. 2015). An example of interaction between memory and environment affecting foraging movements is how GPS-collared elk avoided premature return and reuse of habitat patches but distance of the habitat patches to roads and traffic delayed the return rates to the habitat patches (Seidel and Boyce 2015). Recognition of the role of memory in selecting habitat patches and in movements argues for re-considering habitat to include prior experience and memory as well as environmental attributes (Merkle et al. 2019).

Increasingly, the role of memory and learning are being recognized as factors in seasonal migration through studies based on individual GPS collar-tracking and modeling (Westerly et al. 2018, Bracis and Mueller 2017, Merkle et al. 2019). By defining memory as the route used in the previous year, Merkle et al. (2019) had empirical evidence for the greater influence of memory than the rate of plant green-up in the routes of mule deer during spring migration. However, when green-up occurs during migration, the migrant mule deer take advantage of it for foraging and match their routes and timing to the greening vegetation (Aikens et al. 2017). Elsewhere, snow conditions affect the onset of spring migration which is in anticipation of plant green-up for elk (Rickbeilet al. 2019) and for caribou (Gurairie et al. 2019). Migratory tundra caribou have strong fidelity at the herd scale to their calving ground and as the location of the winter range is annually variable, Cameron et al. (2020) suggested that spatial memory is a likely explanation for the return to the calving grounds. While acquiring spatial memories can be rapid within a year (Jakopak et al. 2019), migration routes are learned and can be passed through generations (Cameron et al. 2020).

Little has been published on the role of learning and memory in monitoring and mitigation although it is difficult to see how learning and memory is not involved as an underlying mechanism. The process is likely complex; although several African wildlife species had learnt to use gaps in fencing, after the fencing was removed use of the 'ghost' gaps continued as the gaps also had reduced risk of predation (Dupuis-Desormeaux et al. 2019)

Migration depends on collective behaviour and increasingly there is understanding of how memory and learning also have a role in collective behaviour especially how information about movements is transferred within a social group. Earlier modeling which showed for example, that individual behaviour such as speed relative to collective behaviour -faster moving individuals reach the front of a group to become the 'leaders' or the group fragments (Gueron et al. 1996). Social groups are more than the sum of individual responses as the individuals also respond to changes in neighbors positioning and behaviour and thus groups can show increased sensitivity to possible threats (Sosna et al. 2019). Added to this collective responsiveness (contagious behaviour) is the concept of leadership which "can emerge as a function of information differences among members of a population, and is therefore transferable"

(Couzin et al. 2005). Individual-based modeling suggested that while a few individuals learning about migration direction from environmental cues, most individuals are followers through social interactions (Guttal et al. 2010).

This idea of informed individuals taking a leadership role is further developed in Berdahl et al.'s (2018) review which introduced theoretical and observational background for collective navigation (navigating within a social context). Collective behaviour can be examined at different scales: fine-scale is direct observations of individuals but it is difficult to identify the relationship among unmarked individuals. A relatively coarser scale approach to screen for collective behaviour is Dalziel et al.'s (2015) use of modeling and collared caribou. That analysis revealed complexity during seasonal migrations with increases and decreases in collective behaviour in the Leaf River caribou herd. Also using satellite and GPS collars, a different approach was the proximity between pairs of individual collared caribou in the Bathurst herd (Gurairie et al. 2020). Calabrese et al. (2018) applied a different modeling approach to describe collective behaviour and movements based on a correlated movement. Their movement correlation indices revealed a tendency to move in the same direction (drift correlation suggesting environmental mechanism) and a stochastic component more revealing of social interactions. Applying the model for pre-calving migration for the Porcupine caribou herd using older data from five VHF collared caribou in 1988 suggested that environmental conditions triggered the onset of pre-calving migration.

The difficulty of keeping simultaneous track of identified individuals (Koger et al. 2019) has led to increasing complexity of methods which includes drones to capture fine-resolution images of individual caribou from the Dolphin and Union caribou herd as they crossed sea-ice during fall migration (Torney et al. 2018). The drone images and GPS collar locations were the input for random-walk modeling which incorporated a social heading based on the headings of nearest neighbor caribou. Large bulls had the least and calves had the most reliance on social cues but adults made greater use of the directional cues from their neighbors. Torney et al. (2018) concluded that the best fit model which weighted the distance to neighboring caribou was the closest approximated decisions underlying the migrations.

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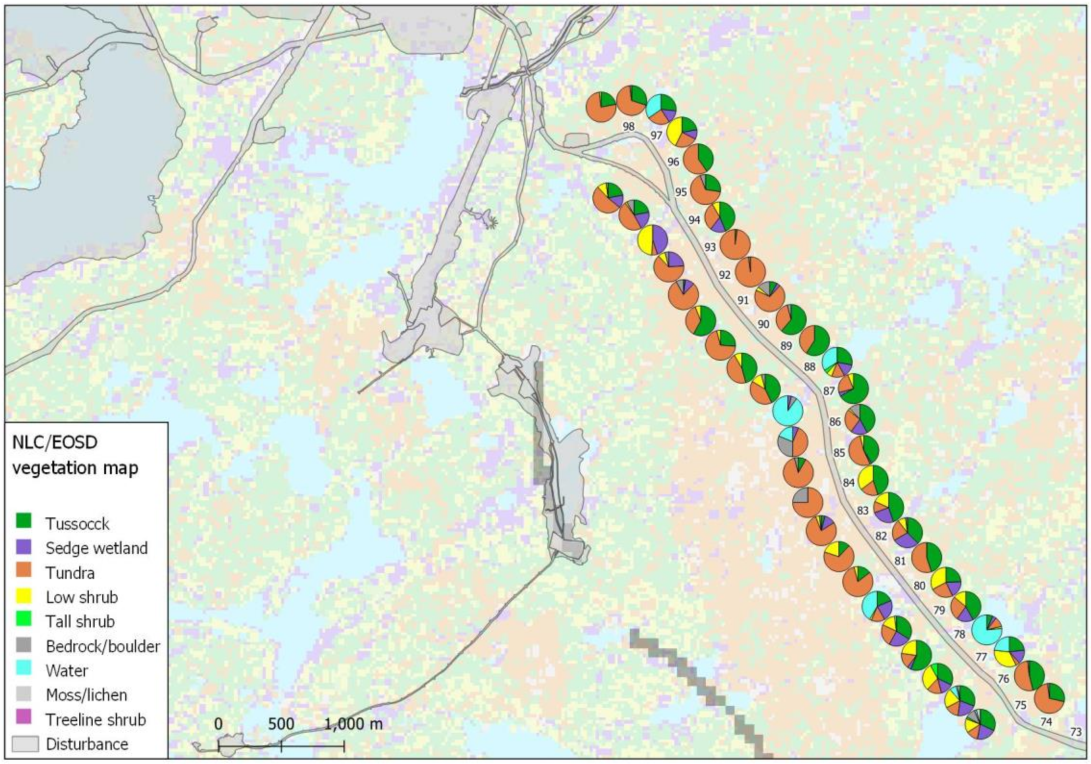
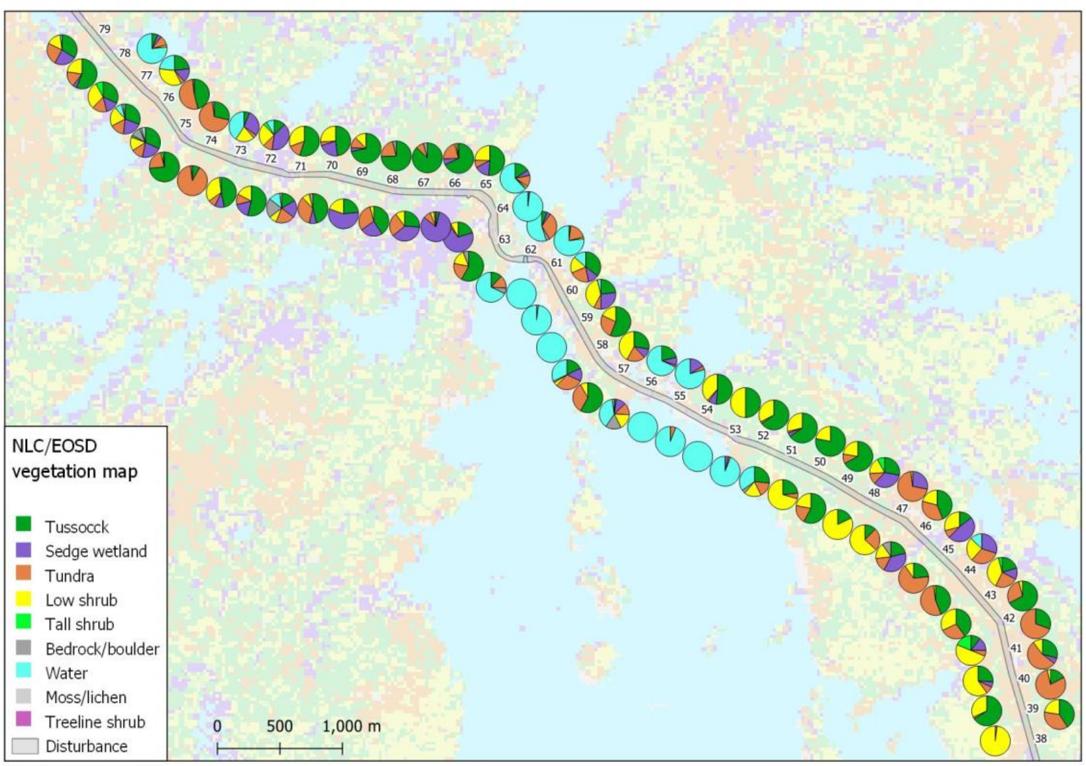
APPENDIX E


NLC/EOSD
vegetation map
Tussocck
Sedge wetland
Tundra
Low shrub
Tall shrub
Bedrock/boulder
Water
Moss/lichen
Treeline shrub
Disturbance
0 500 1,000 m


NLC/EOSD
vegetation map
Tussocck
Sedge wetland
Tundra
Low shrub
Tall shrub
Bedrock/boulder
Water
Moss/lichen
Treeline shrub
Disturbance
0 500 1,000 m

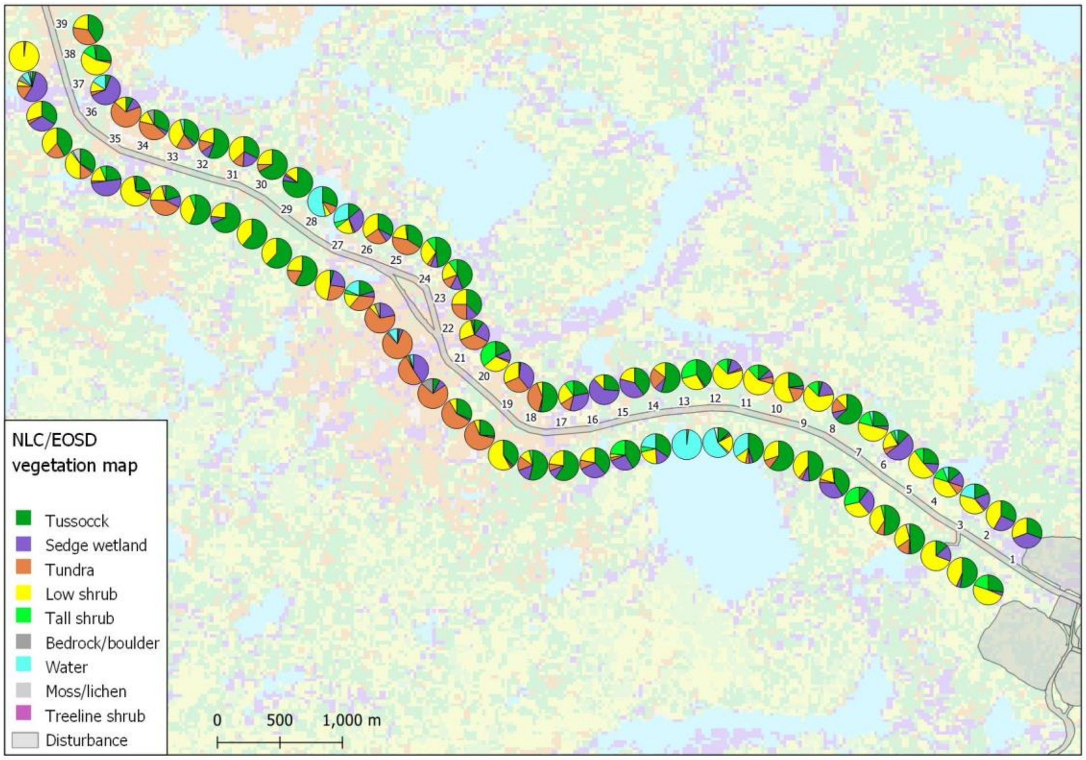


Figure E26. Vegetation classes (see Boulanger et al. 2021) within 100 m radius circles (~50 pixels) spaced 250 m from road edge every 250 m, Misery Road from west to east. Linear grey feature is an esker.