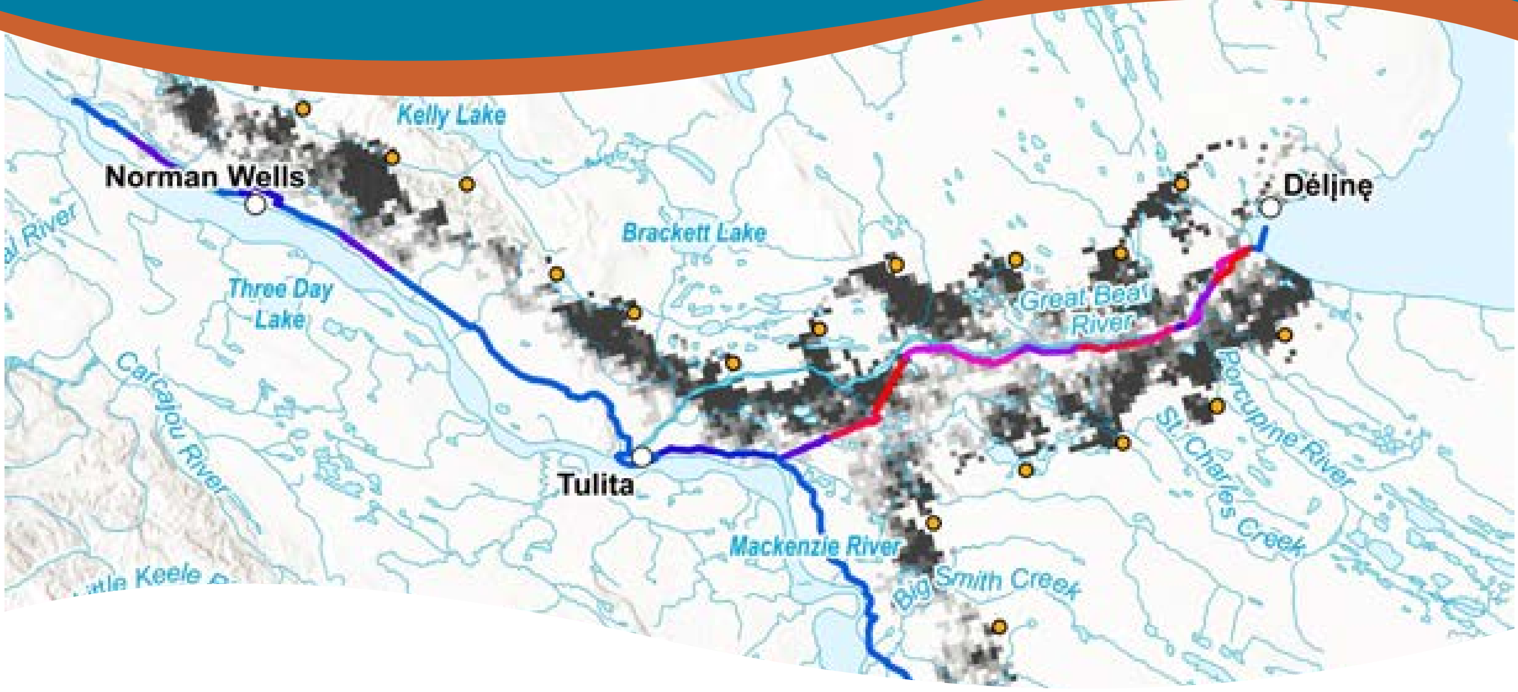
Mackenzie Valley Highway Project: Inferring the Potential Barriers to Boreal Caribou Movement



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ENVIRONMENTAL DYNAMICS INC.
Down to Earth Biology

EXECUTIVE SUMMARY

INTRODUCTION

The Mackenzie Valley Highway Project (the Project) is a proposed 281-km extension of the all-season Mackenzie Highway in Northwest Territories (NWT). The Project parallels the Mackenzie River and will replace the north-south portions of the Mackenzie Valley Winter Road (MVWR) between Hodgson Creek (about 1 km north of Wrigley) and Prohibition Creek (about 28 km south of Norman Wells). During the environmental assessment process, concerns were raised that the Project could amplify the existing effects of the MVWR. There is uncertainty about whether the highway might alter or restrict boreal caribou movement. To address these concerns, EDI Environmental Dynamics Inc. was retained to conduct a technical study on boreal caribou movement.

Our study objectives were to assess the potential for the Project to affect caribou movement patterns and pose a barrier to movement across the landscape. An additional concern was whether sensory disturbance from the Project could affect caribou calving. Because the Project has not yet been constructed, we needed to predict what its effects could be in the future. To do this, we evaluated the current effects of the MVWR to make inferences on potential impacts of the highway, assuming that any future effects from the Project might be greater in magnitude, frequency, and duration due to its permanent footprint and increased year-round traffic.

The study included primary and supplementary investigations that required geographic positioning system (GPS) telemetry data from collared boreal caribou in the Sahtú and Dehcho regions of NWT. We focused on three seasons to assess the MVWR's potential effect on boreal caribou movement: early to mid winter (Oct 26–Mar 15), late winter (Mar 22–Apr 1), and calving to post-calving (May 1–Jul 12)[a,b]. Winter months are when the MVWR is active, and traffic is present, while calving to post-calving is when caribou are most vulnerable and sensitive to disturbances.

Animals move in response to resources, such as forage. Therefore, we examined caribou movement using a modelling framework that included habitat selection and movement processes. First, we developed models that considered habitat selection and movement in the presence and absence of the MVWR's potential influence. Then, we used those models to simulate caribou movement across the landscape and to see if the MVWR's effect on movement would reduce caribou crossings and space use near the winter road. The supplementary investigation assessed how far cows calved from the MVWR and determined whether those locations would expose caribou to sensory disturbance once the all-season highway is established.

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[a] Earliest and latest dates based on seasonal timings in Sahtú and Dehcho regions; seasonal timings differ between the two regions.

[b] In preliminary work, we also examined habitat-dependent movement for several other seasons (pre-calving, summer, rut, and late fall) but found little evidence of the MVWR affecting movement in most of those seasons. We were also constrained by computational requirements to conduct a complete set of analyses (including simulations) for each of these additional seasons. Ultimately, our focus on early to mid winter, late winter, and calving to post-calving was to ensure coverage of the period when the MVWR was actively being used (winter seasons) and the most sensitive season to caribou (calving to post-calving).

METHODS

Effect of the Winter Road on Movement — We generated models to examine caribou habitat selection and movement in all three seasons, considering only those caribou that had the potential to interact with the MVWR (i.e., within a 15 km zone of sensory disturbance). We compared three competing models. The first model, base effects (H1), included variables for habitat (forest type, terrain, water, burns, and linear feature density) and movement (step length and turn angle). The second model (H2) added the effect of the MVWR to the base model. The third model (H3) added the effect of all sources of disturbance correlated with (and including) the MVWR to the base model. Models H2 and H3 allowed boreal caribou movement to vary with the distance to the MVWR to estimate its effect on movement. We tested the prediction accuracy of all models using simulations and comparing model predictions to observed caribou movements.

Altered Habitat Connectivity — If models H2 or H3 had strong predictive abilities, we used them to assess whether the MVWR might reduce habitat connectivity for boreal caribou in the region. Using seasonal models, we simulated caribou movement for two scenarios: (1) *with* the MVWR's effect and (2) *without* the MVWR's effect. For each scenario, we quantified the number of times simulated caribou crossed the MVWR and the relative space use of simulated caribou in the area surrounding the MVWR. We compared the outputs of simulations from both scenarios to determine if the MVWR alters habitat connectivity.

Proximity of Calving Caribou to the Winter Road — To determine how calving might be affected by the MVWR, we assessed the distance of cows from the MVWR during calving events. We identified calving dates of boreal caribou (2007–2022) by calculating three-day average movement rates and identified the calving date as when caribou movements rapidly decreased and remained low over several days. We then calculated the distance of calving events from the MVWR and compared them to a potential zone of influence (15 km).

RESULTS

Effect of the Winter Road on Movement — Only five caribou trajectories crossed the MVWR during the seasons of interest: one during early to mid winter, two during late winter, and two during calving to post-calving. These crossings primarily occurred along the east-west axis of the MVWR (Tulita to Délı̨nę — Délı̨nę Winter Road), while none occurred along the north-south axis (Norman Wells to Wrigley). Observed movement patterns were mostly unchanged by a caribou's distance to the MVWR.

Modelling results suggested that movement rates were only slightly faster near the MVWR during early to mid winter but substantially faster far from the MVWR during calving to post-calving. The frequency of turns by caribou near versus far from MVWR were not very different in either season.

Overall, base models (H1) and disturbance models (H2 or H3) had relatively high predictive accuracy during early to mid winter and calving to post-calving. In contrast, the disturbance model (H3) for late winter did not conform with caribou observations, and the base model (H1) instead had a much higher predictive accuracy. Therefore, we did not use the H3 model to assess habitat connectivity in late winter.

Altered Habitat Connectivity — Habitat connectivity (crossings and space use) was not reduced during calving to post-calving when comparing scenarios with and without the MVWR's effect. During early to mid winter, we identified specific areas along the MVWR's west-east axis (Tulita to Délı̨nę — Délı̨nę Winter Road) that had fewer crossings and reduced space use when including the MVWR's effect on movement. However, these reduced crossings were small in magnitude (only 2.9–7.4% of all nearby simulated movements).

Overall, habitat connectivity was unchanged along the MVWR's north-south axis (Norman Wells to Wrigley) during both seasons because of natural barriers, such as rugged terrain and a wide watercourse (the Mackenzie River), other existing linear disturbances, and the distribution of habitat. In contrast, the lack of natural barriers, fewer linear disturbances, and higher quality habitat along the MVWR's east-west axis could facilitate some crossings.

Based on the simulation outcomes, the potential for crossings along the east-west axis are likely reduced due to the MVWR's effect on boreal caribou movement. However, because the east-west axis will not be a part of the Project footprint, we do not anticipate the highway to pose a barrier to caribou movement.

Proximity of Calving Caribou to the Winter Road — We identified 87 potential calving events by boreal caribou and evaluated their distances from the MVWR. Of these events, only 26 occurred within 30 km of the MVWR. On average, these 26 calving events were 18 km from the MVWR. Caribou with 10% of their locations within 15 km of the road (8 caribou) had calving events at a mean distance of 15 km. Only six predicted calving events occurred within 15 km of the MVWR, the closest being 7.9 km from the road.

CONCLUSIONS

Our results were mixed, but overall, we found a lack of support to suggest caribou movement rates and tortuosity are affected by the MVWR. What effect we did find was relatively low in magnitude.

We found no evidence of reduced habitat connectivity during calving to post-calving along any portion of the MVWR, which is not surprising since the MVWR does not have traffic during this season. The results of habitat connectivity analyses suggest that the MVWR's east-west axis is likely a semi-permeable barrier to caribou movement during early to mid winter when the road is active, and traffic is present.

Currently, the MVWR's north-south axis, where the Project occurs, does not pose a substantial barrier to boreal caribou movement. Natural barriers, other linear features, and habitat distribution would prevent crossings even without the MVWR. Furthermore, calving locations tend to be distant from the MVWR, beyond the zone of potential sensory disturbance (15 km from the road), so it is unlikely that the Project would cause further effects on boreal caribou calving.

Overall, the findings of this study provide a *relative* baseline comparison of effects that investigations during construction and post-construction phases of the Project should supplement.

ACKNOWLEDGEMENTS

The Government of Northwest Territories' Department of Environment and Climate Change provided the data to complete this work. Lead biologists associated with the datasets include:

Ève Lamontagne (*Manager*, Wildlife Research & Monitoring – Dehcho),
Allicia Kelly (*Biologist*, Environmental Assessment – North Slave),
Ashley McLaren (*Manager*, Wildlife Research & Monitoring – South Slave),
Kathy Unger (*Acting Manager*, Habitat and Environmental Assessment – Headquarters), and
Kevin Chan (*Regional Biologist* – Sahtú).

Ève Lamontagne also provided useful discussion and information on boreal caribou movements and calving events.

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<u>Suggested Citation</u>

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ACRONYMS AND ABBREVIATIONS

Acronym/Abbreviation	Definition
AIC	Akaike information criterion
DAR	Developer's Assessment Report
EOSD	Earth Observation for Sustainable Development
GNWT	Government of Northwest Territories
GPS	Geographic positioning system
H1	Base effect model hypothesis
H2	MVWR effect model hypothesis
H3	All correlated disturbances effect model hypothesis
ID	Identification (or identifier)
iSSF	Integrated step selection function
K'alo-Stantec	K'alo-Stantec Limited
km	Kilometres
m	Metres
MVWR	Mackenzie Valley Winter Road
NT1	Northwest Territories (boreal caribou) range
NWT	Northwest Territories
RSF	Resource selection function
SSF	Step selection function
the Project	the Mackenzie Valley Highway Project
TDMA	Three-day moving average
UD	Utilization distribution
ZOI	Zone of influence

1 INTRODUCTION

1.1 BACKGROUND

The Mackenzie Valley Highway Project (the Project) is a proposed extension of the all-season Mackenzie Highway (Highway 1) in the Northwest Territories (NWT). Led by the Government of the Northwest Territories (GNWT) Department of Infrastructure, the Project will replace the existing Mackenzie Valley Winter Road (MVWR) between Hodgson Creek (about 1 km north of Wrigley) and Prohibition Creek (about 28 km south of Norman Wells). The Project will include the construction of approximately 281 kilometres (km) of road and the development of temporary and permanent quarries and borrow sources. The highway extension parallels the Mackenzie River to its east and will pass through the Dehcho Region and a portion of the Tulita District of the Sahtú Region (Map 1).

The Project is subject to an environmental assessment and the requirements of Part 5 of the *Mackenzie Valley Resource Management Act* (Government of Canada 1998). The GNWT Department of Infrastructure hired K'alo-Stantec Limited as the primary environmental consultant to support the assessment process. K'alo-Stantec Limited then retained EDI Environmental Dynamics Inc. as subconsultants to complete the following:

1. A technical data report to support the Developer's Assessment Report as required by the Project's Terms of Reference (MVEIRB 2015). The Technical Data Report describes the existing conditions for boreal woodland caribou (*Rangifer tarandus caribou*), barren-ground caribou (*R. t. groenlandicus*), and moose (*Alces alces*) (EDI Environmental Dynamics Inc 2023).
2. A technical report that assesses the potential effect of the Project on boreal caribou movement.

This document addresses Item #2, including the GNWT's concerns that the Project could pose a potential barrier to boreal caribou movement.

1.2 BOREAL CARIBOU AND HABITAT DISTURBANCE

Boreal woodland caribou are designated as Threatened under Schedule 1 of the *Species at Risk Act* (SARA 2002) and the *Species at Risk (NWT) Act* (Government of the Northwest Territories 2009). The NWT population of boreal caribou occurs within a 441,665 km² contiguous area known as the Northwest Territories Range (NT1) (Environment Canada 2012, Species at Risk Committee 2012), which falls almost entirely within the Taiga Plains Ecoregion (Ecosystem Classification Group 2009). Roughly 6,000–7,000 boreal caribou are estimated to occur in NWT based on the compilation of community and scientific knowledge (Conference of Management Authorities 2017). The Dehcho Region has an estimated 2,318 caribou, and the Sahtú Region has an estimated 1,674 caribou (Species at Risk Committee 2012).

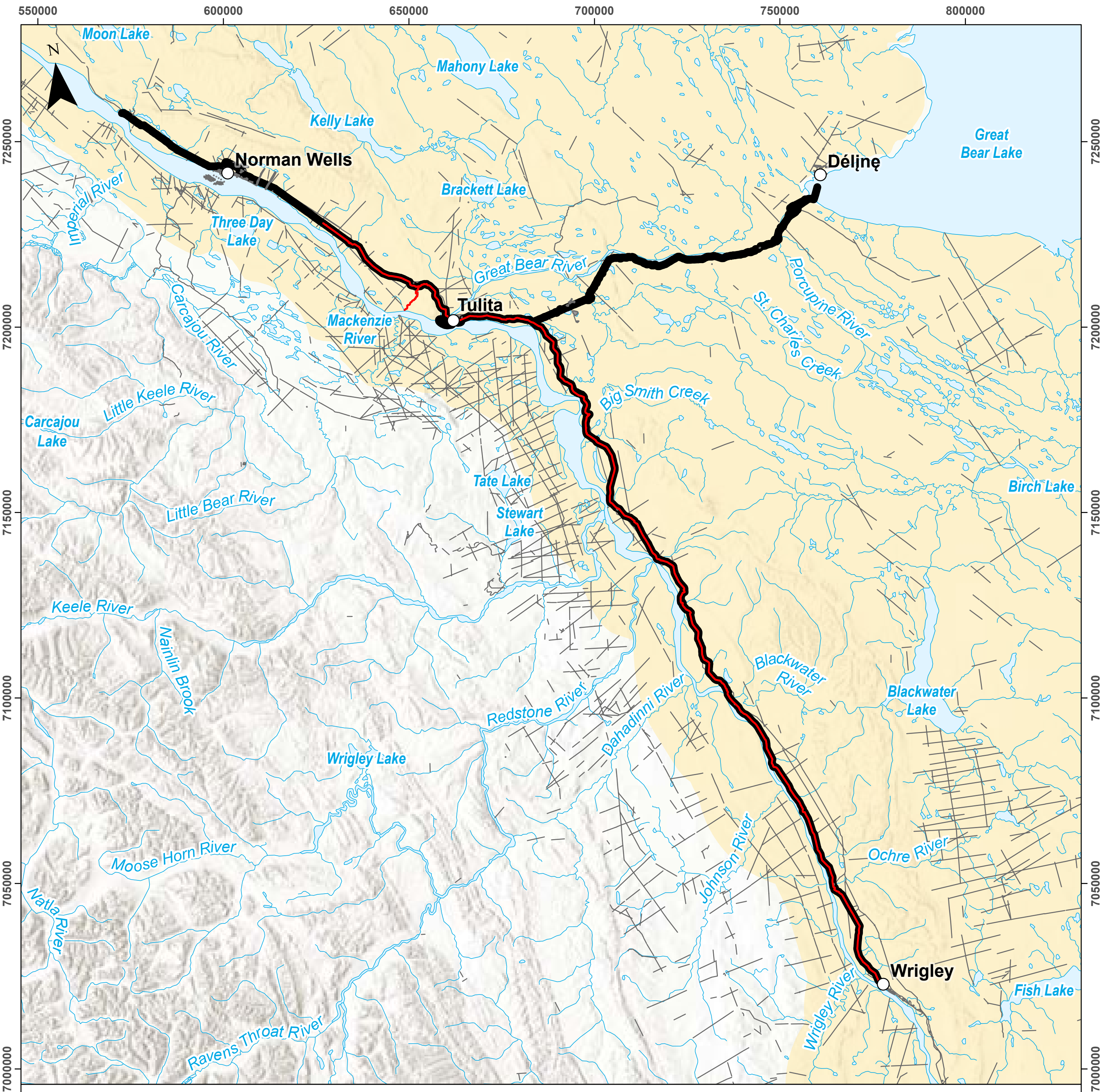
Boreal caribou are generally a non-migratory ecotype of caribou, but seasonal space use and movement patterns can vary by individuals and groups. Some boreal caribou in the Mackenzie Valley region have been documented moving considerable distances between seasons. In contrast, others remain year-round within an area while adjusting their seasonal use of habitat (Species at Risk Committee 2012).

Boreal caribou have experienced population declines across Canada attributed to habitat loss, degradation, and fragmentation from natural and anthropogenic (or human-caused) disturbance regimes (Vors and Boyce 2009, Environment Canada 2012). Environment and Climate Change Canada (ECCC) identified a 35% disturbance threshold within boreal caribou range for populations to remain stable or increase in size. Populations exposed to greater cumulative disturbance have experienced the greatest declines (Environment Canada 2011). Based on this criteria, boreal caribou in the NWT were considered 'likely self-sustaining' given that 31% of the NT1 is disturbed due to fire (approximately 24%) and anthropogenic (approximately 8%) sources (Environment Canada 2012). Severe wildfires in 2014 and 2015 increased the total disturbance amount to 34% (Conference of Management Authorities 2017), and the extent and intensity of wildfires in 2023 may have increased the total disturbance beyond Environment and Climate Change Canada's threshold.

Disturbance-mediated apparent competition, whereby the depredation of caribou by wolves is amplified by alternate prey (e.g., moose) that use disturbed habitats (i.e., early seral-stage stands), is thought to be the proximate mechanism or most direct cause for population declines (Holt 1977, DeMars et al. 2023). Disturbances such as linear features can also enhance predation rates by increasing predator abundance via travel corridors into caribou range and, ultimately, optimize hunting efficiency (Serrouya et al. 2016, Dickie et al. 2017, DeMars and Boutin 2018). The extent of these effects can depend on linear feature density (McKenzie et al. 2012), and the configuration of habitat and linear features in the landscape also drives predator functional responses in habitat selection (Pigeon et al. 2020). Ultimately, the disturbance-mediated apparent competition mechanism depends on the ecological context and location. Recent evidence suggests that it may not apply to northern boreal caribou ranges where net primary productivity and densities of alternate prey species are low (Neufeld et al. 2020, Superbie et al. 2022).

Instead, a more influential process may be the loss of habitat connectivity due to habitat alterations within boreal caribou range (O'Brien et al. 2006, Drake et al. 2018, Superbie et al. 2022). Habitat connectivity is essential to conserve threatened caribou populations by facilitating access to high-quality habitat patches (O'Brien et al. 2006). Functional connectivity is particularly important — the linkage between habitat patches that depends on underlying landscape features and habitat-mediated dispersal and movement (Taylor et al. 1993, O'Brien et al. 2006, Bauduin et al. 2020).

The prevailing view is that reduced habitat connectivity, as a result of increased habitat fragmentation (Fahrig 2003), has contributed to boreal caribou population declines through restricted gene flow, range contraction, and decreased survival, reproduction, and population growth (Johnson and St-Laurent 2011, Beauchesne et al. 2014, Drake et al. 2018, Thompson et al. 2019). For this reason, recovery strategies and management plans often prescribe maintaining connected, large patches of secure habitat to ensure population persistence (e.g., Species at Risk Committee 2012, Environment and Climate Change Canada 2016). Anthropogenic development, such as permanent linear features (e.g., roads), may act as a barrier and reduce connectivity even when the total extent of disturbance is below the 35% disturbance threshold. Reduced habitat connectivity within the NT1 boreal caribou range may have long-lasting negative implications for the population.



Legend

○ Major Settlements

Mackenzie Valley Highway Alignment

Mackenzie Valley Winter Road (MVWR)

Linear Disturbance

Watercourse

Waterbody

NT1 Boreal Caribou Range (GNWT 2016 version)

Polygonal Disturbance

Map 1. Location of the Mackenzie Valley Highway Project, Northwest Territories

K’alo-Stantec Limited

Data Sources

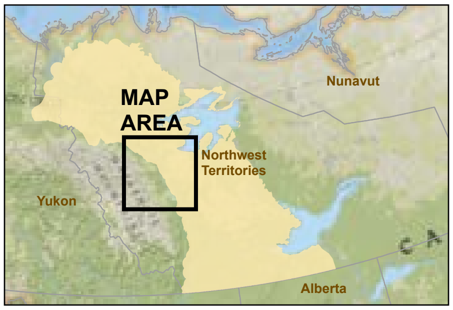
- Inset Basemap. National Geographic World Map: National Geographic, Esri, Garmin, HERE, UNEP-WCMC, USGS, NASA, ESA, METI, NRCAN, GEBCO, NOAA, increment P Corp.
- Main Basemap. World Hillshade: Esri, USGS
- Major Settlements, Mackenzie Valley Highway Alignment, MVWR, Watercourse, Waterbody. CanVec data, Natural Resources Canada, 2023.
- NT1 Boreal Caribou Range. Government of Northwest Territories, 2016.
- Boreal Caribou Observed Trajectories by season. EDI Environmental Dynamics Inc. 2023.

Disclaimer
EDI Environmental Dynamics Inc. has made every effort to verify this map is free of errors. Data has been derived from a variety of digital sources and, as such, EDI does not warrant the accuracy, completeness, or reliability of this map or its data.

0 15 30 45 60 75
Kilometres

Map Scale: 1:1,500,000 (printed on 8.5 x 11)
Map Projection: NAD 1983 UTM Zone 9N

Drawn: O. Leblanc	Checked: K. Bajina	Map 1	Date: 2024-01-08



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1.3 STUDY OBJECTIVES

The effects of the Project on caribou have the potential to be large in magnitude, frequent in occurrence, and long-lasting in duration due to the size of the footprint and the regular use it is likely to receive. A key objective is determining whether and to what extent the highway may pose a barrier to boreal caribou movement on the landscape. To predict these effects, we considered the present influence of the existing MVWR across three boreal caribou seasons (or life cycle periods). Though the MVWR likely does not yield effects identical to those of an all-season highway, it provides an opportunity to evaluate the effects of human activity (e.g., traffic) from the footprint itself (the right-of-way) by evaluating caribou movement during seasons while the winter road is active. Thus, we investigated the following three seasons defined for boreal caribou in the region: (1) early to mid winter and (2) late winter, when the MVWR is open, and (3) calving to post-calving, when the MVWR is closed but when caribou are most vulnerable and sensitive to disturbances[1].

We completed primary and supplementary investigations to assess the current effects of the MVWR and potential effects of the Project on caribou.

The primary investigation focused on two questions:

1. Does the MVWR alter the movement patterns of boreal caribou?
2. Does the MVWR pose a barrier to movement and limit habitat connectivity between habitat patches that boreal caribou would otherwise select?

To answer these questions, we analyzed available geographic positioning system (GPS) telemetry data of boreal caribou in the Sahtú and Dehcho regions of the NWT. We investigated whether caribou changed their movement patterns near the MVWR, including their propensity to approach or cross the winter road. Animals move in response to resources (e.g., forage) across their range, so we examined caribou movement in a habitat-integrated analytical framework.

To answer the first question, we fit and compared competing models considering habitat selection and movement. Two of the models included the MVWR as a model variable. We hypothesized that if the MVWR affected caribou movement, models with the MVWR variable would be selected as the top model. Further, we hypothesized that those model results would indicate caribou step lengths to be shorter (i.e., slowed movements) and turn angles greater (e.g., closer to 180° than 0° to demonstrate deflection or increased tortuosity) as individuals approached the road.

To answer the second question, we used model results to simulate two scenarios, one *with* ('MVWR-mediated') and *without* ('MVWR-free') the MVWR's influence. We hypothesized that if the MVWR acted as a barrier,

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[1] In preliminary work, we also examined and analyzed habitat-dependent movement for several other seasons (pre-calving, summer, rut, and late fall) but found little evidence of the MVWR affecting boreal caribou movements (movement rates and turn angles) in most of those seasons. We were also constrained by computational requirements to conduct a complete set of analyses for each of these additional seasons (i.e., including simulations; see Section 2.1.5 *Altered Habitat Connectivity*). Ultimately, our focus on early to mid winter, late winter, and calving to post-calving was to ensure coverage of the period when the MVWR was actively being used (winter seasons) and the most sensitive season to caribou (calving to post-calving).

scenarios with the MVWR would have fewer crossings and reduced space use than the scenario without the road's influence.

Finally, our supplementary investigation focused on boreal caribou calving near the MVWR. Specifically, we evaluated how far parturient cows remained from the MVWR during calving events and whether those chosen calving locations would expose caribou to sensory disturbance once the all-season highway is established.

These investigations aimed to (a) clarify the *minimum* possible effect that the Project may have on caribou movement, considering that the highway's traffic volume will be much greater than the MVWR; and (b) provide a *relative* baseline comparison for future assessments of boreal caribou movement during construction and post-construction phases of the highway.

2 METHODS

2.1 QUANTIFYING EFFECTS AND BARRIERS TO MOVEMENT

2.1.1 OVERVIEW

Roads have the potential to be semi-permeable barriers to animal movement (Beyer et al. 2016) and may result in several non-exclusive outcomes, including reduced or delayed crossings (Wilson et al. 2016), changes to movement patterns and behaviour (Xu et al. 2021), and general avoidance of areas within historical ranges (Panzacchi et al. 2013). Examining barrier effects typically requires animals to regularly encounter a road so that changes to movement can be quantified. Challenges arise when interactions with a road are infrequent. It becomes unclear whether animals are (a) avoiding or altering their behaviours due to the road, or (b) simply moving in accordance with the distribution of their preferred habitat (which may not be near the road). In such instances, common metrics of observed movements and crossings, or focusing solely on movement patterns (e.g., barrier behaviour analysis; Xu et al. 2021), provide an incomplete picture.

Recent modelling advances allow researchers to better describe and predict wildlife movement. For example, the biased correlated random walk model includes directional persistence (e.g., during migration) in light of environmental or ecological factors to predict movement (Codling et al. 2008). Alternatively, the hidden Markov model can reveal latent (hidden) behavioural states (e.g., resting, feeding, relocating) based on observed movement patterns but model movement independent of habitat and provide no inference on movement changes (e.g., Franke et al. 2004). However, neither of these methods are optimal to investigate how a landscape feature, such as a road, alters the movement and behaviour of boreal caribou, a mostly non-migratory animal.

An approach that simultaneously incorporates movement and habitat selection processes is needed to infer space use. Development of the step selection function (SSF) has made such inference possible (Thurfjell et al. 2014, Duchesne et al. 2015). Furthermore, the integrated step selection function (iSSF) allows direct estimation of interactions between environmental covariates and movement parameters (e.g., step lengths, turn angles) — a habitat-mediated movement model (Avgar et al. 2016). The iSSF is equivalent to a locally biased correlated random walk (Avgar et al. 2016), and we believe that it is the best tool to address movement-related questions while controlling for the effects of habitat.

The MVWR is open, and traffic is present, annually, between December 22 and April 1 based on 20-year average opening and closing dates (https://www.inf.gov.nt.ca/en/services/highways-ferries-and-winter-roads/winter-roads-average-openclose-dates). An overview of the seasons (life cycle periods) defined for boreal caribou in Sahtú and Dehcho regions of the NWT is provided in Table 1. We investigated the effects of the MVWR on boreal caribou movement during winter (early to mid winter and late winter) and calving to post-calving seasons. For the purposes of analysis, we combined early and mid winter into one season and kept late winter as a separate season. Therefore, we had three periods in which to analyze caribou movement (see Section 2.1.2 *GPS Telemetry Data, 2019–2023*). The MVWR is expected to be active during early to mid winter and late winter caribou seasons. Winter is a period when caribou space use is dependent on the access to and abundance of terrestrial and arboreal lichens, which is influenced by snow depth and the extent and age of burns (Species at Risk Committee 2012, DeMars et al. 2020). During calving and post-calving, caribou movement and distribution are driven by predator avoidance, and insect avoidance is another major driver during post-calving, which results in caribou selecting for rivers and lakes (Species at Risk Committee 2012).

Table 1. Boreal caribou seasons (life cycle periods) and timings in Sahtú and Dehcho regions of the Northwest Territories.[1,2]

Seasons (Life Cycle Periods)	Sahtú Region		Dehcho Region	
	Start Date	End Date	Start Date	End Date
Early Winter	Oct 26	Jan 12	Dec 1	Jan 25
Mid winter	Jan 13	Mar 21	Jan 26	Mar 15
Late Winter	Mar 22	Apr 5	Mar 16	Apr 1
Pre-calving (Spring Dispersal)	Apr 6	Apr 30	Apr 2	Apr 30
Calving to Post-calving	May 1	Jul 12	May 1	Jun 30
Summer	Jul 13	Sep 8	Jul 1	Sep 12
Rut	Sep 9	Sep 25	Sep 13	Oct 30
Late Fall	Sep 26	Oct 25	Oct 21	Nov 30

[1] *Season (life cycle periods) start and end dates are taken from Table 2 in DeMars et al. (2020). DeMars et al. (2020) determined these seasonal timings based on movement rate analyses of collared caribou (2002–2018), seasonal delineations from other studies, and expert input from regional government biologists. The seasons selected for analyses are identified in green text.*

[2] *Early and mid winter are eventually combined for analyses (see Section 2.1.2 GPS Telemetry Data, 2019–2023).*

The limited interactions between boreal caribou and the MVWR prevented direct tests with observed data of the potential changes in movement and behaviour, such as reduced crossings. Without direct observations, a simple and effective way to explore possible effects is to generate models and simulations grounded in the species' ecology and life history (Semeniuk et al. 2012, Stewart et al. 2020).

We quantified the potential barrier effects of the MVWR in two ways. First, we fit competing iSSF model structures to determine whether boreal caribou movement was affected by the MVWR or arose due to the availability of habitat across the landscape. We evaluated which model structure was best suited to predict boreal caribou movement. Next, we used population-level iSSFs to simulate caribou trajectories near the MVWR and assessed the differences in movement patterns in the presence and absence of the MVWR. A trajectory refers to the sequence of relocations that create a caribou's movement path in a season.

The workflow and analytical components used to evaluate barriers to caribou movement in the Mackenzie Valley are summarized in Figure 1. First, we selected caribou trajectories that have the potential to interact with the MVWR (i.e., 10% of the locations in a caribou's trajectory occur within 15 km of the MVWR). We developed individual-level iSSF models for three competing model structures. We then used individual-level models to develop population-level models (*Model Development*, yellow box). Next, we validated the predictive performance of population-level models using the following three separate procedures:

1. Examined the correlation of predicted model trajectories to observed locations (*Model Validation*, blue box).
2. Tested for differences between the number of observed and simulated crossings.
3. Compared the distance of observed and simulated caribou to the MVWR (*Movement and Behaviour*, green box).

If valid for prediction, we used those models to conduct habitat connectivity analyses and determine if the MVWR acts as a barrier (*Habitat Connectivity*, red box). These steps are discussed in greater detail in the following sections.

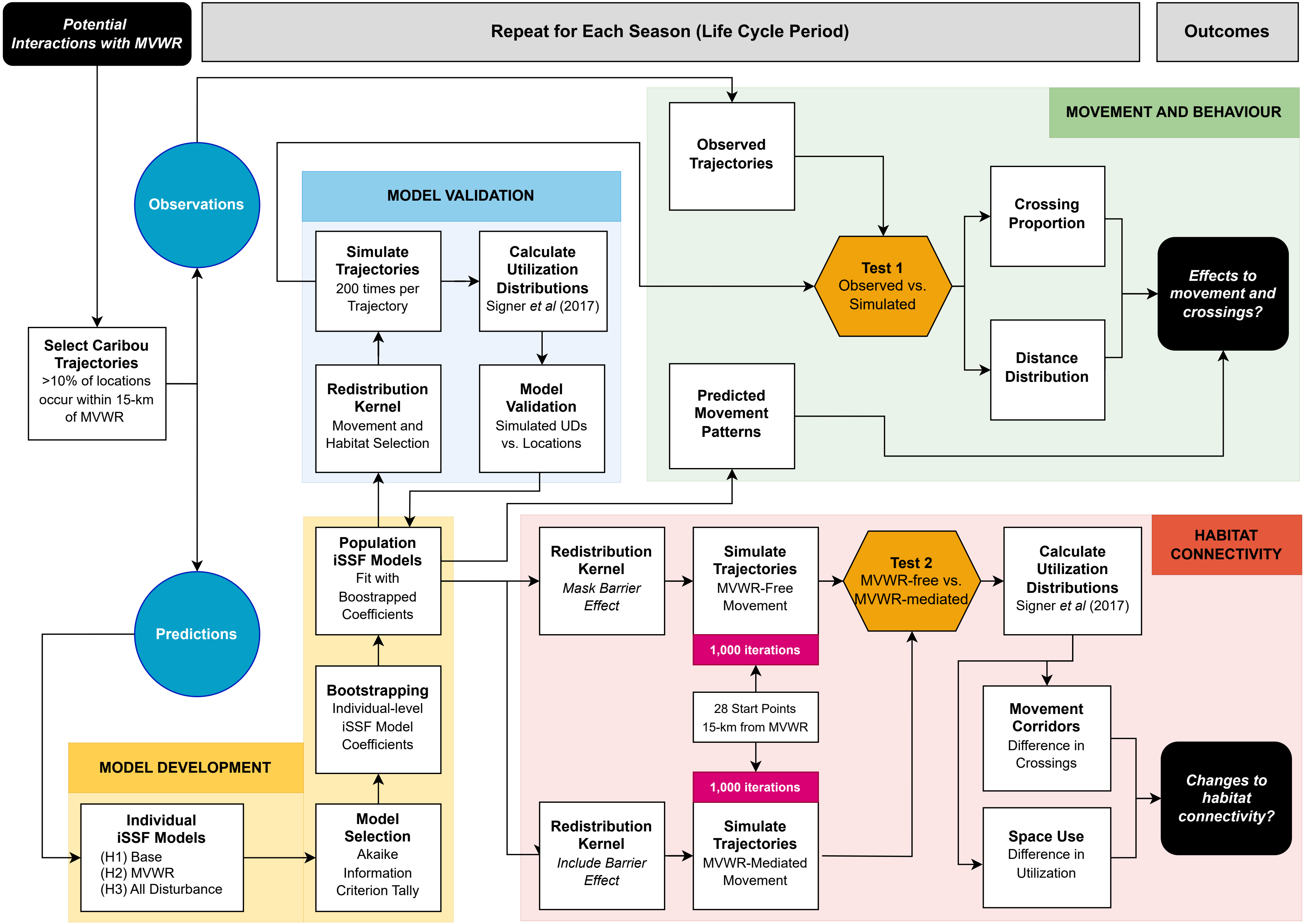


Figure 1. Schematic diagram of the analytical workflow used to assess barriers to boreal caribou movement in the Mackenzie Valley, Northwest Territories.

2.1.2 GPS TELEMETRY DATA, 2019–2023

2.1.2.1 Data Preparation

The GNWT provided GPS collar data for the entire NT1 boreal caribou range (Environment and Climate Change 2023). We completed several data preparation steps before using the telemetry data for modelling. First, we filtered locations to retain caribou in the Sahtú and Dehcho regions and removed all entries with missing coordinates or duplicate datetime stamps. We then assigned seasons to GPS locations based on the timings identified in Table 1, and assigned identifications (IDs) to trajectories based on caribou ID, year, and season combinations. We evaluated each trajectory and retained only those with at least (a) 50% coverage of a season, especially for short seasons (e.g., late winter = 15 days), or (b) 100 total locations. These criteria ensured a reasonable number of steps were present in a trajectory representative of seasonal movements.

The GNWT programmed GPS collars to collect locations on either a 2-hour or 8-hour interval (fix rate). However, assessing movement patterns and movement-related responses to stimuli (e.g., a road) requires short time intervals. It is impossible to infer the movement process if the time interval between locations is too long. For example, with an 8-hour fix rate, one cannot associate a specific response (e.g., change in step length or turn angle) to a given stimuli (e.g., auditory or visual) with any confidence. There is missing information as to the position of the caribou and its approach to a feature like the winter road, creating uncertainty about the caribou's movement path. For this reason, we retained trajectories with 2-hour fix rates to capture fine-resolution movements and discarded trajectories with 8-hour fix rates. In cases where there were missing data or large time gaps between relocations in caribou trajectories, we had to implement a 'regularization' method to ensure each time interval equalled two hours (see Section 2.1.4.1 *Used and Available Steps* for details).

Our final criterion for selecting boreal caribou trajectories was the proximity of locations to the MVWR. To study the potential barrier effects of the MVWR, caribou must first have the potential to interact with it. But the effects on movement may not occur directly at the footprint (i.e., 0 m distance). Caribou could change their movement paths at greater distances if they perceive risk as they approach the MVWR. The area of perceived risk where caribou are affected by anthropogenic development is often referred to as the 'zone of influence' (ZOI). A common, conservative ZOI estimate is approximately 15 km (Boulanger et al. 2012, 2021, Wilson et al. 2016, Government of the Northwest Territories 2019). For example, to evaluate the effect of an industrial road on caribou migration (slowed or reduced crossings), Wilson et al. (2016) limited their sample of caribou to those that occurred within a 15-km distance of the road.

Our investigation retained caribou trajectories with at least 10% of locations within 15 km of the MVWR. The 10% rule balanced the need to maximize sample size while ensuring that caribou could interact with the MVWR. The 15 km distance (buffer) also aligns with the regional study area used in the Technical Data Report to capture potential cumulative effects on wildlife species, including boreal caribou (EDI Environmental Dynamics Inc 2023).

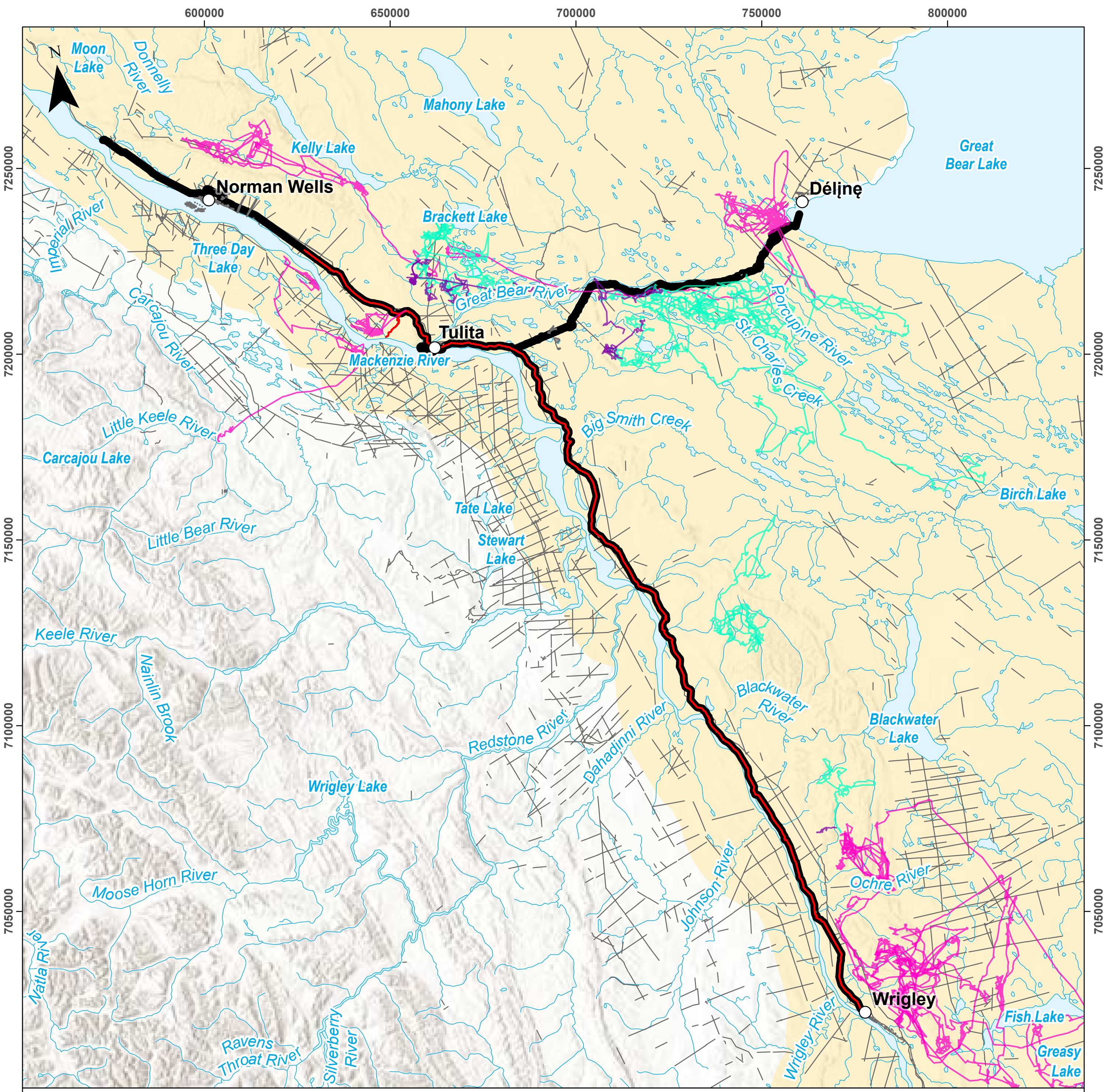
After applying the criteria above, we used the remaining number of caribou trajectories in each season for analyses (Table 2). Due to low sample sizes, we combined the early and mid winter seasons into one season (*n* = 14). Ultimately, we conducted analyses for three seasons: early to mid winter, late winter, and calving to post-calving. The resulting telemetry dataset used for movement analyses consisted of caribou locations from 2019–2023, including 42 unique caribou-season-year trajectories. The total number of unique caribou during this period and across all three seasons was 21 individuals. The caribou trajectories used in the movement analysis are shown in Map 2.

Table 2. Number of boreal caribou individuals and trajectories with 2-hour fix rates per season (life cycle period) in Sahtú and Dehcho regions of the Northwest Territories.[1,2]

Seasons (Life Cycle Periods)	No. of Caribou	No. of Trajectories
Early Winter	3	3
Mid Winter	8	11
Late Winter	9	13
Calving to Post-calving	10	15

[1] *Early and mid winter is grouped into a single season for analysis.*

[2] *The caribou from each season are not necessarily unique, and some individuals may occur across multiple seasons; the total number of unique caribou is 21 individuals.*



Legend

○ Major Settlements

━ Mackenzie Valley Highway Alignment

━ Mackenzie Valley Winter Road (MVWR)

— Linear Disturbance

— Watercourse

▭ Waterbody

▭ NT1 Boreal Caribou Range (GNWT 2016 version)

▨ Polygonal Disturbance

Seasonal Trajectories

— Early to Mid Winter

— Late Winter

— Calving to Post-calving

Map 2. Observed boreal caribou movement trajectories used to analyze the effects of the Mackenzie Valley Winter Road, Northwest Territories

K’alo-Stantec Limited

Data Sources

- Inset Basemap. National Geographic World Map: National Geographic, Esri, Garmin, HERE, UNEP-WCMC, USGS, NASA, ESA, METI, NRCAN, GEBCO, NOAA, increment P Corp.
- Main Basemap. World Hillshade: Esri, USGS
- Major Settlements, Mackenzie Valley Highway Alignment, MVWR, Watercourse, Waterbody. CanVec data, Natural Resources Canada, 2023.
- NT1 Boreal Caribou Range. Government of Northwest Territories, 2016.
- Boreal Caribou Observed Trajectories by season. EDI Environmental Dynamics Inc. 2023.

Disclaimer

EDI Environmental Dynamics Inc. has made every effort to verify this map is free of errors. Data has been derived from a variety of digital sources and, as such, EDI does not warrant the accuracy, completeness, or reliability of this map or its data.

0 15 30 45 60 75

Kilometres

Map Scale: 1:1,500,000 (printed on 8.5 x 11)
Map Projection: NAD 1983 UTM Zone 9N

Drawn: O. Leblanc	Checked: K. Bajina	Map 2	Date: 2024-01-08

EDI

Path: L:\PROJECTS\2022\PR\22C0569_StantecGNWT_MVH_CaribouCollarAnalysis\22C0569_StantecGNWT_MVH_CaribouCollarAnalysis_mapping.aprx\22C0569_Map2_MVH_CaribouTrajectories_20240108

2.1.2.2 Observed Boreal Caribou Movements

Before modelling caribou movement with respect to habitat features, we conducted the following:

1. Visual assessments of caribou trajectories to examine movement patterns relative to landscape features (e.g., the MVWR, rivers, terrain).
2. Formal assessments of boreal caribou movement patterns, such as raw movement rates (m/2-hours) and turn angles, based on the distance of locations to the MVWR.

For the first formal assessment, we were specifically interested in identifying changes to movement parameters within the potential ZOI (15 km). We tested the association between movement rates and distance to the MVWR using a linear mixed model, specifying random intercepts for caribou trajectories to account for the different number of relocations among trajectories. We fit generalized linear mixed models with a gamma-distributed response (and a $\log_e$ link-function) for movement rates using the package 'glmmTMB' in R software for statistical computing, version 4.3.1 (R Development Core Team 2023). To aid with model convergence, we standardized values to have a mean = 0 and a standard deviation = 1.

For model diagnostics, we visually assessed the model residuals for patterns that violated homoskedasticity (constant variance), e.g., the distribution of residuals, fitted versus residuals, and MVWR distance versus residuals plots. We also evaluated plots of simulated residuals for goodness-of-fit, dispersion, and outliers using R package 'DHARMa' (Hartig 2021). In addition to the slope estimates for the rate of change in movement rates from 0–15 km distances, we calculated 95% profile likelihood confidence intervals.

To visualize the directedness versus tortuosity of boreal caribou movements, we plotted the empirical distribution of turn angles (in radians) made by individuals in each season. We compared turn angles within 0–1 km to those made 14–15 km from the MVWR. To visualize the empirical turn angle distributions in a continuous (i.e., density curve) rather than discrete distribution (i.e., histogram), we estimated a smooth surface using a (Gaussian) kernel density estimator that implemented Silverman's rule of thumb for bandwidth selection (Silverman 1986). Empirical turn angle distributions are interpreted based on their 'peakedness' along an axis of $-\pi$ (-3.14) to π (3.14), i.e., a higher peak around the midpoint zero indicates more frequent direct (straight) movements, whereas a flatter distribution with higher densities at $-\pi$ and π indicates more frequent tortuous movements.

2.1.3 SPATIAL HABITAT DATA

The iSSF is grounded in habitat selection and thus requires associating caribou locations to spatial habitat data. We reviewed several data sources for covariates to include in models, balancing the trade-off between spatial grain and extent (pixel size and regional coverage) and temporal resolution (frequency and duration). We chose relevant spatial habitat layers based on what is known about boreal caribou ecology in the region. DeMars et al. (2020) conducted a thorough investigation on boreal caribou habitat selection in the NWT, and their work provided us with initial guidance to select habitat covariates.

2.1.3.1 Landcover and Terrain Characteristics

DeMars et al. (2020) used 2007/2010 Earth Observation for Sustainable Development (EOSD) landcover data (Natural Resources Canada and Government of Northwest Territories 2017) as a primary source to characterize boreal caribou habitat. The EOSD data consists of 24 landcover types at a 30 m by 30 m resolution; each pixel identified a single landcover type. In their 2nd and 3rd order resource selection functions, DeMars et al. (2020) included many EOSD categorical levels but also found that continuous, modified landcover covariates performed well. For example, boreal caribou had a strong selection for sparse conifer forest across seasons and varying selection by season for upland conifer forest (i.e., dense and open conifer).

We used these modified covariates to simplify models and the number of parameters. However, we were limited by which landcover types we could use. We carefully chose landcover types that were sufficiently distributed across the landscape so that they were available to individual caribou trajectories. Similar to DeMars et al. (2020), we used the EOSD spatial layer to calculate the amount (%) of sparse and upland conifer cover within a certain radius of each pixel. We chose a radius of 200 m because it corresponds to the median step length of boreal caribou across all seasons. In addition to the two forest cover types, we developed a layer for the amount (%) of water within a 200-m radius, which would capture caribou space use relative to large or densely concentrated waterbodies and wide rivers. This layer allowed us to partially account for habitat selection relative to the Mackenzie River, ranging from several hundred metres to over a kilometre wide.

We also explored several digital elevation model products (Natural Resources Canada 2017), including elevation, slope, aspect, and terrain ruggedness. Most of these variables had insufficient variation within caribou trajectories. However, the terrain ruggedness index is a useful indicator of topographic heterogeneity (Riley et al. 1999) that captures differential use of high-versus-low elevation and mountainous areas. In many regions across Canada, boreal caribou tend to avoid rugged terrain conditions at various spatial scales and time periods (Leblond et al. 2011, Palm et al. 2022). A large extent of rugged, mountainous regions with high ridges occurs on the east side of the MVWR alignment (between Wrigley and Norman Wells), and such terrain could affect caribou movement and how caribou approach the MVWR. Therefore, we included terrain ruggedness index as a covariate.

2.1.3.2 Anthropogenic and Natural Disturbances

The primary barrier effect of interest was the MVWR. However, we found high correlations between the winter road and other anthropogenic disturbances such as settlements, major roads, and polygonal disturbances ($r > 0.70$ in many cases). Because these other disturbances are often concentrated along the MVWR alignment, it is difficult to differentiate their independent effects. To address this issue, we developed two (30 m by 30 m) spatial layers: (1) distance to the MVWR alignment and (2) closest distance to the MVWR or any settlements, major roads, or polygonal disturbances. We acquired the MVWR alignment from K'alo-Stantec, and settlements, major roads, and polygonal disturbances from the open access online database — GNWT Inventory of Landscape Change (https://www.geomatics.gov.nt.ca/en/services/web-mapping-applications/nwt-cumulative-impact-monitoring-program-cimp-inventory-landscape).

We also considered linear feature density as an additional source of anthropogenic disturbance that was independent of the MVWR. To develop this layer, we acquired linear feature data from the GNWT Inventory of Landscape Change (see above). Similar to DeMars et al. (2020), we calculated linear feature density (km/km^2) within a 400-m radius. We used a single layer for the 2019–2023 period because there were only four additional features beyond 2019 (ranging from 0.1 to 2.3 km for a total length of 2.7 km). We did not use the MVWR footprint to calculate linear feature densities.

We also accounted for natural disturbance in our analysis. Several studies have indicated the importance of fire in shaping the habitat selection of boreal caribou (DeMars et al. 2020, Silva et al. 2020, Konkolics et al. 2021). Caribou generally tend to avoid burns less than 40 years old (Environment Canada 2012), and this avoidance has also been documented in the NT1 range (Stantec Consulting Ltd. 2020).

We implemented a simple approach to account for these effects of fire age. First, we acquired data on historical fires for two date ranges:

1. Fire perimeter data (polygons) from the Canadian National Fire Database for the period 1955–1985 (https://cwfis.cfs.nrcan.gc.ca/ha/nfdb).
2. Fire perimeter data from the National Burn Area Composite for the period 1986–2021 (https://cwfis.cfs.nrcan.gc.ca/datamart/datarequest/nbac).

We rasterized these polygonal data and set the resolution to 30 m by 30 m. We then used a binary classification to identify whether each pixel corresponded to a burn older (=0) or younger (=1) than 40 years. Finally, we calculated the amount (%) of burns less than 40 years old within a 200-m radius of each pixel.

2.1.4 INTEGRATED STEP SELECTION ANALYSIS

We developed iSSFs for boreal caribou for three seasons: early to mid winter, late winter, and calving to post-calving. The iSSF is an extension of the SSF (which is a conditional logistic regression resource selection function [RSF]) that explicitly incorporates covariates related to movement when comparing steps made (or *used*) by an animal to those *available* in the landscape (Avgar et al. 2016).

The models included an interaction between movement metrics (step length and turn angle) and the distance to the MVWR to examine how caribou change their movement patterns as they approach the MVWR (e.g., Prokopenko et al. 2017). First, we developed individual-based iSSFs from the *used* (observed) steps in a caribou trajectory and a set of *available* steps that that caribou could have selected. We then used individual-level iSSF estimates to develop population-level iSSF estimates and infer boreal caribou habitat selection more generally across the landscape.

The advantage of this approach, instead of developing a population-level model outright, is that it allowed us to better account for individual-level variation in habitat selection, movement, and sample size (i.e., number of locations in a trajectory). Though such differences can be accounted for with population-level mixed effect models (e.g., random intercepts and slopes; Muff et al. 2020), the estimation method (i.e., 'shrinkage' in random effects) can still be biased by sample size differences. Furthermore, our workflow for analyses was best suited to the capabilities and functionalities of R package ‘amt’ (Signer et al. 2019), which does not incorporate random effects.

2.1.4.1 Used and Available Steps

We converted caribou location data to ‘step’ data with a step-based observation consisting of a start and end point. Each step had information on the coordinates and datetimes of start and end points, step length, turn angle, and time interval between those points. We then resampled the step data to retain locations equivalent to the most frequent fix rate (i.e., 2-hour fix rate with a 15-minute tolerance for error). Consistent time intervals are needed to make appropriate movement-related inferences and interpretations, such as calculating the average movement rates and responses to disturbances. From the resampled data, we assigned ‘burst IDs’ to sections of the step data with the same relocation schedule (2 hours ± 15 minutes). This produced a ‘regularized’ caribou trajectory. We used these regularized trajectories to identify the *used* steps by caribou, i.e., the step made by a caribou from an initial location. We did not fill the time gaps between bursts (of relocations) because that is not necessary to fit iSSFs — the sample unit is each individual step[2].

An iSSF also requires the generation of *available* (or random) steps to compare against those used by caribou. We generated 20 available steps for every used step (20:1 ratio) based on plausible step lengths and turn angles. For each available step, we drew a step length from a gamma distribution (parameters = *shape* and *scale*) and a turn angle from a von mises distribution (parameter = *kappa*) that we estimated naively (without considering habitat) from a caribou’s trajectory (Avgar et al. 2016, Prokopenko et al. 2017). We determined the coordinates of available steps by applying those step lengths and turn angles from the starting position; this start point was identical for the paired used step. In other words, used and available steps that we compared always had the same start point but a different end point (Figure 2).

---

[2] There are complex methods available for interpolating (predicting) locations along a trajectory that are missing due to time gaps (e.g., time-series kriging; Aiello et al. 2023), but such approaches would require us to fit iSSFs to predicted locations rather than observed locations. Therefore, we did not fill any data gaps along a caribou’s trajectory.

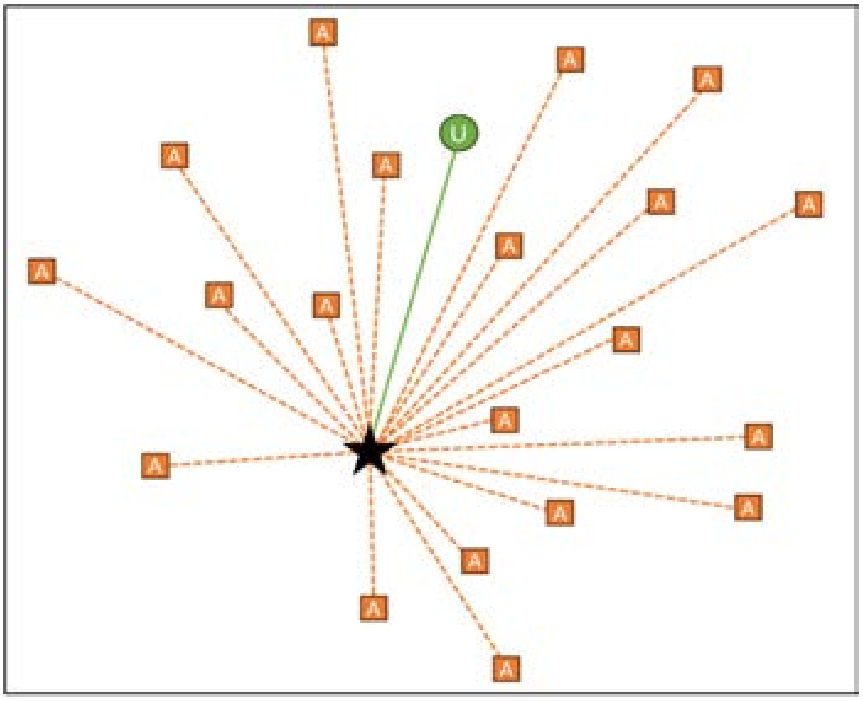


Figure 2. Conceptual diagram of *used* (green [U]) versus *available* (orange [A]) steps in a boreal caribou's trajectory to develop integrated step selection functions.
For each used step, 20 available steps are selected based on potential step lengths and turn angles drawn from a gamma and von mises distribution, respectively. Both used and available steps begin at the same location (black star) but end at a different location.

2.1.4.2 Individual-level Models

We fit and approximated the iSSF model likelihood using conditional logistic regression (Michelot et al. 2023). We matched *used* and *available* steps with the same start points (i.e., matched case-control design) and stratified each step cluster (1:20 used-available). The basic iSSF model structure implemented with conditional logistic regression is as follows:

$$\pi_{tj} = \frac{\exp(\boldsymbol{\beta}^{\top}\boldsymbol{x}_{tj})}{\sum_{i=1}^{J}\exp(\boldsymbol{\beta}^{\top}\boldsymbol{x}_{ti})} \tag{1}$$

where the probability of selection π_{tj}, by an individual caribou at the *t*-th time point and *j*-th location (*used* and *available* steps), is a function of covariate vector $\boldsymbol{x}_{tj}$ and its vector of coefficients $\boldsymbol{\beta}^{\top}$. The right-hand side denominator shows that the term $\exp(\beta^{\top}\boldsymbol{x}_{ti})$ is summed across all *j*-th possible steps (denoted by vector $\boldsymbol{J}$).

In habitat selection studies, the conditional logistic regression is often fit as a stratified Cox proportional hazard model (Muff et al. 2020). We fit these models using R package 'amt', version 2.1.0 (Signer et al. 2019). We evaluated three competing model structures: (H1) base effect, (H2) MVWR effect, and (H3) all correlated disturbances effect (Table 3). The base effect model (H1) included covariates for forest type, terrain ruggedness, fire, linear feature density, step length, the natural logarithm ($\log_e$) of step length, the cosine of turn angle, and step length interactions (i.e., step length and time of day, $\log_e$ step length and time of day). The

MVWR effect model (H2) was the same as the base model but included interactions between each movement parameter (step length, $\log_e$ step length, cosine turn angle) and the $\log_e$ distance to the Mackenzie Valley Winter Road. The correlated disturbances effect model (H3) was the same as the base model but included interactions between each movement parameter (step length, $\log_e$ step length, cosine turn angle) and the $\log_e$ distance to all correlated anthropogenic disturbances (including the MVWR, settlements, major roads, and polygonal disturbances).

Development of these three models aimed to assess which best fit the data and described caribou habitat selection and movement. For example, if the model with the MVWR effect (H2) was the top model, then the MVWR alone may be an important feature affecting caribou habitat selection and movement compared to the base model (H1). It would also suggest that other (correlated) anthropogenic disturbances (H3) do not explain additional variation in caribou movement.

Movement parameter estimates derived from iSSFs correspond to 'corrections' (or modifications) to the naïve parameter estimates once accounting for the habitat selection process. We included three movement parameters in the iSSFs: step length, natural logarithm ($\log_e$) of the step length, and cosine of the turn angle. The step length and $\log_e$ step length correspond to the *scale* and *shape* parameters of the gamma distribution, respectively, whereas the cosine turn angle corresponds to the *kappa* (or concentration) parameter of the von mises distribution (Avgar et al. 2016). We fit these movement parameters as (a) main effects to modify the habitat-independent estimates derived in Section 2.1.4.1 *Used and Available Steps* (see Avgar et al. 2016 for details) and (b) interaction effects to estimate how movement parameters changed due to certain covariates.

When fitting iSSF models (H1–H3, above) to data, the covariate values we used depended on the inferred target process. Covariate values at a step *end point* focus on the habitat selection process, whereas covariate values at a step *start point* focus on the movement process (Signer et al. 2019). Consequently, we extracted habitat-related covariates from the end-point position of a step. In contrast, interactions between movement parameters and other covariates always depended on the start-point position of a step (e.g., Prichard et al. 2020).

This method allowed us to answer the question: what initial conditions cause a caribou to make longer/shorter or directed/tortuous steps? For example, in addition to the covariates outlined in Section 2.1.23 *Spatial Habitat Data,* we estimated caribou movement rates by the time of day (day, night, or twilight), which allowed us to account for the potential effects of daylight on caribou movement. We hypothesized caribou would make faster and more directed movements during daylight compared to night. Different movement rates by time of day could account for traffic levels along the MVWR during winter, and faster movements during the day could increase the potential for caribou to interact with the MVWR. We determined the time of day for NWT (time zone = 'MST7MDT') using daylight times calculated in R package 'suncalc', version 0.5.1 (Thieurmel and Elmarhraoui 2022).

Table 3. Competing integrated step selection function model structures to describe seasonal resource selection by boreal caribou in the Mackenzie Valley, 2019–2023.[1,2,3]

Hypothesis	*K*	Model Structure
H1 Base Effect	13	Upland Conifer (%) + Sparse Conifer (%) + Water (%) + Terrain Ruggedness Index + Fire <40-years (%) + Linear Feature Density + Step Length + Log$_e$ Step Length + Cosine Turn Angle + Step Length : Time of Day (Night) + Log$_e$ Step Length : Time of Day (Night) Step Length : Time of Day (Twilight) + Log$_e$ Step Length : Time of Day (Twilight)
H2 MVWR Effect	16	**Base Effect** + Step Length : Log$_e$ MVWR Distance : Inside 15-km + Log$_e$ Step Length : Log$_e$ MVWR Distance : Inside 15-km + Cosine Turn Angle : Log$_e$ MVWR Distance : Inside 15-km +
H3 All Correlated Disturbances Effect	16	**Base Effect** + Step Length : Log$_e$ All Disturbance Distance : Inside 15-km + Log$_e$ Step Length : Log$_e$ All Disturbance Distance : Inside 15-km + Cosine Turn Angle : Log$_e$ All Disturbance Distance : Inside 15-km +

[1] *A Cox proportional hazard model specification does not include an intercept term. Time of day 'Day' is the reference category.*

[2] *Covariate values for the model terms in green text are associated with the 'start point' of a step, whereas all others are associated with the 'end point'.*

[3] *Three-way interaction terms between movement parameters (step lengths and turn angle) and the distance to disturbance (MVWR or all correlated disturbance sources) depend on the indicator variable 'Inside 15-km'. The interaction is only relevant if locations occur within 15 km of the disturbance (set 'Inside 15-km' = 1) and is otherwise equal to zero (set 'Inside 15-km' = 0).*

The hypothesized (or expected) effect of the MVWR on boreal caribou movement is shown in Figure 3. An effect would be evident if the caribou could make a long, directed movement to cross the MVWR (*available* step in Figure 3) but instead made a short, tortuous movement as it approached the MVWR (*used* step in Figure 3). We captured this expectation using a three-way interaction term in the iSSFs.

Three-way interactions between movement parameters and the distance to the MVWR (H2) or all correlated disturbances (H3) allowed us to determine whether caribou step lengths and turn angles depended on a caribou's proximity to the MVWR (e.g., Prokopenko et al. 2017). These three-way interaction terms were only relevant when a caribou's location occurred within a 15-km distance from those disturbance features, which was identified using an indicator variable ('Inside 15 km' = 1 or 0) (Table 3). If a caribou's location was outside the 15 km zone, then the three-way interaction equalled zero (i.e., the first two terms are multiplied by zero; see Aiello et al. 2023 for a similar approach).

Including these interactions in the model structures allowed us to evaluate patterns in caribou movement that emerged naturally because of the MVWR without explicitly specifying an avoidance effect (e.g., DeMars et al. 2020). We also applied log$_e$ transformations to distance values ('Log MVWR Distance' and 'Log All Disturbance Distance'; Table 3) so that the effect of the MVWR on caribou movement would diminish at greater distances (closer to 15 km).

We fit models H1–H3 for each trajectory to assess the estimated coefficients and variance explained by those model structures. We used corrected Akaike information criterion (AIC$_c$; Burnham and Anderson 2002) to select the model that explained the greatest amount of variation (log-likelihood) with the fewest number of parameters. We tallied the number of times H1, H2, or H3 represented the best model structure in every season (e.g., Prokopenko et al. 2017). We identified the top model, which best explained caribou habitat selection and movement, as the model with the highest tally.

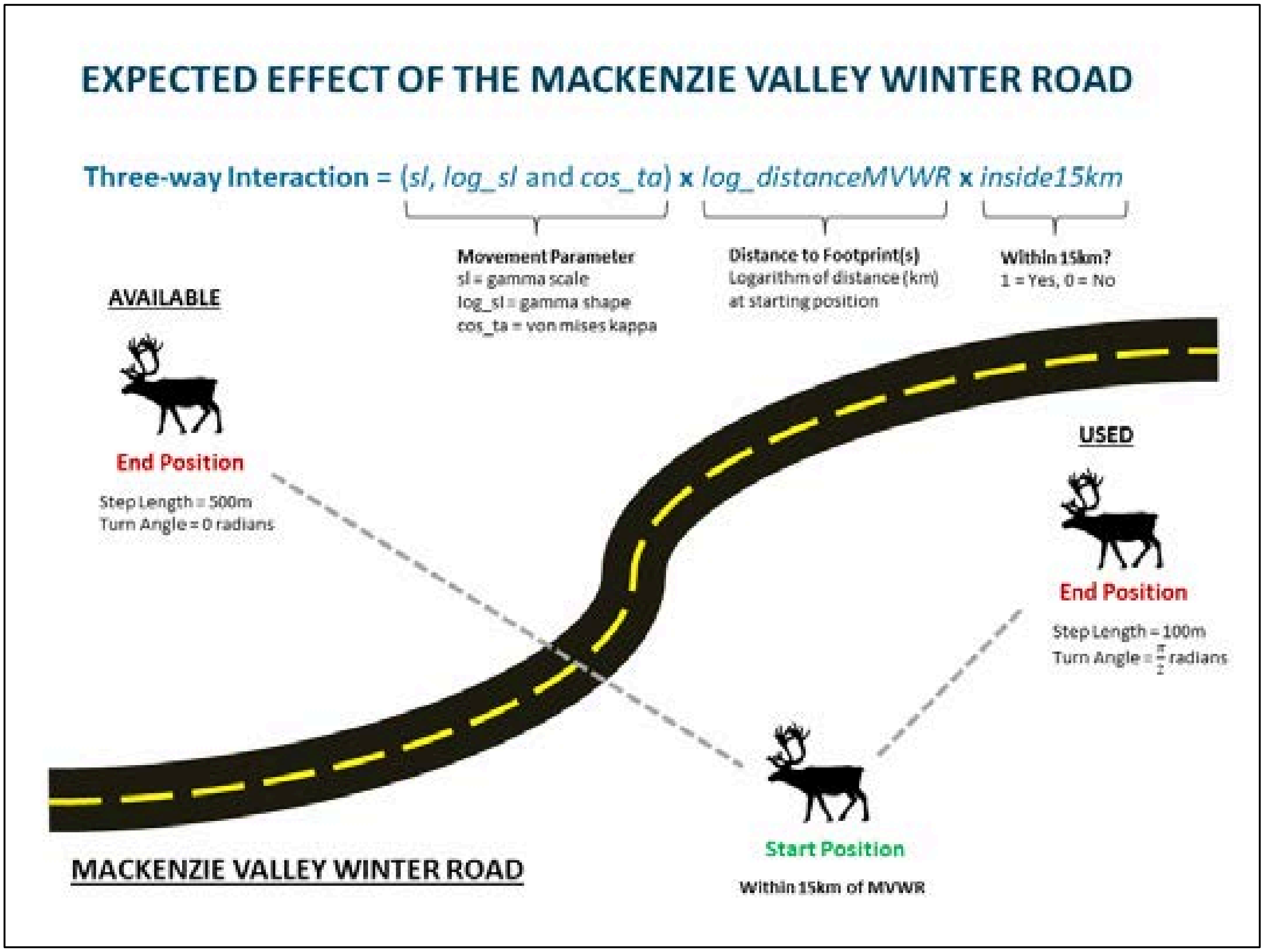


Figure 3. **Conceptual diagram of the expected effect of the Mackenzie Valley Winter Road on boreal caribou movement when fitting caribou trajectories to integrated step selection functions.**
Note: the winter road does not consist of a paved footprint; its depiction in this figure as such is simply for illustrative purposes.

2.1.4.3 Population-level Inference

We used the outputs of individual-level iSSFs to create population-level models for each season and, thus, generalize movement patterns to the boreal caribou population. The goal was to develop one base (H1) and one disturbance effects (H2 or H3) population-level model for each season and determine their predictive abilities. The utility of a model is not only based on its fit to the data (i.e., the AIC model selection tally outcomes) but also its ability to make predictions that are consistent with observations. The choice between H2 and H3 for population-level inference depended on which model had the highest selection tally.

We estimated population-level iSSFs using non-parametric bootstrapped estimates of individual-based iSSF model coefficients (Prokopenko et al. 2017). We resampled each iSSF coefficient randomly and with replacement 1,000 times to develop a sampling distribution and estimate the population-level mean (Davison and Hinkley 1997). In certain instances, individual-based models did not include estimates associated with burns (<40 years) or linear feature density (km/km^2) due to failures in maximum likelihood estimation (i.e., coefficients could not be estimated). This occurred because *used* caribou steps avoided entire areas with burns or linear features (i.e., complete avoidance), and even *available* steps occurred infrequently in such areas.

We had two options to deal with these two covariates to develop population-level estimates:

1. Use only the estimated coefficients from individual-level models for the bootstrapping procedure.
2. In addition to the estimated coefficients, assign values to the iSSFs without those coefficients and then use all individual-level models to produce bootstrapped estimates.

However, to ignore missing coefficients would disregard the observed (and complete) avoidance by caribou and underestimate effects at the population level. Therefore, we assigned individual-level models without coefficients for burns and linear feature density with a strong, negative value (–1.0) for those parameters to use in bootstrap resampling.

2.1.4.4 Effect of the Winter Road on Movement Patterns

We were interested in how caribou movement changed with the distance from the MVWR. To examine this, we used the movement parameter estimates from either the H2 or H3 population-level iSSFs, whichever of these two models had the most support (lowest AIC$_c$ score), to estimate the movement rates and tortuosity of boreal caribou based on their distance to the MVWR. Using the iSSF parameter estimates allowed us to account for other habitat-related effects on caribou movement (e.g., terrain ruggedness). We expected average movement rates to be lowest near the MVWR (1 km) and highest farther from the MVWR (15 km). Similarly, we expected caribou movements to be more tortuous (more frequent turns) closer to the MVWR and more directed (less turns) farther from the MVWR.

Using model coefficients, we calculated predicted movement parameters (*sl*, *log_sl*, and *cos_ta*) for caribou relative to time of day (day, night, twilight) and distance to the MVWR for models H2 and H3. From the predicted movement distributions, we calculated the average movement rate (m/2-hrs) of boreal caribou as the product of the updated gamma *shape* (log$_e$ step length) and *scale* (step length) parameters, which equals the mean of the gamma distribution (Prokopenko et al. 2017). Because three-way interactions with movement parameters were only relevant when caribou occurred within a 15-km distance from the MVWR, we evaluated changes to movement parameters at 1 km, 7.5 km, and 15 km distance intervals.

2.1.4.5 Validation of Base and Disturbance Effects Models

If the MVWR affected caribou movement, model H2 or H3 (both included the MVWR) would have better predictive ability than model H1 (base effect), which did not account for the MVWR. We used computer simulations to validate the predictions of the population-level H1 model and the top-ranking disturbance effect model (H2 or H3) in each season. We simulated caribou trajectories that made a total number of steps (at 2-hour intervals) equivalent to observed trajectories. In total, we developed 200 simulations per observed caribou trajectory — 100 iterations each beginning at the start and end positions of those trajectories.

Simulations combined the estimated movement kernel (i.e., movement process) with the habitat-selection kernel (i.e., habitat-selection process) to create a redistribution kernel (Avgar et al. 2016), which we then used to estimate the most likely steps made by caribou. The redistribution kernel required recalculation after every step in a simulated trajectory because iSSF models consisted of interaction terms between movement parameters and start-position covariate values, i.e., the time of day and distance to MVWR/disturbance (see Section 2.1.3 *Spatial Habitat Data* and Table 3). Put differently, each new step made by a simulated caribou depended on its previous location, so we needed to re-evaluate where a caribou would move next after every step it made. This process was computationally intensive, requiring weeks to complete. For a relevant example, see Aiello et al. (2023).

We implemented three methods to thoroughly validate the population-level iSSF models. The first method was a qualitative approach. We visually compared the simulation outputs to observed caribou trajectories to confirm that general patterns of movement and habitat selection were consistent with observations. For instance, if a real caribou moved across the landscape by avoiding ridges and selecting greater amounts of sparse conifer forest, then the simulated caribou should too.

The second method was semi-quantitative and compared simulated caribou trajectories to observed caribou trajectories. We compared the crossings and space use of observations and simulations relative to the MVWR. First, we visually compared the frequency distribution of observed and simulated caribou locations as a function of distance to the MVWR. Rather than comparing categorized (discrete) distance bins using a histogram with arbitrary distance intervals, we developed continuous distance distributions using (Gaussian) kernel density estimators that implemented Silverman's rule of thumb for bandwidth selection (Silverman 1986). Second, we calculated the proportion of caribou trajectories that crossed the MVWR and examined the differences between observed and simulated trajectories using a chi-square (χ^2) test of proportions. These two tests demonstrated whether model simulations of caribou movement across the landscape matched observed caribou movements.

Finally, an intensive quantitative method was also used to assess model performance, but this approach was more complicated than what is typically done to validate habitat models. K-fold cross-validation is the standard model validation procedure for RSFs. It compares known animal locations to a map of predicted selection probabilities (Boyce et al. 2002, Johnson et al. 2006). However, Signer et al. (2017) demonstrated that these 'naïve' predictive maps are unsuitable for SSFs (and similarly iSSFs) because, unlike RSFs, habitat availability is dynamic in space and time. Instead, a simulation-based approach is necessary to develop utilization distributions (UDs) to compare against observed animal locations (e.g., Aiello et al. 2023).

The following steps outline the procedures used to implement the simulation-based approach for each season and model type (H1 and H2/H3):

1. Compute the minimum convex polygon around all *observed* caribou locations and apply a 5-km buffer around that extent (allowing additional space for simulated trajectories) to define the spatial bounds of the UD. These spatial bounds correspond to the population-level scale for model validation. Within these bounds, create an empty grid (without any values).
2. Superimpose *simulated* caribou trajectories on the empty grid and count the frequency of their locations in each grid cell. Since the resolution of the grid (cell size) can affect the frequency of locations (i.e., smaller cells are likely to fit fewer locations), repeat the process using eight different cell-size dimensions: 30 m by 30 m, 60 m by 60 m, 90 m by 90 m, 120 m by 120 m, 150 m by 150 m, 180 m by 180 m, 210 m by 210 m, and 240 m by 240 m.
3. Scale the grid frequencies so that all grid values sum to one, which creates a UD. Reclassify the frequencies in grid cells to deciles (10-percentile intervals), effectively ranking cells from 1–10.
4. Superimpose *observed* caribou locations on the UD, extract the corresponding decile (rank) value for each location, and calculate the proportion of observed locations in each decile bin. As per Aiello et al. (2023), divide the proportion of locations in each decile bin by the total number of cells comprising that bin, resulting in area-corrected proportions or 'densities'.
5. Calculate the mean and standard errors for (a) the density of caribou locations in each decile bin and (b) spearman rank correlations (r_S) between observed caribou densities and decile bins based on the eight cell-sizes used to create UDs.

2.1.5 ALTERED HABITAT CONNECTIVITY

Roads can act as semi-permeable barriers, which may reduce habitat connectivity. To investigate whether the MVWR reduces habitat connectivity, we developed caribou simulations for two scenarios: one *with* and one *without* the MVWR's effects. These scenarios aimed to identify (a) potential movement corridors that may be 'blocked' by the MVWR, and (b) changes in landscape utilization or space use. We used population-level model coefficients from H2/H3 models to simulate caribou trajectories *with* the MVWR's effects ('MVWR-mediated movement'). For the scenario *without* the MVWR's effects ('MVWR-free movement'), we set the movement-related three-way interactions to equal zero (see Table 3). To mask the habitat disturbance associated with the MVWR right-of-way in the scenario without the MVWR's effects, we used nearest-neighbour interpolation to change EOSD landcover values along the right-of-way to match those of adjacent, undisturbed pixels. Comparison between these two scenarios allowed us to identify whether the MVWR's influence on boreal caribou movement results in reduced crossings and space use near the road.

We simulated 1,000 caribou trajectories at 28 different start points approximately 15 km from the MVWR. These start points were spaced (relatively) evenly to cover the extent of the MVWR between Wrigley and Norman Wells — the section of the MVWR to be replaced by the all-season Mackenzie Highway. There were two hypotheses:

1. If a caribou approaches the MVWR's potential ZOI (15 km), the MVWR's effect would limit how close the animal gets to the road and should frequently result in the animal travelling distances farther from the road.
2. If a caribou does come near the MVWR, it will do so infrequently because of the MVWR's effects, resulting in few crossings.

We used simulated caribou trajectories to calculate UDs and the number of MVWR crossings for each scenario. We calculated utilization at a 1 km by 1 km pixel size to quantify broader space use patterns, especially given the large extent of the MVWR. We summed the number of MVWR crossings within 10-km (approximate length) segments of the MVWR to determine specific regions that might be movement corridors. We then calculated the difference in utilization and number of crossings between the two scenarios.

Differences in UDs identified whether the MVWR's effects reduced space use near the road. Similarly, differences in the number of crossings identified whether the MVWR's effects reduced crossings and 'blocked' potential movement corridors. To highlight and present those differences, we generated maps with decile ranks assigned to pixels in the UDs and 10-km segments of the MVWR footprint.

2.2 PROXIMITY OF CALVING CARIBOU TO THE WINTER ROAD

Another goal of this study was to evaluate how the MVWR might affect boreal caribou calving. In particular, how far parturient cows positioned themselves from the MVWR during a calving event. We selected caribou locations from all years (2007–2022) regardless of the fix rates (i.e., 2-hour or 8-hour time intervals) and evaluated daily movements to identify approximate calving dates. The period used to assess calving ranged from April 25 until the end of the calving season, which varied between Dehcho and Sahtú regions.

As described in Section 2.1.2 *GPS Telemetry Data, 2019–2023*, we regularized caribou trajectories to only include relocations taken at 2-hour or 8-hour intervals, depending on the fix rate set for a given collar. We initially considered all caribou occurring within 100 km of the MVWR. We then removed the top 1% of all step lengths to focus the data on the shorter step lengths and, thus, subtle changes in movement.

To identify the calving event, we needed to isolate the day when caribou slowed their trajectory substantially and maintained those low movement rates over several days. To do this we calculated three-day moving averages (TDMAs; DeMars et al. 2013) during the calving period. However, unlike DeMars et al. (2013), we did not have known calving events to establish a movement rate threshold to identify potential calving events. Instead, we had to assess relative changes in TDMAs by implementing the following ruleset to identify potential calving events (dates):

1. Assign TDMAs per day in the caribou trajectory.

2. Retain dates with TDMAs at the 30th percentile and lower and exclude all others.
3. For every remaining date, calculate the average TDMA over the subsequent 4-day period ('Avg_4-day'), the negative change in TDMA from the previous date ('delta_TDMA'), and the sum of the TDMA and 'delta_TDMA' ('diff_TDMA'). The latter metric assesses the trade-off in the rate of change and the absolute value of, the TDMA for a given date. A pregnant cow is expected to move urgently toward a calving area and slow down dramatically during parturition and delivery. Thus, the 'delta_TDMA' would be large, negative value and the TDMA would be a small, positive value.
4. If the 'Avg_4-day' values were relatively flat across all remaining dates (i.e., Avg_4-daymax – Avg_4-daymin < 150 m), then the earliest date with the largest 'delta_TDMA' or lowest 'Avg_4-day' was selected. Otherwise, the earliest date with the lowest 'diff_TDMA' or lowest 'Avg_4-day' was selected.

After applying the criteria above, we qualitatively evaluated the selected calving dates using (a) probable calving thresholds estimated from the caribou trajectory data (approximately $\leq$50 m/2-hours or $\leq$200 m/8-hours) and (b) a visual assessment of movement rates, including drastic changes in rates at the onset of parturition and maintained low movement rates thereafter. We also evaluated a random subset of caribou trajectories and their estimated calving dates in a GIS (QGIS Development Team 2023), looking for slowed, focal movements on the calving date relative to the preceding days.

After identifying calving dates and locations for all caribou in the study area, we evaluated the frequency distribution of calving events at different distances from the MVWR. The distribution of calving events, including the mean and variance, depends on the scale of analysis. The mean distance from the MVWR will be very far if we include all caribou within a 100-km radius of the MVWR and, thus, will not be representative of parturient females that could be affected by the winter road. So, we subset the calving location data to include only those that occurred within 30 km of the MVWR, a distance twice the size of the expected ZOI (15 km).

We $\log_e$ transformed distance values to develop a roughly normal distribution (i.e., mean with normally distributed errors and equal variance), which we confirmed using the Shapiro-Wilk test for normality and visual assessment of the $\log_e$ transformed distribution. We then conducted a one-sample *t*-test to determine if the (geometric) mean distance varied significantly from the potential ZOI (15 km) used in Section 2.1 *Quantifying Effects and Barriers to Movement* to evaluate movement effects. To visualize the continuous distance distribution in a plot, we used a (Gaussian) kernel density estimator and applied Silverman's rule of thumb for bandwidth selection (Silverman 1986) but adjusted the bandwidth with a multiplier of 0.25 (1/4th) to identify finer-resolution changes in the distribution.

3 RESULTS

3.1 MOVEMENT AND BEHAVIOUR

3.1.1 OBSERVED BOREAL CARIBOU MOVEMENTS

3.1.1.1 Visual Assessment

Spatial assessment of observed trajectories provided insight into caribou movement patterns and potential barriers to movement. For instance, there appears to be a relatively strong avoidance of rugged terrain (Figure 4). This phenomenon is exemplified by animal BWCA21109 during the 2021 calving to post-calving period. This caribou followed a sharp, high ridgeline on the east side of the MVWR for many days but never crossed it (Figure 4) and consistently occupied less rugged terrain throughout its trajectory, primarily along valley bottoms.

Natural and anthropogenic linear features, such as the Mackenzie River and the MVWR, also appear to form semi-permeable barriers to boreal caribou movement in the region (Figure 5). For example, animals BWCA23114 and BWCA21108 can be seen moving parallel to, but not crossing, the Great Bear River during the 2023 mid winter period (Figure 5). However, the barrier effect of the Mackenzie River and the MVWR appears to vary by individual. Animal BWCA20100, during the rut to late fall period, made parallel movements to the MVWR (and Mackenzie River) that did not cross, whereas BWCA21101 crossed both the MVWR and Mackenzie River several times during the same season (Figure 6). Only five of 30 caribou trajectories crossed the MVWR during the seasons of interest: one during early to mid winter, two during late winter, and two during calving to post-calving. These crossings primarily occurred along the east-west axis of the MVWR (Tulita to Délįnę — Délįnę Winter Road).

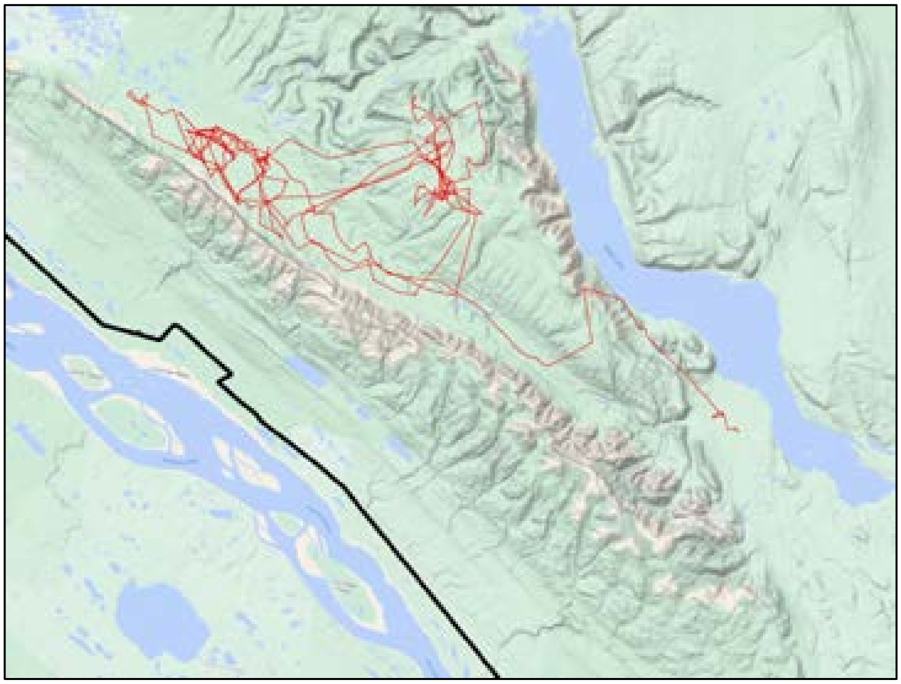


Figure 4. Animal BWCA21109 during the 2021 calving to post-calving period following the ridgeline to the east of the Mackenzie Valley Winter Road near Norman Wells.

Red lines indicate the movement path of the caribou. The black line indicates the Mackenzie Valley Winter Road.

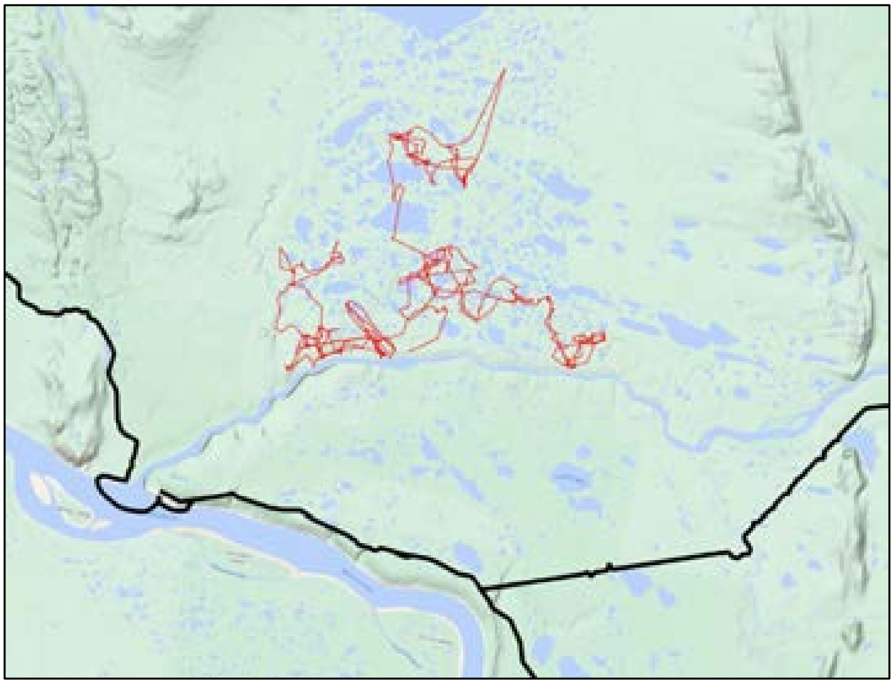


Figure 5. BWCA23114 and BWCA21108 (red) during the 2023 mid winter period, moving parallel to the Mackenzie River northeast of Tulita.

Red lines indicate the movement path of the caribou. The black line indicates the Mackenzie Valley Winter Road.

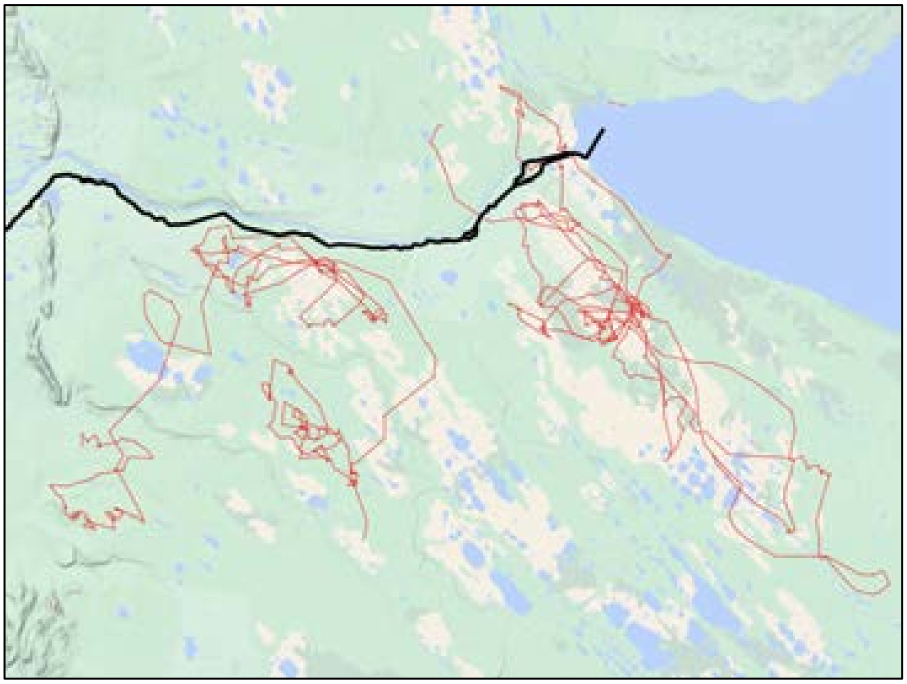


Figure 6. Animal BWCA20100 (left) seen making parallel movements along the Mackenzie Valley Winter Road during rut/ late fall 2020 between Tulita and Délı̨nę. Animal BWCA21101 (right) seen crossing the Mackenzie Valley Winter Road during rut/ late fall 2021 between Tulita and Délı̨nę.
Red lines indicate the movement paths of the caribou. The black line indicates the Mackenzie Valley Winter Road.

3.1.1.2 Movement Rates and Turn Angles

Formal assessments of movement rates and turn angles revealed little differences between near versus far from the MVWR. Average movement rates of boreal caribou did not change between 0–15 km from the MVWR during early to mid winter (β = –0.04 [95% CI = –0.10, 0.03]) or late winter (β = –0.01 [95% CI = –0.14, 0.14]). The distribution of movement rates, at distances ranging 0–15 km from the MVWR, and the fitted regression lines from mixed effect models are shown in Figure 7.

During both early to mid winter and late winter, movement rates are consistently variable across the range of MVWR distances. However, there was some evidence that movement rates decreased at farther distances (closer to 15 km) from the MVWR during calving to post-calving (β = –0.08 [95% CI = –0.13, –0.03]). This decrease in movement rate corresponds to a decreased average rate of 436 m/2-hours (0 km distance) to 309 m/2-hours (15 km distance). However, the apparently higher movement rates near the MVWR during calving to post-calving may be an artifact of fewer samples at those close distances with higher movement rates (Figure 7).

Turn angles made by boreal caribou were relatively consistent between 0–1 km and 14–15 km from the MVWR during early to mid winter and late winter (Figure 8). The empirical distributions at both distances mostly overlapped. In contrast, there was a greater peak at zero radians at the 0–1 km distance than the 14–15 km distance during calving to post-calving, which indicates more frequent directed (straight) movements at distances close to the MVWR.

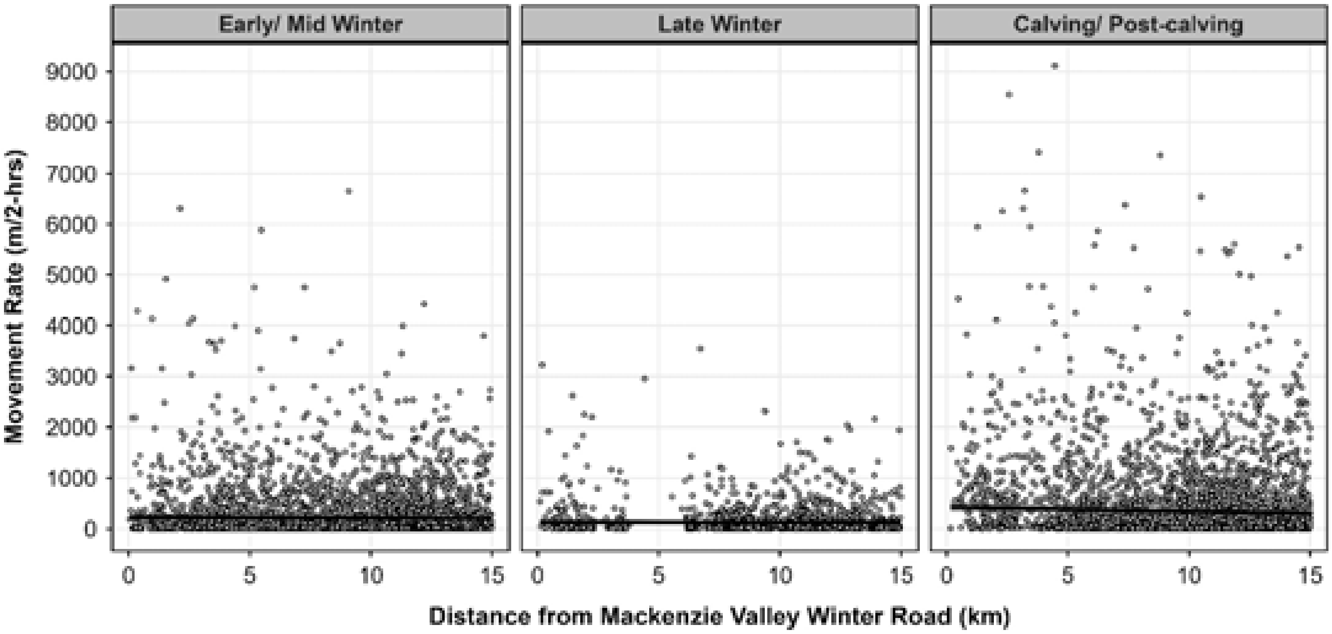


Figure 7. **Natural logarithm of movement rates (m/2-hours) by boreal caribou at distances from the Mackenzie Valley Winter Road during early to mid winter, late winter, and calving to post-calving.**
Grey circles indicate movement rates from all caribou trajectories in a season; black line and grey band indicate the linear mixed model regression line and 95% confidence intervals, respectively.

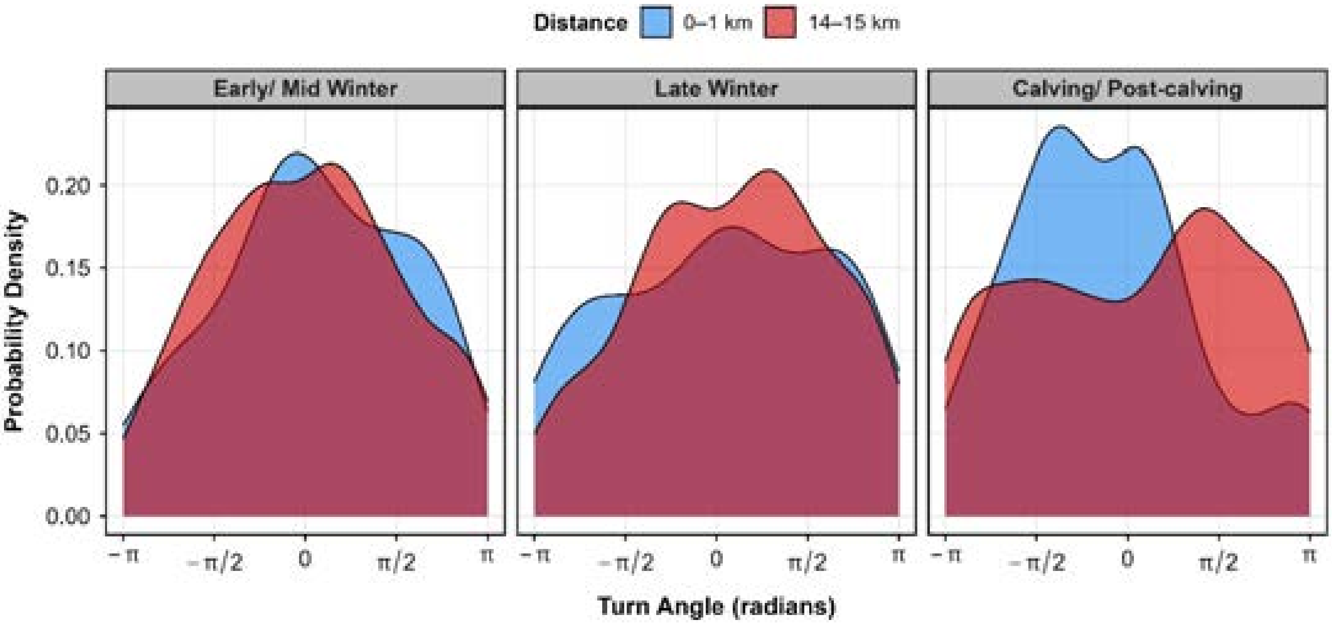


Figure 8. **Empirical turn angle distributions of boreal caribou movements at distance intervals from the Mackenzie Valley Winter Road during early to mid winter, late winter, and calving to post-calving.**
Blue distribution indicates 0–1 km and red distribution indicates 14–15 km from the Mackenzie Valley Winter Road.

3.1.2 FACTORS AFFECTING CARIBOU HABITAT SELECTION AND MOVEMENT

The most supported individual-based iSSF models (H1–H3) were not consistent across seasons (Table 4), nor were the magnitude and direction of model coefficients at the population level (Figure 9). During early to mid winter, model H2 was most supported. During calving to post-calving, model H3 received the greatest support, but the tally for H1 and H2 models was only lower by 1 and 2 individuals, respectively. However, cumulatively, there was more support for some form of disturbance (whether the MVWR or all correlated disturbances) affecting boreal caribou movement during calving to post-calving. During late winter, there was greater overall support for model H1, absent of the MVWR's effects. The model selection results for every individual caribou trajectory in each season can be found in Appendix A *Individual-Based Model Selection Results*.

Table 4. Akaike Information Criterion (AIC$_c$) model selection tally for three models H1 to H3 fit to boreal caribou trajectories during three seasons in the Mackenzie Valley, 2019–2023.[1]

Season	***N***	**AIC$_c$ Model Selection Tally**		
		H1 Base Habitat Effect	**H2 Winter Road Effect**	**H3 All Disturbances Effect**
Early to Mid Winter	14	4 (0.68)	**9** (0.98)	1 (1.00)
Late Winter	13	**8** (0.65)	1 (0.90)	4 (0.74)
Calving to Post-calving	15	5 (0.78)	4 (0.95)	**6** (0.99)

[1] *Tallies correspond to the number of times a given model structure had the highest AICc rank in each season. Numbers in brackets correspond to the median AIC$_c$ weight.*

Population-level iSSF (bootstrapped) coefficient estimates and 95% confidence intervals for parameters related to habitat selection related parameters are provided in Figure 9. These parameter estimates correspond to model H2 for early to mid winter, model H3 for late winter, and model H3 for calving to post-calving. We provide habitat-related coefficients only for these disturbance models because coefficients are relatively unchanged from base models. During early to mid winter and calving to post-calving seasons, boreal caribou selected upland conifer and sparse conifer forests. During late winter, boreal caribou selected sparse conifer forests but avoided upland conifer forests.

In all seasons, caribou demonstrated differing degrees of avoidance of water and rugged terrain. Water avoidance was greater during calving to post-calving than during early to mid winter but was greatest overall during late winter. Regarding natural and anthropogenic disturbances, caribou consistently avoided areas with burns (<40 years old) and high linear feature densities.

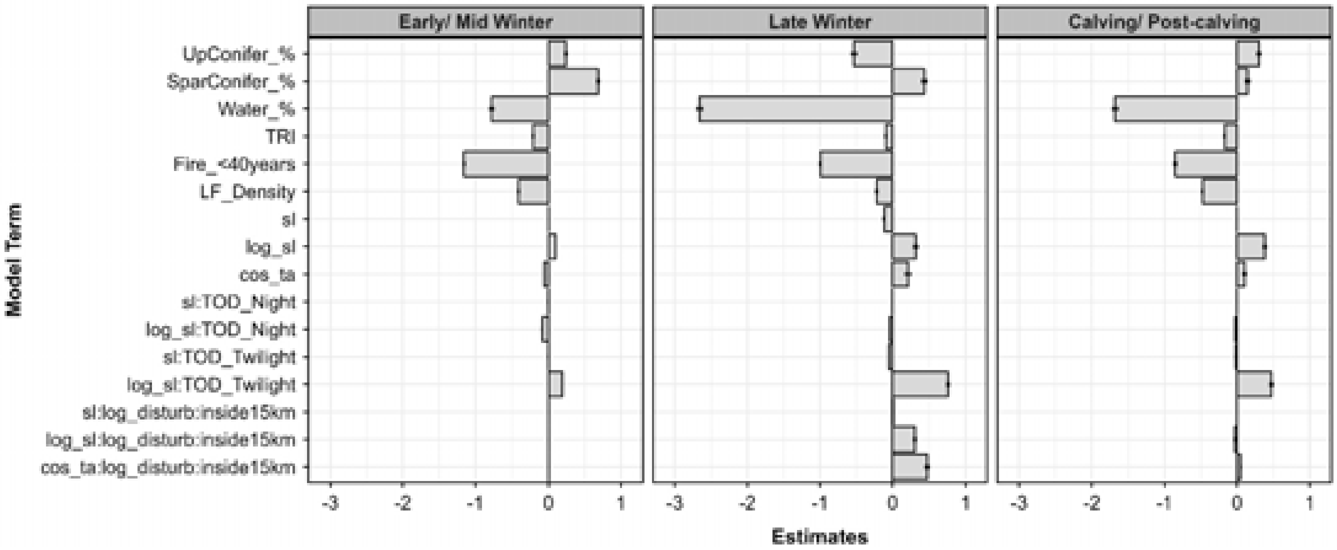


Figure 9. Population-level model parameter estimates of boreal caribou habitat selection and movement during three seasons in the Mackenzie Valley, 2019–2023.

Error bars indicate lower and upper 95% bootstrapped confidence intervals. The model for early to mid winter includes the effect of the Mackenzie Valley Winter Road (H2) while models for late winter and calving to post-calving include the effects of all disturbances correlated with the winter road (H3).

Three-way interaction terms between movement parameters and the distance to the MVWR (or all correlated disturbances) are not easily interpreted by the model coefficients. Instead, we estimated average movement rates and turn angle distributions at different distances from the MVWR.

Boreal caribou movement patterns varied by the time of day, distance to the MVWR (or all correlated disturbances), and across seasons (Figure 10). For example, daytime movements during early to mid winter subtly decreased from 1 km (287.80 m/2-hrs) to 15 km (268.01 m/2-hrs) from the MVWR. In contrast, daytime movement rates during calving to post-calving nearly tripled at 1 km (343.23 m/2-hrs) to 15 km (912.78 m/2-hrs) from the MVWR. We also identified anomalously high movement rates during late winter at a 15-km distance from the MVWR (3,304 m/2-hrs), which is likely the result of several factors (e.g., interindividual variation, restricted movements, proximity to MVWR) that yielded uninformative population-level parameter estimates (see Section 4 *Discussion*).

The tortuosity of caribou movement paths showed minimal change at varying distances from the MVWR, but those changes corresponded to greater tortuosity close to the MVWR and more direct (straight) paths farther from the MVWR (Figure 11). This pattern was most evident during calving to post-calving. Note that the very directed movements during late winter were also anomalous, yielding uninformative population-level parameter estimates (see Section 4 *Discussion*).

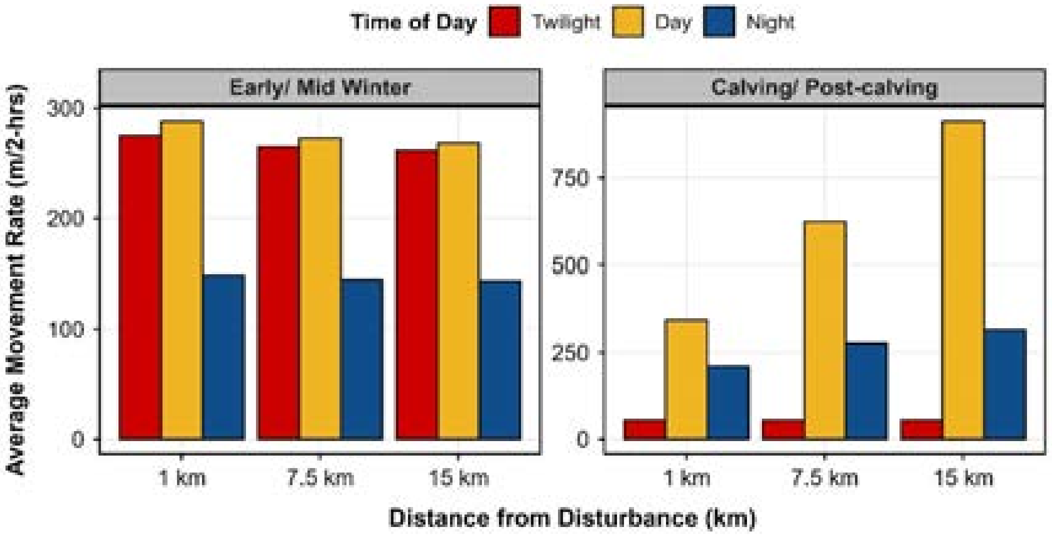


Figure 10. **Population-level average movement rates (m/2-hrs) during early to mid winter, late winter, and calving to post-calving, conditional on the time of day and distance from sources of disturbance in the Mackenzie Valley, 2019–2023.**

During early to mid winter, the distance is relative to the Mackenzie Valley Winter Road (H2). During calving to post-calving, the distance is relative to all correlated sources of disturbance (H3).

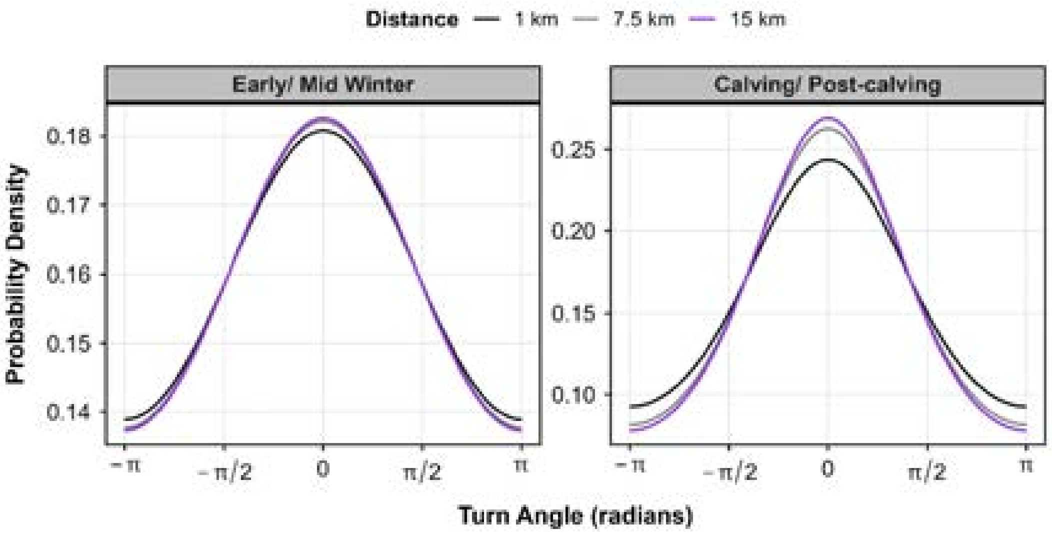


Figure 11. **Population-level turn angle distributions of boreal caribou during early to mid winter, late winter, and calving to post-calving conditional on the distance from sources of disturbance in the Mackenzie Valley, 2019–2023.**

During early to mid winter, the distance is relative to the Mackenzie Valley Winter Road (H2). During calving to post-calving, the distance is relative to all correlated sources of disturbance (H3).

3.1.3 VALIDATION OF BASE AND DISTURBANCE EFFECT MODELS

3.1.3.1 Visual Assessment — Observed Versus Simulated Trajectories

An example of observed versus simulated trajectories during early to mid winter is provided in Figure 12. The observed trajectory of animal BWCA20105 (2023, red) occurs in a mountainous region but this individual primarily moves through lower valleys, moderate slopes, and avoids the rugged, high-elevation areas. The 20 simulation iterations for each of H1 and H2 models also follow this pattern (Figure 12).

Sometimes, simulated trajectories diverged from those observed but remained in similar habitat components. For example, the observed trajectories of caribou during calving to post-calving span a large area on the east side of the Mackenzie River and MVWR, as shown in Figure 13. The H3 simulated trajectories (blue) tended to move farther eastward into regions with greater amounts of sparse and upland conifer forest, low to moderate terrain ruggedness, few recent burns (<40 years old), and low densities of linear features. In contrast, H1 simulated trajectories (green) remained closer to the MVWR and made fewer long-distance movements eastwards.

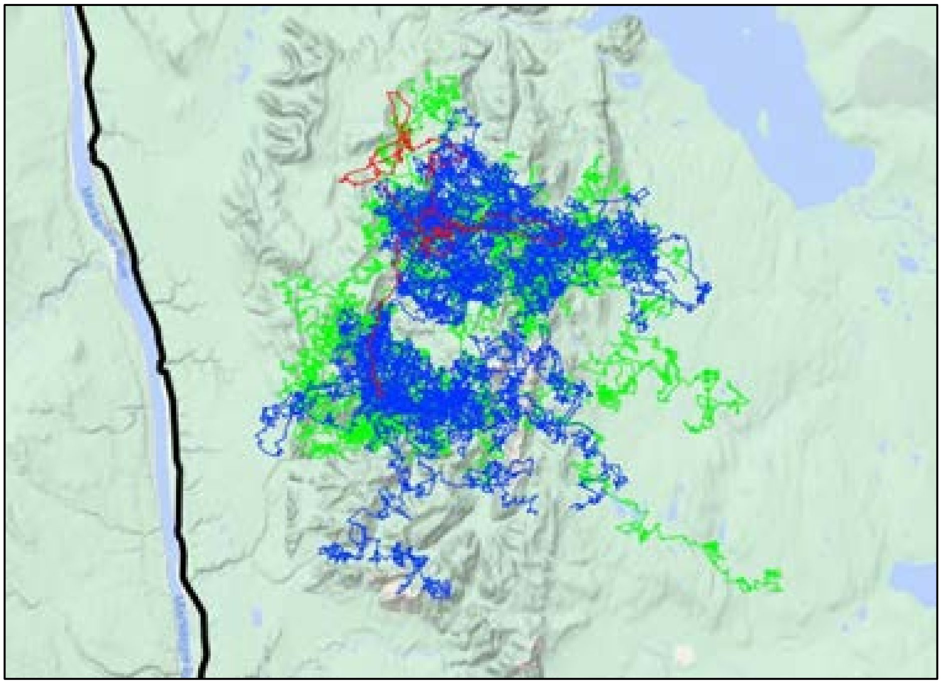


Figure 12. Population-level model simulations of disturbance effects (H2) and base effects (H1) trajectories during early to mid winter relative to the observed trajectory of Animal BWCA20105 (mid winter 2023).

Simulations: blue = disturbance effects; green = base effects. Red lines indicate the observed movement path of the caribou. The black line indicates the Mackenzie Valley Winter Road.

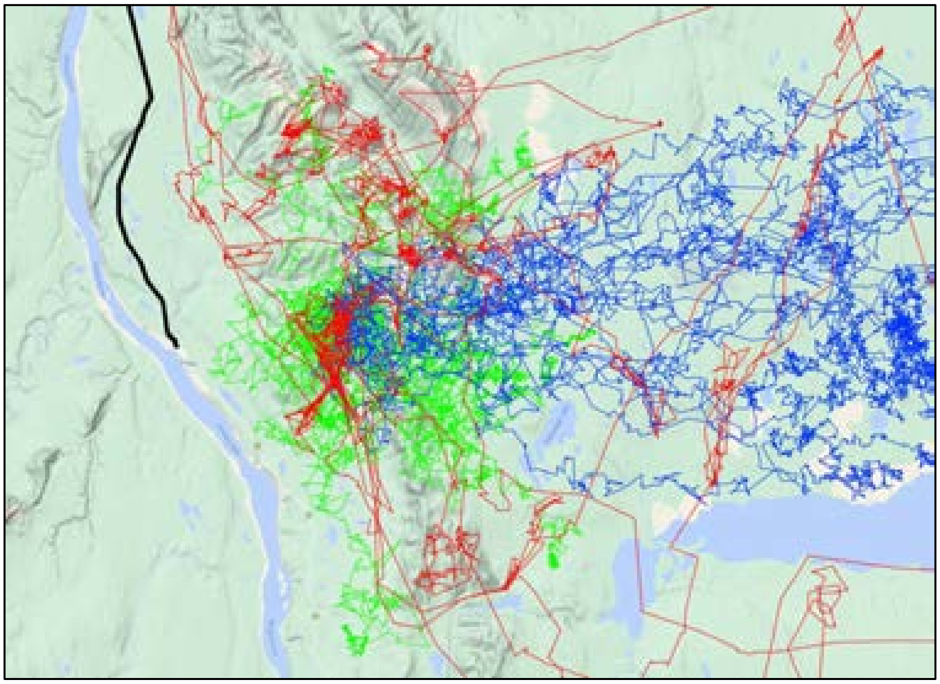


Figure 13. Population-level model validation simulations of disturbance effects (H3) and base effects (H1) trajectories during calving to post-calving relative to the observed trajectories of several caribou. *Simulations: blue = disturbance effects; green = base effects. Red lines indicate the observed movement paths of the caribou. The black line indicates the Mackenzie Valley Winter Road.*

3.1.3.2 Proximity and Crossings — Observed Versus Simulated Trajectories

The simulated proportions of crossings did not differ significantly from the observed proportions of crossings, further validating the models (Table 5). The relatively high *P*-values (i.e., $P > 0.05$) are likely the result of comparing chi-square-distributed (χ^2) proportions derived from small (observed) versus large (simulated) sample sizes. The proportions of crossings H2 (early to mid winter) and H3 (calving to post-calving) simulations tended to be closer to the observed proportions, e.g., within 0.03 during early to mid winter and equivalent during calving to post-calving (Table 5). The proportion of crossings in disturbance-based simulations was still quite different from those observed during late winter (0.08), but this difference is not statistically significant ($P = 0.27$).

Frequency distributions of caribou locations as a function of distance to the MVWR revealed a greater similarity between H1 simulations and observed caribou trajectories (Figure 14). During late winter, the distance distribution of H1 simulations closely matched the observed distribution of caribou locations, with most occurring within 15 km of the MVWR, whereas disturbance effects (H3) simulations tended to have frequent locations well beyond 15 km from the MVWR.

A similar pattern was evident during calving to post-calving: H1 simulations had an overlapping distribution with observed trajectories but H3 simulations had a distribution more frequent at far distances. The tendency of H3 simulations to have trajectories move farther (east) away from the MVWR is also shown in Figure 13 (above). However, during early to mid winter, distance distributions from H1 and H2 simulations were similar (overlapping).

Table 5. **The proportion of observed and simulated (base effects [H1] and disturbance effects [H2 or H3]) trajectories that crossed the Mackenzie Valley Winter Road during three seasons.**

Season	Caribou Trajectory	Proportion of Crossings	Test of Proportions Relative to Observed Trajectories	
			χ^2-statistic	*P*
Early to Mid Winter	Observed	0.07	—	—
	Simulated – Base Effects (H1)	0.11	0.17	0.68
	Simulated – MVWR Effects (H2)	0.10	0.13	0.72
Late Winter	Observed	0.15	—	—
	Simulated – Base Effects (H1)	0.07	1.20	0.27
	Simulated – All Disturbances Effects (H3)	0.09	0.55	0.46
Calving to Post-calving	Observed	0.13	—	—
	Simulated – Base Effects (H1)	0.06	0.97	0.33
	Simulated – All Disturbances Effects (H3)	0.13	0.00	0.96

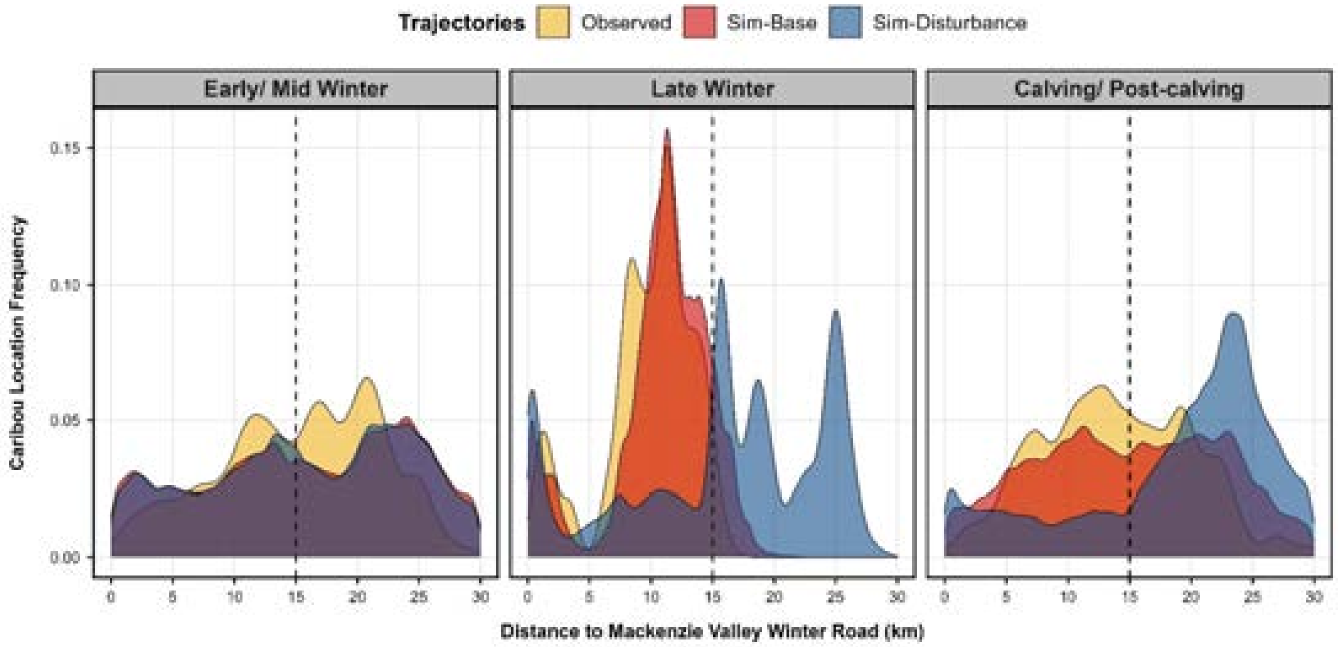


Figure 14. **Frequency distribution of boreal caribou locations relative to the Mackenzie Valley Winter Road during three seasons.**

Observed (yellow shade) and simulated (base effects [H1, red shade] and disturbance effects [H2 or H3, blue shade]) trajectories are compared. The dashed (vertical) line identifies a 15-km distance from the winter road.

3.1.3.3 Utilization Distributions and Observed Caribou Densities

The association between the density of observed caribou locations and UD rank bins are summarized in Table 6. A high correlation coefficient indicates a model with good predictive ability. The most supported models had excellent predictive ability, with r_s values between 0.93–0.98 (Table 6).

Disturbance effects associated with the MVWR during early to mid winter (H2) and all correlated disturbances during calving to post-calving (H3) had greater predictive performance compared to the base model (H1) without those effects. However, during late winter, the base model (r_s=0.95, Table 6) had greater predictive performance as compared to H3, which performed very poorly (r_s= 0.04, Table 6). Refer to Appendix B *Model Validation Plots* to see plots of the association between observed caribou densities and UD rank bins.

Table 6. Spearman rank correlation (r_s) of utilization distribution decile bins and the density of caribou locations in each season and model type.[1]

Season	Model	Mean r_s	Std. Error r_s
Early to Mid Winter	Base Effect (H1)	0.97	0.01
	MVWR Effect (H2)	0.98	0.02
Late Winter	**Base Effect (H1)**	0.95	0.01
	All Disturbances Effect (H3)	0.04	0.09
Calving to Post-calving	Base Effect (H1)	0.83	0.06
	All Disturbances Effect (H3)	0.93	0.03

[1] *Mean and standard errors of correlations calculated at the population level (combining all trajectories) from all eight cell-size resolutions. Bolded models are the most supported model for that season.*

3.2 ALTERED HABITAT CONNECTIVITY

We investigated the potential barrier effects of the road on caribou movement using caribou simulations under scenarios *with* and *without* the MVWR's effect[3]. We did not complete a connectivity analysis for late winter because those model predictions did not match the observed trajectories of boreal caribou (i.e., poor predictive performance of model H3).

Based on simulated scenarios, we did not identify a substantially reduced number of crossings during calving to post-calving. During the calving to post-calving season, the number of crossings were either equivalent

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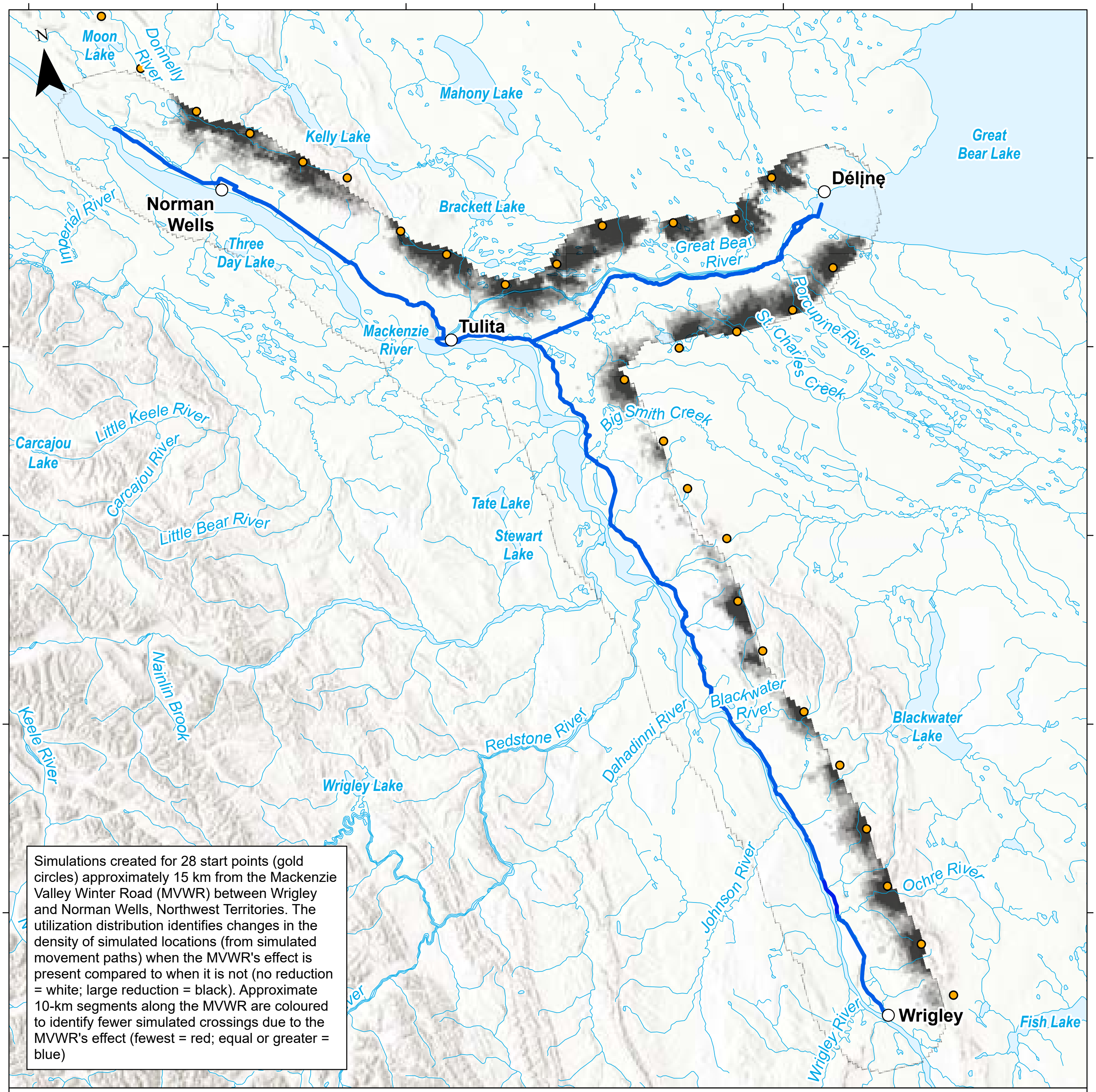
[3] The habitat connectivity analyses presented in this report are derived from iSSF model predictions that did not correct datetimes of caribou locations, which consequently altered the average predicted movement rates during different times of day (i.e., time-of-day covariate; day, night, and twilight). In **Appendix C** *Time-Corrected Versus Time-Uncorrected Models and Simulations*, we provide a comparison between time-corrected and time-uncorrected iSSF model predictions and simulations to demonstrate their equivalence. Time-corrected and time-uncorrected simulations of caribou movements were (a) consistent in their patterns of habitat selection across the landscape and (b) similar in their predicted utilization and association with observed caribou locations. Therefore, the results presented here are invariant to the 'time-of-day effect' and provide valuable information of the Project's potential impacts to caribou movement and habitat.

between the two scenarios or greater for the MVWR scenario, except for one 10-km segment of the MVWR north of Wrigley, where there were six fewer crossings (Map 3).

The greater number of crossings for the MVWR scenario occurred along the east-west axis of the MVWR. Further, an inspection of crossings from the simulation without the MVWR's effect demonstrates that, even in the absence of the MVWR, boreal caribou do not cross the MVWR's north-south axis. Movement within a few kilometres of the MVWR was relatively unchanged between the two scenarios, except for east of Tulita where the number of trajectories was reduced when the MVWR's effect was present in the calving to post-calving season. Instead, the greatest reduction in trajectories occurred approximately 10–15 km from the MVWR.

During early to mid winter, we identified specific segments along the MVWR that could be potential movement corridors. The difference in crossings and space use by caribou under the scenarios with and without the MVWR's effect are identified in Map 4. Along the west-east axis of the MVWR (Tulita to Déline — Déline Winter Road), there were several segments that had reduced crossings (red segments, approximately 100–294 fewer) and reduced space use close to those crossing locations.



Simulations created for 28 start points (gold circles) approximately 15 km from the Mackenzie Valley Winter Road (MVWR) between Wrigley and Norman Wells, Northwest Territories. The utilization distribution identifies changes in the density of simulated locations (from simulated movement paths) when the MVWR's effect is present compared to when it is not (no reduction = white; large reduction = black). Approximate 10-km segments along the MVWR are coloured to identify fewer simulated crossings due to the MVWR's effect (fewest = red; equal or greater = blue)

Legend

- ● Start Points
- ○ Major Settlements
- — Watercourse
- ▨ Waterbody

Decreased Frequency of Caribou Locations

- Large Reduction
- No Reduction

Fewer Caribou Crossings due to Barrier Effect

- 1 (Large Reduction)
- 2
- 3
- 4
- 5
- 6
- 7
- 8
- 9
- 10 (No Reduction)

Map 3. The difference in simulated boreal caribou crossings and space use between scenarios with and without the Mackenzie Valley Winter Road's effect during Calving to Post-calving

K'alo-Stantec Limited

Data Sources

- Inset Basemap. National Geographic World Map: National Geographic, Esri, Garmin, HERE, UNEP-WCMC, USGS, NASA, ESA, METI, NRCAN, GEBCO, NOAA, increment P Corp.
- Main Basemap. World Hillshade: Esri, USGS
- Major Settlements, Mackenzie Valley Highway Alignment, MVWR, Watercourse, Waterbody. CanVec data, Natural Resources Canada, 2023.
- Caribou modelling. EDI Environmental Dynamics Inc. 2023.

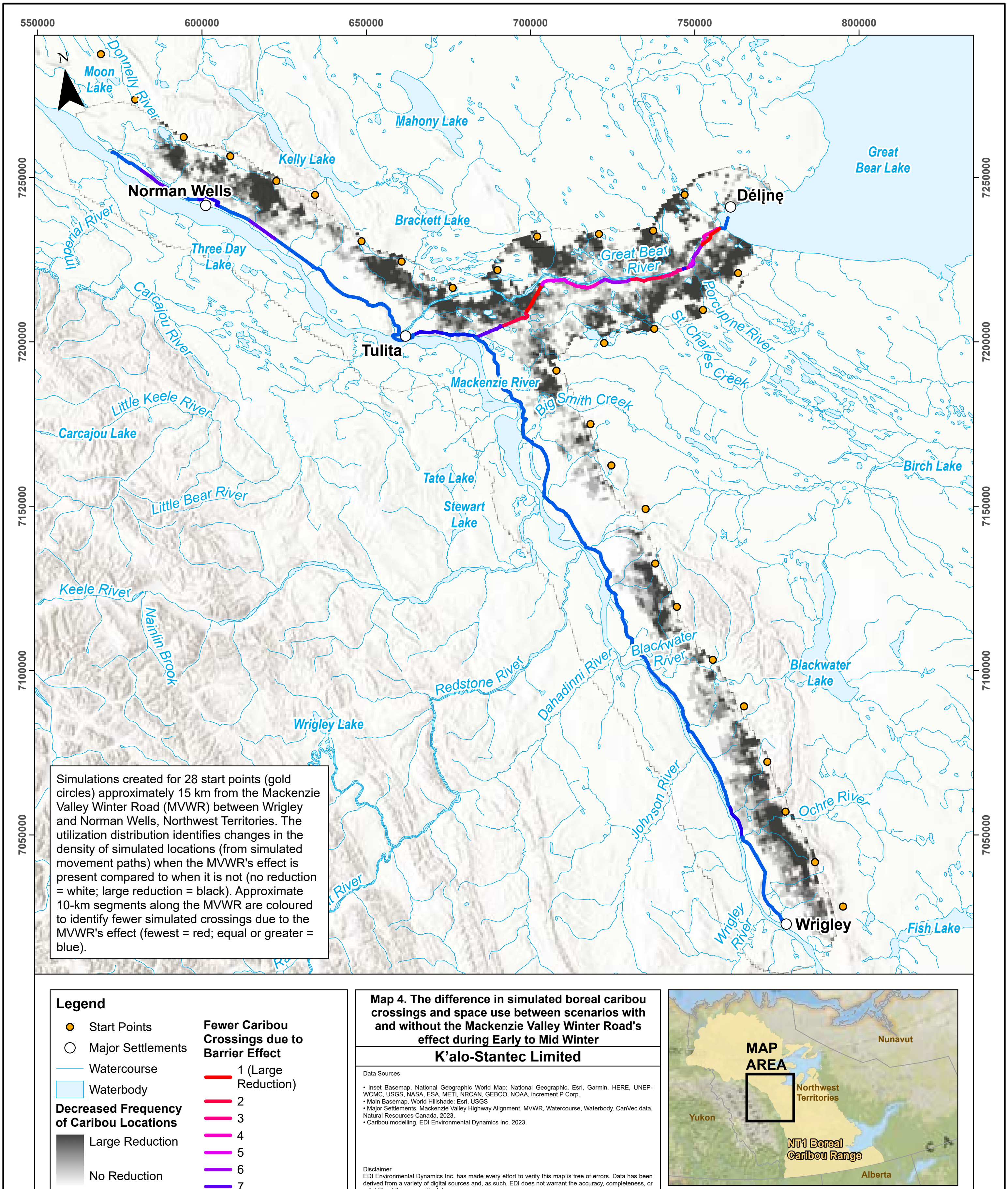
Disclaimer
EDI Environmental Dynamics Inc. has made every effort to verify this map is free of errors. Data has been derived from a variety of digital sources and, as such, EDI does not warrant the accuracy, completeness, or reliability of this map or its data.

0 15 30 45 60 75
Kilometres

Map Scale: 1:1,500,000 (printed on 8.5 x 11)
Map Projection: NAD 1983 UTM Zone 9N

Drawn: O. Leblanc	Checked: K. Bajina	Map 3	Date: 2024-01-08

Path: L:\PROJECTS\2022\PR\22C0569_StantecGNWT_MVH_CaribouCollarAnalysis\22C0569_StantecGNWT_MVH_CaribouCollarAnalysis_mapping.aprx\22C0569_Map3_UtilizationDist_CalvPostCalving_20231024



Simulations created for 28 start points (gold circles) approximately 15 km from the Mackenzie Valley Winter Road (MVWR) between Wrigley and Norman Wells, Northwest Territories. The utilization distribution identifies changes in the density of simulated locations (from simulated movement paths) when the MVWR's effect is present compared to when it is not (no reduction = white; large reduction = black). Approximate 10-km segments along the MVWR are coloured to identify fewer simulated crossings due to the MVWR's effect (fewest = red; equal or greater = blue).

Legend

- ● Start Points
- ○ Major Settlements
- Watercourse
- Waterbody

Decreased Frequency of Caribou Locations

- Large Reduction
- No Reduction

Fewer Caribou Crossings due to Barrier Effect

- 1 (Large Reduction)
- 2
- 3
- 4
- 5
- 6
- 7
- 8
- 9
- 10 (No Reduction)

Map 4. The difference in simulated boreal caribou crossings and space use between scenarios with and without the Mackenzie Valley Winter Road's effect during Early to Mid Winter

K'alo-Stantec Limited

Data Sources

- Inset Basemap. National Geographic World Map: National Geographic, Esri, Garmin, HERE, UNEP-WCMC, USGS, NASA, ESA, METI, NRCAN, GEBCO, NOAA, increment P Corp.
- Main Basemap. World Hillshade: Esri, USGS
- Major Settlements, Mackenzie Valley Highway Alignment, MVWR, Watercourse, Waterbody. CanVec data, Natural Resources Canada, 2023.
- Caribou modelling. EDI Environmental Dynamics Inc. 2023.

Disclaimer
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0 15 30 45 60 75
Kilometres

Map Scale: 1:1,500,000 (printed on 8.5 x 11)
Map Projection: NAD 1983 UTM Zone 9N

Drawn: O. Leblanc	Checked: K. Bajina	Map 4	Date: 2024-01-08

EDI

Path: L:\PROJECTS\2022\PR\22C0569_StantecGNWT_MVH_CaribouCollarAnalysis\22C0569_StantecGNWT_MVH_CaribouCollarAnalysis_mapping.aprx\22C0569_Map4_UtilizationDist_EarlyMidWinter_20231019

3.3 PROXIMITY OF CALVING CARIBOU TO THE WINTER ROAD

The ruleset we used to evaluate boreal caribou calving identified 85/87 (97.7%) potential calving events. As examples of the results, the daily TDMA and estimated calving date of caribou BWCA21104 (2-hour fix rate) is shown in Figure 15, and caribou BWCA264 (8-hour fix rate) in Figure 16. Animal BWCA21104 in 2021 had a daily TDMA below 50 m/2-hrs for over a week following the estimated calving date (Figure 15). Animal BWCA264 in 2019 had a daily TDMA well below 200 m/8-hrs for over a week following the estimated calving date (Figure 16).

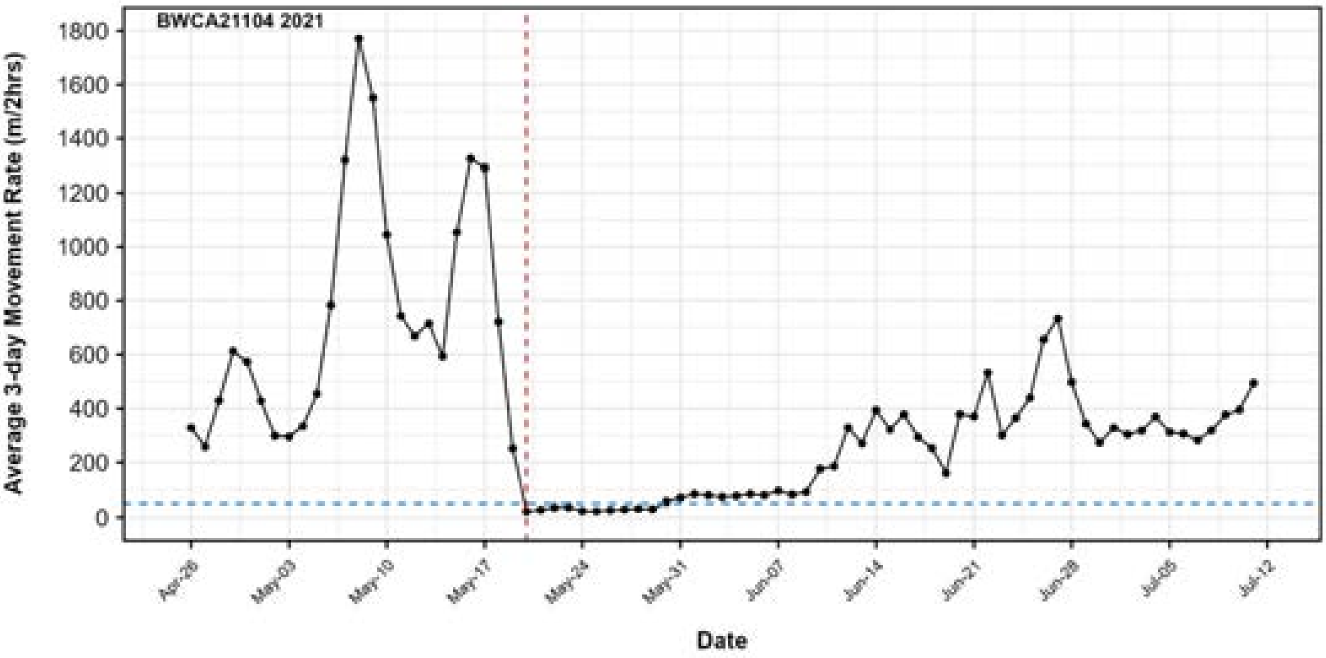

Figure 15. Average 3-day movement rates (2-hour fix rates) used to identify the calving date and location of a parturient boreal caribou cow in the Mackenzie Valley in 2021.
The dashed (horizontal) blue line indicates the potential threshold (50 m/2 hrs) used for a caribou with a 2-hour fix rate. The dashed (vertical) red line is the identified calving date.

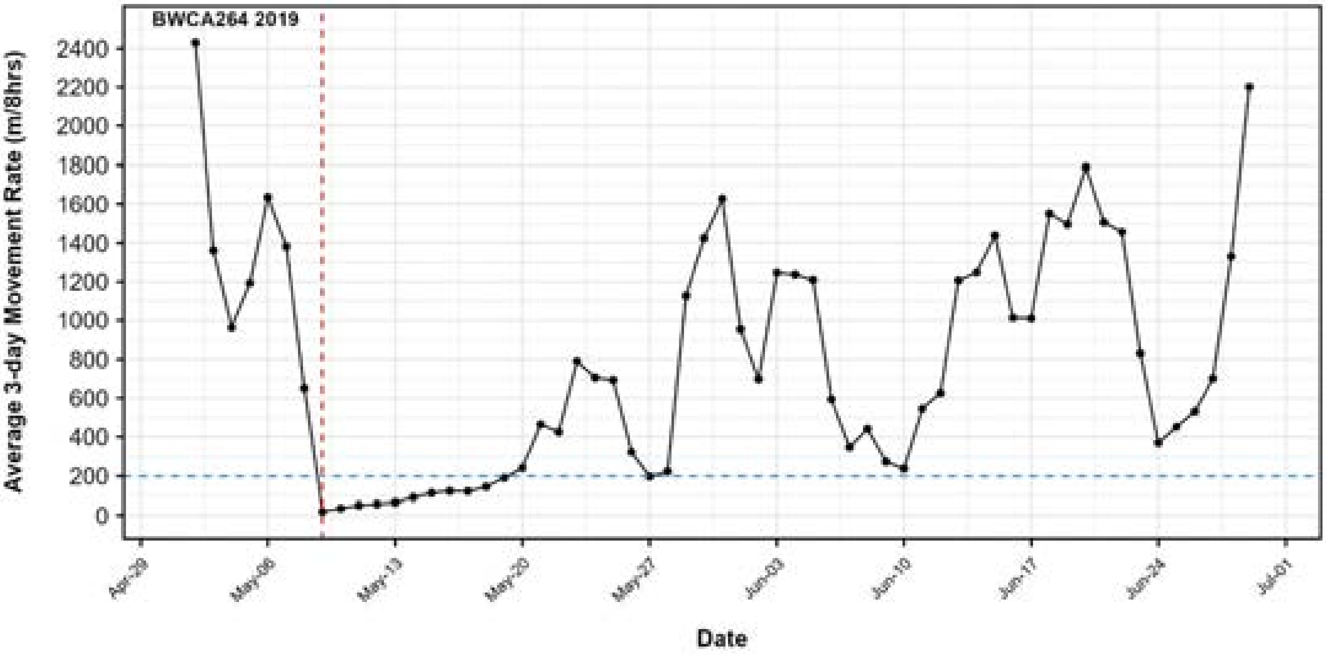

Figure 16. Average 3-day movement rates (8-hour fix rates) used to identify the calving date and location of a parturient boreal caribou cow in the Mackenzie Valley in 2019.

The dashed (horizontal) blue line indicates the potential threshold (200 m/8 hrs) used for a caribou with an 8-hour fix rate. The dashed (vertical) red line is the identified calving date.

Two of the estimated calving dates differed from the expected date ranges for calving. However, we believe this was either due to (a) consistently low movement rates for a caribou (BWCA16000) in early June, likely due to hotter temperatures (personal communication, E. Lamontagne), or (b) reduced movement rates for four consecutive days after an initial, drastic reduction in movement rates for two days (i.e., the likely calving event but possibly with calf mortality). We manually adjusted these two calving dates based on visual assessments of time-series plots and trajectories.

For the subset of calving events occurring within 30 km of the MVWR (26 total locations), the (geometric) mean distance from the MVWR was 18.42 km (95% CI = 16.17–20.99 km). Results of the one-sample *t*-test demonstrated that, on average, parturient cows gave birth at distances beyond the expected ZOI of 15 km ($t_{1,25} = 3.24$, $P = 0.003$).

We further refined the analysis to examine caribou used in iSSF analyses (i.e., if 10% of the caribou's trajectory occurred within 15 km of the MVWR). Of the eight iSSF-related trajectories with calving events within 30 km of the MVWR, the (geometric) mean distance of calving events was 15.32 km (95% CI = 11.68–20.12 km). For these caribou, parturient cows gave birth at distances equal to the expected ZOI of 15 km ($t_{1,7} = 0.19$, $P = 0.86$).

A 'stacked' frequency distribution is depicted in Figure 17 to show the relative difference in frequency between caribou used in iSSF analyses (dark grey) and all other boreal caribou (light grey). Only six predicted calving events occurred within 15 km of the MVWR, the closest being 7.88 km from the road.

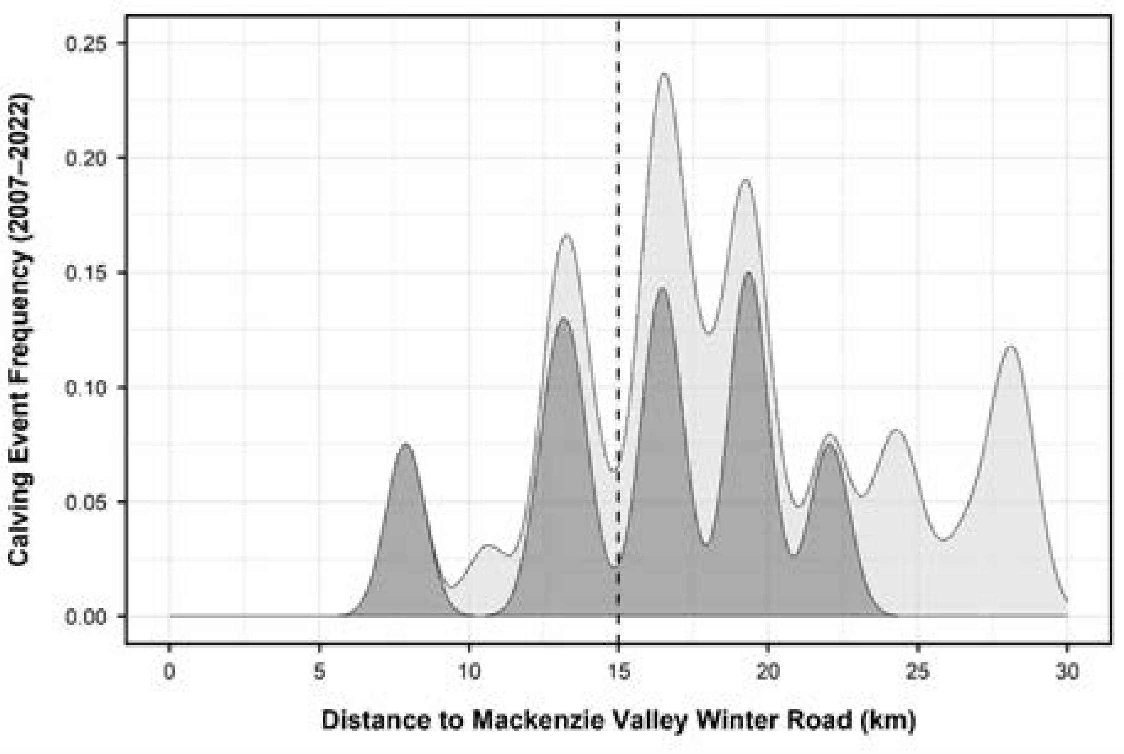

Figure 17. Stacked frequency distribution of calving events (2007–2022) at distances from the Mackenzie Valley Winter Road (km) in the Mackenzie Valley.

The dark and light grey shading identify distributions of caribou used in integrated step selection function analyses and all other caribou, respectively. The dashed (vertical) line identifies a 15-km distance from the Mackenzie Valley Winter Road.

4 DISCUSSION

4.1 BOREAL CARIBOU MOVEMENT PATTERNS

Due to the size of the proposed Mackenzie Valley Highway Project, there has been concern that it could reduce habitat connectivity and significantly affect caribou habitat and distribution. However, based on the current response of caribou to the existing MVWR, modelled (estimated) movements, and simulated movements *with* and *without* the MVWR's influence, there is mixed support for the notion that the MVWR poses a barrier to caribou movement or that the highway would.

Initial assessments of boreal caribou movement patterns during early to mid winter, late winter, and calving to post-calving identified little difference in movement parameters with increasing distance to the MVWR. Movement rates and turn angles were nearly identical at close and far distances from the MVWR during early to mid winter and late winter.

During calving to post-calving, there were statistically significant differences in movement rates resulting in faster movements near the MVWR, and more directed (straight) movements at 0–1 km than at 14–15 km from the MVWR. However, differences during calving to post-calving may have been an artifact of low sample sizes near the MVWR. Contrary to our prediction, caribou observations indicated that tortuosity near the MVWR did not increase substantially in any season. In fact, during the calving to post-calving season, more directed movements were observed closer to the MVWR than farther away. Overall, the movement rate and tortuosity caribou observations failed to support our predictions, except for a potentially weak effect on movement rate in the calving to post-calving season.

These movement parameter estimates were naïve in that they considered only the raw movement data without accounting for the habitat selection of boreal caribou. Thus, considering iSSF modelling results, which incorporated habitat, is also important.

Results from the iSSF models were mixed, and in some cases, were opposite of those found with caribou observations. Models with the MVWR (H2) or all (correlated) disturbances (H3) as a covariate were the top-ranked models during two seasons: early to mid winter and calving to post-calving. However, the base model (H1) was most supported during late winter, suggesting that distance to the MVWR did not influence caribou in this season.

For disturbance models during early to mid winter (H2) and calving to post-calving (H3), interactions with movement parameters were statistically significant (did not overlap zero) at the population level, suggesting that the MVWR and all disturbances influenced boreal caribou movement in each of those seasons, respectively. We also note that caribou avoided high linear feature densities in all three seasons; thus, while the response of caribou to the MVWR may be mixed, there appears to be an overall avoidance of areas dense with linear features.

Predicted movement rates based on iSSF model results indicate that caribou movement rates increase with distance from all disturbances during the calving to post-calving period, lending partial support for our prediction during this season since the MVWR is included in that effect. However, there appears to be a very low effect of distance to MVWR on the movement rates of caribou during early to mid winter. For tortuosity, there was minimal difference with distance to the MVWR (H2) or all disturbances (H3) during early to mid winter and calving to post-calving, respectively. For other habitat variables, early to mid winter and calving to post-calving models predicted faster, directed movements by caribou across patches with low amounts of sparse and upland conifer and high amounts of young burns and dense linear features.

The most supported population-level iSSF models validated very well under all three tests. Their predictions matched closely with observations in all three seasons. However, the H3 model in late winter (which was not the top-ranked model) validated very poorly, further suggesting that distance to disturbances (including the MVWR) has no significant effect on caribou movement during this season.

The patterns of habitat selection predicted during early to mid winter and calving to post-calving were consistent with what is known about boreal caribou ecology. Boreal caribou strongly avoid burns, especially during winter, because they are typically associated with lower lichen abundance (Palm et al. 2022). Historically, boreal caribou in the region have experienced large, frequent wildfires, which have likely contributed to this learned avoidance (Lafontaine et al. 2019).

Avoidance of high linear feature densities was most apparent during calving to post-calving. DeMars et al. (2020) also found avoidance of high linear densities during calving to post-calving, but the response of individual caribou varied during mid to late winter, with some caribou selecting and some avoiding high linear feature densities. This may have been due to the selection scale they investigated (2nd and 3rd order relative to population and individual home ranges, respectively). Conditional on the steps made by boreal caribou, we found avoidance of high linear feature densities during early to mid winter. As expected, we also determined that boreal caribou avoided rugged terrain conditions in all seasons (Leblond et al. 2011, Palm et al. 2022). This result was consistent with observed caribou trajectories that avoided crossing hard ridgelines and peaks to the east of the MVWR and instead moved along valley bottoms and gorges (e.g., Figure 4). Similar to DeMars et al. (2020), we found boreal caribou selected sparse and upland conifer forests during early to mid winter and calving to post-calving, though the degree of selection varied depending on the season.

The outcomes of modelling exercises are dependent on the underlying datasets used, and it is important to understand their limitations when interpreting results. First, boreal caribou GPS telemetry data has two interrelated caveats:

1. The relatively small sample size during each season.
2. The limited number of interactions between boreal caribou and the MVWR.

In total, there were 14 trajectories (11 individuals) during early to mid winter, 13 trajectories (9 individuals) during late winter, and 15 trajectories (10 individuals) during calving to post-calving. More trajectories (and individual animals) may have refined the predictive performance of population-level iSSFs and led to more realistic parameter estimates (e.g., the H3 late winter model).

A final caveat is that we could not account for winter traffic levels when quantifying the MVWR's effect on movement. Several studies have demonstrated the effect of traffic intensity on ungulate movement patterns (Dyer et al. 2002, Prichard et al. 2022, Smith and Johnson 2023). In contrast, there is evidence that ungulate responses can occur when road traffic is low or to the footprint itself (Wilson et al. 2016, Jones et al. 2022). Not considering traffic levels has disadvantages because it constitutes a potential mechanism for movement barriers — mortality, whereas, in most cases, a footprint in the absence of traffic poses no physical barrier or direct mortality but may be perceived as a mortality risk.

4.2 HABITAT CONNECTIVITY IN BOREAL CARIBOU RANGE

Simulated trajectories of caribou under scenarios *with* and *without* the MVWR's influence provided additional insights into the potential for the MVWR to pose a barrier to movement. Results of caribou simulations suggest that the north-south axis (Norman Wells to Wrigley) of the MVWR is not crossed frequently, even without the MVWR's influence.

These findings are also consistent with observed caribou trajectories. For example, there are several natural barriers to caribou movement along the MVWR's north-south axis: high ridges and rugged terrain to the east of the MVWR and a wide watercourse (the Mackenzie River) to the west of the MVWR. These natural barriers limit crossings and cause boreal caribou to make tortuous movements (e.g., Figure 4). In portions of the north-south axis within 15 km of the MVWR that do not have terrain barriers (e.g., just south of Tulita), the habitat quality is typically low (e.g., low amounts of sparse and upland conifer forest, large extents of young burns, and higher linear feature densities) and caribou naturally avoid this area, irrespective of the MVWR.

In several instances during calving to post-calving, the greatest reduction in space use occurred between 10–15 km from the north-south axis, resulting in caribou trajectories moving even farther away from the MVWR (and all correlated disturbances). This expectation was consistent with our hypothesis that, if starting at 15 km from the MVWR, on average, a caribou should exit the ZOI and move farther away. In contrast, in the absence of the MVWR, caribou had a greater occurrence 10–15 km from disturbances (such as the MVWR) during calving to post-calving. These results further support other research (Boulanger et al. 2012, Wilson et al. 2016) that caribou might avoid all disturbances at longer distances (e.g., 10–15 km) if such disturbances are frequent (or dense) and widespread.

Simulated trajectories revealed that one portion of the MVWR had the potential to act as a barrier. Simulated caribou movement was 'blocked' during early to mid winter in several portions of MVWR's east-west axis, as demonstrated by the reduced number of crossings and space use when the MVWR's effect was present. In this area of the MVWR, habitat quality is relatively high (e.g., high amounts of sparse conifer forest, moderate amounts of upland conifer forest, relatively few young burns, and low linear feature densities), and movement is less likely to be obstructed by natural features due to flatter terrain and a narrower watercourse (Great Bear River). This east-west axis is also where boreal caribou crossings were observed (e.g., Figure 6), which suggests that this section of the MVWR is likely a semi-permeable barrier during early to mid winter.

Though present, the degree of reduced habitat connectivity along the MVWR's east-west axis during early to mid winter is small in magnitude. A maximum of 294 reduced crossings occurred between Tulita and Délı̨nę during early to mid winter. This number is relatively small compared to the total number of simulations along the MVWR's east-west axis — 10,000 each (from 10 start points) for scenarios *with* and *without* the MVWR's effect — and is equivalent to 2.9% of all trajectories within the vicinity. Even if considering the four closest start points (thereby reducing the denominator), the reduced crossings amount to 7.4% of all relevant trajectories.

We also found little evidence for a barrier effect along any portions of the MVWR (including the east-west axis) during calving to post-calving, which is unsurprising given that the MVWR would be a right-of-way (or clearing), without traffic, outside of winter months. Furthermore, the absence of an effect along the east-west axis during calving to post-calving is consistent with movement parameters being affected by all (correlated) sources of disturbance, of which there are much fewer farther east from the Mackenzie River.

Despite their realism, boreal caribou simulations can be sensitive to starting conditions. Each new step depends on the previous step and the surrounding combination of (habitat and disturbance) covariate values within the extent of the redistribution kernel. In the analyses presented, a possible step made by a simulated caribou could occur anywhere within the maximum observed step length in a season. Therefore, simulated trajectories do not necessarily replicate the exact movements of an observed caribou trajectory.

Sometimes, a simulated trajectory may go opposite to an observed trajectory but still select similar habitat components (e.g., Figure 13). We circumvented this issue in our habitat connectivity analyses by choosing starting points approximately 15 km from the MVWR (i.e., the potential zone of sensory disturbance) and spaced relatively evenly across the footprint length. This approach allowed us to identify whether any movement corridors may exist that could be missed along the MVWR's footprint depending on the starting conditions.

Although we identified the MVWR's east-west axis as a potential barrier to boreal caribou movement, we cannot discount that it could have emerged due to the study design. The starting points for simulations occurred on both sides of the east-west axis of the MVWR, whereas in the north-south axis, starting points occurred only on one side. We chose this study design because most caribou observations occur on the east side of the MVWR's north-south axis, and that is also where GNWT focuses its survey and collaring efforts (personal communication, J. Hodson; preliminary results meeting on September 21, 2023). Additionally, the NT1 boreal caribou range only extends a few kilometres west of the Mackenzie River (Map 2), so few caribou are expected to occur on this west side. Therefore, the effect along the east-west axis presented here may be greater than the true effect on caribou movement (due to the higher number of starting points), whereas the study design choice had little influence on outcomes and interpretations for the MVWR's north-south axis.

Ultimately, the habitat connectivity analyses for early to mid winter and calving to post-calving demonstrate the following:

1. The MVWR's north-south axis is not a barrier to boreal caribou movement.

2. The MVWR's east-west axis is likely a semi-permeable barrier to movement during winter when the road is active.

Several lines of evidence support these conclusions. We observed boreal caribou crossings almost entirely along the winter road's east-west axis. We identified one crossing along the north-south axis during calving to post-calving and another during summer while conducting data exploration exercises.

Crossings along the north-south axis are likely limited because of the Mackenzie River. In a Traditional Ecological Knowledge (TEK) study of boreal caribou, Gunn (2009) reported that caribou often do not cross the Hay or Mackenzie rivers. A similar barrier effect was observed for GPS-collared cows from 2002–2011 (Species at Risk Committee 2012). Additionally, caribou rarely crossed the north-south axis in simulations without the MVWR's effect.

In general, mortality risk for boreal caribou in NWT is lowest during winter, but non-predation mortality risk (i.e., starvation) is greatest following peak calving (Kelly 2020). Reduced habitat connectivity might influence mortality risk if caribou cannot access resources within their range. Based on the location and alignment (north-south axis) of the proposed Project, our results suggest that the highway is unlikely to reduce habitat connectivity or the ability of boreal caribou to access their range any further than existing natural barriers (terrain and the Mackenzie River) and habitat distribution.

4.3 BOREAL CARIBOU CALVING EVENTS

We identified 87 potential calving events from boreal caribou that occurred within 100 km of the MVWR. The movement rates associated with these calving dates met our expectations: a pregnant cow would move urgently toward a calving area and slow down dramatically during parturition and delivery. Only 26 of the total calving events occurred within 30 km of the MVWR. From these 26 calving events, we calculated the distribution of cows away from the MVWR and found most calving events occurred far from the winter road. From caribou used in iSSF analyses (i.e., 10% of their trajectory occurring within 15 km of the MVWR), calving events, on average, occurred at the same distance as the farthest limit of the ZOI (15 km). Only six events occurred within 15 km of the MVWR, the closest being 7.9 km from the road.

These results suggest that boreal caribou are not calving close to the MVWR, either along the north-south (Norman Wells to Wrigley) or east-west axis (Tulita to Délı̨nę). Therefore, the total risk or potential effect of sensory disturbance to calving caribou by the proposed Project is likely minimal.

5 CONCLUSIONS

We found mixed evidence to support the hypothesis that the MVWR would negatively affect boreal caribou movement, including movement rates and turn angles, once accounting for habitat selection. The model incorporating the MVWR's effect (H2) was only the top-ranked model in one season, early to mid winter. However, during this season, the MVWR had little to no effect on movement rate and tortuosity in either the observed data or the predicted model results. Based on the observed caribou data and the modelling results, there is little evidence to support the notion that the MVWR affects local and regional (habitat connectivity) caribou movement patterns.

The east-west axis (Tulita to Délı̨nę — the Délı̨nę Winter Road) appears to pose a semi-permeable barrier to movement during early to mid winter, when the winter road has traffic. However, this portion of the MVWR will not be a part of the Mackenzie Valley Highway footprint.

The weight of evidence from (a) historical and GPS telemetry observations, (b) predicted habitat selection and its conformity to boreal caribou ecology, and (c) simulated movements of boreal caribou on the landscape suggests that portions of the winter road being replaced by the Project (north-south axis from Norman Wells to Wrigley) do not currently pose a major barrier to boreal caribou movement.

It is also unlikely that the Project would decrease habitat connectivity any further than existing natural barriers (terrain and the Mackenzie River) and habitat distribution. However, with its increased traffic and physical footprint, the Mackenzie Highway could result in direct mortality (road accidents) and indirect habitat loss, which may cause boreal caribou to avoid the area to a greater degree than at present. Given the historical (2007–2022) distribution of boreal caribou calving locations, such effects would likely not be consequential to calving. On average, boreal caribou tend to calve at far distances from the MVWR and the proposed Project alignment.

Overall, the findings of this study provide a *relative* baseline comparison of effects that investigations during construction and post-construction phases of the Project should supplement.

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APPENDICES

APPENDIX A INDIVIDUAL-BASED MODEL SELECTION RESULTS

HYPOTHESIS TESTING — MODEL SELECTION

Appendix Table A-1. Corrected Akaike Information Criterion (AIC$_c$) model selection results for each caribou-season-year trajectory.[1]

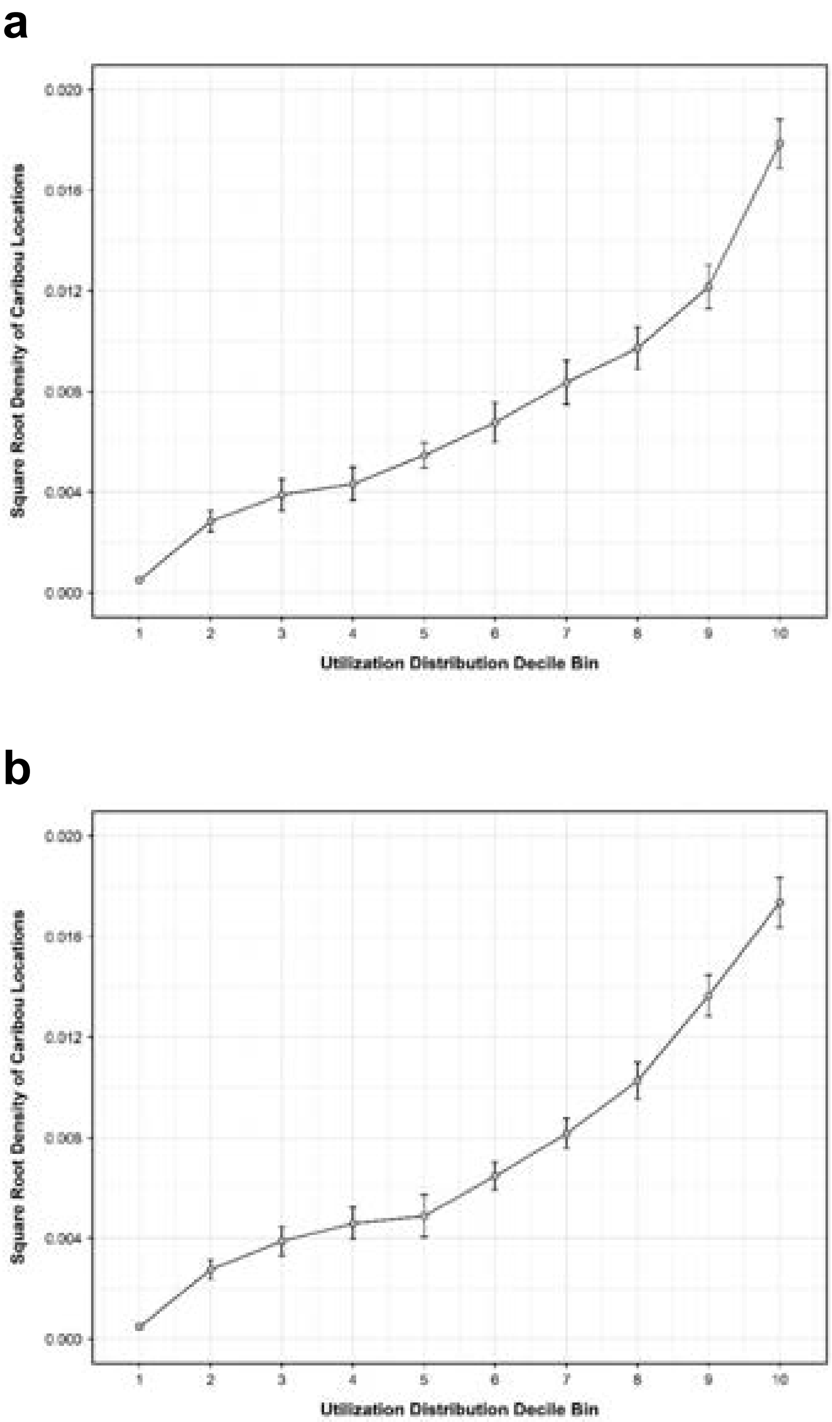
Season	Trajectory ID	Model	K	AIC$_c$	ΔAIC$_c$	wAIC$_c$	log *L*
Early/ Mid Winter	BWCA20105 Early-winter 2020	H1	13	4299.31	0.00	0.49	-2136.64
Early/ Mid Winter	BWCA20105 Early-winter 2020	H2	16	4300.64	1.33	0.25	-2134.30
Early/ Mid Winter	BWCA20105 Early-winter 2020	H3	16	4300.64	1.33	0.25	-2134.30
Early/ Mid Winter	BWCA20100 Early-winter 2020	H1	11	4991.18	0.00	0.66	-2484.58
Early/ Mid Winter	BWCA20100 Early-winter 2020	H2	14	4993.88	2.70	0.17	-2482.93
Early/ Mid Winter	BWCA20100 Early-winter 2020	H3	14	4993.98	2.81	0.16	-2482.98
Early/ Mid Winter	BWCA21101 Early-winter 2021	H2	14	3909.62	0.00	0.54	-1940.80
Early/ Mid Winter	BWCA21101 Early-winter 2021	H3	14	3910.02	0.40	0.45	-1940.99
Early/ Mid Winter	BWCA21101 Early-winter 2021	H1	11	3917.46	7.84	0.01	-1947.72
Early/ Mid Winter	BWCA20105 Mid-winter 2023	H1	11	4019.98	0.00	0.90	-1998.98
Early/ Mid Winter	BWCA20105 Mid-winter 2023	H3	14	4025.68	5.70	0.05	-1998.82
Early/ Mid Winter	BWCA20105 Mid-winter 2023	H2	14	4025.72	5.75	0.05	-1998.85
Early/ Mid Winter	BWCA20105 Mid-winter 2021	H2	15	3287.23	0.00	0.40	-1628.59
Early/ Mid Winter	BWCA20105 Mid-winter 2021	H3	15	3287.23	0.00	0.40	-1628.59
Early/ Mid Winter	BWCA20105 Mid-winter 2021	H1	12	3288.70	1.47	0.19	-1632.34
Early/ Mid Winter	BWCA20107 Mid-winter 2021	H2	15	3635.01	0.00	1.00	-1802.49
Early/ Mid Winter	BWCA20107 Mid-winter 2021	H3	15	3648.49	13.48	0.00	-1809.23
Early/ Mid Winter	BWCA20107 Mid-winter 2021	H1	12	3651.96	16.95	0.00	-1813.97
Early/ Mid Winter	BWCA20100 Mid-winter 2021	H2	15	3925.22	0.00	1.00	-1947.59
Early/ Mid Winter	BWCA20100 Mid-winter 2021	H1	12	3981.14	55.91	0.00	-1978.56
Early/ Mid Winter	BWCA20100 Mid-winter 2021	H3	15	3984.82	59.60	0.00	-1977.39
Early/ Mid Winter	BWCA21101 Mid-winter 2022	H2	14	3017.72	0.00	0.72	-1494.84
Early/ Mid Winter	BWCA21101 Mid-winter 2022	H1	11	3020.39	2.67	0.19	-1499.18
Early/ Mid Winter	BWCA21101 Mid-winter 2022	H3	14	3021.84	4.11	0.09	-1496.90
Early/ Mid Winter	BWCA23114 Mid-winter 2023	H1	11	2629.01	0.00	0.69	-1303.49
Early/ Mid Winter	BWCA23114 Mid-winter 2023	H3	14	2631.40	2.39	0.21	-1301.68
Early/ Mid Winter	BWCA23114 Mid-winter 2023	H2	14	2632.98	3.97	0.10	-1302.47
Early/ Mid Winter	BWCA21108 Mid-winter 2023	H2	16	3804.97	0.00	1.00	-1886.46
Early/ Mid Winter	BWCA21108 Mid-winter 2023	H1	13	3818.42	13.45	0.00	-1896.20
Early/ Mid Winter	BWCA21108 Mid-winter 2023	H3	16	3822.53	17.56	0.00	-1895.25
Early/ Mid Winter	BWCA21108 Mid-winter 2022	H2	15	3716.74	0.00	0.98	-1843.35
Early/ Mid Winter	BWCA21108 Mid-winter 2022	H1	12	3725.48	8.74	0.01	-1850.73
Early/ Mid Winter	BWCA21108 Mid-winter 2022	H3	15	3725.70	8.96	0.01	-1847.83
Early/ Mid Winter	BWCA23116 Mid-winter 2023	H2	15	2584.03	0.00	1.00	-1276.99
Early/ Mid Winter	BWCA23116 Mid-winter 2023	H1	12	2600.67	16.64	0.00	-1288.32
Early/ Mid Winter	BWCA23116 Mid-winter 2023	H3	15	2601.21	17.19	0.00	-1285.58
Early/ Mid Winter	BWCA21102 Mid-winter 2023	H3	15	4805.65	0.00	1.00	-2387.81
Early/ Mid Winter	BWCA21102 Mid-winter 2023	H1	12	4817.84	12.18	0.00	-2396.91
Early/ Mid Winter	BWCA21102 Mid-winter 2023	H2	15	4822.20	16.55	0.00	-2396.09
Early/ Mid Winter	BWCA21102 Mid-winter 2022	H2	15	4669.28	0.00	0.86	-2319.63
Early/ Mid Winter	BWCA21102 Mid-winter 2022	H1	12	4673.80	4.52	0.09	-2324.89
Early/ Mid Winter	BWCA21102 Mid-winter 2022	H3	15	4675.10	5.82	0.05	-2322.54

Season	Trajectory ID	Model	K	AIC$_c$	ΔAIC$_c$	wAIC$_c$	log *L*
Late Winter	BWCA20105 Late-winter 2023	H1	11	831.41	0.00	0.44	-404.66
Late Winter	BWCA20105 Late-winter 2023	H3	14	832.18	0.77	0.30	-402.02
Late Winter	BWCA20105 Late-winter 2023	H2	14	832.50	1.09	0.26	-402.18
Late Winter	BWCA20107 Late-winter 2021	H1	12	916.46	0.00	0.78	-446.18
Late Winter	BWCA20107 Late-winter 2021	H2	15	920.33	3.87	0.11	-445.09
Late Winter	BWCA20107 Late-winter 2021	H3	15	920.48	4.02	0.10	-445.17
Late Winter	BWCA20100 Late-winter 2021	H1	12	961.39	0.00	0.42	-468.65
Late Winter	BWCA20100 Late-winter 2021	H2	15	961.75	0.36	0.35	-465.80
Late Winter	BWCA20100 Late-winter 2021	H3	15	962.63	1.24	0.23	-466.24
Late Winter	BWCA21101 Late-winter 2021	H1	13	827.32	0.00	0.63	-400.60
Late Winter	BWCA21101 Late-winter 2021	H2	16	829.64	2.32	0.20	-398.72
Late Winter	BWCA21101 Late-winter 2021	H3	16	830.00	2.68	0.17	-398.90
Late Winter	BWCA21101 Late-winter 2022	H1	11	849.95	0.00	0.40	-413.93
Late Winter	BWCA21101 Late-winter 2022	H2	14	850.52	0.58	0.30	-411.19
Late Winter	BWCA21101 Late-winter 2022	H3	14	850.52	0.58	0.30	-411.19
Late Winter	BWCA23114 Late-winter 2023	H3	15	902.13	0.00	0.87	-435.99
Late Winter	BWCA23114 Late-winter 2023	H2	15	906.10	3.97	0.12	-437.98
Late Winter	BWCA23114 Late-winter 2023	H1	12	912.52	10.39	0.00	-444.21
Late Winter	BWCA23116 Late-winter 2023	H2	15	853.76	0.00	0.90	-411.80
Late Winter	BWCA23116 Late-winter 2023	H3	15	858.23	4.47	0.10	-414.03
Late Winter	BWCA23116 Late-winter 2023	H1	12	865.67	11.91	0.00	-420.78
Late Winter	BWCA21108 Late-winter 2023	H1	13	702.09	0.00	0.68	-337.97
Late Winter	BWCA21108 Late-winter 2023	H3	16	704.63	2.54	0.19	-336.20
Late Winter	BWCA21108 Late-winter 2023	H2	16	705.43	3.33	0.13	-336.60
Late Winter	BWCA21108 Late-winter 2022	H1	11	807.43	0.00	0.72	-392.67
Late Winter	BWCA21108 Late-winter 2022	H3	14	810.37	2.93	0.17	-391.11
Late Winter	BWCA21108 Late-winter 2022	H2	14	811.24	3.81	0.11	-391.55
Late Winter	BWCA21103 Late-winter 2021	H3	15	945.76	0.00	0.74	-457.81
Late Winter	BWCA21103 Late-winter 2021	H2	15	947.93	2.16	0.25	-458.89
Late Winter	BWCA21103 Late-winter 2021	H1	12	955.12	9.36	0.01	-465.51
Late Winter	BWCA21102 Late-winter 2021	H3	15	1082.89	0.00	0.75	-526.38
Late Winter	BWCA21102 Late-winter 2021	H2	15	1085.32	2.43	0.22	-527.59
Late Winter	BWCA21102 Late-winter 2021	H1	12	1089.18	6.29	0.03	-532.55
Late Winter	BWCA21102 Late-winter 2023	H3	14	901.72	0.00	0.60	-436.79
Late Winter	BWCA21102 Late-winter 2023	H2	14	903.49	1.77	0.25	-437.68
Late Winter	BWCA21102 Late-winter 2023	H1	11	904.58	2.85	0.15	-441.25
Late Winter	BWCA21102 Late-winter 2022	H1	12	1044.33	0.00	0.66	-510.12
Late Winter	BWCA21102 Late-winter 2022	H3	15	1046.44	2.12	0.23	-508.15
Late Winter	BWCA21102 Late-winter 2022	H2	15	1047.90	3.58	0.11	-508.88
Calving/ Post-calving	BWCA338 Calving/Post-calving 2022	H3	16	1750.56	0.00	1.00	-859.24
Calving/ Post-calving	BWCA338 Calving/Post-calving 2022	H1	13	1797.75	47.19	0.00	-885.85
Calving/ Post-calving	BWCA338 Calving/Post-calving 2022	H2	16	1803.78	53.22	0.00	-885.85
Calving/ Post-calving	BWCA300 Calving/Post-calving 2020	H3	15	1436.32	0.00	1.00	-703.11
Calving/ Post-calving	BWCA300 Calving/Post-calving 2020	H2	15	1482.97	46.65	0.00	-726.44
Calving/ Post-calving	BWCA300 Calving/Post-calving 2020	H1	12	1486.44	50.12	0.00	-731.19
Calving/ Post-calving	BWCA296 Calving/Post-calving 2020	H3	16	1483.21	0.00	1.00	-725.56

Season	Trajectory ID	Model	K	AIC_c	ΔAIC_c	$wAIC_c$	log L
Calving/ Post-calving	BWCA296 Calving/Post-calving 2020	H1	13	1505.57	22.35	0.00	-739.75
Calving/ Post-calving	BWCA296 Calving/Post-calving 2020	H2	16	1511.60	28.39	0.00	-739.75
Calving/ Post-calving	BWCA303 Calving/Post-calving 2020	H3	16	1079.12	0.00	0.72	-523.49
Calving/ Post-calving	BWCA303 Calving/Post-calving 2020	H1	13	1081.37	2.25	0.23	-527.64
Calving/ Post-calving	BWCA303 Calving/Post-calving 2020	H2	16	1084.80	5.68	0.04	-526.33
Calving/ Post-calving	BWCA301 Calving/Post-calving 2021	H1	12	990.19	0.00	0.88	-483.05
Calving/ Post-calving	BWCA301 Calving/Post-calving 2021	H2	15	995.19	5.00	0.07	-482.52
Calving/ Post-calving	BWCA301 Calving/Post-calving 2021	H3	15	995.79	5.61	0.05	-482.83
Calving/ Post-calving	BWCA296 Calving/Post-calving 2021	H2	14	1208.67	0.00	1.00	-590.29
Calving/ Post-calving	BWCA296 Calving/Post-calving 2021	H3	14	1225.25	16.58	0.00	-598.58
Calving/ Post-calving	BWCA296 Calving/Post-calving 2021	H1	11	1232.12	23.45	0.00	-605.03
Calving/ Post-calving	BWCA303 Calving/Post-calving 2022	H1	12	840.24	0.00	0.89	-408.07
Calving/ Post-calving	BWCA303 Calving/Post-calving 2022	H2	15	845.66	5.42	0.06	-407.75
Calving/ Post-calving	BWCA303 Calving/Post-calving 2022	H3	15	845.91	5.67	0.05	-407.87
Calving/ Post-calving	BWCA303 Calving/Post-calving 2021	H3	15	908.80	0.00	0.99	-439.33
Calving/ Post-calving	BWCA303 Calving/Post-calving 2021	H2	15	918.14	9.35	0.01	-444.01
Calving/ Post-calving	BWCA303 Calving/Post-calving 2021	H1	12	919.75	10.95	0.00	-447.83
Calving/ Post-calving	BWCA295 Calving/Post-calving 2020	H2	15	1061.82	0.00	0.83	-515.85
Calving/ Post-calving	BWCA295 Calving/Post-calving 2020	H3	15	1064.94	3.12	0.17	-517.41
Calving/ Post-calving	BWCA295 Calving/Post-calving 2020	H1	12	1112.03	50.20	0.00	-543.97
Calving/ Post-calving	BWCA295 Calving/Post-calving 2019	H2	14	1211.44	0.00	0.93	-591.67
Calving/ Post-calving	BWCA295 Calving/Post-calving 2019	H1	11	1217.23	5.79	0.05	-597.58
Calving/ Post-calving	BWCA295 Calving/Post-calving 2019	H3	14	1218.97	7.52	0.02	-595.43
Calving/ Post-calving	BWCA21103 Calving/Post-calving 2022	H3	16	1050.86	0.00	0.99	-509.36
Calving/ Post-calving	BWCA21103 Calving/Post-calving 2022	H2	16	1061.47	10.61	0.00	-514.66
Calving/ Post-calving	BWCA21103 Calving/Post-calving 2022	H1	13	1066.44	15.59	0.00	-520.17
Calving/ Post-calving	BWCA21103 Calving/Post-calving 2021	H1	12	1008.24	0.00	0.78	-492.08
Calving/ Post-calving	BWCA21103 Calving/Post-calving 2021	H3	15	1011.59	3.35	0.15	-490.73
Calving/ Post-calving	BWCA21103 Calving/Post-calving 2021	H2	15	1013.04	4.81	0.07	-491.46
Calving/ Post-calving	BWCA21101 Calving/Post-calving 2021	H2	15	934.33	0.00	0.98	-452.09
Calving/ Post-calving	BWCA21101 Calving/Post-calving 2021	H3	15	943.34	9.01	0.01	-456.60
Calving/ Post-calving	BWCA21101 Calving/Post-calving 2021	H1	12	944.18	9.85	0.01	-460.04
Calving/ Post-calving	BWCA21102 Calving/Post-calving 2022	H1	13	885.11	0.00	0.64	-429.50
Calving/ Post-calving	BWCA21102 Calving/Post-calving 2022	H3	16	887.10	1.99	0.24	-427.47
Calving/ Post-calving	BWCA21102 Calving/Post-calving 2022	H2	16	888.41	3.30	0.12	-428.12
Calving/ Post-calving	BWCA21109 Calving/Post-calving 2021	H1	13	800.16	0.00	0.64	-387.02
Calving/ Post-calving	BWCA21109 Calving/Post-calving 2021	H2	16	801.82	1.66	0.28	-384.82
Calving/ Post-calving	BWCA21109 Calving/Post-calving 2021	H3	16	804.29	4.14	0.08	-386.05

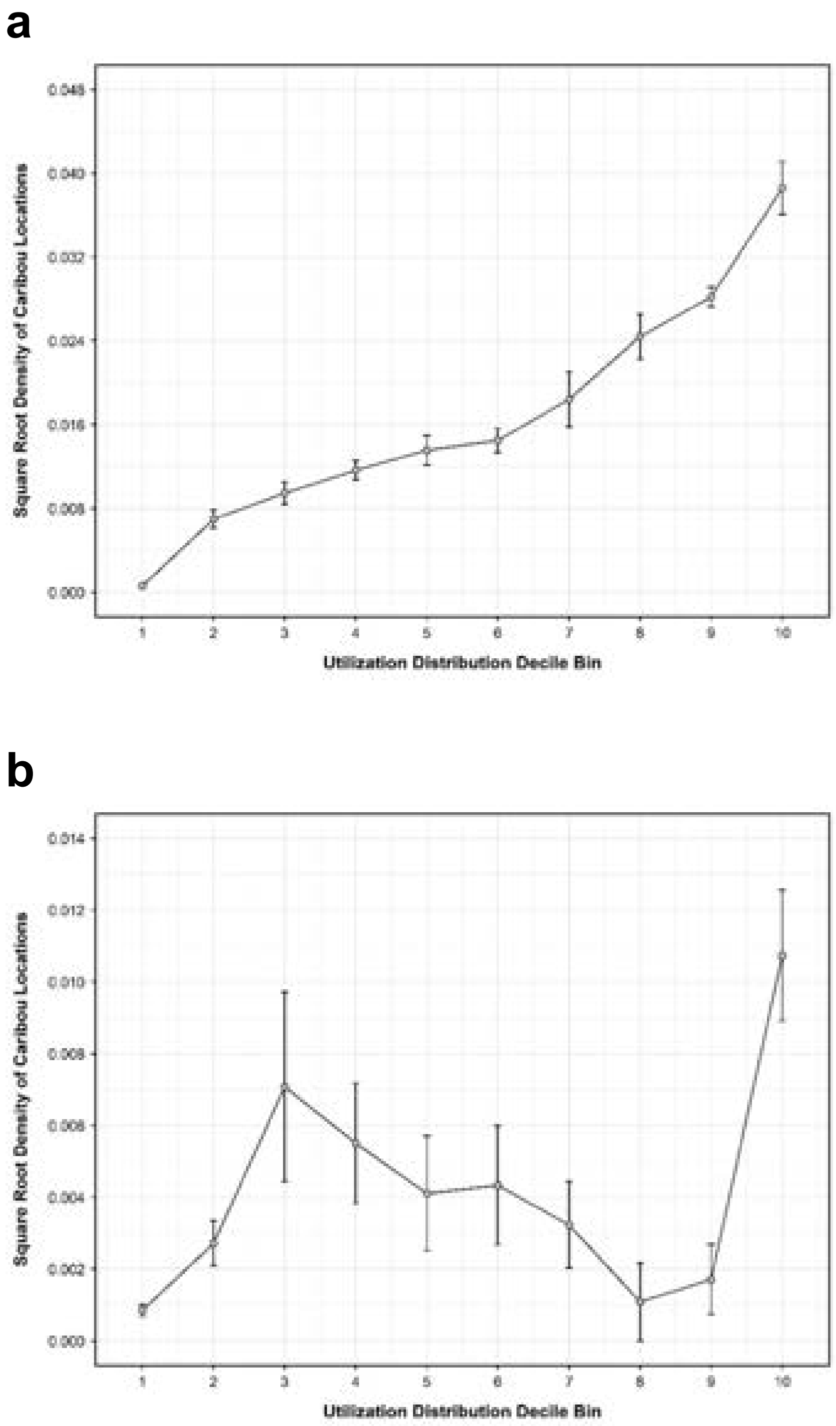
[1] *Models refer to three hypotheses: H1 = base habitat effects, H2 = Mackenzie Valley Winter Road effects, H3 = all correlated disturbance effects.*

APPENDIX B MODEL VALIDATION PLOTS

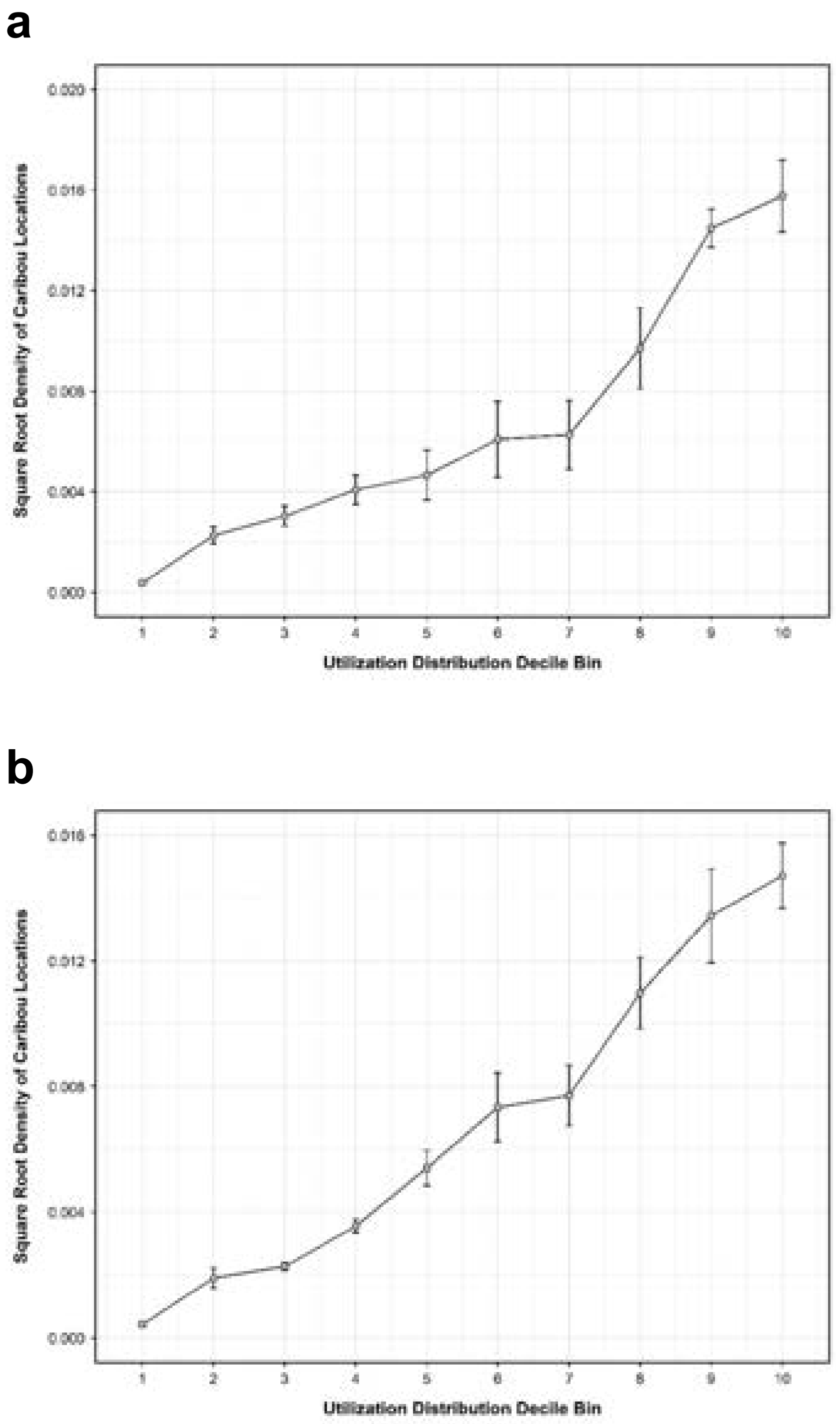


Appendix Figure B-1. **Density of boreal caribou locations in simulation-derived utilization distribution decile bins predicted by (a) base effects (H1) and (b) disturbance effects (H2) models during early to mid winter.**

Densities calculated at the population level (combining all trajectories) from all eight cell-size resolutions. Points and error bars correspond to mean densities and standard errors, respectively.



Appendix Figure B-2 **Density of boreal caribou locations in simulation-derived utilization distribution decile bins predicted by (a) base effects (H1) and (b) disturbance effects (H3) models during late winter.** *Densities calculated at the population level (combining all trajectories) from all eight cell-size resolutions. Points and error bars correspond to mean densities and standard errors, respectively.*



Appendix Figure B-3 **Density of boreal caribou locations in simulation-derived utilization distribution decile bins predicted by (a) base effects (H1) and (b) disturbance effects (H3) models during calving to post-calving.**

Densities calculated at the population level (combining all trajectories) from all eight cell-size resolutions. Points and error bars correspond to mean densities and standard errors, respectively.

APPENDIX C TIME-CORRECTED VERSUS TIME-UNCORRECTED MODELS AND SIMULATIONS

Context and Purpose

Initial iSSF model development, prediction, and subsequent simulations (including model validation and habitat connectivity analyses) used uncorrected datetimes that were not converted from Greenwich Mean Time (GMT) to Mountain Standard Time (MST). When converted from GMT to MST, there was a 7-hour delay in datetimes that changed the time of day (day, night, twilight) associated with boreal caribou locations. Recall that we used a time-of-day covariate in iSSF models to predict the average movement rate of caribou during different times of day. Once we converted datetimes to the MST time zone, average movement rates predicted for early to mid winter, late winter, and calving to post-calving changed, often resulting in higher movement rates during daytime and lower movement rates during nighttime. These movement rates do not directly affect the three-way interaction term in iSSFs that we used to determine the effect of the MVWR (or all correlated disturbances) on boreal caribou movement (Figure 3). However, we believed it was important to determine whether the updated time-of-day covariate values affected the model simulations used to assess habitat connectivity (Section 3.2 *Altered Habitat Connectivity*). Below, we provide a comparison between time-corrected and time-uncorrected iSSF model predictions and simulations to demonstrate and verify their equivalence.

Methods

We limited the time-corrected versus time-uncorrected comparison to early to mid winter and calving to post-calving because we only conducted habitat connectivity analyses for those seasons. First, we assessed a subset of simulated trajectories derived from time-corrected and time-uncorrected iSSFs in a GIS to determine their spatial extents and degree of overlap. As with simulations in Section 2.1.4.5 *Validation of Base and Disturbance Effect Models* we qualitatively determined how simulated trajectories moved across the landscape in accordance with predicted habitat selection strategies.

We also used a quantitative approach that compared the model validation results of time-corrected and time-uncorrected iSSFs (see Section 2.1.4.5 *Validation of Base and Disturbance Effects Models* for the methods used to validate models; see Section 3.1.3 *Validation of Base and Disturbance Effect Models* for the results). Specifically, we tested the association between the density of caribou locations (across 10 decile bins) in time-corrected versus time-uncorrected utilization distributions (UDs). Recall that we developed UDs at eight different spatial resolutions (or cell-size dimensions), so the comparison occurred across all eight UDs. To test the association, we implemented quantile regression (R package ‘quantreg’; Koenker 2023) because it does not require assumptions about (a) the error distribution (i.e., it is non-parametric) or (b) the patterns of variance relative to the mean (e.g., unequal variance) (Cade and Noon 2003). Quantile regression was required because (a) the data had non-normally distributed errors and (b) we expected the density of caribou locations at higher decile bins to be more variable than those at lower decile bins, resulting in greater variance at larger density values. Before fitting the quantile regression, we also square-root-transformed caribou densities so that intercept and slope estimates were more sensitive to deviations from unity (i.e., a 1:1 relationship between time-corrected and time-uncorrected caribou location densities).

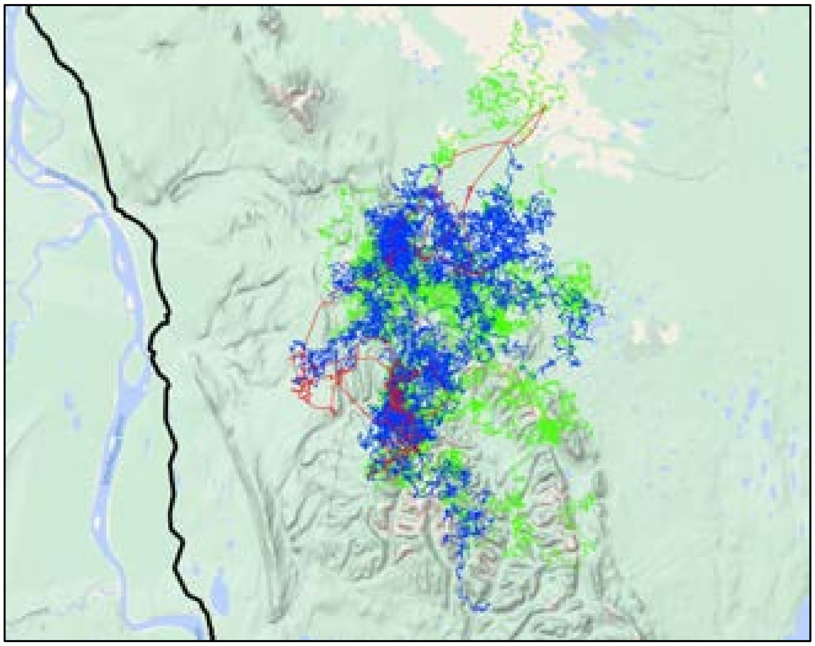
Results

Qualitatively, time-corrected and time-uncorrected simulations of caribou movements yielded nearly identical patterns of habitat selection across the landscape. Simulation trajectories from both iSSF models overlapped each other and were consistent with observed caribou trajectories during early to mid winter (Appendix Figure C-1) and calving to post-calving (Appendix Figure C-3). Though some deviations do occur, it is likely a result of the stochastic process of simulations, i.e., random variation from sampling the habitat and movement kernels. When simulated trajectories deviate from the large overlapping portions between time-corrected (blue) and time-uncorrected (green) scenarios, the patterns of habitat selection are still consistent (e.g., selection of sparse conifer forest, upland conifer forest, low to moderate terrain ruggedness, low proportions of recent burns [<40-years old], and low densities of linear features).

Quantitatively, the density of caribou locations in time-corrected and time-uncorrected UDs were strongly associated. Quantile regressions demonstrated that intercepts and slopes did not differ significantly from zero at the 50% (median) quantile for early to mid winter (intercept = 0.00002 [–0.00001, 0.00018], slope = 1.00759 [0.97727, 1.05975]) and calving to post-calving (intercept = 0.00025 [–0.00001, 0.00086], slope = 0.94828 [0.85887, 1.06493]). Appendix Figure C-2 (early to mid winter) and Appendix Figure C-4 (calving to post-calving) show the association between the density of caribou locations in time-corrected versus time-uncorrected scenarios and demonstrate how the quantile regression estimates (black line) and 95% confidence intervals (grey shading) match the expectation of unity (dashed red line).

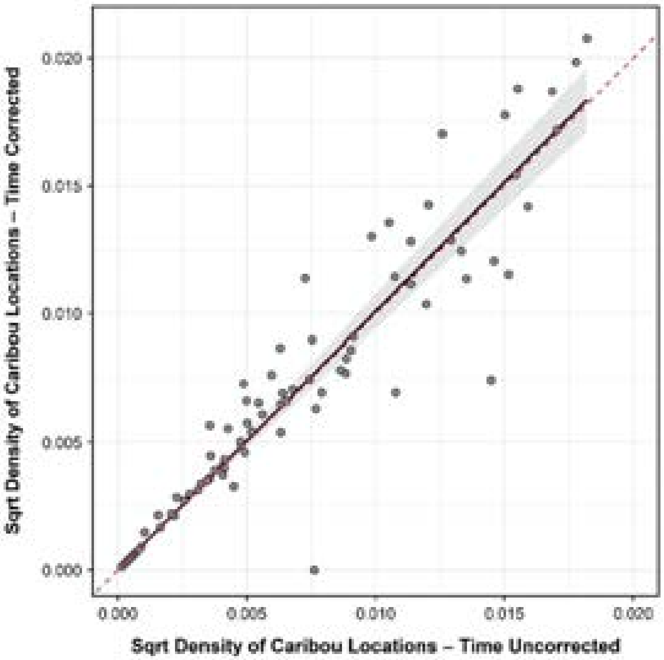
Conclusion

Time-corrected and time-uncorrected simulations of caribou movements were (a) consistent in their patterns of habitat selection across the landscape and (b) similar in their predicted utilization and association with observed caribou locations. Therefore, the results presented in Section 3.2 *Altered Habitat Connectivity* are invariant to the 'time-of-day effect' and will be useful to inform the Project's environmental assessment.



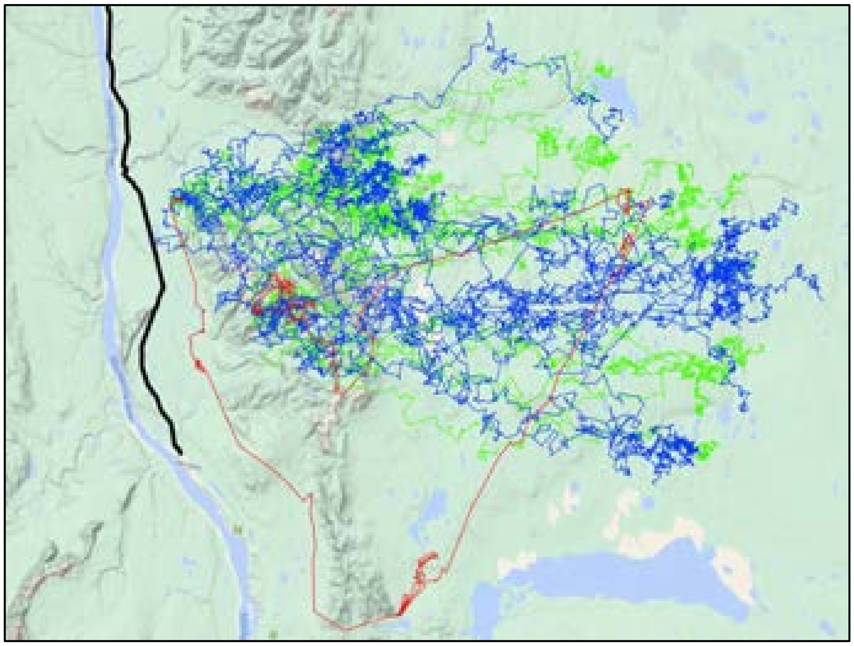
Appendix Figure C-1. **Comparison between time-uncorrected and time-corrected model simulations relative to the observed trajectory of Animal BWCA20105 during early-winter (2020).**

Simulations: blue = time-corrected; green = time-uncorrected. Red lines indicate the observed movement paths of the caribou. The black line indicates the Mackenzie Valley Winter Road.

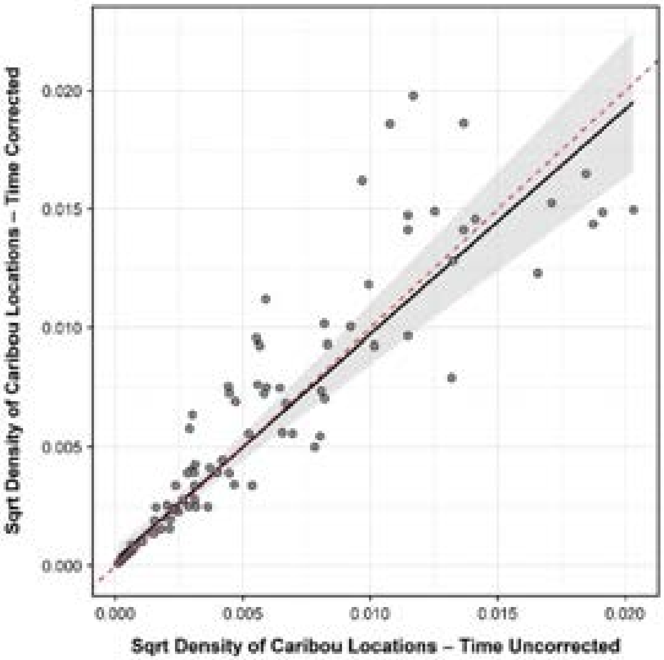


Appendix Figure C-2. **Quantile regression of square-root transformed caribou location densities in utilization distribution decile bins from time-uncorrected (x-axis) and time-corrected (y-axis) 'MVWR Effects' model validation simulations, early to mid winter.**

Black line = median (50% quantile) fit, grey band = 95% confidence interval, grey circles = caribou location densities paired for each decile and pixel resolution. The dashed red line identifies the line of unity (1:1 relationship).



Appendix Figure C-3. **Comparison between time-uncorrected and time-corrected model simulations relative to the observed trajectory of Animal BWCA303 during calving to post-calving (2020).**
Simulations: blue = time-corrected; green = time-uncorrected. Red lines indicate the observed movement paths of the caribou. The black line indicates the Mackenzie Valley Winter Road.



Appendix Figure C-4. **Quantile regression of square-root transformed caribou location densities in utilization distribution decile bins from time-uncorrected (x-axis) and time-corrected (y-axis) 'All Disturbances Effects' model validation simulations, calving to post-calving.**
Black line = median (50% quantile) fit, grey band = 95% confidence interval, grey circles = caribou location densities paired for each decile and pixel resolution. The dashed red line identifies the line of unity (1:1 relationship).