BEHAVIOURAL, PHYSIOLOGICAL, AND MOVEMENT RELATIONSHIPS BETWEEN BARREN-GROUND CARIBOU AND INDUSTRIAL INFRASTRUCTURE IN THE NORTHWEST TERRITORIES

by

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Abstract

I investigated the behavioural, physiological, and movement responses of barren-ground caribou to the Tibbitt to Contwoyto Winter Road in the central Northwest Territories. Previous research on the zone of influence around industrial infrastructure indicates that caribou avoid these industrial disturbances. This response implies changes in the behaviour, physiology, and movement of caribou as well. I used a multi-method approach to investigate these hypothesized changes for caribou adjacent to the road, employing behavioural observations, assessment of levels of fecal glucocorticoids, and GPS collar data. My results suggest that caribou change their behaviour and movement near the winter road. They engaged in more walking and less foraging near the road, though no relationship was found between the level of fecal glucocorticoids and proximity to the winter road. Using a novel estimation of traffic activity, I demonstrated that caribou crossing of the winter road was negatively correlated with the level of traffic. This barrier effect was not just related to the road's right-of-way as caribou crossed roads when they were closed to traffic and the probability of selecting a crossing site was extremely low when normal levels of traffic occurred. My results provide new insights on the spatial, behavioural, and physiological responses of caribou when adjacent to industrial features. These findings can guide monitoring and mitigation of existing infrastructure and assist with the evaluation of impacts of proposed mines and roads.

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"When I was sitting in my English class one day in Inuvik, they were stockpiling sand across the road and they may have had 300 loads or something like this and it was quite high, but the way people would come to school, they wouldn't go around it, they would go over it. As we were looking out the window, my teacher said, isn't it ironic that people go over things instead of around. I think this is true about the animals too."

- Ross Laycock (aged 15), Berger Inquiry, 1975

"What will be the results of a decision in favour of the pipeline? Chaos, and what will be the results of a decision against the pipeline, a depression and more chaos."

- Georgia Laycock, Berger Inquiry, 1975

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Thank you mom, dad, and sister for the support over the years. Not something I can quantify, and therefore out of my domain. I am who I am because of you folks. My maternal uncle and grandmother (quoted above) are a part of my history in the north. It's strange to be a part of a settler tradition, strange to discover that my home is not my own – that my place is the result of a history of trauma and displacement. Industry brought my family north, but I know that isn't the last chapter for my family here. I hope this thesis is part of me finding a more nuanced understanding of the place, the people, the critters, and myself.

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Chapter 1: Introduction

Globally, many populations of caribou and reindeer (*Rangifer tarandus*) are in decline (Vors and Boyce 2009, Mallory and Boyce 2017). That trend extends to Canada, where most populations are assessed as either Threatened or Endangered (Thomas and Gray 2002, COSEWIC 2016). The decline and loss of caribou has important consequences for the functioning of Boreal and Arctic ecosystems (Bernes et al. 2015) as well as the people that are found in those places (Legat et al. 2001, Gordon 2005). Caribou are of immense cultural and economic value to many Indigenous people, and these declines present a significant threat to a way of life. Concern about declining populations of caribou across the north is motivating research seeking to understand the factors that influence their abundance and distribution. Responsible management of caribou requires an understanding of the factors affecting the decline of this widespread and culturally important animal.

Declines of *Rangifer* have been attributed to a variety of causes that include changes in ecosystem conditions related to plant phenology and extreme weather (Vors and Boyce 2009), as well as anthropogenic activities that have resulted in habitat loss or change, disturbance and displacement of caribou, and increased predation (Festa-Bianchet et al. 2011). The local histories of decline vary across the distribution of *Rangifer*. As such, describing and untangling the proximate and ultimate drivers of population abundance is region- and even population-specific. Nevertheless, the growth of industrial infrastructure and human activity is of particular concern, as it has been tied to the decline and extirpation of numerous caribou types from across Canada (Vors et al. 2007, Johnson et al. 2015).

Barren-ground caribou

Barren-ground caribou (*R. t. groenlandicus*) are a subspecies and conservation unit (i.e., Designatable Unit, which also includes the Porcupine caribou herd *R. t. granti;* COSEWIC et al. 2016) of caribou that are found throughout the Arctic in North America. They are characterized by long migrations between their winter and calving ranges and highly gregarious behaviour (COSEWIC 2016). Relative to other types of caribou, they can occur at a high density and over very broad areas. Barren-ground caribou are a keystone species as they are important determinants of predator and plant dynamics across many Arctic ecosystems (Wal 2006, Musiani et al. 2007, Bernes et al. 2015, Klaczek et al. 2016). Also, barren-ground caribou were a strong driver of the migration of people into the Canadian Arctic (Gordon 2005, Bourgeon et al. 2017). They play a central role in the north for people that rely on caribou for sustenance hunting and cultural continuity (Kuhnlein and Receveur 1996, Legat et al. 2001).

Barren-ground caribou occupy seasonal ranges that include the calving and post-calving, summer, fall migration and rut, winter, and spring migration (Gunn et al. 2013). The longest migration is from wintering grounds at or near the tree line to the calving grounds near the Arctic Ocean. These caribou occupy a diverse range of ecosystems including the Taiga Plains, Taiga Shield, and the Southern Arctic in the Northwest Territories and Nunavut (Ecosystem Classification Group 2008, 2009, 2012).

Fidelity to a specific calving ground is used to identify herd membership (Gunn and Miller 1986, Fisher et al. 2009). Although calving grounds are stable over the short term, they can shift over long periods of time (Taillon et al. 2012). Calving grounds for the study herds, including the Bluenose East, Bathurst, and Beverly/Ahiak herds, are situated near the Arctic

Ocean in the Tundra Plains Low Arctic ecoregion (Ecosystem Classification Group 2012). They are located west of Bathurst Inlet for the Bathurst herd, west of Kugluktuk for the Bluenose-East herd, and south of the Queen Maude Gulf for the Beverly/Ahiak herd.

Compared to the calving grounds, the wintering grounds of these herds are larger, and use is spatially more variable. These wintering grounds are located below or near the tree line, primarily in the Taiga Plains and Taiga Shield High Subarctic ecoregions (Ecosystem Classification Group 2009). Range area scales with herd size (Skoog 1968, Messier et al. 1988, Hinkes et al. 2005), influencing the southern extent of the wintering grounds. With the decline in barren-ground caribou across the central Arctic, many of the winter ranges have contracted north.

As long as people have been in the north, they have had a relationship with barren-ground caribou (Gordon 2005, Bourgeon et al. 2017). Barren-ground caribou are known by different languages and dialects variously as tuktu (Inuvialuktun, Inuinnaqtun, Inuktitut), ɂekwę (North Slavey), ɂetthën (Denesuline) and ekwǫ (Tłı̨chǫ). Caribou are important for cultural continuity and subsistence hunting by Aboriginal communities (Kuhnlein and Receveur 1996, Legat et al. 2001). Recent declines of the Bathurst and Bluenose East herds have resulted in harvest restrictions and wolf management programs, implemented through co-management between the Indigenous governments and the Government of the Northwest Territories (GNWT).

Barren-ground caribou have declined by 56% over the past three caribou generations. Several large herds have declined by over 80% in the same period. Recognizing the significance of this decline, the Committee on the Status of Endangered Wildlife in Canada (COSEWIC) assessed this Designatable Unit of caribou as Threatened (COSEWIC 2016). The Conference of

Management Authorities in the Northwest Territories also listed barren-ground caribou as Threatened under territorial Species At Risk legislation (Species at Risk Committee 2017).

There is likely no single cause of decline for barren-ground caribou. Rather, a set of threats are acting cumulatively to drive the decline of these populations (Adamczewski et al. 2009). This cumulative effect is the product of climate change, and associated shifts in the functioning of Arctic ecosystems (Post et al. 2009, Mallory and Boyce 2017), natural population fluctuations (Zalatan et al. 2006), and human activities (Plante et al. 2018).

Management of barren-ground caribou is focused on oversight of hunting and industrial activity, as direct manipulation of caribou or their habitats is not feasible at the scale required for population recovery. Though population declines have not been linked to anthropogenic disturbances, management of these human activities is in keeping with the precautionary principle (United Nations 1972). This is true especially when considering the well documented, negative effects of human developments on woodland caribou in southern Canada (Johnson et al. 2015). Furthermore, this management can be conducted using established legislative and regulatory tools (Festa-Bianchet et al. 2011).

The steep decline in the abundance of barren-ground caribou in the Northwest Territories has prompted harvest restrictions, wolf management measures, and increased government oversight of industrial development (Government of the Northwest Territories 2019). Given those concerns, and the corresponding need for a management response, the GNWT and Indigenous governments have collaboratively developed a range plan for the Bathurst barren-ground caribou herd, which has had the steepest decline (Government of the Northwest Territories 2019). The Bathurst herd is at historically low numbers, having declined by

>98% since 1986 (Nishi et al. 2014, Boulanger et al. 2017). The adjacent Bluenose East herd has also declined (Boulanger et al. 2019), prompting an ongoing management response from the GNWT and Indigenous governments. Other adjacent herds, such as the Beverly/Ahiak herd, have declined at a less precipitous rate (though see Adamczewski et al. 2015).

The relationships between caribou and human disturbance have been studied extensively along a spectrum of biological phenomena, from population-level effects, including distribution and abundance, to individual or group-level effects such as movement behaviour and stress physiology (Johnson and St-Laurent 2011). Those scales of response are interrelated across an ecological and disturbance continuum. Consequently, describing a mechanistic relationship between the distribution and abundance of caribou and any single driver, such as disturbance from industrial development, is challenging.

For some populations of caribou, we understand with some certainty the primary mechanisms of decline. For example, declines of boreal woodland caribou have been linked to shifting predator-prey dynamics that are the result of extensive habitat alteration caused by human activities (Environment Canada 2011, Johnson et al. 2020). That is not the case for barren-ground caribou, where the causes of population decline are not clear. Historically, these caribou have demonstrated cyclical population dynamics (R. Zalatan et al. 2006), which could obscure the relationship between their abundance and contemporary changes in the Arctic environment. These changes include both the effects of human activities (Wolfe et al. 2000, Johnson et al. 2005) as well as those brought about by climate change (Post et al. 2009, Rickbeil et al. 2018). Given the relatively small footprint of human activity across the Arctic (Government of the Northwest Territories 2019), the effect of human disturbance may not be as dramatic as for more southern woodland caribou. This means that it may be difficult to relate the effects of human disturbance to the fitness and demography of barren-ground caribou.

Cumulative effects and barren-ground caribou research

The concept of cumulative effects provides a framework through which we can document and understand the contribution of multiple interacting drivers of change in wildlife populations. Johnson and St-Laurent (2011) defined cumulative effects as "the synergistic, interactive, or unpredictable outcomes of multiple land-use practices or development, that aggregate over time and space" (also see Ross 1998, Harriman and Noble 2008). They proposed a hierarchy of impacts across biological scales, and that the effect of human activities increased with area, intensity, and duration. Thus, finer scale effects are more likely to affect individuals in transitory ways, while broader scale effects can impact the larger population or biological community (Figure 1.1).

A low-intensity, short-duration disturbance will have a limited ecological impact, being constrained to the behavioural or physiological response of individual animals (Johnson and St-Laurent 2011). These impacts may be fleeting and not result in fitness, and ultimately population-level, consequences. These same low-level behavioural and physiological stress responses are also present in response to disturbance at a broader scale and form the mechanistic link between the experience of individual animals and impacts to a larger population. Thus, individual responses to disturbance can be theorized to underlie, cumulatively, phenomena at a broader scale such as changes in population abundance and distribution. The corollary applies: individual changes in behaviour, physiology, and use of space near a disturbance can be hypothesized where broader-scale changes in distribution, population, and abundance of a population are observed.

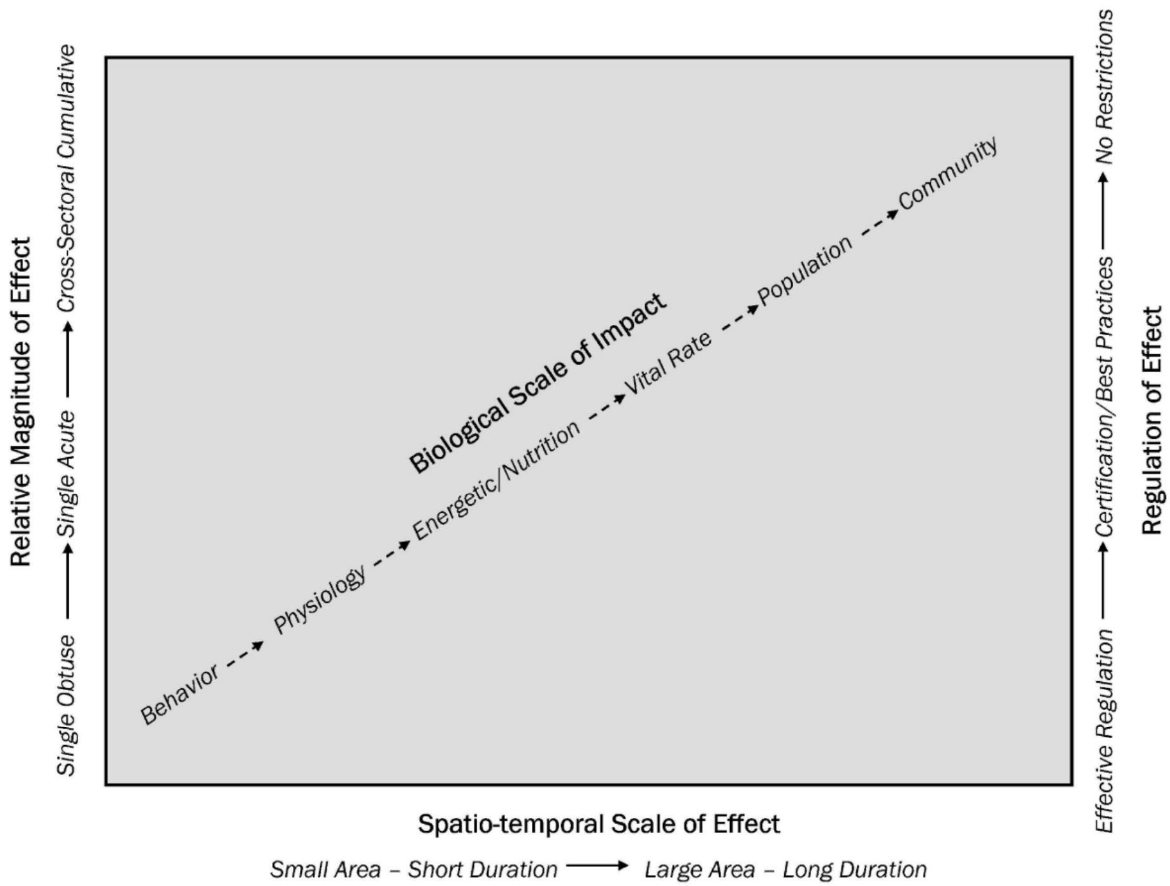

Figure 1.1 The framework of cumulative effects set out by Johnson and St-Laurent (2011) outlining the relationship between the spatio-temporal scale of effect, the relative magnitude of the effect, and the biological scale of the impact of a disturbance. Regulation was also explicitly addressed by a second y-axis on the right-hand side, describing the effects of regulatory regimes on the biological outcomes of cumulative effects. Figure reproduced from Energy Development and Wildlife Conservation in Western North America with permission from Island Press.

Research focused on the response of caribou to anthropogenic disturbance has considered relatively broad-scale distribution-disturbance relationships. Caribou have been shown to avoid anthropogenic disturbance in a broad range of settings and using a range of methods including expert-based estimates (Leblond et al. 2014) and statistical models describing resource selection (Boulanger et al. 2012, Johnson and Russell 2014, Plante et al. 2018), distribution (Nellemann et al. 2001, Vistnes et al. 2001), and movement (Wilson et al. 2016), amongst others. Changes in use of habitat adjacent to mine sites has also been linked to particulate matter that is generated by industrial activities and covers forage plants and lichens (Chen et al. 2017). From this and other work, various Zones of Influence (ZOI) have been reported, ranging from ≤1 km for woodland caribou around roads (Dussault et al. 2012) and up to 14 km for barren-ground caribou around diamond mines (Boulanger et al. 2012).

The ZOIs describe an area around sites of anthropogenic disturbance across which animals change their behaviour, habitat selection, or distribution. Zones of Influence can be inferred from a range of responses, making them a flexible tool for quantifying the singular or cumulative area of disturbance associated with many types of human development. Despite a lack of consensus on the most effective approaches for quantifying ZOIs (Ficetola and Denoël 2009), they are a common and widely accepted technique for quantifying the area of effect of human activities and infrastructure.

Zones of influence have been used to estimate the extent of human-caused disturbance for barren-ground caribou in northern Canada. For example, 5.6% (21,898 km^2) of the annual range of the Bathurst herd is disturbed by human disturbance, including estimated ZOIs (Government of the Northwest Territories 2019). Though disturbance from mining makes up only a portion of this area, it extends across a large portion of the winter range of the Bathurst herd. The quantification of ZOIs around these mines (Johnson et al. 2005, Boulanger et al. 2012) is important for measuring cumulative disturbance and managing the habitats of barren-ground caribou in the Northwest Territories. The Bathurst Caribou Range Plan (Government of the Northwest Territories 2019) uses these ZOIs to quantify the degree to which the Bathurst herd is at risk from disturbance by development, including displacement by future development activities. These estimates of disturbance are used in the range plan to identify thresholds that describe the level of human activity that would merit a management response. This management approach relying on thresholds derived from ZOI estimates is an attempt to establish a systematic method for quantifying the effects of multiple threats to a wildlife population.

Changes in use of space by ungulates has also been shown for roads (Johnson and Russell 2014, Paton et al. 2017, Plante et al. 2018), which in the Northwest Territories would include the permanent and seasonal roads that support the movement of equipment and materials to mines. These roads present a major source of disturbance with a potentially less intense (e.g., traffic vs. blasting) but much greater spatial extent than that from mines. Roads affect caribou's use of space, including migratory movements and timing (Wilson et al. 2016) as well as the use of habitat (Johnson and Russell 2014, Plante et al. 2018). Roads also facilitate access for hunters, increasing mortality of caribou (Plante et al. 2017, McNamara et al. 2022). Although roads can influence the distribution and behaviour of caribou, most of that work has focused on all-weather roads (e.g. Murphy and Curatolo 1987, Vistnes et al. 2001, Dyer et al. 2002, Beauchesne et al. 2013, Wilson et al. 2016). There has been little research on the impacts of seasonal or winter roads. Given the known and likely relationships between caribou and roads, an investigation of the effect of winter roads on caribou is an important part of the responsible management of threatened populations of barren-ground caribou.

Research purpose

The dramatic change in abundance and distribution of barren-ground caribou in the Northwest Territories has not been linked to any one causal mechanism (Adamczewski et al. 2009). Climate change, population fluctuations, and anthropogenic disturbance are implicated, but untangling their effects is difficult. Previous research has largely focused on mid- to broad-scale changes in distribution inferred from GPS collar and survey data (Johnson et al. 2005, Boulanger et al. 2012). These distributional changes imply additional effects that occur at the level of the individual animal (e.g. behaviour, physiology, movement, habitat use) (Johnson and St-Laurent 2011).

In this thesis, I investigated the relationship between industrial infrastructure and the behavioural, stress, and movement ecology of barren-ground caribou from the Bathurst, Bluenose East, and Beverly/Ahiak herds in the Northwest Territories. To this end, I used multiple methods and metrics to quantify the responses of caribou to a major industrial feature in the Northwest Territories: the Tibbitt to Contwoyto Winter Road. This approach allowed me to provide a more mechanistic understanding of the effect of winter roads on the physiology and behaviour of barren-ground caribou, as well as the effect of winter roads on their movement and distribution. My specific research objectives were:

A. through direct observation, measure the behavioural response of barren-ground caribou at a range of distances from the Tibbitt to Contwoyto Winter Road and assess any changes in key behaviours such as foraging;
B. collect and assay glucocorticoid stress hormones in the fecal pellets of caribou from a range of distances from the Tibbitt to Contwoyto Winter Road and test for a relationship between physiological stress and distance to the winter road; and
C. use GPS collar location data to investigate a range of ecological and disturbance factors, including vehicle traffic, that may influence the road-crossing decisions of caribou.

In addition to this introductory Chapter, this thesis includes 2 research chapters and a synthesis chapter. I present methods and discuss results in Chapters 2 (for objectives A and B) and 3 (for objective C). Finally, in Chapter 4, I synthesize the results and place the findings of chapters 2 and 3 in the context of research and management for barren-ground caribou. Results from my thesis will help inform management of barren-ground caribou in the Northwest Territories, including site-level mitigation such as acceptable levels of road activity, as well as measures of cumulative environmental change associated with the indirect footprint of diamond mines and associated roads. To acknowledge the contributions of many to this work, chapters 2 and 3 are written in the first-person plural; the introduction (Chapter 1) and synthesis (Chapter 4) are written in the first-person singular.

Study Area

The study area encompasses the overlapping ranges of the Bathurst, Bluenose-East, and Beverly/Ahiak barren-ground caribou herds. Chapter 2, which comprises both the behavioural and hormone analyses, focuses on the area adjacent to the Gahcho Kué diamond mine and its winter spur road. The analyses for Chapter 3 include the extent of caribou use of the Tibbitt to Contwoyto Winter Road (Figure 1.2).

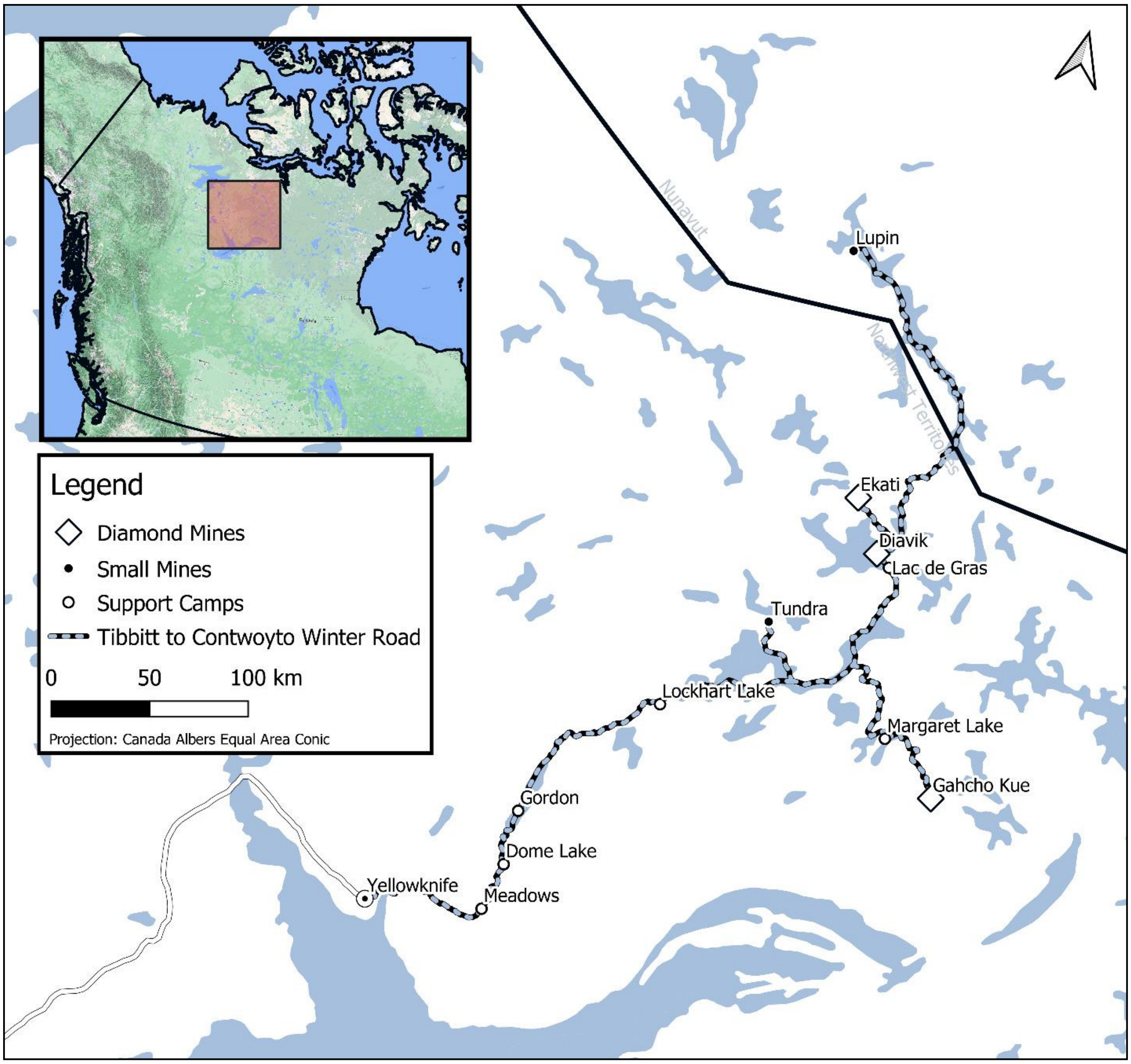

Figure 1.2 Map of the Tibbitt to Contwoyto Winter Road network in the central Northwest Territories, including active diamond mines as of 2019.

Climate data for the study area are collected by weather stations at the diamond mines as well as stations maintained by Environment and Climate Change Canada. The average annual temperature varies between -4–-9°C, with frost common in every month except July and August. Topography is characterized by rolling and eroded till veneers and blankets over bedrock in the south with hummocky till uplands in the north. The vegetation communities include open spruce woodlands at the southern extent. The rest of the study area is characterized by shrub tundra with scattered tree groves in sheltered areas, such as next to the plentiful small lakes. Extensive esker networks crisscross the region (Ecosystem Classification Group 2008).

Industrial development in the Canadian Arctic includes mineral exploration and exploitation, as well as associated winter roads and support camps. Other disturbance sources include municipalities, cabins, and non-industrial roads, which all contribute to the cumulative effect of disturbance to caribou. In the Northwest Territories, recent industrial development is the result of the discovery of diamonds, resulting in several mines including Diavik, Ekati, Snap Lake, and Gahcho Kué. The Lupin gold mine is found at the centre of the study area but is currently not in production. The 495 km Tibbitt to Contwoyto Winter Road is a joint venture between De Beers Group, Rio Tinto, and Arctic Canadian Diamond Company. It is active from January to April and supports the resupply of these mineral operations. The road is primarily constructed on frozen lakes where it varies from 2 lanes up to three multilane parallel roads. It also includes portages overland between lakes, which are often single lane. The snow berms adjacent to the road – generated from snow plowed off the road – are frequently shortened to allow passage by wildlife. Typically, the road has a high volume of traffic, except when closed for inclement weather. Recreational use of the winter road is permitted, though given the remoteness and lack of support this use is primarily limited to self-sufficient hunters that drive the road and use snowmobiles to access adjacent areas. Hunting and fishing camps are a secondary source of disturbance for barren-ground caribou. Most camps are located across the southern portion of the range of the Bluenose East, Bathurst, and Beverly/Ahiak herds.

Chapter 2: Barren-ground Caribou Behavioural and Stress Responses to an Industrial Winter Road

Abstract

Recent declines of barren-ground caribou in northern Canada have been associated with the effects of climate change, natural population fluctuations, and anthropogenic disturbance. The mechanisms through which human disturbance affects caribou are not well understood. Human disturbance, however, has been shown to alter the distribution of barren-ground caribou across northern Canada. These broad-scale distributional changes imply fine-scale effects on caribou behaviour and stress physiology. In the central Northwest Territories, diamond mines and their supporting infrastructure, including winter roads, lie across much of the winter range currently used by the Bluenose East, Bathurst, and Beverly/Ahiak caribou herds. We investigated the fine-scale, mechanistic effect of these disturbance features on the behavior and stress physiology of caribou adjacent to the Tibbitt to Contwoyto Winter Road. We modelled the relationship between the prevalence of observed behavioural category as well as glucocorticoids extracted from fecal pellets and a variety of environmental and disturbance variables, including the distance to the winter road. Proximity to the winter road was associated with a decrease in time spent foraging and an increase in walking behaviour. We did not find a relationship between levels of glucocorticoids in fecal pellets and proximity to the winter road. These results contribute to efforts to understand and manage the effect of industrial disturbance on barren-ground caribou.

Introduction

Anthropogenic disturbance plays a key role in the current biodiversity crisis (Pimm et al. 2014), though most population declines are caused by the cumulative and interacting effects of multiple threats (Brook et al. 2008). Declines of caribou (*Rangifer tarandus*) populations across Canada are a recent and concerning example. In this case, multiple and interacting factors (Thomas and Gray 2002, Vors and Boyce 2009, Johnson et al. 2015, COSEWIC 2016) have resulted in the decline or extirpation of populations of caribou across an extensive area of Canada's boreal, mountain, and Arctic ecosystems. Disentangling the effects of anthropogenic disturbance from other environmental factors, including natural population fluctuations, is complex (Wolfe et al. 2000), especially given the diverse ecology and long-term dynamics of caribou.

Anthropogenic disturbance has been implicated in the declines of many caribou populations in Canada (Thomas and Gray 2002). A large body of research focused on woodland caribou (*R. t. caribou*) has revealed that industrial activities are a major cause of range contractions and decreases in population abundance (Chubbs et al. 1993, Vors et al. 2007, Wittmer et al. 2007, Zbyryt et al. 2018). Unlike woodland caribou in the south, caribou populations in northern Canada are subject to relatively low levels of industrial disturbance (Government of the Northwest Territories 2019). Nevertheless, barren-ground caribou (*R. t. groenlandicus*), a migratory subspecies of caribou, are declining in abundance. Recent and rapid declines have led to this type of caribou being assessed as Threatened at a federal and territorial level (COSEWIC 2016, Species at Risk Committee 2017). The causes of these declines are not well understood (Gunn et al. 2011), but likely include the interacting effects of climate change, natural population fluctuations, and anthropogenic disturbance (Zalatan et al. 2006, Government of the Northwest Territories 2019).

Research has often identified an area around industrial infrastructure where barren-ground caribou alter their distribution in response to human activities (Johnson et al. 2005, Boulanger et al. 2012). The area over which caribou are subject to this effect is termed a zone of influence (ZOI). Measured ZOIs for caribou range from <1 km (roads) to >14 km (mines) for a range of disturbance features that include mines, roads, and oil and gas infrastructure. Most of these ZOIs are based on data from satellite telemetry and GPS collars, surveys of animal distribution, or assessments based on expert opinion (Johnson et al. 2005, Schaefer and Mahoney 2007, Boulanger et al. 2012, Leblond et al. 2013, Panzacchi et al. 2013, Plante et al. 2018). These methods, and the resulting ZOIs, represent a general, anticipated disturbance effect, and not a mechanistic understanding of how caribou are influenced by human activities (Boulanger et al. 2021). The behavioural and physiological responses of caribou, likely the causal mechanisms for observed changes in distribution (Johnson and St-Laurent 2011), are rarely used to generate ZOIs. As behaviour and physiological effects are theorized to be one type of response that is interrelated to the broader scale phenomena of distribution (Wolfe et al. 2000, Johnson and St-Laurent 2011), distribution-based ZOIs imply the occurrence of these finer-scale phenomena.

Stress in an individual animal can be initiated by a large number of potentially interacting or cumulative stimuli, both extrinsically (e.g., predation, human disturbance, challenging thermal conditions) and intrinsically (e.g., nutritional deficit). Stress can manifest as a range of physiological and behavioural responses, adaptations suited to helping the animal in escaping life-threatening situations (Wingfield et al. 1998). When the stress response is extreme or chronic, however, it can have negative effects on fitness (Sheriff et al. 2009).

The assessment of stress through measurement of changes in behaviour and physiology can reveal the energetic and nutritional implications of disturbance. For example, disturbance that increases movement or vigilance can result in a decrease in the time spent foraging and nutritional intake. Likewise, an increase in stress hormones resulting from frequent human disturbance can influence behaviour, leading to less time foraging, and more directly the energetic costs associated with maintaining that state of stress (Wingfield et al. 1998, Joly et al. 2015). Ultimately, frequent or a high level of stress can influence the survival and reproductive productivity of individual animals (Charbonnel et al. 2007).

Recent studies have measured the stress response of caribou in a variety of ways, including assessing levels of stress hormones in hair and feces and changes in behaviour (Freeman 2008, Wasser et al. 2011, Witter et al. 2012, Carlsson et al. 2016). Fecal glucocorticoids are metabolites of glucocorticoids, which are produced by the adrenal gland during the stress response (Wingfield et al. 1998). The level of fecal glucocorticoids provides an index of the physiological stress of an individual caribou over the short term (Özkan Gülzari et al. 2019). Ruminants, including *Rangifer*, have a relatively slow digestive process occurring over hours. Following acute adrenal stimulation, Ashley et al. (2011) reported that caribou (*R.t. granti*) and reindeer (*R.t. tarandus*) exhibited a peak increase in glucocorticoids in fecal material 8 hours following an adrenocorticotropic hormone challenge.

There have been many studies on the behavior of barren-ground caribou, with a particular emphasis on the disturbance responses of caribou to insects during summer

(Morschel and Klein 1997, Colman et al. 2001, 2003, Hagemoen and Reimers 2002, Witter et al. 2012). Behavioural observations have also shown that caribou demonstrate a disturbance or avoidance response when adjacent to roads and other industrial features (Murphy and Curatolo 1987). Despite an abundance of behavioural work on barren-ground caribou, there are few data describing the context-specific behaviour of caribou during winter.

Previous research has reported a large ZOI for barren-ground caribou found near diamond mines in the central Northwest Territories (Boulanger et al. 2012). This effect likely extends to the winter roads which support these mines. When compared to activities at mine sites, roads are potentially a less intense source of disturbance (e.g., traffic vs. blasting). Nonetheless, roads have a much broader presence extending across the seasonal range of caribou and can potentially act as a semi-permeable barrier to movement (Dyer et al. 2002).

In this study, we used behavioural observations and glucocorticoid stress hormones to measure the disturbance response of caribou to the Tibbitt to Contwoyto Winter Road in the central Northwest Territories, Canada. This is one of the first studies to evaluate the fine-scale responses of caribou to high volumes of traffic on an industrial, winter road. We hypothesised that the behavioural and physiological stress response of caribou is a function of the distance of individual animals from the winter road. For the behavioural analysis, we predicted that caribou would feed more and rest more as the distance from the road increased. This activity would be in keeping with an uninterrupted active-rest cycle of behaviour. For the stress hormone analysis, we predicted that stress hormones would decrease as distance from the road increased (Zbyryt et al. 2018).

We used multiple methods to assess the relationship between the behaviour and physiological responses of barren-ground caribou to the winter roads associated primarily with the Gahcho Kué, Ekati, and Diavik diamond mines in the central Northwest Territories. That assessment was premised on the direct observation of behaviour of individual and groups of caribou as well as the measurement of glucocorticoid stress hormones in fecal pellets collected at incrementally greater distances from infrastructure. In total, these analyses provide new insights on the ecological mechanisms that dictate the established ZOI for barren-ground caribou.

Methods

We used a set of integrated field-based methods to assess the behavioural and stress response of barren-ground caribou to the hypothesized disturbance environment around an industrial winter road. This included scan and focal observations of groups of caribou as well as an assessment of glucocorticoid hormones in fecal pellets to measure the behavioural and physiological responses to the disturbance environment of the winter road. In combination, and using a common set of hypothesized models, these methods provided a broad measure of the effects of a winter road on the behavioural and stress response of caribou.

Study Design

We developed a set of a priori models to relate observed behaviour and measured levels of fecal glucocorticoids of caribou to the disturbance environment at varying distances from the winter road. We used fractional logistic regression with robust standard errors (SE) (White 1980) to model the proportion of foraging and levels of hormones and multinomial logistic regression to represent variation in the relative dominant behaviour observed for individual and groups of caribou (Witter et al. 2012).

We collected data along and adjacent to the Tibbitt to Contwoyto Winter Road (Figure 1.2). These data included measured behaviour and collection of fecal pellets for assessment of levels of stress hormones as well as a suite of environmental covariates hypothesized to affect both. The Tibbitt to Contwoyto Winter Road is a seasonal ice road constructed annually to supply diamond mines and other mineral operations on the barren-lands north of Great Slave Lake. The road is a joint venture between De Beers Group, Rio Tinto, and Arctic Canadian Diamond Company. Several camps support the construction and maintenance of the road, as well as the industrial traffic that uses the road. Construction begins in January, for a late January or early February opening. The road is closed in late March or early April and melts off the landscape over the spring. The majority of industrial traffic is present during February and March. Recreational use of the winter road is permitted, though given the remoteness and lack of support along the road this is primarily limited to self-sufficient hunters that drive along the road, camp, and hunt by snowmobile.

Caribou were unevenly distributed across the study area. The location of groups of caribou and resulting sampling locations were informed by sightings provided by recent flights, staff at the Gahcho Kué mine, and GPS collar data supplied daily by staff from the Government of the Northwest Territories (GNWT). This information was supplemented with reconnaissance flights that were conducted before the commencement of fieldwork in February and March of 2020. The fixed-wing Aviat Husky aircraft flew along the Gahcho Kué spur road, as well as on lines parallel with both sides of the road at 10 and 15 km. The pilot reported the location of caribou and caribou sign, and those locations were visited by field crews for sampling of behaviour and fecal pellets.

We used a truck to establish observation sites for caribou that were on or adjacent to the winter road and a helicopter to access caribou that were more distant (>1.5 km) from the road. Fieldwork was based out of the Gahcho Kué Diamond Mine. Sampling occurred primarily along and adjacent to the Gahcho Kué spur of the Tibbitt to Contwoyto Winter Road (Figure 1.2) due to the limited daylight hours and extensive travel time between the mine and sampling locations.

Groups of caribou were selected for behavioural observations if there were >10 individuals and they were not moving behind a visual obstruction. We separated observations from the same location by 5 km or 2 days to reduce the chance of observing the same animals. We assumed that vehicle traffic was a near continuous disturbance for caribou adjacent to the winter road. Thus, we began the behavioural observations immediately when locating caribou by road. When arriving by helicopter, we waited 30 min to allow the group of caribou to acclimate to our presence, and to determine if the group was stationary or if it was moving out of observational range. We always remained >100 m from caribou. Collection of fecal pellets was opportunistic before and after behavioural observations. Despite both sampling efforts taking place concurrently and at often adjacent locations we could not confirm that the pellets originated from the observed group of caribou. Consequently, analyses were conducted separately on these datasets. A set of fecal pellets was supplied by the staff from the GNWT, collected from field work efforts adjacent to the study area.

Behaviour Data

We used two observational methods to quantify the behaviour of caribou observed at a range of distances from the Tibbitt to Contwoyto Winter Road. These data included group scans as well as focal activity and foraging observations (Altmann 1974). We adopted established methods for observing woodland and barren-ground caribou (Witter et al. 2012, Lesmerises et al. 2016). Similar behavioural observation methods have been employed within the study area, but those methods were not standardized and differed from the methods used in this analysis. As such, those data were not included in this work. Upon selecting a group for behavioural observations, we recorded geographic location, the distance and direction of caribou from the observers, time, weather, and site features (Appendix A).

We used instantaneous group scans (Witter et al. 2012) to quantify the behaviour of discrete aggregations of caribou at a relatively consistent point in time. For each group (>10 caribou) we observed the number of animals engaged in each of 5 mutually exclusive behaviours: lying, standing, walking, running or trotting, and foraging. Lying behaviour was characterized by resting the body on the ground, standing by being on all feet with the head erect while not moving, walking by movement without the head down, running or trotting by a fast gait that brought at least two feet off the ground simultaneously, and foraging was a stationary standing behaviour but with the head down. We conducted a scan every 15 min and used a labelled hand-held tally counter (Model H-7350, Uline, Pleasant Prairie, WI) to count the number of individuals demonstrating each behaviour. The scan was typically performed by 2 observers, with one person using the tally counter and the other observing the group through a spotting scope or binoculars. With large groups, the scan could require the full 15-min interval. For each scan, we attempted to count every caribou in each group.

Concurrent with the group scans, we identified a sample of individual caribou for focal activity and foraging surveys (Altmann 1974). For both surveys, target animals were randomly selected using a random number (limited to the group size) without replacement. If a selected caribou was unavailable (i.e., it was obscured or too far away to view properly or not engaged in foraging for the focal foraging survey or non-lying behaviour for the focal activity survey) then the closest eligible caribou to the random individual was chosen.

For the focal foraging survey, a single observer recorded the total time over a 10-min interval that the focal animal spent head down and foraging during a foraging bout. Two timers were used for this survey: one recorded the total survey time and the other tracked time spent head down. Due to the distance from observer to caribou in the survey and the obstruction of the snow, we could not determine the time spent biting at plants versus time spent with head down and searching. As such, foraging was defined as head down behaviour. Identifying the end of a foraging bout is difficult, as each bite could be the end of a bout (Gillingham et al. 1997). The end of a foraging bout was determined if 15 sec passed between instances of head down foraging behaviour.

For the focal activity survey, the observer recorded the activity of an individual caribou for a maximum of 30 min. Every 30 sec the behaviour of the focal animal was recorded as one of standing, walking/trotting, or foraging. Running animals were easily lost by observers, so the behaviour was not captured during the focal activity scan. Also, we ended the focal observation if the caribou began to run. A single observer recorded each focal activity survey.

Fecal Glucocorticoid Data

Collection of fecal pellets was performed concurrently with behavioural observations as well as opportunistically during travel to and from observation sites. We collected pellets from known groups of caribou as well as by locating recent caribou tracks and feeding craters. We did not gather weather data at the collection site, as the time that pellets were deposited was unknown. At each sampling location, we collected 5 pellet groups, each with at least 20 pellets. Pellet freshness could be estimated from the state of the pellets, including the presence of fine ice crystals and hardness of the snow in caribou tracks and feeding craters. Preference was given to intact pellet "cookies" on top of the snow over dispersed or buried pellet groups.

Pellets were stored in labelled whirlpacs and kept at -10° C in a freezer prior to shipment. Samples were shipped to the Endocrine Services Lab at the University of Saskatchewan for processing and assessment of levels of metabolites of the glucocorticoids cortisol and corticosterone. At the lab the samples were ground and dried by lyophilization then extracted with alcohols and steroid diluents. Concentrations of cortisol and corticosterone were established using a double antibody radioimmunoassay for each composite fecal pellet sample (~3 pellets) and reported as nanogram per gram of feces.

Ecological and Disturbance Covariates

We identified a number of factors hypothesized to affect the behaviour and stress physiology of caribou adjacent to or distant from the Tibbitt to Contwoyto Winter Road. These included environmental and disturbance variables reported to influence the distribution, movements, or behaviour of caribou (Table 2.1).

Table 2.1 Description, mechanism, and predicted effect (positive or negative) of covariates hypothesized to influence the behaviour or stress physiology of barren-ground caribou near the Tibbitt to Contwoyto Winter Road in the central Northwest Territories, Canada. Covariates in the behavioural analysis are marked with “Be”; covariates in the stress hormone analysis are marked with “H”.

Covariate	Type	Description
Distance to road $^{Be/H}$	Continuous	Distance from observed caribou to the winter road. A measure of the gradient of disturbance environments.
In no-hunting zone ^{H}	Binary	Observations from within Bathurst mobile no-hunting zone. A measure of hunting pressure.
Observer upwind ^{Be}	Binary	Observers upwind of caribou. A measure of response of caribou to the presence of observers.
Group size ^{Be}	Continuous	The total number of animals recorded from the first group scan at a site.
Day of year $^{Be/H}$	Continuous	Number of days since January 1st.
Year $^{Be/H}$	Categorical	The year of observation.
Survey duration ^{Be}	Continuous	The duration of the behavioural survey, in number of scans completed. Accounts for different survey effort at each site.
Windchill $^{\dagger Be/H}$	Continuous	A measure of the most extreme windchill over the previous 1 or 3 days (behaviour or stress analyses, respectively). A measure of thermal stress experienced by caribou.
Cloud cover ^{Be}	Ordinal	Cloud cover during observation.
Site id ^{H}	Random	A random effect to control for multiple samples taken from each location.

†Windchill defined in eq. 2.1.

We used right-of-way data from the GNWT (J. Williams, Government of the Northwest Territories, personal communication), Mackenzie Valley Land and Water Board (Mackenzie Land and Water Board 2020), and De Beers Canada (Ryan Marshall, De Beers Canada, personal communication), along with a portion digitized from satellite imagery (NASA SENTINEL-2 dataset) to develop a GIS shapefile denoting an estimated annual alignment of the Tibbitt to Contwoyto Winter Road. Despite some variation in road alignment among years to bypass ice ridges and overflow, the road right-of-way is limited by permits issued by the Mackenzie Valley Land and Water Board. This includes the overland sections (portages) as well as the sections on frozen lakes. Consequently, the alignment of the road is very similar year-to-year. Distance to road was estimated using this road alignment as well as the recorded position of the observed caribou.

We used the boundaries of the Bathurst mobile no-hunting zone to estimate the presence or absence of hunting activity. The Bathurst mobile no-hunting zone was established by the GNWT and Indigenous governments as a joint management action in response to the decline of the Bathurst herd (Government of the Northwest Territories 2019). The boundaries of the mobile zones and the open and close dates were provided by the North Slave office of the Department of Environment and Natural Resources, GNWT.

At behavioural observation sites, weather variables were collected; at fecal pellet collection sites, weather variables were estimated from remote sensing products. We directly observed and recorded cloud cover as “clear/scattered” or “broken/overcast”. We estimated wind speed and temperature using NASA’s Modern Era Retrospective Analysis for Research and Applications (MERRA-2) dataset (Gelaro et al. 2017). From these data, we modelled the windchill at the observation site (eq. 2.1).

Equation 2.1: $T_{wc} = 13.12 + 0.6215T_a – 11.37v^{0.16} + 0.3965T_av^{0.16}$, where:

T_{wc}: Wind chill index (kg*cal/m^2/h);

T_a: air temperature (°C);

v: wind speed (km/h).

For the behavioural observations, we used the lowest estimated hourly windchill during the day previous. For the stress hormone samples, for which the exact deposition time of pellets was difficult to determine, we used the lowest estimated hourly windchill over the 3 days previous to sampling. Windchill was calculated using an equation (eq. 2.1) that was developed for humans (Osczevski and Bluestein 2005). Though not quantified for *Rangifer*, that windchill value provides an estimate of the relative thermal loss experienced by caribou. The combination of solar radiation and estimated windchill were used to estimate the thermoregulatory stress that caribou were experiencing.

Development and Assessment of Statistical Models

We used generalized linear models to relate the behaviour and stress hormone data to a set of environmental and disturbance covariates. For each analysis, we developed a set of models to test the factors that were hypothesised to influence the behaviour or stress hormone levels of caribou near to the Tibbitt to Contwoyto Winter Road (Table 2.2).

We used fractional logistic regression with robust SEs (White 1980) to model variation in the observed behaviour of caribou for the group scans and focal feeding surveys. With fractional logistic regression the response can be a fraction or proportion, and the models can be used with strongly heteroscedastic data (White 1980). The response for the group scan data was the proportion of caribou engaged in foraging or lying averaged across all observations at a site. This is a proxy for the degree to which the observed group of caribou was engaged in foraging and ruminating, which are energetically important during winter. For the focal foraging survey, the response was the proportion of time spent head down foraging, averaged across all observations at a site.

Table 2.2 Candidate generalized linear models designed to test a range of factors hypothesized to influence the behaviour of barren-ground caribou near the Tibbitt to Contwoyto Winter Road in the central Northwest Territories, Canada. For each model, "~" separates the dependent variable from the set of independent variables.

Model group	Hypothesis	Model Structure (behaviour / hormone)
Distance	The disturbance regime near the road presents frequent threat instances from traffic and hunters. In this environment, caribou spend less time foraging and ruminating and more time engaged in vigilance behaviour.	*Behaviour* ~ distance to road + year + observer upwind + survey duration† + group size† *Hormone* ~ distance to road + year + site id
Time of year	As the year progresses from mid-winter toward spring migration, caribou are moving more directionally across the landscape.	*Behaviour* ~ day of year + year + observer upwind + survey duration† + group size† *Hormone* ~ day of year + year + site id
Hunting pressure	Presence of hunters induces a greater level of vigilance behaviour at the expense of foraging.	*Behaviour* ~ in no-hunting zone + year + observer upwind + survey duration† + group size† *Hormone* ~ in no-hunting zone + year + site id
Weather	The thermal environment affects energy output in caribou and the associated activity budget.	*Behaviour* ~ cloud cover + windchill + year + observer upwind + survey duration† + group size† *Hormone* ~ windchill + year + site id
Global model	All covariates are important.	*Behaviour* ~ distance to road + in no-hunting zone + cloud cover + windchill + year + day of year†† + observer upwind + survey duration† + group size† *Hormone* ~ distance to road + in no-hunting zone + windchill + year + day of year + site id
Null model	Model covariates are not important for explaining behaviour or stress response of caribou.	1

Note: Covariates are described in Table 2.1.
† Survey duration and group size were only included in the group scan model.
†† Day of year removed from focal activity global model due to high multicollinearity.

We used multinomial logistic regression to model the relative dominant behaviour recorded using focal surveys of individual caribou (Witter et al. 2012). When applying this method, the prevalence of each behaviour in a survey was given a percentile score relative to the observed scores for that behaviour across all surveys. Each behaviour was then ranked according to the respective percentile score for that survey. That ranking served as the ordered category for each case, modeled with the multinominal logistic regression. This method is useful when some behaviour categories are dominant (Witter et al. 2012).

We used linear regression to model variation in the measured level of fecal glucocorticoids. The response was measured as the nanograms of hormones per gram of dry fecal matter. We conducted independent analyses for cortisol and corticosterone, but used the same model set for each analysis. We used a random effect for each collection site (Gillies et al. 2006).

We used the variance inflation factor (VIF) to assess each model for excessive multicollinearity (Shrestha 2020). Parameters were removed if they had a VIF > 10, which is a common threshold used to determine problematic correlations among one or more covariates (Vittinghoff et al. 2012). We used an information theoretic approach to identify the most parsimonious models of the set as ranked by the Akaike Information Criterion corrected for small sample sizes (AIC_c) (Hurvich and Tsai 1989). The AIC_c measures the relative fit of the model to the data while penalising the ranking of models with a greater number of parameters (Burnham and Anderson 2004). The most parsimonious model has the smallest AIC_c, measured as the difference between each model and the top-ranked model (ΔAIC_c). We considered all models with ΔAIC_c <2.0 as informative (Anderson et al. 2002, Burnham and Anderson 2002).

The AIC_c provides a relative measure of model fit, but not predictive accuracy. Predicted values were generated from a leave-one-out cross-validation (LOOCV), where each predicted value was re-estimated with the predictor and response values from that observation held back from model estimation. We assessed predictive capacity for the group scan and hormone models using these predicted values from the LOOCV by checking if the set of values predicted were significantly different from the measured response as determined by a Mann-Whitney U test (Fielding and Bell 1997, Pearce and Ferrier 2000). The non-parametric test was used as all predicted value sets were tested for normality and all found to be non-normal. We used the area under the curve (AUC) of the receiver operating characteristic (ROC) curve to measure the predictive accuracy of the focal activity models. Area under the curve values between 0.7 and 1 were considered to have good predictive ability, and models with an AUC of approximately 0.5 were assessed as having no predictive capacity (Fielding and Bell 1997, Boyce et al. 2002). We used 95% confidence intervals to assess the relative strength of the set of covariates in each regression model. All data handling and modelling for both the behavioural and hormone analyses was conducted using R (R Core Team 2021) and ArcGIS (ESRI 2020).

Results

Behavioural observations and fecal pellet samples were collected from a range of distances from the winter road during the 2019 and 2020 field seasons (Figure 2.1). We observed the behaviour of 36 groups of caribou. Concurrent with field efforts to sample behavioural data, we collected 64 sets of fecal pellets, including 19 sets contributed by staff from the Department of Environment and Natural Resources (ENR) from the GNWT. Sampling in 2020 was more limited than in 2019 due to a lack of caribou near the Gahcho Kué diamond mine as well as the onset of the COVID-19 pandemic, which limited available staff as well as the duration of the field season.

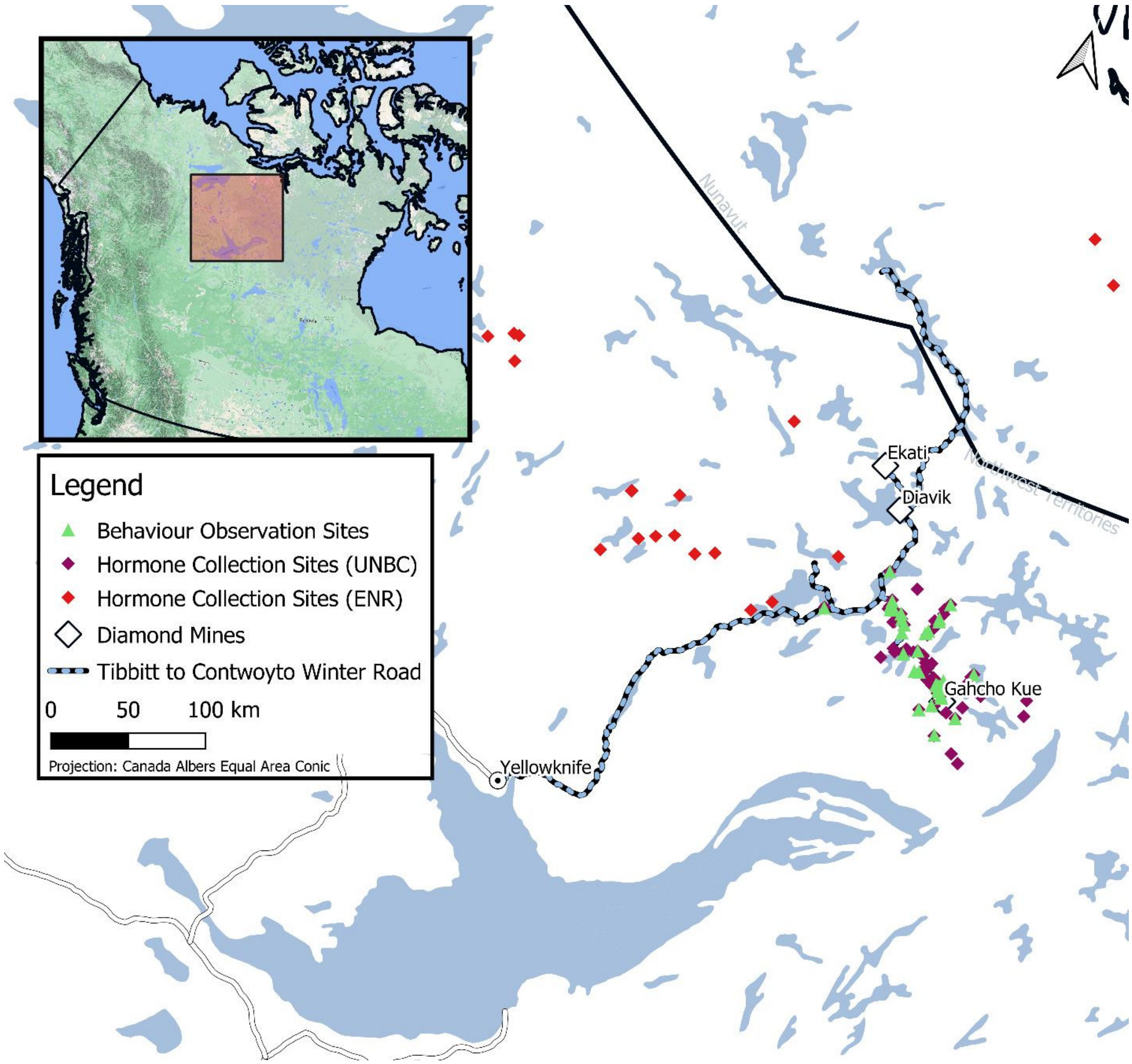

Figure 2.1 Location of the field sites for collection of behaviour and hormone data in February and March of 2019 and 2020. ENR hormone collections sites were visited by Government of the Northwest Territories staff in March of 2020.

Behaviour data were collected for all 3 observation techniques across 36 sites. At each site, we collected a minimum of one group scan and at 28 of those sites we completed 108 focal activity surveys. At 15 sites we also collected 69 surveys of foraging intensity. We removed surveys that did not adhere to survey protocols, as well as surveys that were <2 min, leaving a total of 36 group scans, 107 focal activity surveys, and 63 focal foraging surveys (Figure 2.2).

The behaviour data from the group surveys, averaged across sites, were dominated by a high proportion of foraging and lying at 0.61 (SD 0.29; n = 36), with walking, trotting/running, and standing tending towards a lower proportion of behaviour in observed groups. Focal activity surveys, revealed a similar high proportion of foraging at 0.65 (SD 0.34; n = 107) compared with other behaviours. The focal foraging data had a low degree of variation, with most focal foraging scans showing a similar proportion of time spent head down at 0.72 (SD 0.14; n = 63) of scan duration.

We collected 5 samples of pellets from 53 locations in 2019 and 11 locations in 2020. Staff from ENR provided 5 samples from 19 locations in 2020. One sample from the GNWT and all samples from one site from our field efforts did not provide successful lab results and were excluded from the analysis. In the analysis, collection site was assigned as a random effect, leaving an effective sample size of 82. Glucocorticoid values were variable both within sampling locations and between sampling years, particularly when comparing cortisol (Figure 2.3).

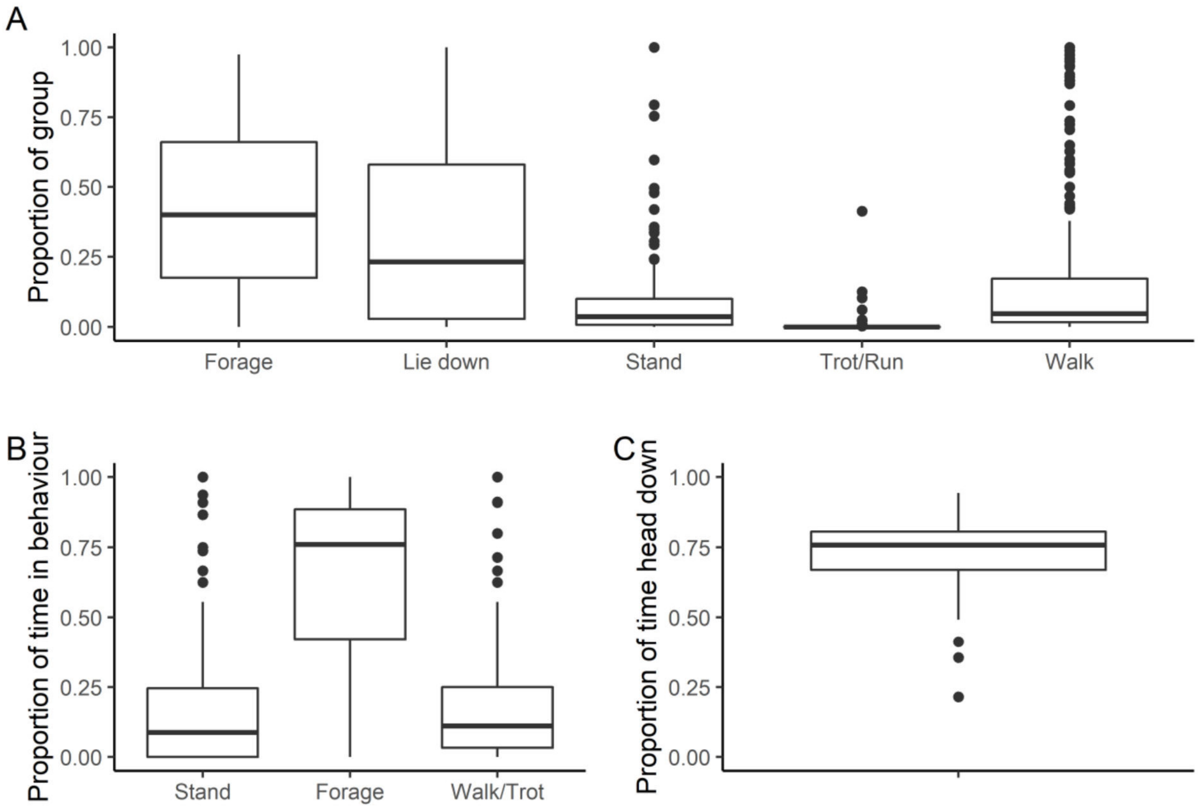

Figure 2.2 Boxplots of observed behaviours during group surveys (A), focal activity scans (B), and focal foraging scans (C) from behavioural observations collected near the Tibbitt to Contwoyto Winter Road, Northwest Territories, Canada. Data from A include all observations from each site summarized as proportion of the behaviour observed in the group total (n = 36). Data from B show the resulting proportion of a behaviour from each focal activity scan (n = 107). Data from C show the proportion of time during a focal foraging scan where the target caribou was head down foraging (n = 63).

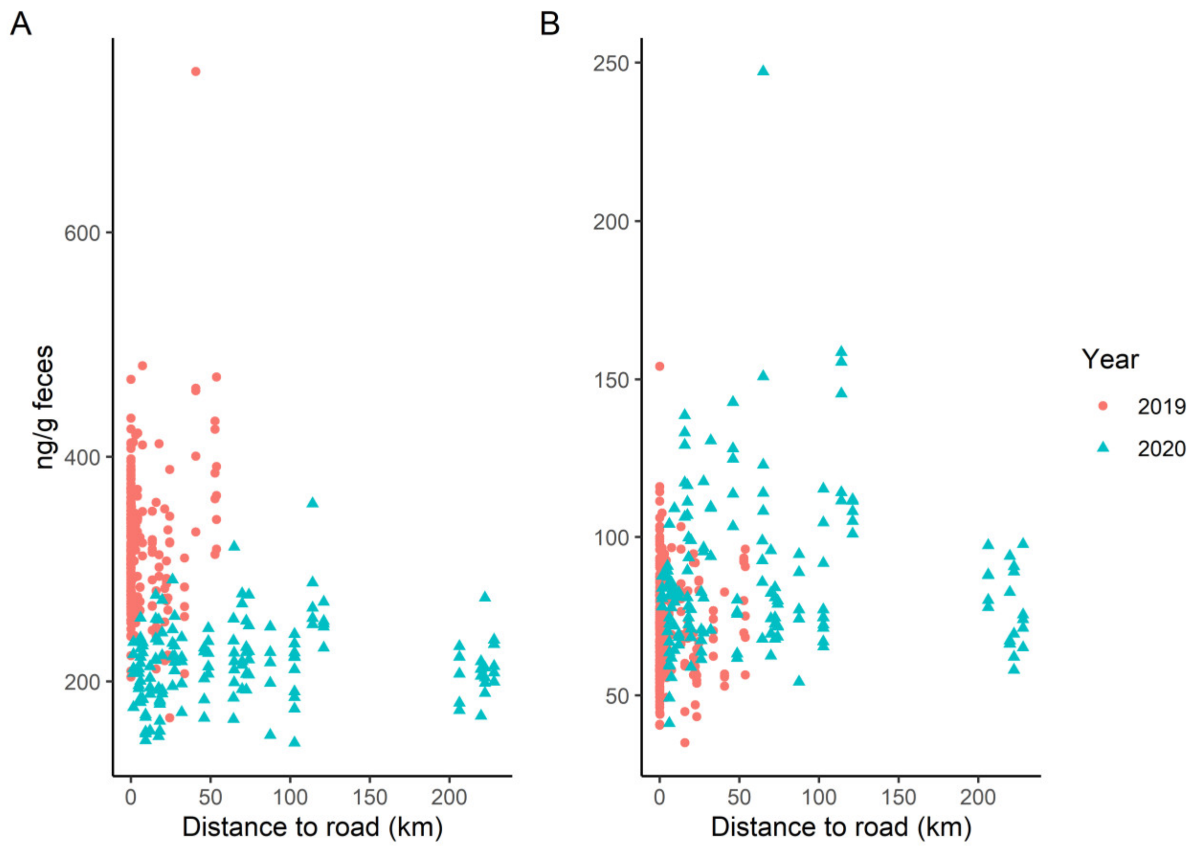

Figure 2.3 Observed levels of metabolites of the fecal glucocorticoids cortisol (n = 82) (A) and corticosterone (n = 82) (B) from fecal pellets of barren-ground caribou collected at varying distances from the Tibbitt to Contwoyto Winter Road, Northwest Territories, Canada.

The distance model was the most parsimonious of the set of model hypotheses representing the group survey data (Table 2.3). That model indicated that more caribou were engaged in foraging or lying as the distance from the road increased. It also showed that the magnitude of the observed behaviour was influenced by the duration of the observation period (Figure 2.4). This was likely due to caribou engaging in movement behaviour and leaving the range of observation, where resting and foraging caribou were more stationary and able to be observed for longer periods. Also, there was a possible disturbance effect of the field activities as the number of caribou foraging and lying decreased when the group was located downwind from the observers (Figure 2.5); there was also a strong effect of year on the predicted response. The top-ranked model had good predictive accuracy (values generated in a leave-one-out-cross-validation not significantly different from those generated by the model, Mann-Whitney U, $p = 0.61$).

Table 2.3 Ranking of fractional logistic regression models (with robust SEs) representing the mean proportion of caribou in groups engaged in foraging or lying near the Tibbitt to Contwoyto Winter Road, Northwest Territories, Canada.

Model		***K***	**AIC_c**	**ΔAIC_c**
Distance	Distance to road + year + observer upwind + survey duration + group size	6	42.6	0
Time of year	Day of year + year + observer upwind + survey duration + group size	6	45.4	2.52
Hunting	In no-hunting zone + year + observer upwind + survey duration + group size	6	45.6	2.71
Weather	Cloud cover + windchill + year + observer upwind + survey duration + group size	7	46.8	3.97
Null	NA	1	48.4	5.54
Global	Distance to road + in no-hunting zone + day of year + cloud cover + windchill + year + observer upwind + survey duration + group size	10	55.1	12.3

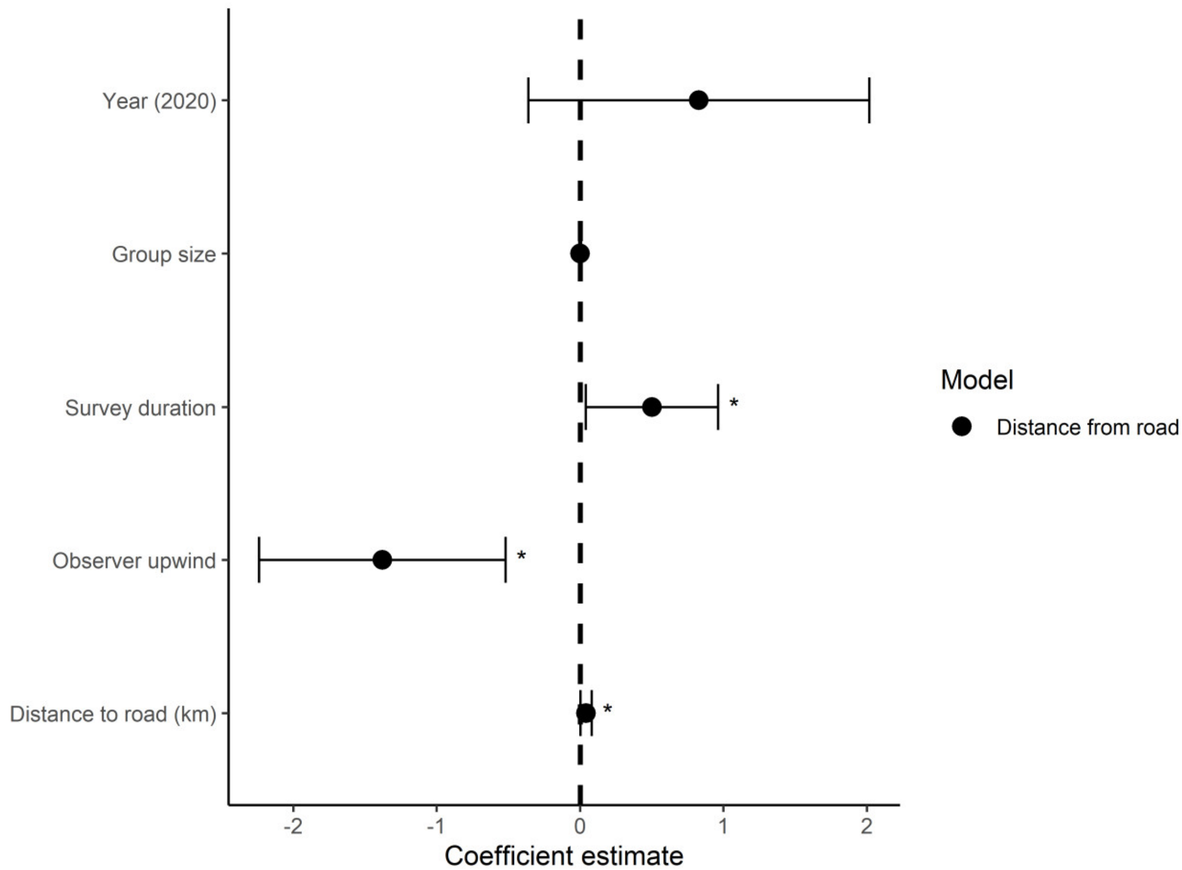

Figure 2.4 Coefficients and 95% confidence intervals from top-ranked group survey model ($\Delta AIC_c < 2$) for barren-ground caribou adjacent to the Tibbitt to Contwoyto Winter Road, Northwest Territories, Canada. The asterisk indicates confidence intervals that do not overlap zero.

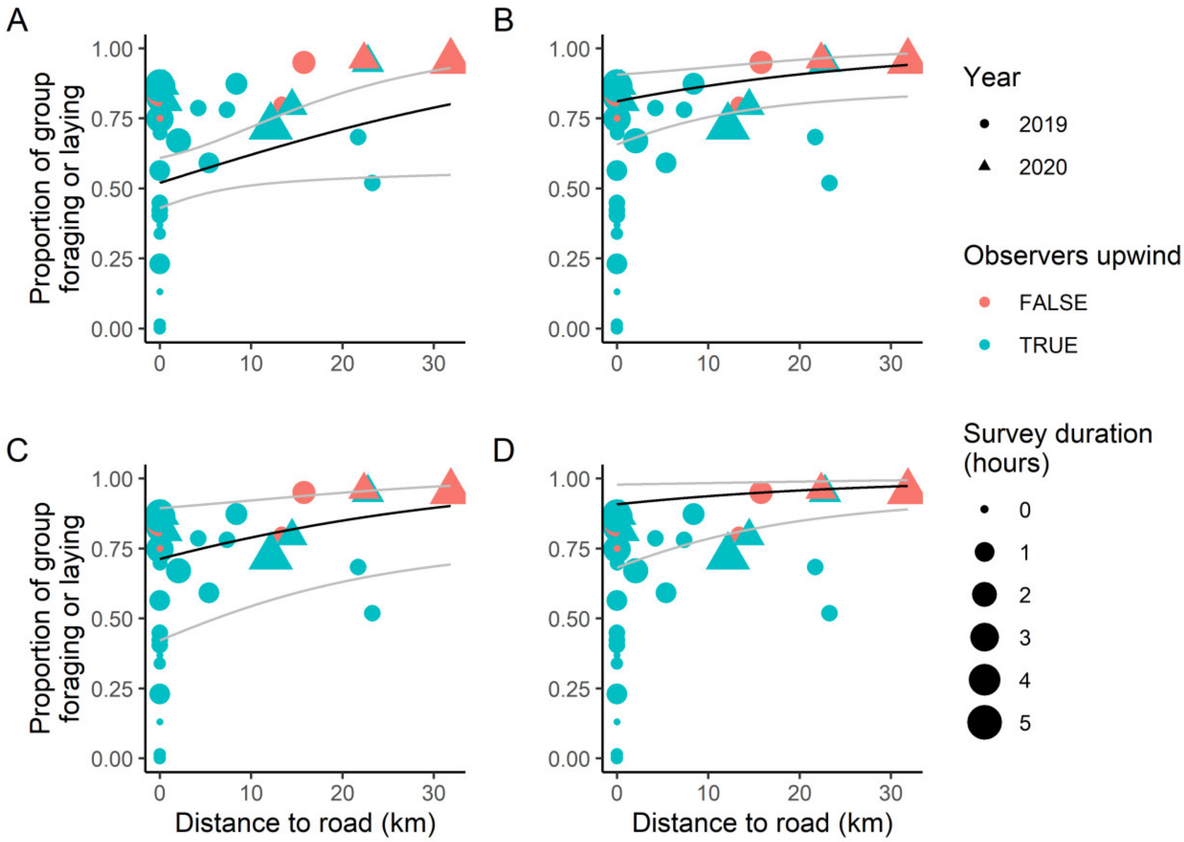

Figure 2.5 Proportion of barren-ground caribou foraging or lying averaged across scans at an observation site. Results from the top-ranked model (Table 2.3) show a significant relationship between distance to the Tibbitt to Contwoyto Winter Road, Northwest Territories, Canada, and the proportion of caribou observed foraging or lying. Grey lines indicate 95% confidence intervals. The panels show predicted values for 2019 (A and B) or 2020 (C and D) and with observers upwind (A and C) or observers downwind (B and D). The circles and triangles represent the data used to parameterise the models, summarized for each observation site. Survey duration indicates the duration of caribou observations at a site.

The distance to road model was the top-ranked model for the data representing the observations of individual (focal) caribou (Table 2.4). The coefficients for the standing and the walking categories indicated an increase in both behaviours in 2020, relative to foraging (reference category), and suggested that walking was negatively correlated with distance to the road (Figure 2.6). Although the top-ranked model was more parsimonious than the null, and included coefficients that did not overlap 0, the predictive accuracy was poor (AUC_{stand} = 0.498, SE = 0.06, $AUC_{walk/trot}$ = 0.537, SE = 0.06) (Boyce et al. 2002). Thus, inference drawn from the top model should be interpreted with caution (Table 2.5).

Table 2.4 Ranking of multinomial regression models representing the behaviour of animals observed during focal activity surveys near the Tibbitt to Contwoyto Winter Road, Northwest Territories, Canada. AUC scores are from ROC curves and are based on predicted outputs from a leave-one-out cross-validation procedure. The SEs of the AUC scores are presented in brackets.

Model		***K***	**AIC_c**	**ΔAIC_c**	**AUC_{stand}**	**$AUC_{walk/trot}$**
Distance	Distance to road + year + observer upwind	8	211	0	0.498 (0.06)	0.537 (0.06)
Null	NA	2	216	4.98	0 (0)	0.424 (0.06)
Hunting	In no-hunting zone + year + observer upwind	8	217	6.23	0.499 (0.06)	0.502 (0.06)
Time of year	Day of year + year + observer upwind	8	218	7.35	0.597 (0.07)	0.487 (0.06)
Global	Distance to road + in no-hunting zone + cloud cover + windchill + year + observer upwind	18	219	8.35	0.602 (0.07)	0.477 (0.06)
Weather	Cloud cover + windchill + year + observer upwind	14	222	11.8	0.632 (0.06)	0.481 (0.06)

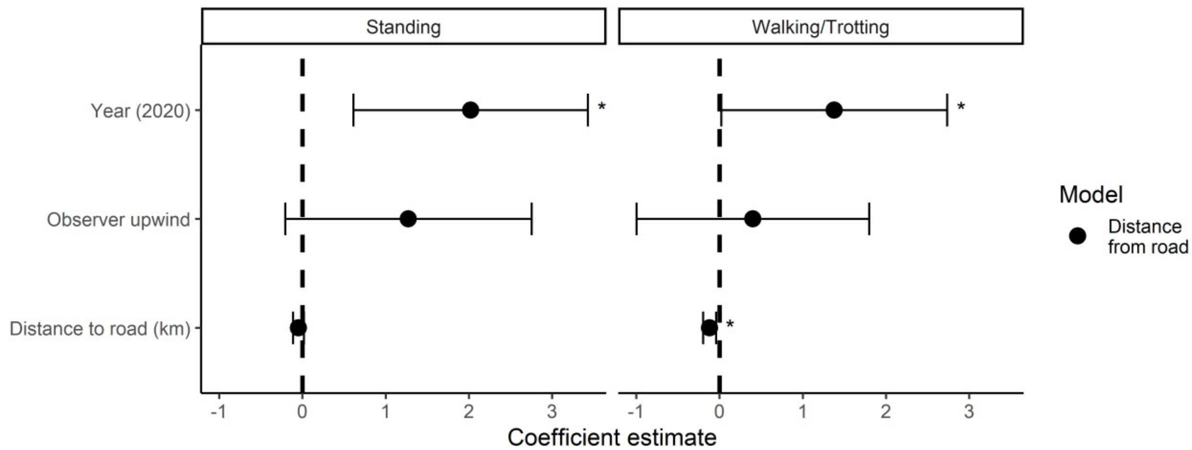

Figure 2.6 Coefficients of the top-ranked model ($\Delta AIC_c < 2$) for the focal activity scans for barren-ground caribou adjacent to the Tibbitt to Contwoyto Winter Road, Northwest Territories, Canada. The asterisk indicates confidence intervals that do not overlap 0. The coefficients for the Standing and Walking/Trotting categories are interpreted relative to the Foraging category (i.e., reference category). The predictive accuracy for the top-ranked model was poor (AUC_{stand} = 0.498, SE = 0.06, $AUC_{walk/trot}$ = 0.537, SE = 0.06). Thus, model coefficients should be interpreted with caution.

None of the models for the focal feeding analysis were more parsimonious than the null model (Table 2.5). This suggests that the hypothesised explanatory variables had relatively little effect in explaining variation in the proportional time that caribou were observed feeding.

The level of stress hormones in fecal material was best explained by models representing day of year of sample collection (cortisol) and the recent windchill (cortisol and corticosterone) (Table 2.6). The top-ranked models had good predictive accuracy, with values generated in a leave-one-out-cross-validation not significantly different from those generated by the model as assessed using the Mann-Whitney U test. Day of year of sampling and inferred windchill were positively associated with the level of cortisol and corticosterone, respectively, measured in caribou feces. Cortisol and corticosterone levels differed significantly between the years of sampling, but with opposite signs. In 2020, there were lower values of cortisol and greater values of corticosterone when compared to samples collected in 2019. There was no statistical support for models indicating a relationship between the distance to the winter road and levels of stress hormones.

Table 2.5 Model coefficients, SEs, Z, and P for the top model of the relative dominant behaviour of caribou near the Tibbitt to Contwoyto Winter Road, Northwest Territories, Canada. The coefficients for the Standing and Walking/Trotting categories are interpreted relative to the Foraging category (i.e., reference category). The predictive accuracy for the top-ranked model was poor (AUC_{stand} = 0.498, SE = 0.06, $AUC_{walk/trot}$ = 0.537, SE = 0.06). Thus, model coefficients should be interpreted with caution.

Coefficient	Response	Estimate	SE	Z	P
Distance to road (km)	Stand	-0.048	0.033	-1.46	0.145
	Walk/trot	-0.119	0.040	-2.99	0.003
Observer upwind	Stand	1.27	0.755	1.69	0.092
	Walk/trot	0.401	0.713	0.563	0.574
Year (2020)	Stand	2.02	0.719	2.81	0.005
	Walk/trot	1.38	0.692	1.99	0.046

Table 2.6 Ranking of fractional logistic regression models (with robust SEs) representing the proportion of time that individual caribou spent foraging near the Tibbitt to Contwoyto Winter Road, Northwest Territories, Canada.

Model		***K***	**AIC$_c$**	**ΔAIC$_c$**
Null	NA	1	43.4	0
Hunting	In no-hunting zone + year + observer upwind	3	49.4	6.01
Time of year	Day of year + year + observer upwind	3	50.0	6.10
Distance	Distance to road + year + observer upwind	3	50.0	6.31
Weather	Cloud cover + windchill + year + observer upwind	4	52.2	8.78
Global	Distance to road + in no-hunting zone + cloud cover + windchill + year + observer upwind	6	59.0	15.1

Table 2.7 Ranking of linear regression models representing the level of stress hormones cortisol and corticosterone observed from barren-ground caribou fecal pellets collected near the Tibbitt to Contwoyto Winter Road, Northwest Territories, Canada. Results are presented for models of both cortisol (left columns) and corticosterone (right columns).

Model		***K***	**Cortisol**		**Corticosterone**	
			AIC$_c$	**ΔAIC$_c$**	**AIC$_c$**	**ΔAIC$_c$**
Time of year	Day of year + year + site id	3	4383	0	3566	5.55
Weather	Windchill + year + site id	3	4385	1.50	3560	0
Hunting	In no-hunting zone + year + site id	3	4386	2.89	3574	13.7
Distance	Distance to road + year + observer upwind	3	4387	3.30	3574	14.0
Global	Distance to road + in no-hunting zone + windchill + day of year + year + site id	6	4389	5.55	3564	4.17
Null	1	1	4486	103	3591	31.2

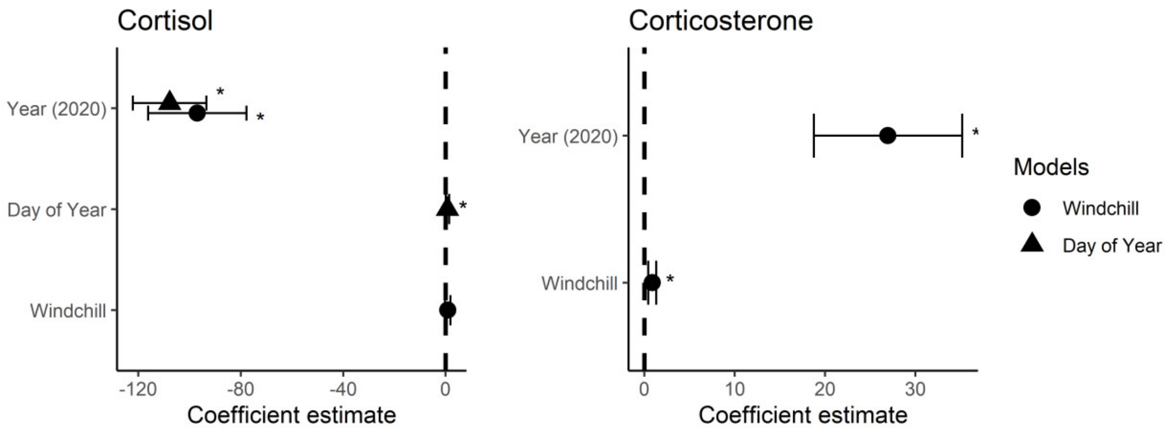

Figure 2.7 Model results from the set of a priori models on the levels of stress hormones cortisol and corticosterone observed from barren-ground caribou fecal pellets collected adjacent to the Tibbitt to Contwoyto Winter Road, Northwest Territories, Canada. The asterisk indicates confidence intervals that do not overlap 0.

Discussion

This is one of the first studies to report a negative response of migratory caribou to industrial winter roads in the Arctic. Both focal and scan sampling revealed that barren-ground caribou foraged less and walked more when near the Tibbitt to Contwoyto Winter Road. Despite marked variation in observed levels of cortisol and corticosterone, neither of these measures of stress showed a relationship with distance from disturbance features. Findings from our research are consistent with past studies that reported that human disturbances influenced the behaviour of migratory caribou (Murphy and Curatolo 1987, Tyler 1991, Wolfe et al. 2000, Reimers and Colman 2006).

Previous work in the Northwest Territories has focused on the relatively coarse-scale distributional effects of the diamond mines and supporting roads (Johnson et al. 2005, Boulanger et al. 2012). The response of caribou to the winter road that supports these mines is less studied but is a wide-spread disturbance feature with the potential to influence caribou across a much larger geographic area. Roads influence ungulates in a variety of ways, including effects on movement rates (Wilson et al. 2016), use of space at broad scales (Johnson and Russell 2014), level of stress hormones (Joly et al. 2015, Zbyryt et al. 2018), and behaviour (Murphy and Curatolo 1987).

The relationship between adjacency to winter road and behaviour substantiates the hypothesized presence of a ZOI for the Tibbitt to Contwoyto Winter Road, as has been found for the associated diamond mines (Boulanger et al. 2012). We, however, did not attempt to estimate a novel ZOI. This requires a sophisticated analysis and the results can vary substantially based on ecological circumstance (Ficetola and Denoël 2009, Boulanger et al. 2021). Nor did we attempt to measure a change in the abundance of caribou in proximity to industrial features. Instead, we measured a change in behaviour that increased with adjacency to the winter road. That relationship is consistent with the definition and interpretation of ZOIs as applied to project decision making and mitigation. Also, the findings of our work provide some mechanistic explanation of broader-scale disturbance-avoidance responses that were measured with GPS or satellite collar data (Johnson et al. 2005, Boulanger et al. 2012). The mechanistic relationship between disturbance and behaviour provides new avenues for guiding mitigation designed to minimise the disturbance effects of the winter road (Leblond et al. 2013). Also, those relationships provide new insights on methods to monitor the response of caribou to road placement and traffic.

Results from the observational data suggested that caribou moderated their behaviour when adjacent to the winter road, spending less time foraging and more time walking. The predictive accuracy from models of focal activity was poor. Nonetheless, models showing a response of caribou to the disturbance environment near the winter road were ranked high relative to a null model using AIC (Anderson et al. 2002), consistent with ecological theory of response by animals to disturbance (Johnson and St-Laurent 2011), and in line with previous research (Murphy and Curatolo 1987, Lesmerises et al. 2016). Despite their weak predictive ability, these models are useful for drawing inference about disturbance-response relationships.

These findings indicate that caribou are engaging less efficiently in their forage-rest cycles (van Oort et al. 2005), which could have implications for their energetic balance during winter. That time of year is energetically difficult, as caribou must contend with the challenges of cold weather and foraging through crusted snow for liches that are low in digestible protein (Fancy and White 1985, Trondrud et al. 2021). The increased walking that we observed could be a response to disturbance, as caribou are known to move away from traffic (Plante et al. 2018), snowmobiles (Seip et al. 2007), and other forms of human disturbance (Lesmerises et al. 2018). The magnitude of a disturbance's effect on energy balance can be inferred from behavioural measurements (Tyler 1991, White et al. 2014). The unknown amount of time that caribou spent near the winter road, however, precluded a detailed examination of the energetic implications of the behavioural data. Energetic modelling for barren-ground caribou could incorporate these findings (White et al. 2014).

A physiological reaction to a perceived threat is part of a hypothetical continuum of responses to disturbance (Johnson and St-Laurent 2011). Thus, the change in behaviour observed for caribou near the winter road implies a corresponding change in stress physiology. We did not, however, detect a signal in the fecal glucocorticoids, a proxy for physiological stress that has been employed in numerous other studies (Wasser et al. 2011, Joly et al. 2015, Ewacha et al. 2017, Özkan Gülzari et al. 2019). The lack of an observed relationship between stress hormones in fecal pellets and distance to the winter road does not lead to an irrefutable conclusion that caribou do not have a physiological response to the disturbance caused by vehicle traffic or hunters. The data we collected revealed a high degree of variation in cortisol and corticosterone after controlling for distance from road (Figure 2.3). Similarly, other studies focused on migratory caribou have reported significant inter-animal or inter-sample variability in measures of the same stress hormones (Joly et al. 2015). In our study, that variability could be caused by a number of ecological or environmental factors that were related to nutritional or environmental stress, but not measured (Millspaugh and Washburn 2003).

In general, the stress hormones, cortisol and corticosterone, are involved in complex biochemical relationships between the individual's environment and body condition (Carlsson et al. 2016). Maternal status, sex, the presence of predators, or nutritional status could influence hormone levels to a greater extent than adjacency to the winter road. Also, the dose-response relationship between vehicle traffic and stress hormones expressed in fecal pellets may not capture the transient nature of disturbance experienced by caribou near the road (Özkan Gülzari et al. 2019).

We did not identify or empirically establish the specific causes of the change in behaviour by caribou near the winter road. The environment around the winter road includes numerous sources of disturbance, of which only coarse data were available. In particular, the presence of hunters was estimated using the no-hunting zones established and enforced by the GNWT. This is a very broad measure of the spatial occurrence of hunters that does not closely measure the level of hunter disturbance experienced by caribou. Reports of the presence of hunters from enforcement officers were not available at the time of analysis; future work may use those data to develop a more detailed understanding of the effects of hunting activity on caribou. An obvious disturbance source on the winter road is traffic. An inability to record the amount of vehicle traffic at the same time scale as the deposition of stress hormones in fecal pellets prevented a direct analysis of the effect of traffic.

Our field efforts along the winter road as well as in the helicopter were limited by weather and daylight, resulting in a maximum 6-hr observation period. There is the possibility of variation in behaviour relative to the 24-hr day. Similarly, when traffic was restricted by adverse weather conditions, observations were not possible, limiting the variation in traffic levels during data collection. Our coarse-scale modelling of vehicle activity suggested that traffic volumes were relatively consistent when the road was open (see Chapter 3). Nonetheless, the behavioural data suggested a response of caribou to the road infrastructure (Murphy and Curatolo 1987, Dyer et al. 2002), the associated traffic (Leblond et al. 2013), or the hunters present along the winter road (Plante et al. 2017) though we cannot discount the possibility of other ecological factors, such as forage that is of lower quality or availability, influencing the activity of caribou that used habitats adjacent to the winter road.

Management Implications

We demonstrated that monitoring of the behaviour and stress hormones of caribou is feasible in winter. There are, however, significant logistical challenges including short field days, the availability of helicopter transport, the inability to access field sites and to work productively during extreme weather, as well as the unpredictable and broad distribution of caribou. There are few caribou in the herds that range across the study area (Boulanger et al. 2019), with a corresponding low density of caribou near the winter road. With the possibility of a sparse distribution of caribou around the diamond mines and the difficulty working in winter, much time and effort are necessary to collect a large sample of behavioural observations or fecal pellets at regular intervals distant from disturbance sources. These methods may be applicable to community-led monitoring protocols. To obtain a sufficient sample for monitoring changes in caribou behaviour, however, will require a relatively large number of field days and considerable funding for that work.

Our results do not reveal the implications of changed behaviour for survival or reproduction of caribou, the two vital rates of most importance to population change. The behavioural data collected for this study can, however, help further parameterize the energy-protein model of White et al. (2014) that has been adapted and applied to the Bathurst population. That model could provide insights on the population-level implications of reduced foraging and increased walking, as measured in this project. Our data suggested that measurements of stress hormones sampled from caribou fecal pellets were too imprecise to assess the physiological stress response of caribou to relatively dispersed or low-magnitude disturbance features such as the Tibbitt to Contwoyto Winter Road. There is, however, the possibility that refinements in sampling protocol could improve the sensitivity or applicability of stress hormones as a measure of the response of caribou to human disturbance during winter. Improvements would include time-specific measurements of the intrinsic (e.g., body condition and maternal status) and extrinsic (e.g., human disturbance, hunting, predation) factors influencing stress levels.

Previous ZOI research has indicated that barren-ground caribou in the Northwest Territories have avoided diamond mines and their related infrastructure (Johnson et al. 2005, Boulanger et al. 2012). This interaction occurs predominantly during winter when caribou are resident on the tundra or moving toward the more northerly calving ground and summer range. Our research confirms the relationships implied by the ZOI between barren-ground caribou and industrial infrastructure and provides an avenue for future research and mitigation. Given the broad extent of the Tibbitt to Contwoyto Winter Road, the potential effect on caribou could be large, affecting other ecological processes, such as habitat use and nutritional intake, the energetics associated with movement, and the timing and implications of seasonal migration. All of those outcomes could 'scale-up' to ultimately affect vital rates and population trend (Johnson and St-Laurent 2011). Future research could refine our measurements of caribou response to industrial disturbance to further understand the effects of this relationship. Mitigation that aims to decrease the response of caribou to industrial disturbances are an obvious avenue for future management of industrial activity in the central Northwest Territories.

Chapter 3: Why Didn't the Caribou Cross the Road? The Barrier Effect of Traffic on an Industrial Winter Road

Abstract

Barren-ground caribou are in steep decline due to the combined effects of climate change, natural population fluctuations, and anthropogenic disturbance. For the Indigenous peoples that rely on caribou for subsistence and cultural continuity, this decline presents a grave threat to a way of life. Wildlife managers are concerned about the potential effects of winter roads on the use of space by caribou. Roads, especially those with high levels of traffic, act as barriers to movement by ungulates. In the central Northwest Territories, Canada, the Tibbitt to Contwoyto Winter Road services diamond mines located on the winter range of the Bluenose East, Bathurst, and Beverly/Ahiak barren-ground caribou herds. Impeded movement could restrict the distribution or influence the habitats used by caribou during winter. We investigated the influence of traffic volume and other disturbance and environmental variables on the road-crossing decisions of caribou. We used logistic regression to contrast observed and available crossing events by caribou that were recorded using high-precision geofence GPS collars during 2018–2020. Of those 62 collared caribou, only 33 crossed the winter road, for a total of 100 crossing events. We used vehicle dispatch records to estimate the location and volume of traffic along the road. Caribou rarely crossed the road with any level of traffic present. These results will help direct efforts to mitigate the impact of winter roads on the distribution and movements of barren-ground caribou.

Introduction

Animal movement occurs across a range of temporal and spatial scales, from foraging decisions to annual migration (Borger et al. 2011), and is a key ecological process that dictates the life-history requirements of mammals (Nathan et al. 2008). Movement choices are a fundamental building block of many ecological processes, including habitat selection, interspecific competition, and predator-prey interactions (Van Moorter et al. 2016). Thus, natural and unrestricted movement dynamics is a key process for maintaining fitness in many species.

Across many ecosystems, movement processes are limited or altered by rapid and wide-spread anthropogenic development, which has contributed to population declines and a breakdown in key ecological relationships (Bolger et al. 2008, Tucker et al. 2018). Central to these changes are barriers that prevent or limit movement choices by animals. Such impediments to the timing of movement or choice of a movement path can alter distribution and habitat use, expose individuals to higher degrees of risk from predators or people, and potentially change or eliminate life history strategies such as migration (Beyer et al. 2016). Mitigating the effects of movement barriers requires an understanding of the mechanisms by which those barriers alter movement.

Movement is central to the life history of barren-ground caribou, a subspecies of caribou (*Rangifer tarandus groenlandicus*) found across an area greater than 4,000,000 km^2 in northern North America (COSEWIC 2016). These caribou migrate many hundreds of kilometers from wintering grounds in or near the boreal forest to calving grounds near the Arctic Ocean (Gunn and Miller 1986). This migration evolved under various selective pressures (Dingle and Drake 2007) including seeking nutritional resources and avoiding predation (Fryxell and Sinclair 1988).

The annual and seasonal ranges of caribou vary with herd size (Klaczek et al. 2016), food availability (Rickbeil et al. 2018), landscape disturbance from fire (Barrier and Johnson 2012, Anderson and Johnson 2014, Rickbeil et al. 2017) and human activities (Johnson and Russell 2014). In particular, their winter ranges are relatively large and variable, as caribou seek access to adequate forage to maintain body condition through cold northern winters in a resource-poor habitat. Restrictions to available winter range or increased energetic costs to access winter range could reduce the fitness benefits of such a highly mobile life history.

Of the factors affecting range use of barren-ground caribou, human activities and disturbances are of great concern to management authorities (Government of the Northwest Territories 2019). Though present declines of barren-ground caribou are not directly attributable to human disturbance (Vors and Boyce 2009), the potential for disruption to their use of space is cause for concern. Caribou alter their distribution in response to human activities at both broad (Johnson and Russell 2014) and fine (Bradshaw et al. 1997, Seip et al. 2007, Lesmerises et al. 2018) spatiotemporal scales. In the Northwest Territories, research has demonstrated that caribou avoid diamond mines for up to 14 km (Boulanger et al. 2012). The area across which caribou change their use of space in relation to disturbances, known as a Zone of Influence (ZOI), is the result of many fine-scale interactions with disturbance (Johnson and St-Laurent 2011). Zones of Influence do not provide a mechanistic understanding of how the movement of caribou or other wildlife is influenced by human activities and infrastructure. Nonetheless, ZOIs are commonly used to assess and regulate industrial practices to reduce impacts to wildlife. That includes the management and mitigation of the effects of mining infrastructure relative to the movements and habitat used by caribou (Government of the Northwest Territories 2019).

Relative to other jurisdictions, many industrial developments in the Northwest Territories are remote and are often supported by seasonal winter roads. These “ice roads” are built in mid-winter, with short over-land portages linking the more easily cleared and maintained lake sections. Roads are an industrial feature with a relatively small spatial footprint, but considerable extent and much capacity to obstruct caribou movement. Resource roads are known to act as semi-permeable barriers to caribou movements, particularly when traffic intensity is high (Dyer et al. 2002, Leblond et al. 2013). Roads can delay caribou during migration, sometimes by weeks (Wilson et al. 2016), and have been shown to cause avoidance of portions of seasonal range in reindeer (*R. t. tarandus*) (Nellemann et al. 2001). Roads also facilitate hunting by both humans and other predators, increasing risk for caribou that are distributed nearby (Plante et al. 2017, Blagdon and Johnson 2021).

We investigated the crossing choices of barren-ground caribou for an industrial winter road in the Northwest Territories. We quantified where and when caribou crossed the Tibbitt to Contwoyto Winter Road and the ecological factors and type and intensity of human-caused disturbances that affected that choice. We predicted that the road would act as a semi-permeable barrier to movements of caribou, with crossing decisions negatively related to the level of traffic and hunting activity at crossing sites. Understanding how movement is affected by human disturbances is an important goal for managing and conserving highly mobile or migratory wildlife. Findings from this research can inform the placement of winter roads or the mitigation of the barrier effects of roads faced by caribou and reindeer that range across Arctic ecosystems.

Methods

We investigated the disturbance factors hypothesized to influence the selection of crossing events (including both the crossing location and time) by barren-ground caribou on an industrial winter road. For this analysis, we used logistic regression to contrast observed crossing events with a set of randomly identified available crossings events. We hypothesized that the road-crossing decisions of caribou would be influenced by human disturbance in the form of traffic and hunting pressure as well as factors known to influence caribou movement, such as weather, time of year, and previous movement by the individual animal.

Modelling Approach

We developed a set of a priori models that represented a combination of factors that we hypothesised to influence the road-crossing decisions of caribou. The modelling approach parallels methods used in resource selection analyses (Boyce et al. 2002), where observed events are contrasted against ecologically realistic opportunities (i.e. available movements or locations). These observed and available crossings of an industrial winter road were derived from GPS collar data for caribou in the Bathurst, Bluenose East and Beverly/Ahiak herds. Using these methods, we quantified relationships between the observed road crossings of caribou and a range of human and ecological disturbance factors.

Crossing Data

Caribou crossings were observed for the Tibbitt to Contwoyto Winter Road in the Northwest Territories, Canada. This is a seasonal ice road constructed annually to supply mines, primarily Diavik, Ekati, and Gahcho Kué, located on the tundra north of Great Slave Lake. The road is a joint venture between De Beers Group, Rio Tinto, and Arctic Canadian Diamond Company. Several camps support the construction and maintenance of the road, as well as the industrial traffic that uses the road. Road construction begins in mid-December for a late January or early February opening. The road is closed in late March or early April and melts off the landscape over the spring. The majority of industrial traffic is present during February and March during the official open period. The volume and timing of industrial traffic on the road can be inferred through vehicle dispatch records (Rudolph Swanepoel, Det'on Cho Logistics, personal communication). These are records kept by the company responsible for traffic management along the Tibbitt to Contwoyto Winter Road, and include the date, time, and locations of each vehicle's trip along the road, from start to end. Recreational use of the winter road is permitted, though given the remoteness and lack of support along the road this is primarily limited to self-sufficient hunters that drive along the road, camp, and hunt by snowmobile.

Crossing events of the Tibbitt to Contwoyto Winter Road by barren-ground caribou were observed from movement paths generated from GPS collar data (Telonics and Iridium; model TGW-4577-4s) provided by the Government of the Northwest Territories (GNWT). This ongoing program of caribou collaring started in 1995 (Gunn et al. 2013, Adamczewski and Boulanger 2016). The collars were programmed to gather locations 3 times per day, with some collars programmed to collect 24 locations per day when in proximity to the Tibbitt to Contwoyto Winter Road and the diamond mines in the area (so-called "geofence" collars). We used only the data from the geofence collars, resulting in a relatively high-precision estimate of the time and location of crossing events. Dispatch records for industrial traffic were only available for 2018–2020. Consequently, we limited the analyses to GPS collar data collected during that period.

We used the GPS collar data to measure the location and time of each road crossing event by collared caribou. For each observed crossing event, we generated 5 available locations and times where caribou could have crossed the road (Northrup et al. 2013), termed the available crossing events. This high level of available crossings allows a reasonable measure of the variability in associated predictors. Though this high level of available crossing events results in a disproportionate ratio of observed to available crossings, and can change the magnitude of modelled relationships, it does not change the shape and resulting inference (King and Zeng 2001). We used the available crossings to represent the range of ecologically realistic crossing opportunities for collared caribou during the study period. We generated the available crossings from GPS collar locations of caribou near the road during the study period.

To generate each of these available crossings, the geographic origin of an available crossing was selected randomly from an observed GPS-collar caribou location that was within 5.2 km of the road. That distance was defined by the 97.5th percentile of straight-line distances of caribou locations to the winter road which were recorded immediately before a road crossing. The location for each available crossing event was set as the point where a straight-line from the randomly selected location intersected the nearest segment of the winter road. The definition of resource availability can influence the strength of selection or avoidance of a resource (Johnson and Gillingham 2008). I chose an availability threshold (5.2 km) that was representative of the distribution of caribou that were adjacent to the road and represented plausible crossing locations for comparison with the observed crossing locations. The dates and times for the available crossing events were taken from the timestamp of the random locations used to generate them.

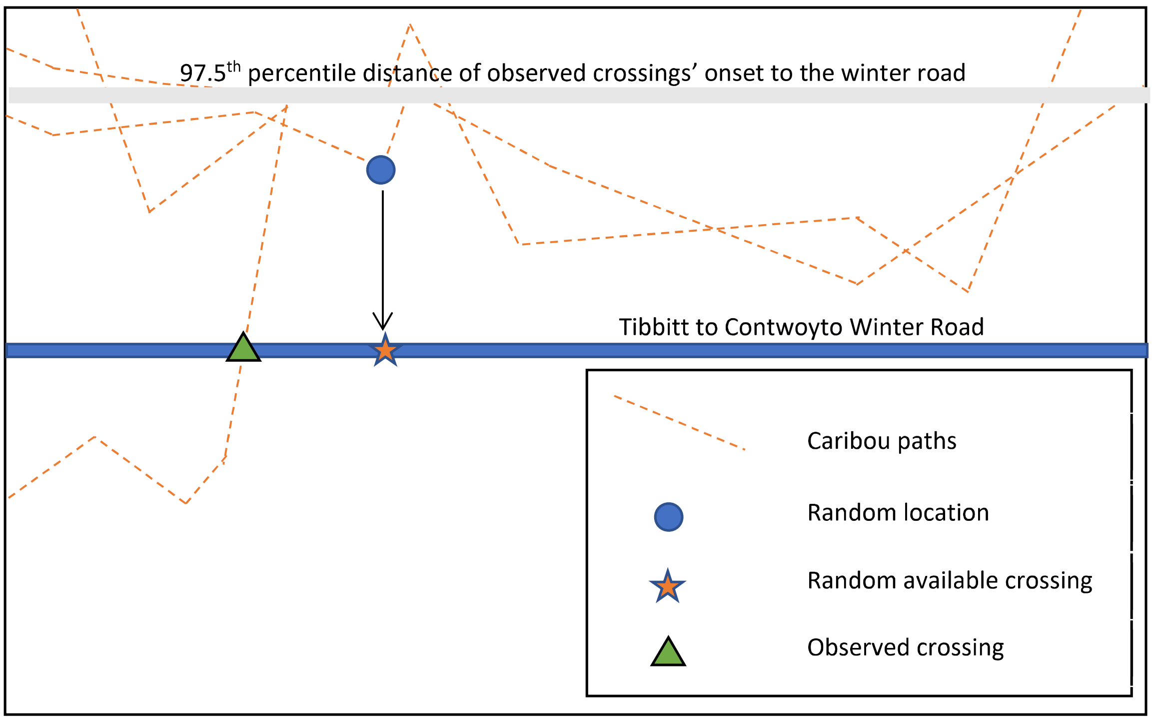

Figure 3.1 Schematic representation of the sampling design used to identify available crossing locations using data from GPS collared barren-ground caribou. Locations were selected randomly from known locations within the 97.5th percentile distance to the road at the onset of observed crossing trajectories. The available crossing locations were the nearest points along the Tibbitt to Contwoyto Winter Road to these random points.

We used dispatch records to estimate traffic volume as well as the persistence of the road during each study year. We limited crossing events, both observed and available, to only those that occurred in a $\pm$ 2-week time window of estimated traffic presence at a crossing location. A preliminary review of satellite imagery for a section along Contwoyto Lake did confirm the presence of the road beyond the $\pm$ 2-week time window. Thus, restricting the crossing analysis to only that period for which vehicle traffic occurred ($\pm$ 2-weeks) provided a conservative estimate of the effect of the road on caribou movements.

Ecological and Disturbance Covariates

We identified factors that were hypothesized to affect the crossing choices of caribou for the Tibbitt to Contwoyto Winter Road. These included environmental and disturbance variables that were previously reported to influence the distribution, movements, and behaviour of caribou (Table 3.1).

Table 3.1 Description, mechanism, and predicted effect (positive or negative) of covariates hypothesized to influence the crossing choice of barren-ground caribou on the Tibbitt to Contwoyto Winter Road in the central Northwest Territories, Canada.

Covariate	Type	Description
Open road	Binary	Open period of the winter road for that year, from official open/close dates.
Active road	Binary	Road was in use and caribou may encounter traffic when crossing the road. Represented by any traffic on the winter road at the crossings location for up to 3 days prior to the crossing event.
Traffic count	Continuous	Index of traffic activity during the crossing event. Represented by an estimated count of vehicles 8 hrs prior to and 2 hrs after the crossing event.
In no-hunting zone	Binary	Crossing occurred within the Bathurst mobile no-hunting zone.
Windchill	Continuous	Measure of thermal stress derived from temperature and wind speed.
Directionality coefficient	Continuous	Average persistence in directionality of caribou movements over the previous 7 movement steps.
Day of year	Continuous	Number of days since January 1st as an index of onset of migration.
Year	Categorical	Year of observation.
Individual id	Random	Random effect to control for multiple locations for individual caribou.

We used right-of-way data from the GNWT (J. Williams, Government of the Northwest Territories, personal communication), Mackenzie Valley Land and Water Board (Mackenzie Land and Water Board 2020), and De Beers Canada (Ryan Marshall, De Beers Canada, personal communication), along with a portion digitized from satellite imagery (NASA SENTINEL-2 dataset) to develop a shapefile denoting an estimated annual alignment of the Tibbitt to Contwoyto Winter Road. The placement of the road right-of-way is limited by permits issued by the Mackenzie Valley Land and Water Board, with the exception of some variation year-to-year in the road alignment to bypass ice ridges and overflow. Consequently, the alignment of the road is very similar year-to-year.

We used dispatch records of industrial traffic provided by the company managing traffic on the winter road to estimate traffic trips along the Tibbitt to Contwoyto Winter Road. The dispatch records provided the location and times of departure and arrival of each trip. These trips were predominantly by large trucks moving material to and from the mines. From these data, we estimated the passage of industrial vehicles along the road. The trips were assumed to take the shortest path and travel at a constant speed. Using these data, we estimated traffic presence at 2-km intervals every hour.

We used the boundaries of the Bathurst mobile no-hunting zone to estimate the presence or absence of hunting activity. The Bathurst mobile no-hunting zone was established by the GNWT and Indigenous governments as a joint management action in response to the decline of the Bathurst barren-ground caribou herd (Government of the Northwest Territories 2019). The boundaries of the mobile zones and the open and close dates were provided by the North Slave office of the Department of Environment and Natural Resources, GNWT.

We used NASA's Modern Era Retrospective Analysis for Research and Applications [MERRA-2] dataset to estimate wind speed and temperature (Gelaro et al. 2017). From these data, we modelled the windchill at the crossing site (eq. 3.1).

Equation 3.1: $T_{wc} = 13.12 + 0.6215T_a – 11.37v^{0.16} + 0.3965T_av^{0.16}$, where:

T_{wc}: wind chill index (kg*cal/m^2/h)

T_a: air temperature (°C)

v: wind speed (km/h)

The windchill equation (eq. 3.1) was developed for humans, not *Rangifer* (Osczevski and Bluestein 2005). Those values, however, do provide a measure of relative change in the combined thermal effect of air temperature and wind speed across the winter. We used the lowest calculated windchill over the 3 days prior to a crossing as an index of thermoregulatory stress experienced by caribou.

We summarized the directional persistence of individual caribou prior to the observed or available crossing event. Directionality was calculated as the relative mean resultant distance of previous steps. We calculated this metric by summing the vector distance of 7 steps prior to the crossing event, setting each step to a distance of one and dividing the resulting distance by the number of steps. For the step direction we used the relative turning angles (i.e., the angle between successive steps). This value indicates the degree of tortuosity of movement, from which the type of movement the animal was engaged in can be inferred (Benhamou 2004). Values close to one, generated from consecutive steps in the same direction, indicate directional persistence in travel and values close to zero, generated from high angle turns, indicate low directional persistence, possibly associated with foraging behaviour (Benhamou 2004).

Development and Assessment of Statistical Models

We used logistic regression to contrast observed and available crossings of the Tibbitt to Contwoyto Winter Road. We developed a set of a priori model hypotheses to test the factors that may influence the crossing choices of caribou adjacent to the winter road (Table 3.2). We used a random effect for each collared caribou to account for repeated crossings by individuals. We used the variance inflation factor (VIF) to test models for multicollinearity. No parameters had a VIF > 10, which is a common threshold to determine problematic multicollinearity (Vittinghoff et al. 2012). We used an information theoretic approach to identify the most parsimonious models of the set as ranked by the Akaike Information Criterion (Anderson et al. 2002, Burnham and Anderson 2002) corrected for small sample sizes (AIC_c; Hurvich and Tsai 1989). The top-ranked model has the greatest degree of fit to the data with the fewest parameters. We reported the ΔAIC_c, the difference between the AIC_c for each model and the smallest AIC_c from the top-ranked model. We considered all models with a ΔAIC_c of <2.0 as informative and we included them in the best set of models.

The AIC_c provides a relative measure of model fit, but not predictive accuracy. We used the area under the curve (AUC) of the receiver operating characteristic (ROC) curve to measure the predictive accuracy of each model (Boyce et al. 2002). We used a leave-one-out cross-validation (LOOCV) to generate independent predicted probabilities for each observed and available crossing event (Fielding and Bell 1997, Pearce and Ferrier 2000). Using that procedure, each predicted value was generated after sequentially withholding the respective crossing event from model estimation. Area under the curve values between 0.7 and 1 were considered to have good predictive ability, and models with an AUC of approximately 0.5 were assessed as having no predictive capacity (Fielding and Bell 1997, Boyce et al. 2002). We used 95% confidence intervals to assess the strength of model covariates. Confidence intervals that included a value of zero were assumed to have some combination of small effect size and low precision. All data generation and modelling were conducted using R (R Core Team 2021) and ArcGIS (ESRI 2020). Mapping was conducted using the QGIS software (QGIS Development Team 2022).

Table 3.2 Candidate logistic regression models designed to test a range of factors hypothesized to influence the crossing choice of barren-ground caribou on the Tibbitt to Contwoyto Winter Road in the central Northwest Territories, Canada. Each model group may contain several models.

Model group	Hypothesis	Model Structure
Traffic	Presence of the active winter road or the level of traffic on the winter road will reduce crossing events by caribou.	Open road + year Active road + year Traffic count + year
Hunting	Presence of hunters on the winter road will reduce crossing events of caribou.	In no-hunting zone + year
Movement	Crossing of the winter road is primarily driven by factors that influence movement rate. Such influences include seasonal needs, ambient weather, and previous movement by the individual animal.	Day of year + year Windchill + year Directionality coefficient (relative) + year Windchill + directionality coefficient (relative) + year
Global model	Additive effect of all model covariates is important.	Traffic count + day of year + directionality coefficient (relative) + in no-hunting zone + windchill + year
Null model	Model covariates are not important for explaining crossing decisions of caribou.	1

Note: Covariates are described in Table 1. Individual id of collared caribou was included as a random effect in all models.

Results

During the study period (2018–2020), a total of 62 barren-ground caribou equipped with geofence GPS collars were located within 5.2 km of the Tibbitt to Contwoyto Winter Road. Of those caribou, 33 engaged in a total of 100 crossings of the road. Crossing events were recorded during January–April of each year, with most crossings occurring towards the end of the winter road season (Figure 3.1). The distribution of caribou equipped with geofence GPS collars was not uniform along the length of the winter road throughout the study period, and crossings predominantly occurred on the main trunk road and the Tundra spur, which is located north of the main trunk west of the spur to Gahcho Kué (Figure 3.2).

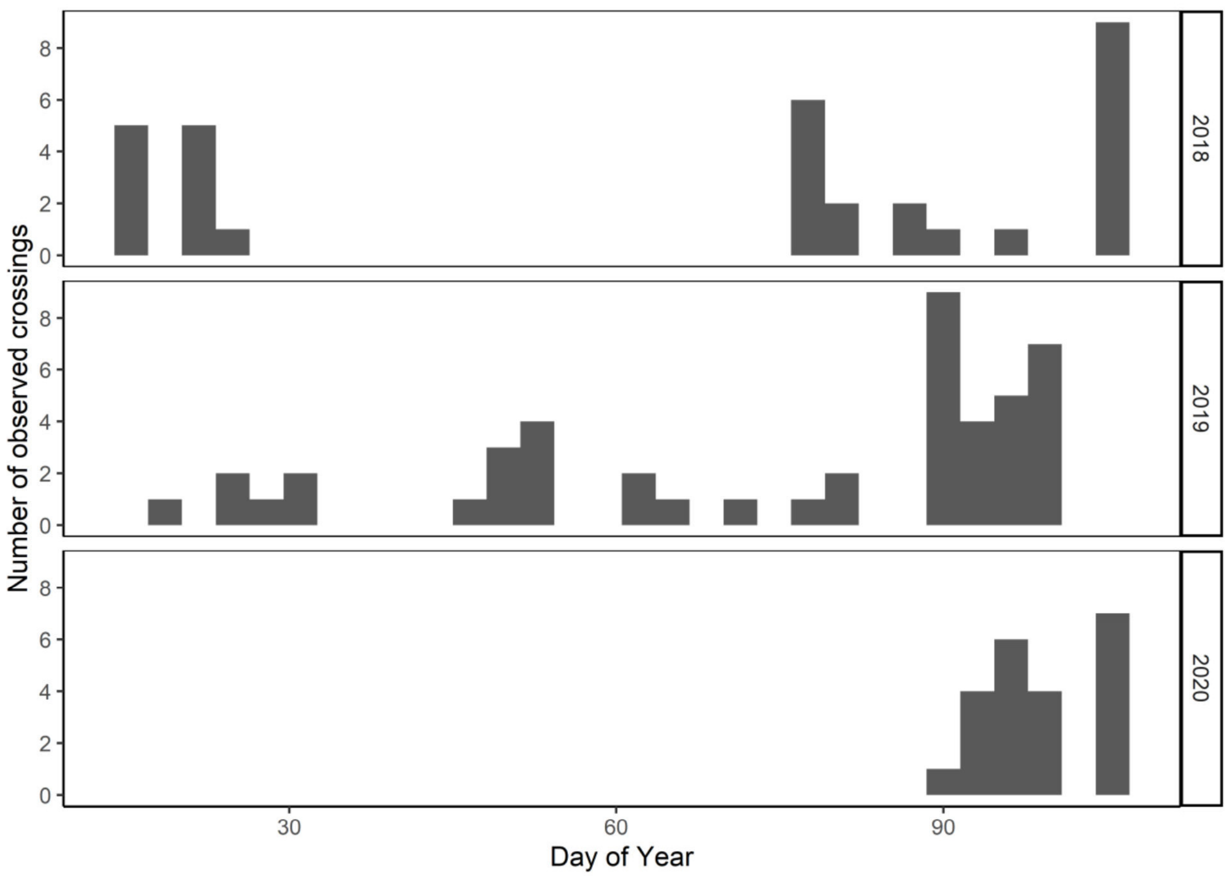

Figure 3.2 Histogram of crossing events (n = 100) by barren-ground caribou equipped with GPS collars for 2018–2020 on the Tibbitt to Contwoyto Winter Road, Northwest Territories, Canada, displayed by the day of year. January 1st is day 1, and the study period extended up to the beginning of April, approximately day of year 100.

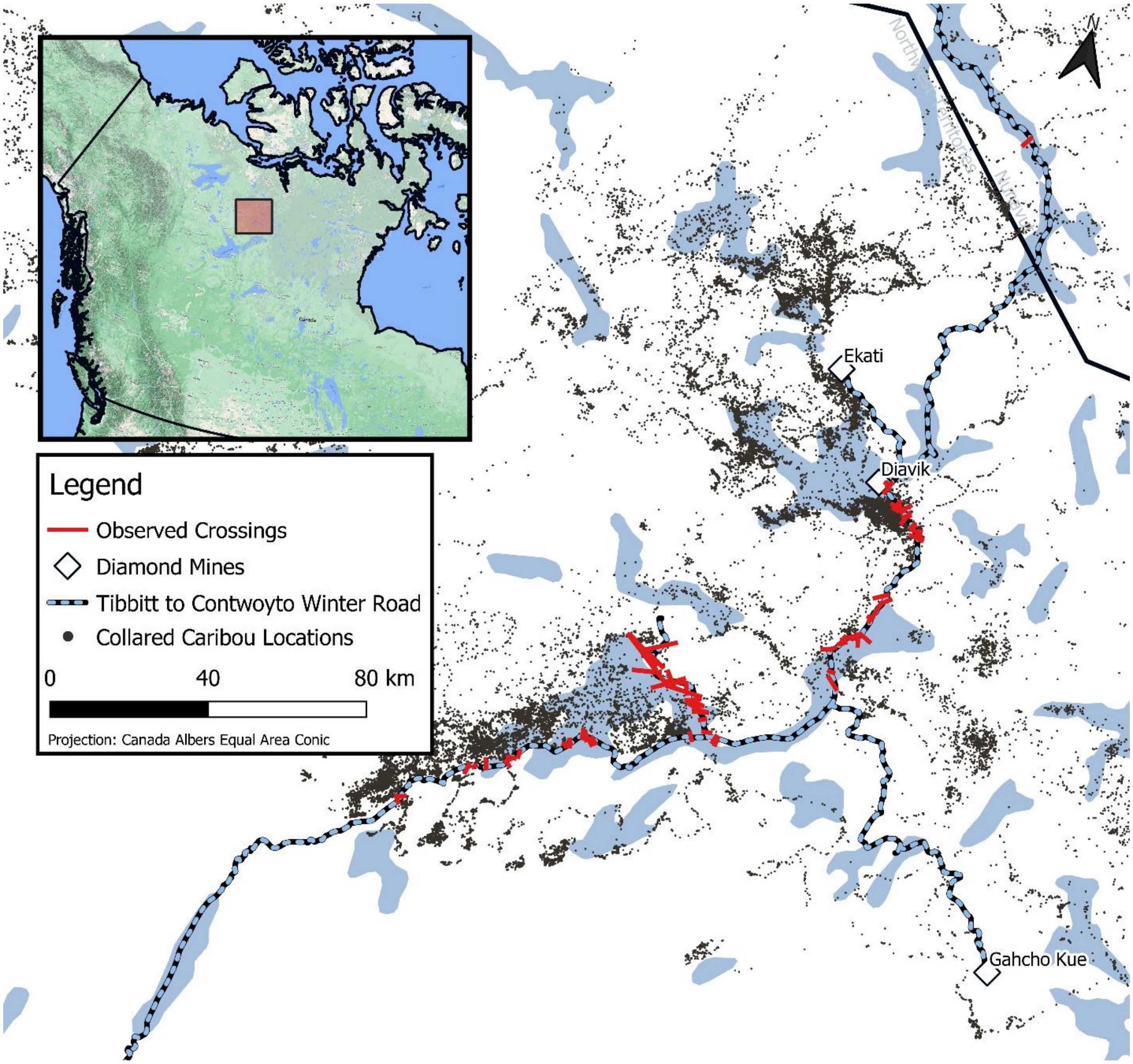

Figure 3.3 Distribution of GPS collared caribou and crossing trajectories across the Tibbitt to Contwoyto Winter Road, Northwest Territories, Canada, 2018–2020. Collar locations were restricted to the approximate period of active use of the winter road (February–March). The Tundra spur is located north of the main trunk west of the spur to Gahcho Kué.

Using the set of a priori models, we quantified the relationship between the observed road crossings of caribou and human disturbance and ecological covariates. Of that set, the traffic count ($\Delta AIC_c = 0$) and global models ($\Delta AIC_c = 1.67$) were the most parsimonious and top-ranked models (Table 3.3). For all models, traffic volume had a negative effect suggesting that there was reduced relative probability of a caribou crossing the road when traffic was present (Figure 3.3). All top-ranked models ($\Delta AIC_c < 2$) were very good predictors of the observed and available crossing events of monitored caribou (AUC > 0.8; Table 3.3.). The global model suggested that caribou were less likely to cross the road when within the no-hunting zone, though movement directionality and day of year were not significantly related to the road-crossing decisions of monitored caribou. The fact that the no-hunting zone model was not included in the top model set indicates that this variable was less important than traffic for caribou crossing decisions.

Predictions from the top-ranked model (traffic count, Table 3.3) revealed that the relative probability of crossing declined rapidly with the presence of traffic and was near 0 with moderate levels of traffic (Figure 3.4). This relationship held across the study years, even with a strong year effect for 2020, when crossings were less likely when compared to 2018 and 2019.

Table 3.3 Ranking of logistic regression models representing the selection of crossing events by barren-ground caribou near the Tibbitt to Contwoyto Winter Road, Northwest Territories, Canada. The standard errors (SE) of the AUC scores are presented in brackets.

Model	*K*	AIC$_c$	ΔAIC$_c$	AUC
Traffic count (traffic count + year)	5	356	0	0.892 (0.02)
Global model (Traffic count + day of year + directionality coefficient (relative) + in no-hunting zone + windchill + year)	9	357	1.67	0.897 (0.02)
Active road (active road + year)	5	380	23.9	0.871 (0.02)
Open road (open road + year)	5	422	66.7	0.844 (0.03)
Windchill (windchill + year)	5	455	99.6	0.812 (0.03)
Movement combined (windchill + directionality coefficient + year)	6	457	101	0.809 (0.03)
Day of year (day of year + year)	5	458	102	0.805 (0.03)
Hunting (in no-hunting zone + year)	5	458	103	0.804 (0.03)
Directional persistence (directionality coefficient + year)	5	460	105	0.800 (0.03)
Null	1	543	187	0.500 (0.00)

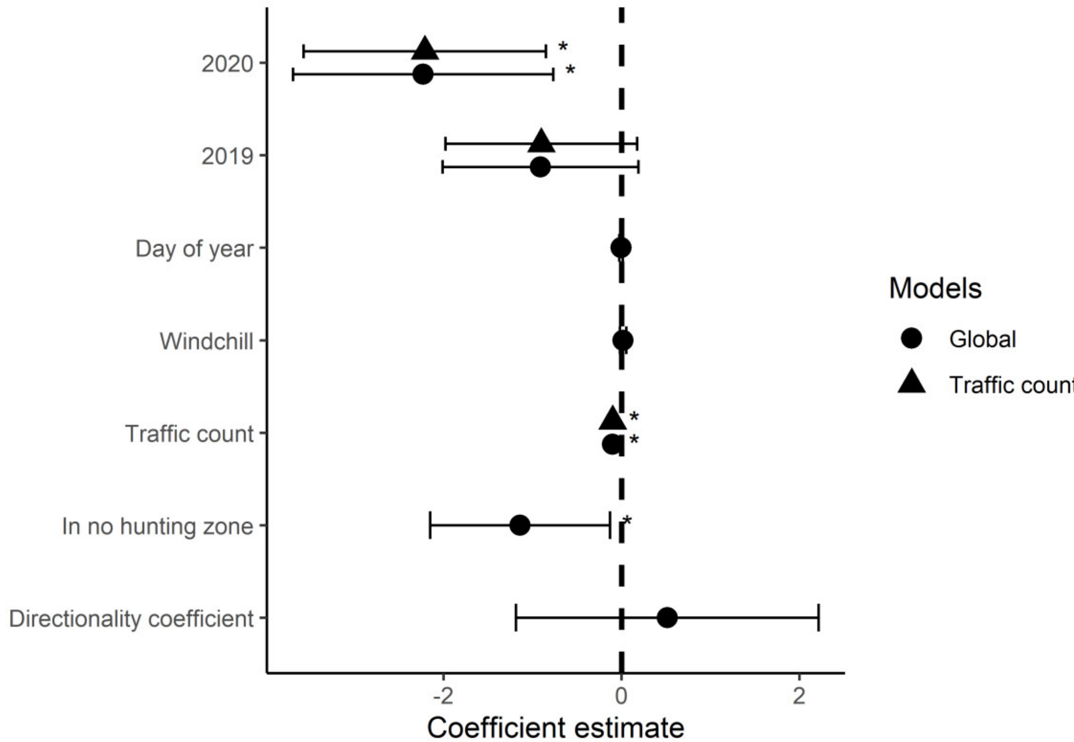

Figure 3.4 Coefficients of top-ranked models (ΔAICc < 2) for crossing of the Tibbitt to Contwoyto Winter Road, Northwest Territories, Canada. The asterisk indicates coefficients for which the 95% confidence intervals did not overlap 0.

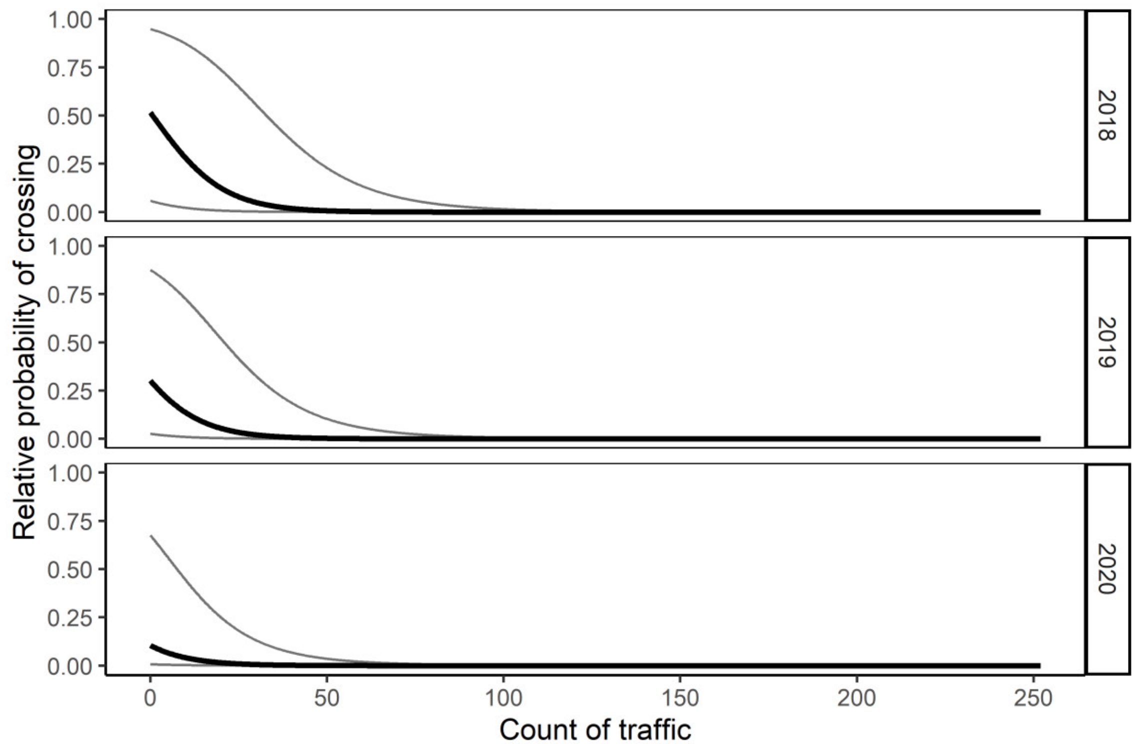

Figure 3.5 Predicted relative probability of crossing the Tibbitt to Contwoyto Winter Road by GPS-collared barren-ground caribou across the range of estimated traffic levels. Predictions were generated from coefficients in the top-ranked logistic regression model (traffic count). Light lines indicate 95% confidence intervals. Count of traffic is the number of vehicles passing the crossing location in the 8 hrs prior to the crossing event.

Discussion

Roads are known to have a wide range of effects on the ecology of caribou (Leblond et al. 2013, Johnson and Russell 2014, Plante et al. 2017, 2018). Although numerous studies have considered the barrier effects of roads, most of that work considered coarse-scale responses of individual animals that encountered roads (Beyer et al. 2016, Wilson et al. 2016). This is one of the first studies to quantify the effect of fine-scale changes in traffic on the crossing behaviour of caribou on a seasonal winter road.

We used a novel method and dispatch records to estimate the location of individual industrial vehicles and traffic volume on the Tibbitt to Contwoyto Winter Road. Those data in combination with GPS collar locations suggested that a key industrial winter road in the Northwest Territories was a semi-permeable barrier to movement by barren-ground caribou. Monitored caribou rarely crossed the winter road, despite many available crossing opportunities. Crossing occurred primarily outside the main operating season of the winter road. The few observed crossings during the operating period occurred when low levels of traffic were present, typically during weather-related road closures.

Results from our study are consistent with previous work that has considered the barrier and disturbance effects of roads for both migratory and woodland caribou. For example, a strong barrier effect of a mining road was reported for the movements of caribou of the Leaf River population of northern Quebec (Plante et al. 2018). For that same study, the adjacent George River population did not demonstrate avoidance of a different mining road, but caribou increased their movement rate when crossing the feature. The movement rates, and ultimately the duration of migration, of caribou of the Western Arctic and Teshekpuk populations were also shown to be influenced by an industrial road (Wilson et al. 2016). A large number of other studies conducted over the past two decades have reported a disturbance effect of a range of road types for caribou or reindeer, often attributing traffic volume as an explanatory factor (Dyer et al. 2002, Polfus et al. 2011, Beauchesne et al. 2013, Leblond et al. 2013, Panzacchi et al.

2013, Johnson and Russell 2014, Johnson et al. 2015). In many cases, however, traffic volume was not measured, but instead considered constant or associated with road type.

We demonstrated that the level of traffic and not just the right-of-way was a semi-permeable barrier to the movement of caribou. The dispatch data revealed that there were few times over the three analysis years when the road was closed or relatively few vehicles used the road during each of the approximately 8-week operating seasons (Figure 3.6). From this we can infer that the winter road is a barrier to caribou for much of the road's operation throughout February and March of each year. Highlighting this key finding is the Tundra spur: in contrast to the main trunk of the winter road, it had a consistent, but low level of traffic during 2018 and 2019, providing a natural experiment of caribou response to variable traffic. During that period there was a high level of crossing relative to the busy main trunk of the winter road.

The Tibbitt to Contwoyto Winter Road lies across much of the distribution of the Bluenose East, Bathurst, and Beverly/Ahiak barren-ground caribou herds. The footprint of the road is small compared to the size of these winter ranges, even when considering a liberal estimate for the ZOI. This area, in combination with the area disturbed by mines and other developments, is used to measure the risk to caribou populations and the level of management response required (Government of the Northwest Territories 2019). Given the barrier that the Tibbitt to Contwoyto Winter Road presents to caribou with normal levels of traffic, the risk to caribou could be greater than that anticipated from this area-based framework.

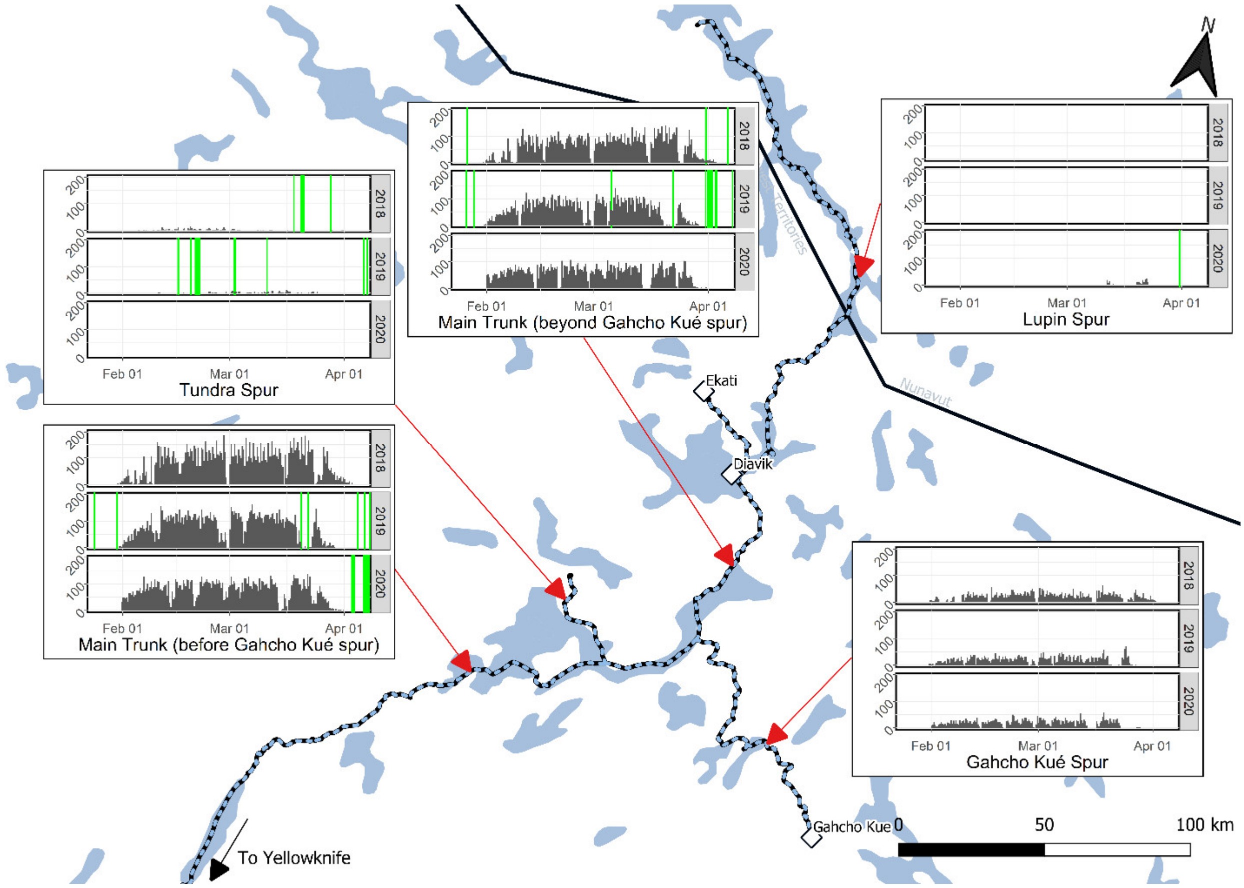

Figure 3.6 Estimated traffic levels on the Tibbitt to Contwoyto Winter Road, Northwest Territories, Canada. The histograms capture the level of traffic each 8 hrs, the same window used in modelling of traffic intensity. Vertical green lines indicate the time of crossings along the indicated section of road. Note: 2020 was a leap year, so 2018 and 2019 have “missing” data for February 29th; few collared caribou were near the Lupin or Gahcho Kué spurs during the active season of the winter road.

The barrier effect of the winter road could limit access to forage (Nellemann et al. 2001, Vistnes et al. 2004), and increase vulnerability to hunters (Plante et al. 2017). At the most extreme, the road could alter the location, timing, and success of migration to the more northern calving range (Veiberg et al. 2017). Calving is a critical time of the year, with high energetic demands to support lactation and the rearing of neonates. To support these activities caribou need to access high-quality forage, which requires matching the timing of calving to optimal plant phenology (Post and Forchhammer 2008). Consequently, the timing of migration is important (Gurarie et al. 2019). Barren-ground caribou are able to maintain sizeable populations due in large part to their long-distance migrations which provide access to this high-quality forage and a relatively predator-free environment (Fryxell and Sinclair 1988, Fryxell et al. 1988, Bergerud 1996, Klaczek et al. 2016). Any changes in successful use of the calving grounds could lead to population declines or at the least individual-level effects relative to nutrition, energy expenditure, and exposure to predation (Cameron et al. 2010).

The Tibbitt to Contwoyto Winter Road is likely a semi-permeable barrier to movement for caribou throughout the duration of its active season. The extent to which the barrier effect interacts with other disturbance factors is unclear. For instance, one of the top models indicated an effect of hunting activity on caribou crossing decisions – namely, being in the no hunting zone decreased crossings. This counter-intuitive finding could be the result of a strong spatial correlation between the level of traffic and hunting along the road, as the coarse-scale hunting zones coincide with the busiest portions of the road. Government staff monitor the winter road and record the presence of hunters. Those data were not available, but could be applied to future analyses focused on understanding the effects of hunting activity on caribou.

Only 62 individual collared caribou interacted with the road over three years of monitoring; thus, there were relatively few data to statistically represent the disturbance relationship. Nonetheless, I found a strong effect (Figure 3.5). As of 2021, there were an estimated 6240 caribou in the Bathurst population, whereas in the 1980s, when the winter road was first constructed, there were approximately 203,800 caribou (Boulanger et al. 2011). A greater sample of caribou near the road would likely result in a more precise relationship between vehicle traffic and crossing decisions. However, there may be an interaction between caribou density and disturbance response that is difficult to test given the historic lows for the three herds that interact with the winter road. That may include a relationship between individual movement choices and the size of the group the caribou is travelling with. Also, this analysis does not distinguish between types of road or industrial traffic, nor the effect of the ZOI around mines. Despite these limitations, the key findings remain clear.

Management Implications

With herds of barren-ground caribou at drastic lows, there is concern for the future of these populations. The Northwest Territories Species at Risk Committee and the national Committee on the Status of Endangered Wildlife in Canada (COSEWIC) have assessed these caribou as Threatened. Concerns for the future of caribou in northern Canada come with a strong mandate for responsible management of the species. Unfortunately, many of the factors influencing barren-ground caribou populations are largely beyond the control of northern authorities: climate change and cyclical population dynamics. Human disturbance is an issue affecting wildlife that can be dealt with using existing regulatory and legislative tools and is therefore an important consideration.

The findings of our research suggest that the Tibbitt to Contwoyto Winter Road is a strong barrier to movement by barren-ground caribou. Furthermore, that barrier effect is not a function of the road right-of-way, but instead the presence of industrial traffic. While the demographic and fitness consequences of the winter road are unclear, in the context of recent and dramatic declines of barren-ground caribou, this strong and broad-scale effect is concerning. Previous work has focused on barriers encountered during migration (e.g. Wilson et al. 2016), where the negative consequences can be dramatic (Bolger et al. 2008). The Tibbitt to Contwoyto Winter Road, however, is active only during approximately two months of the year, during a period in which caribou spend much of their time foraging and ruminating (Chapter 2) with few long-distance movements (Anderson and Johnson 2014).

We provided new insights on the fine-scale movements of caribou near the road including the associated barrier effect. Our research did not address potential changes in the broader scale ecology of caribou, such as deflection of movement paths (Wilson et al. 2016), changes in distribution (Fortin et al. 2013), or altered migration (Gurarie et al. 2017). Evidence of these effects could link changes in demography and fitness to the mine-road complex. Further exploration of how the changes in movement outlined in this paper affect broader scale distribution and population dynamics of caribou is crucial for responsible management.

Despite the uncertain implications of the barrier effect, it is clear that efforts for mitigation will need to be improved if unobstructed movement is a desired outcome of management. Our findings revealed that traffic was the disturbance causing the barrier effect – not simply the road's right-of-way. This presents several options for mitigation that could include less traffic, scheduled gaps, or a shorter hauling season. An adaptive management framework could be used to investigate the response of caribou to changes in traffic volume or activity.

Resource extraction is expected to continue or increase across the seasonal ranges of barren-ground caribou. Those activities will require more roads and greater vehicle traffic. Our results provide some insights on the negative effects of such traffic for the movement and distribution of caribou. Further research will be required to understand how the consequences of these developments affect caribou, and how they can be mitigated.

Chapter 4: Synthesis and Next Steps

Barren-ground caribou, a migratory population of caribou, are in decline across much of their distribution (Vors and Boyce 2009). In Canada, they were assessed as Threatened at both a federal and territorial level (COSEWIC 2016, Species at Risk Committee 2017). Widespread declines of caribou have been the result of multiple interacting factors (Vors and Boyce 2009, Johnson et al. 2015), including the effects of climate change (Post et al. 2009, Mallory and Boyce 2017), natural population fluctuations (Zalatan et al. 2006), and human disturbance (Wolfe et al. 2000, Johnson et al. 2005, Plante et al. 2018). Wildlife managers are particularly concerned about increases of industrial infrastructure and human activity, as these disturbances have been linked to the decline and extirpation of numerous caribou types across southern Canada (Vors et al. 2007, Johnson et al. 2015). There is less human disturbance across the Arctic (Government of the Northwest Territories 2019). Nonetheless, barren-ground caribou have been shown to avoid human disturbance at broad spatial and temporal scales (Boulanger et al. 2012, Johnson and Russell 2014), though much of how they relate to disturbance at a fine scale is still uncertain. Describing caribou's relationship to disturbance at multiple scales can help establish how the cumulative effect of development influences the distribution and abundance of Threatened populations of barren-ground caribou.

I investigated changes in behaviour, stress physiology, and movement of barren-ground caribou in winter near the Tibbitt to Contwoyto Winter Road located in the central Northwest Territories. Previous research has demonstrated that caribou avoided industrial disturbances near the road (Boulanger et al. 2012). Such disturbance-distribution responses were consistent with similar work on *Rangifer* more broadly (Nellemann et al. 2001, Johnson and Russell 2014, Plante et al. 2018). The broad-scale changes in the distribution of caribou caused by disturbance implies fine-scale changes in the ecology of caribou, including the phenomena that I studied (Johnson and St-Laurent 2011). I demonstrated that caribou in proximity to the winter road changed their behaviour and movement, though I did not detect a relationship between the disturbance environment of the road and changes in the stress physiology of caribou. Caribou spent less time foraging and more time walking when adjacent to the winter road, and rarely crossed the road during the operating season. I demonstrated that the level of traffic was responsible for that barrier effect, not simply the road's right-of-way.

My findings corroborate previous research that demonstrated that caribou avoided industrial sites in the central Northwest Territories (Johnson et al. 2005, Boulanger et al. 2012, Johnson and Russell 2014). Of my findings, the most concerning was the barrier caused by industrial traffic on the Tibbitt to Contwoyto Winter Road. That barrier and associated changes in the movement or distribution of caribou could limit access to forage during a nutritionally difficult time of year (Nellemann et al. 2001, Vistnes et al. 2004), increase vulnerability to predators and hunters (Plante et al. 2017), and potentially influence the location, timing, and success of migration to summer calving grounds (Veiberg et al. 2017). The changes in behaviour that I recorded, including less foraging and more walking by caribou adjacent to the road, provide some mechanistic understanding of these effects of the road. My research could be used to parameterise energetics models, such as those developed for the Porcupine population and later adapted to the Bathurst population (Gunn et al. 2011, White et al. 2014), that would allow one to explore the population-level effects of altered behaviour and distribution near the Tibbitt to Contwoyto Winter Road.

Despite these measured responses to the winter road, the spatial extent of industrial infrastructure in the central Northwest Territories, including the Tibbitt to Contwoyto Winter Road, is small relative to the annual and seasonal ranges of affected herds of barren-ground caribou. The range plan for the Bathurst caribou herd, the most at risk population in the study area, uses the cumulative area of disturbance from both the footprint of development as well as the surrounding zone of influence to assess the level of risk to caribou, and advises a proportionate management response (Government of the Northwest Territories 2019). The current level of development for the range assessment area that includes the majority of mining activity is assessed at a "moderate" level of disturbance, which includes suggestions for "enhanced traffic management". Despite this reference to the importance of managing traffic, the assessment of risk does not include a measure of the barrier effect from current or proposed roads.

The demographic and fitness consequences of the barrier described in this study are unclear. The road is active during a short period of the year, during which caribou engage in few long-distance movements, and hunting of caribou is restricted along much of its length. Also, there are few reported collisions between caribou and industrial traffic. Present management of traffic on the road includes a convoy policy and mandatory right-of-way for wildlife, which may reduce disturbance to caribou. Nevertheless, in the context of recent and dramatic declines of populations across the Northwest Territories, this strong and broad-scale effect is concerning.

Literature Cited

Adamczewski, J., and J. Boulanger. 2016. Technical Rationale to Increase the Number of Satellite Collars on the Bathurst Caribou Herd. Manuscript Report No. 254. Yellowknife, NT, Canada.

Adamczewski, J., J. Boulanger, B. Croft, D. Cluff, B. Elkin, J. Nishi, A. Kelly, A. D'Hont, and C. Nicolson. 2009. Decline in the Bathurst Caribou Herd 2006–2009: a Technical Evaluation of Field Data and Modelling. Technical Report, Government of the Northwest Territories, Yellowknife, NT.

Adamczewski, J., A. Gunn, K. G. Poole, A. Hall, J. Nishi, and J. Boulanger. 2015. What happened to the Beverly caribou herd after 1994? ARCTIC 68:407–421.

Altmann, J. 1974. Observational Study of Behavior: Sampling Methods. Behaviour 49:227–266.

Anderson, D. R., K. P. Burnham, and W. L. Thompson. 2002. Null hypothesis testing: problems, prevalence, and an alternative. Journal of Wildlife Management 64:912–923.

Anderson, T. A., and C. J. Johnson. 2014. Distribution of barren-ground caribou during winter in response to fire. Ecosphere 5:1–17.

Ashley, N. T., P. S. Barboza, B. J. Macbeth, D. M. Janz, M. R. L. Cattet, R. K. Booth, and S. K. Wasser. 2011. Glucocorticosteroid concentrations in feces and hair of captive caribou and reindeer following adrenocorticotropic hormone challenge. General and Comparative Endocrinology 172:382–391.

Barrier, T. A., and C. J. Johnson. 2012. The influence of fire history on selection of foraging sites by barren-ground caribou. Ecoscience 19:177–188.

Beauchesne, D., J. AG. Jaeger, and M.-H. St-Laurent. 2013. Disentangling woodland caribou movements in response to clearcuts and roads across temporal scales. PLoS ONE 8:1–11.

Benhamou, S. 2004. How to reliably estimate the tortuosity of an animal's path: straightness, sinuosity, or fractal dimension? Journal of Theoretical Biology 229:209–220.

Bergerud, A. T. 1996. Evolving perspectives on caribou population dynamics, have we got it right yet? Rangifer 16:95–115.

Bernes, C., K. A. Bråthen, B. C. Forbes, J. D. Speed, and J. Moen. 2015. What are the impacts of reindeer/caribou (*Rangifer tarandus L.*) on arctic and alpine vegetation? A systematic review. Environmental Evidence 4:1–26.

Beyer, H. L., E. Gurarie, L. Börger, M. Panzacchi, M. Basille, I. Herfindal, B. Van Moorter, S. R. Lele, and J. Matthiopoulos. 2016. 'You shall not pass!': quantifying barrier permeability and proximity avoidance by animals. J. Fryxell, editor. Journal of Animal Ecology 85:43–53.

Blagdon, D., and C. J. Johnson. 2021. Short term, but high risk of predation for endangered mountain caribou during seasonal migration. Biodiversity and Conservation 30:719–739.

Bolger, D. T., W. D. Newmark, T. A. Morrison, and D. F. Doak. 2008. The need for integrative approaches to understand and conserve migratory ungulates. Ecology Letters 11:63–77.

Borger, L., J. Matthiopoulos, R. M. Holdo, J. M. Morales, I. Couzin, and D. E. McCauley. 2011. Migration quantified: constructing models and linking them with data. Pages 111–128 *in*

E. J. Milner-Gulland, J. M. Fryxell, and A. R. E. Sinclair, editors. Animal migration: a synthesis. Oxford University Press, Oxford, UK.

Boulanger, J., J. Adamczewski, J. Nishi, D. Cluff, J. Williams, H. Sayine-Crawford, and L. M. LeClerc. 2019. Estimates of breeding females & adult herd size and analyses of demographics for the Bluenose-east herd of barren-ground caribou: 2018 calving ground photographic survey. Government of the Northwest Territories Manuscript Report, Government of the Northwest Territories, Yellowknife, NT.

Boulanger, J., B. Croft, J. Adamczewski, D. Cluff, M. Campbell, D. Lee, and N. Larter. 2017. An estimate of breeding females and analyses of demographics for the Bathurst herd of barren-ground caribou: 2015 calving ground photographic survey. Government of the Northwest Territories Manuscript Reports, Government of the Northwest Territories, Yellowknife, NT.

Boulanger, J., A. Gunn, J. Adamczewski, and B. Croft. 2011. A data-driven demographic model to explore the decline of the Bathurst caribou herd. The Journal of Wildlife Management 75:883–896.

Boulanger, J., K. G. Poole, A. Gunn, J. Adamczewski, and J. Wierzchowski. 2021. Estimation of trends in zone of influence of mine sites on barren-ground caribou populations in the Northwest Territories, Canada, using new methods. Wildlife Biology 2021:1–16.

Boulanger, J., K. G. Poole, A. Gunn, and J. Wierzchowski. 2012. Estimating the zone of influence of industrial developments on wildlife: a migratory caribou *Rangifer tarandus groenlandicus* and diamond mine case study. Wildlife Biology 18:164–179.

Bourgeon, L., A. Burke, and T. Higham. 2017. Earliest Human Presence in North America Dated to the Last Glacial Maximum: New Radiocarbon Dates from Bluefish Caves, Canada. PLOS ONE 12:1–15.

Boyce, M. S., P. R. Vernier, S. E. Nielsen, and F. K. A. Schmiegelow. 2002. Evaluating resource selection functions. Ecological Modelling 157:281–300.

Bradshaw, C. J. A., S. Boutin, and D. M. Hebert. 1997. Effects of Petroleum Exploration on Woodland Caribou in Northeastern Alberta. The Journal of Wildlife Management 61:1127–1133.

Brook, B., N. Sodhi, and C. Bradshaw. 2008. Synergies among extinction drivers under global change. Trends in Ecology & Evolution 23:453–460.

Burnham, K. P., and D. R. Anderson. 2002. Model selection and multimodel inference: a practical information-theoretic approach. 2nd edition. Springer-Verlag, New York, USA.

Burnham, K. P., and D. R. Anderson. 2004. Multimodel Inference: Understanding AIC and BIC in Model Selection. Sociological Methods & Research 33:261–304.

Cameron, R. D., W. T. Smith, R. G. White, and B. Griffith. 2010. Central Arctic Caribou and Petroleum Development: Distributional, Nutritional, and Reproductive Implications. ARCTIC 58:1–9.

Carlsson, A. M., G. Mastromonaco, E. Vandervalk, and S. Kutz. 2016. Parasites, stress and reindeer: infection with abomasal nematodes is not associated with elevated glucocorticoid levels in hair or faeces. Conservation Physiology 1–15.

Charbonnel, N., Y. Chaval, K. Berthier, J. Deter, S. Morand, R. Palme, and J.-F. Cosson. 2007. Stress and demographic decline: a potential effect mediated by impairment of reproduction and immune function in cyclic vole populations. Physiological and Biochemical Zoology 81:63–73.

Chen, W., S. Leblanc, H. P. White, C. Prevost, B. Milakovic, C. Rock, G. Sharam, H. O'Keefe, L. Corey, B. Croft, A. Gunn, S. Wielen, A. Football, B. Tracz, J. Pellissey, and J. Boulanger. 2017. Does dust from arctic mines affect caribou forage? Journal of Environmental Protection 8:258–276.

Chubbs, T. E., L. B. Keith, S. P. Mahoney, and M. J. McGrath. 1993. Responses of woodland caribou (*Rangifer tarandus caribou*) to clear-cutting in east-central Newfoundland. Canadian Journal of Zoology 71:487–493.

Colman, J. E., C. Pedersen, D. O. Hjermann, O. Holand, S. R. Moe, and E. Reimers. 2001. Twenty-four-hour feeding and lying patterns of wild reindeer *Rangifer tarandus tarandus* in summer. Canadian Journal of Zoology 79:2168–2175.

Colman, J. E., C. Pedersen, D. O. Hjermann, O. Holand, S. R. Moe, and E. Reimers. 2003. Do wild reindeer exhibit grazing compensation during insect harassment? The Journal of Wildlife Management 67:11–19.

COSEWIC. 2016. COSEWIC assessment and status report on the caribou, *Rangifer tarandus*, barren-ground population, in Canada. Committee on the Status of Endangered Wildlife in Canada, Ottawa, ON.

Dingle, H., and V. A. Drake. 2007. What is migration? BioScience 57:113–121.

Dussault, C., V. Pinard, J.-P. Ouellet, R. Courtois, and D. Fortin. 2012. Avoidance of roads and selection for recent cutovers by threatened caribou: fitness-rewarding or maladaptive behaviour? Proceedings of the Royal Society B: Biological Sciences 279:4481–4488.

Dyer, S. J., J. P. O'Neill, S. M. Wasel, and S. Boutin. 2002. Quantifying barrier effects of roads and seismic lines on movements of female woodland caribou in northeastern Alberta. Canadian Journal of Zoology 80:839–845.

Ecosystem Classification Group. 2008. Ecological Regions of the Northwest Territories - Taiga Shield. Government of the Northwest Territories, Yellowknife, NT.

Ecosystem Classification Group. 2009. Ecological Regions of the Northwest Territories - Taiga Plains. Government of the Northwest Territories, Yellowknife, NT.

Ecosystem Classification Group. 2012. Ecological Regions of the Northwest Territories - Southern Arctic. Government of the Northwest Territories, Yellowknife, NT.

Environment Canada. 2011. Scientific assessment to inform the identification of critical habitat for woodland caribou (*Rangifer tarandus caribou*), boreal population, in Canada: 2011 update. Environment Canada, Ottawa, ON.

ESRI. 2020. ArcGIS Desktop: Release 10. Environmental Systems Research Institute, Redlands, CA.

Ewacha, M. V. A., J. D. Roth, W. G. Anderson, D. C. Brannen, and D. L. J. Dupont. 2017. Disturbance and chronic levels of cortisol in boreal woodland caribou: Stress in Boreal Woodland Caribou. The Journal of Wildlife Management 81:1266–1275.

Fancy, S. G., and R. G. White. 1985. Energy expenditures by caribou while cratering in snow. The Journal of Wildlife Management 49:987–993.

Festa-Bianchet, M., J. C. Ray, S. Boutin, S. D. Côté, and A. Gunn. 2011. Conservation of caribou (*Rangifer tarandus*) in Canada: an uncertain future. Canadian Journal of Zoology 89:419–434.

Ficetola, G. F., and M. Denoël. 2009. Ecological thresholds: an assessment of methods to identify abrupt changes in species–habitat relationships. Ecography 32:1075–1084.

Fielding, A. H., and J. F. Bell. 1997. A review of methods for the assessment of prediction errors in conservation presence/absence models. Environmental Conservation 24:38–49.

Fisher, J. T., L. D. Roy, and M. Hiltz. 2009. Barren-ground caribou management in the Northwest Territories: an independent peer review. Alberta Research Council Sustainable Ecosystems Unit Ecological Conservation Management Program, Vegreville, AB.

Fortin, D., P.-L. Buono, A. Fortin, N. Courbin, C. Tye Gingras, P. R. Moorcroft, R. Courtois, and C. Dussault. 2013. Movement Responses of Caribou to Human-Induced Habitat Edges Lead to Their Aggregation near Anthropogenic Features. The American Naturalist 181:827–836.

Freeman, N. 2008. Motorized backcountry recreation and stress response in mountain caribou (*Rangifer tarandus caribou*). MSc. Thesis, The University of British Columbia, Vancouver, BC.

Fryxell, J. M., J. Greever, and A. R. E. Sinclair. 1988. Why are migratory ungulates so abundant? The American Naturalist 131:781–798.

Fryxell, J. M., and A. R. E. Sinclair. 1988. Causes and consequence of migration by large herbivores. Trends in Ecology & Evolution 3:237–241.

Gelaro, R., W. Mccarty, M. J. Su, R. Todling, A. Molod, L. Takacs, C. A. Randles, A. Darmenov, M. G. Bosilovich, R. Reichle, K. Wargan, L. Coy, R. Cullather, C. Draper, S. Akella, V. Buchard, A. Conaty, A. M. D. Silva, W. Gu, G.-K. Kim, R. Koster, R. Lucchesi, D. Merkova, J. E. Nielsen, G. Partyka, S. Pawson, W. Putman, M. Rienecker, S. D. Schubert, M. Sienkiewicz, and B.

Zhao. 2017. The modern-era retrospective analysis for research and applications, version 2 (MERRA-2). Journal of Climate 30:5419–5454.

Gillies, C. S., M. Hebblewhite, S. E. Nielsen, M. A. Krawchuk, C. L. Aldridge, J. L. Frair, D. J. Saher, C. E. Stevens, and C. L. Jerde. 2006. Application of random effects to the study of resource selection by animals: Random effects in resource selection. Journal of Animal Ecology 75:887–898.

Gillingham, M. P., K. L. Parker, and T. A. Hanley. 1997. Forage intake by black-tailed deer in a natural environment: bout dynamics. Canadian Journal of Zoology 75:1118–1128.

Gordon, B. C. 2005. 8000 years of caribou and human seasonal migration in the canadian barrenlands. Rangifer 25:155–162.

Government of the Northwest Territories. 2019. Bathurst caribou range plan. Government of the Northwest Territories, Yellowknife, NT.

Gunn, A., A. D'Hont, J. Williams, and J. Boulanger. 2013. Satellite collaring in the Bathurst herd of barren-ground caribou 1996–2005. Manuscript Report, Government of the Northwest Territories, Yellowknife, NT.

Gunn, A., C. J. Johnson, J. Nishi, C. J. Daniel, D. E. Russell, M. Carlson, and J. Adamczewski. 2011. Understanding the cumulative effects of human activities on barren-ground caribou. Pages 113–132 *in* P. R. Krausman and L. K. Harris, editors. Cumulative Effects in Wildlife Management. CRC Press, Boca Raton, FL.

Gunn, A., and F. L. Miller. 1986. Traditional behaviour and fidelity to caribou calving grounds by barren-ground caribou. Rangifer Special Issue No. 1:151–158.

Gurarie, E., F. Cagnacci, W. Peters, C. H. Fleming, J. M. Calabrese, T. Mueller, and W. F. Fagan. 2017. A framework for modelling range shifts and migrations: asking when, whither, whether and will it return. Journal of Animal Ecology 86:943–959.

Gurarie, E., M. Hebblewhite, K. Joly, A. P. Kelly, J. Adamczewski, S. C. Davidson, T. Davison, A. Gunn, M. J. Suitor, W. F. Fagan, and N. Boelman. 2019. Tactical departures and strategic arrivals: Divergent effects of climate and weather on caribou spring migrations. Ecosphere 10:1–32.

Hagemoen, R. I. M., and E. Reimers. 2002. Reindeer summer activity pattern in relation to weather and insect harassment. Journal of Animal Ecology 71:883–892.

Harriman, J. A. E., and B. F. Noble. 2008. Characterizing project and strategic approaches to region cumulative effects assessment in Canada. Journal of Environmental Assessment Policy and Management 10:25–50.

Hinkes, M. T., G. H. Collins, L. J. Van Daele, S. D. Kovach, A. R. Aderman, J. D. Woolington, and R. J. Seavoy. 2005. Influence of population growth on caribou herd identity, calving ground fidelity, and behaviour. Journal of Wildlife Management 69:1147–1162.

Hurvich, C. M., and C.-L. Tsai. 1989. Regression and time series model selection in small samples. Biometrika 76:297–307.

Johnson, C. A., G. D. Sutherland, E. Neave, M. Leblond, P. Kirby, C. Superbie, and P. D. McLoughlin. 2020. Science to inform policy: Linking population dynamics to habitat for a threatened species in Canada. K. Suryawanshi, editor. Journal of Applied Ecology 57:1314–1327.

Johnson, C. J., M. S. Boyce, R. J. Gau, A. Gunn, and R. Mulders. 2005. Cumulative effects of human developments on Arctic wildlife. Wildlife Monographs 160:1–36.

Johnson, C. J., L. P. W. Ehlers, and D. R. Seip. 2015. Witnessing extinction – Cumulative impacts across landscapes and the future loss of an evolutionarily significant unit of woodland caribou in Canada. Biological Conservation 186:176–186.

Johnson, C. J., and M. P. Gillingham. 2008. Sensitivity of species-distribution models to error, bias, and model design: An application to resource selection functions for woodland caribou. Ecological Modelling 213:143–155.

Johnson, C. J., and D. E. Russell. 2014. Long-term distribution responses of a migratory caribou herd to human disturbance. Biological Conservation 177:52–63.

Johnson, C. J., and M.-H. St-Laurent. 2011. Chapter 3. Unifying Framework for Understanding Impacts of Human Developments on Wildlife. Pages 27–54 *in* D. E. Naugle, editor. Energy Development and Wildlife Conservation in Western North America. Island Press, Washington, DC.

Joly, K., S. K. Wasser, and R. Booth. 2015. Non-invasive assessment of the interrelationships of diet, pregnancy rate, group composition, and physiological and nutritional stress of barren-ground caribou in late winter. PLOS ONE 10:e0127586.

King, G., and L. Zeng. 2001. Logistic Regression in Rare Events Data. Political Analysis 9:137–163.

Klaczek, M. R., C. J. Johnson, and H. D. Cluff. 2016. Wolf-caribou dynamics within the central Canadian Arctic. The Journal of Wildlife Management 80:837–849.

Kuhnlein, H. V., and O. Receveur. 1996. Dietary change and traditional food systems of Indigenous peoples. Annual Review of Nutrition 16:417–442.

Leblond, M., C. Dussault, and J.-P. Ouellet. 2013. Avoidance of roads by large herbivores and its relation to disturbance intensity. Journal of Zoology 289:32–40.

Leblond, M., C. Dussault, and M.-H. St-Laurent. 2014. Development and validation of an expert-based habitat suitability model to support boreal caribou conservation. Biological Conservation 177:100–108.

Legat, A., G. Chocolate, B. Gon, S. A. Zoe, and M. Chocolate. 2001. Caribou migration and the state of their habitat. West Kitikmeot Slave Study Society, Yellowknife, NT.

Lesmerises, F., F. Déry, C. J. Johnson, and M.-H. St-Laurent. 2018. Spatiotemporal response of mountain caribou to the intensity of backcountry skiing. Biological Conservation 217:149–156.

Lesmerises, F., C. J. Johnson, and M.-H. St-Laurent. 2016. Refuge or predation risk? Alternate ways to perceive hiker disturbance based on maternal state of female caribou. Ecology and Evolution 7:845–854.

Mackenzie Land and Water Board. 2020. Public Registry. Public Registry. <https://mvlwb.com/>. Accessed 4 Aug 2020.

Mallory, C. D., and M. S. Boyce. 2017. Observed and predicted effects of climate change on Arctic caribou and reindeer. Environmental Reviews 26:13–25.

McNamara, J. A., J. A. Schaefer, G. Bastille-Rousseau, and S. P. Mahoney. 2022. Landscape features and caribou harvesting during three decades in Newfoundland. Écoscience 29:39–53.

Messier, F., J. Huot, D. Le Hénaff, and S. Luttich. 1988. Demography of the George River caribou herd: Evidence of population regulation by forage exploitation and range expansion. Arctic 41:279–287.

Millspaugh, J. J., and B. E. Washburn. 2003. Within-sample variation of fecal glucocorticoid measurements. General and Comparative Endocrinology 132:21–26.

Morschel, F. M., and D. R. Klein. 1997. Effects of weather and parasitic insects on behavior and group dynamics of caribou of the Delta Herd, Alaska. Canadian Journal of Zoology 75:1659–1670.

Murphy, S. M., and J. A. Curatolo. 1987. Activity budgets and movement rates of caribou encountering pipelines, roads, and traffic in northern Alaska. Canadian Journal of Zoology 65:2483–2490.

Musiani, M., J. A. Leonard, H. D. Cluff, C. C. Gates, S. Mariani, P. C. Paquet, C. Vilà, and R. K. Wayne. 2007. Differentiation of tundra/taiga and boreal coniferous forest wolves: genetics, coat colour and association with migratory caribou. Molecular Ecology 16:4149–4170.

Nathan, R., W. M. Getz, E. Revilla, M. Holyoak, R. Kadmon, D. Saltz, and P. E. Smouse. 2008. A movement ecology paradigm for unifying organismal movement research. Proceedings of the National Academy of Sciences of the United States of America 105:19052–19059.

Nellemann, C., I. Vistnes, P. Jordhøy, and O. Strand. 2001. Winter distribution of wild reindeer in relation to power lines, roads and resorts. Biological Conservation 101:351–360.

Nishi, J., B. Croft, J. Boulanger, J. Adamczewski, and A. Kelly. 2014. An estimate of breeding females in the Bathurst herd of barren-ground caribou, June 2009. Government of the Northwest Territories File Reports, Government of the Northwest Territories, Yellowknife, NT.

Northrup, J. M., M. B. Hooten, C. R. Anderson, and G. Wittemyer. 2013. Practical guidance on characterizing availability in resource selection functions under a use–availability design. Ecology 94:1456–1463.

van Oort, B. E. H., N. J. C. Tyler, M. P. Gerkema, L. Folkow, A. S. Blix, and K.-A. Stokkan. 2005. Circadian organization in reindeer. Nature 438:1095–1096.

Osczevski, R., and M. Bluestein. 2005. The new wind chill equivalent temperature chart. Bulletin of the American Meteorological Society 86:1453–1458.

Özkan Gülzari, Ş., G. H. M. Jørgensen, S. M. Eilertsen, I. Hansen, S. B. Hagen, I. Fløystad, and R. Palme. 2019. Measuring faecal glucocorticoid metabolites to assess adrenocortical activity in reindeer. Animals 9:987–1000.

Panzacchi, M., B. Van Moorter, P. Jordhøy, and O. Strand. 2013. Learning from the past to predict the future: using archaeological findings and GPS data to quantify reindeer sensitivity to anthropogenic disturbance in Norway. Landscape Ecology 28:847–859.

Paton, D. G., S. Ciuti, M. Quinn, and M. S. Boyce. 2017. Hunting exacerbates the response to human disturbance in large herbivores while migrating through a road network. Ecosphere 8. <https://onlinelibrary.wiley.com/doi/10.1002/ecs2.1841>. Accessed 2 Feb 2022.

Pearce, J., and S. Ferrier. 2000. Evaluating the predictive performance of habitat models developed using logistic regression. Ecological Modelling 133:225–245.

Pimm, S. L., C. N. Jenkins, R. Abell, T. M. Brooks, J. L. Gittleman, L. N. Joppa, P. H. Raven, C. M. Roberts, and J. O. Sexton. 2014. The biodiversity of species and their rates of extinction, distribution, and protection. Science 344:987–999.

Plante, S., C. Dussault, and S. D. Côté. 2017. Landscape attributes explain migratory caribou vulnerability to sport hunting. The Journal of Wildlife Management 81:238–247.

Plante, S., C. Dussault, J. H. Richard, and S. D. Côté. 2018. Human disturbance effects and cumulative habitat loss in endangered migratory caribou. Biological Conservation 224:129–143.

Polfus, J. L., M. Hebblewhite, and K. Heinemeyer. 2011. Identifying indirect habitat loss and avoidance of human infrastructure by northern mountain woodland caribou. Biological Conservation 144:2637–2646.

Post, E., and M. C. Forchhammer. 2008. Climate change reduces reproductive success of an Arctic herbivore through trophic mismatch. Philosophical Transactions of the Royal Society B: Biological Sciences 363:2367–2373.

Post, E., M. C. Forchhammer, M. S. Bret-Harte, T. V. Callaghan, T. R. Christensen, B. Elberling, A. D. Fox, O. Gilg, D. S. Hik, T. T. Hoye, R. A. Ims, E. Jeppesen, D. R. Klein, J. Madsen, A. D. McGuire, S. Rysgaard, D. E. Schindler, I. Stirling, M. P. Tamstorf, N. J. C. Tyler, R. van der Wal, J. Welker, P. A. Wookey, N. M. Schmidt, and P. Aastrup. 2009. Ecological dynamics across the arctic associated with recent climate change. Science 325:1355–1358.

QGIS Development Team. 2022. QGIS Geographic Information System. QGIS Association. <https://www.qgis.org/>.

R Core Team. 2021. R: A language and environment for statistical computing 4.1.0. R, R Foundation for Statistical Computing, Vienna, Austria.

Reimers, E., and J. E. Colman. 2006. Reindeer and caribou (*Rangifer tarandus*) response towards human activities. Rangifer 26:55–71.

Rickbeil, G. J. M., T. Hermosilla, N. C. Coops, J. C. White, and M. A. Wulder. 2017. Barren-ground caribou (*Rangifer tarandus groenlandicus*) behaviour after recent fire events; integrating caribou telemetry data with Landsat fire detection techniques. Global Change Biology 23:1036–1047.

Rickbeil, G. J. M., T. Hermosilla, N. C. Coops, J. C. White, M. A. Wulder, and T. C. Lantz. 2018. Changing northern vegetation conditions are influencing barren ground caribou (*Rangifer tarandus groenlandicus*) post-calving movement rates. Journal of Biogeography 45:702–712.

Ross, W. A. 1998. Cumulative effects assessment: learning from Canadian case studies. Impact Assessment and Project Appraisal 16:267–276.

Schaefer, J. A., and S. P. Mahoney. 2007. Effects of progressive clearcut logging on Newfoundland caribou. Journal of Wildlife Management 71:1753–1757.

Seip, D. R., C. J. Johnson, and G. S. Watts. 2007. Displacement of mountain caribou from winter habitat by snowmobiles. Journal of Wildlife Management 71:1539–1544.

Sheriff, M. J., C. J. Krebs, and R. Boonstra. 2009. The sensitive hare: sublethal effects of predator stress on reproduction in snowshoe hares. Journal of Animal Ecology 78:1249–1258.

Shrestha, N. 2020. Detecting Multicollinearity in Regression Analysis. American Journal of Applied Mathematics and Statistics 8:39–42.

Skoog, R. O. 1968. Ecology of the caribou (*Rangifer tarandus granti*) in Alaska. Dissertation, University of California, Berkeley, Berkeley, CA.

Species at Risk Committee. 2017. Species status report for porcupine caribou and barren-ground caribou (Tuktoyaktuk Peninsula, Cape Bathurst, Bluenose-West, Bluenose-East, Bathurst, Beverly, Ahiak, and Qamanirjuaq herds) (*Rangifer tarandus groenlandicus*) in the Northwest Territories. Species at Risk Committee, Yellowknife, NT.

Taillon, J., M. Festa-Bianchet, and S. D. Côté. 2012. Shifting targets in the tundra: Protection of migratory caribou calving grounds must account for spatial changes over time. Biological Conservation 147:163–173.

Thomas, D. C., and D. R. Gray. 2002. Update COSEWIC status report on the woodland caribou *Rangifer tarandus caribou* in Canada. Committee on the Status of Endangered Wildlife in Canada, Ottawa, ON.

Trondrud, L. M., G. Pigeon, S. Albon, W. Arnold, A. L. Evans, R. J. Irvine, E. Król, E. Ropstad, A. Stien, V. Veiberg, J. R. Speakman, and L. E. Loe. 2021. Determinants of heart rate in Svalbard reindeer reveal mechanisms of seasonal energy management. Philosophical Transactions of the Royal Society B: Biological Sciences 376:1–10.

Tucker, M. A., K. Böhning-Gaese, W. F. Fagan, J. M. Fryxell, B. Van Moorter, S. C. Alberts, A. H. Ali, A. M. Allen, N. Attias, T. Avgar, H. Bartlam-Brooks, B. Bayarbaatar, J. L. Belant, A. Bertassoni, D. Beyer, L. Bidner, F. M. van Beest, S. Blake, N. Blaum, C. Bracis, D. Brown, P. J. N. de Bruyn, F. Cagnacci, J. M. Calabrese, C. Camilo-Alves, S. Chamaillé-Jammes, A. Chiaradia, S. C. Davidson, T. Dennis, S. DeStefano, D. Diefenbach, I. Douglas-Hamilton, J. Fennessy, C. Fichtel, W. Fiedler, C. Fischer, I. Fischhoff, C. H. Fleming, A. T. Ford, S. A. Fritz, B. Gehr, J. R. Goheen, E. Gurarie, M. Hebblewhite, M. Heurich, A. J. M. Hewison, C. Hof, E. Hurme, L. A. Isbell, R. Janssen, F. Jeltsch, P. Kaczensky, A. Kane, P. M. Kappeler, M. Kauffman, R. Kays, D. Kimuyu, F. Koch, B. Kranstauber, S. LaPoint, P. Leimgruber, J. D. C. Linnell, P. López-López, A. C. Markham, J. Mattisson, E. P. Medici, U. Mellone, E. Merrill, G. de Miranda Mourão, R. G. Morato, N. Morellet,

T. A. Morrison, S. L. Díaz-Muñoz, A. Mysterud, D. Nandintsetseg, R. Nathan, A. Niamir, J. Odden, R. B. O'Hara, L. G. R. Oliveira-Santos, K. A. Olson, B. D. Patterson, R. Cunha de Paula, L. Pedrotti, B. Reineking, M. Rimmler, T. L. Rogers, C. M. Rolandsen, C. S. Rosenberry, D. I. Rubenstein, K. Safi, S. Saïd, N. Sapir, H. Sawyer, N. M. Schmidt, N. Selva, A. Sergiel, E. Shiilegdamba, J. P. Silva, N. Singh, E. J. Solberg, O. Spiegel, O. Strand, S. Sundaresan, W. Ullmann, U. Voigt, J. Wall, D. Wattles, M. Wikelski, C. C. Wilmers, J. W. Wilson, G. Wittemyer, F. Zięba, T. Zwijacz-Kozica, and T. Mueller. 2018. Moving in the Anthropocene: Global reductions in terrestrial mammalian movements. Science 359:466–469.

Tyler, N. J. C. 1991. Short-term behavioural responses of Svalbard reindeer *Rangifer tarandus platyrhynchus* to direct provocation by a snowmobile. Biological Conservation 56:179–194.

United Nations. 1972. Report of the United Nations Conference on the Human Environemtn. United Nations, New York, NY.

Van Moorter, B., C. M. Rolandsen, M. Basille, and J.-M. Gaillard. 2016. Movement is the glue connecting home ranges and habitat selection. Journal of Animal Ecology 85:21–31.

Veiberg, V., L. E. Loe, S. D. Albon, R. J. Irvine, T. Tveraa, E. Ropstad, and A. Stien. 2017. Maternal winter body mass and not spring phenology determine annual calf production in an Arctic herbivore. Oikos 126:980–987.

Vistnes, I., C. Nellemann, P. Jordhoy, and O. Strand. 2001. Wild reindeer: impacts of progressive infrastructure development on distribution and range use. Polar Biology 24:531–537.

Vistnes, I., C. Nellemann, P. Jordhøy, and O. Strand. 2004. Effects of infrastructure on migration and range use of wild reindeer. Journal of Wildlife Management 68:101–108.

Vittinghoff, E., D. V. Glidden, S. C. Shiboski, and C. E. McCulloch. 2012. Regression Methods in Biostatistics: Linear, Logistic, Survival, and Repeated Measures Models. 2nd edition. Statistics for Biology and Health, Springer Science+Business Media, Berlin, DE.

Vors, L. S., and M. S. Boyce. 2009. Global declines of caribou and reindeer. Global Change Biology 15:2626–2633.

Vors, L. S., J. A. Schaefer, B. A. Pond, A. R. Rodgers, and B. R. Patterson. 2007. Woodland caribou extirpation and anthropogenic landscape disturbance in Ontario. Journal of Wildlife Management 71:1249–1256.

Wal, R. van der. 2006. Do herbivores cause habitat degradation or vegetation state transition? Evidence from the tundra. Oikos 114:177–186.

Wasser, S. K., J. L. Keim, M. L. Taper, and S. R. Lele. 2011. The influences of wolf predation, habitat loss, and human activity on caribou and moose in the Alberta oil sands. Frontiers in Ecology and the Environment 9:546–551.

White, H. 1980. A heteroskedasticity-consistent covariance matrix estimator and a direct test for heteroskedasticity. Econometrica 48:817–838.

White, R. G., D. E. Russell, and C. J. Daniel. 2014. Simulation of maintenance, growth and reproduction of caribou and reindeer as influenced by ecological aspects of nutrition, climate change and industrial development using an energy-protein model. Rangifer 34:1–126.

Wilson, R. R., L. S. Parrett, K. Joly, and J. R. Dau. 2016. Effects of roads on individual caribou movements during migration. Biological Conservation 195:2–8.

Wingfield, J. C., D. L. Maney, C. W. Breuner, J. D. Jacobs, S. Lynn, M. Ramenofsky, and R. D. Richardson. 1998. Ecological bases of hormone—behavior interactions: The "emergency life history stage." American Zoologist 38:191–206.

Witter, L. A., C. J. Johnson, B. Croft, A. Gunn, and M. P. Gillingham. 2012. Behavioural trade-offs in response to external stimuli: time allocation of an Arctic ungulate during varying intensities of harassment by parasitic flies: Rangifer time allocation during insect harassment. Journal of Animal Ecology 81:284–295.

Wittmer, H. U., B. N. Mclellan, R. Serrouya, and C. D. Apps. 2007. Changes in landscape composition influence the decline of a threatened woodland caribou population. Journal of Animal Ecology 76:568–579.

Wolfe, S. A., B. Griffith, and C. A. G. Wolfe. 2000. Response of reindeer and caribou to human activities. Polar Research 19:63–73.

Zalatan, R., A. Gunn, and G. H. R. Henry. 2006. Long-term abundance patterns of barren-ground caribou using trampling scars on roots of *Picea mariana* in the Northwest Territories, Canada. Arctic, Antarctic, and Alpine Research 38:624–630.

Zbyryt, A., J. W. Bubnicki, D. P. J. Kuijper, M. Dehnhard, M. Churski, and K. Schmidt. 2018. Do wild ungulates experience higher stress with humans than with large carnivores? B. Wong, editor. Behavioral Ecology 29:19–30.

Appendix A: Field Data Sheets

Site Description Form

Caribou?:_____ Pellets?: _____ Site Number: ____________

SITE DESCRIPTION SHEET

Date:________________ Start Time: ___________End time:__________

Observers: 1.________________________ 2.________________________

3. ________________________

Location: lat______________________ long______________________

GPS# (gps code and wpt #): ______________

Site Description: ____

____

____

____

Distance (m; from obs to caribou) _________ Direction (Deg; from obs to caribou):______________

Approximate distance and direction to industrial feature road/pit/mine/etc.):__________________

Description of Industrial Feature:____

<u>Weather Conditions:</u>

Temp____________ Wind (m/s):_______ Wind Direction: _______

Cloud cover: Clear _____Scattered ____Broken ____Overcast ____

Snow: Light _______Moderate _________Severe ___________

Position (from obs to caribou): Upwind_______ Downwind _______Crosswind __________

Total # caribou in group:_______

Group Composition: #bulls _______#cows ________ #yearlings _______#calves _______

Condition of caribou is generally: skinny _____healthy _____ fat _______

Pellet notes (recency, predator presence):____

____

____

____

Group scan form 1 of 2

GROUP SCAN Date:_________ Site number:____ Start Time:______End time:________ Observers: 1.___________________2.___________________

Total # caribou in group:_________Group Comp: #bulls______#cows________#yearlings______#calves______Condition: skinny____healthy____fat________

	#Standing	#Lying	#Walking	#Trot/Running	#Foraging	# Sparring	# Nursing	Stressr Start	Stressr End	Stressor Type	Notes
Start 0											
15 min											
30 min											
45 min											
1 hr											
1 hr 15 min											
1 hr 30 min											
1 hr 45min											

Group scan form 2 of 2

	#Standing	#Lying	#Walking	#Trot/Running	#Foraging	# Sparring	# Nursing	Stressr Start	Stressr End	Stressor Type	Notes
2 hr											
2 hr 15 min											
2 hr 30 min											
2 hr 45 min											
3 hr											
3 hr 15 min											
3 hr 30 min											
3 hr 45min											

Focal activity survey form 1 of 2

FOCAL ANIMAL – Active period (one datasheet per animal)

Date:_____________________________ Start Time:________End Time:__________

Site number:_________________________ Focal animal is: cow_____cow with calf______yearling cow____

Observer:____________________________ Condition of focal caribou: skinny______healthy______fat______

	Stand	Walk	Trot/ Run	Forage (head down)	Alert/ Alarm Stand	Nurse	Start Time of Stressor	End Time of Stressor	Stressor Type	Other (sparring , etc.)	Notes: (e.g. time spent nursing; unusual observations; why observations stopped – animal laid down, moved out of site, etc.)
E.g.					X		10:15		Vehicle - light		
0											
30 s											
1 min											
1 min 30s											
2 min											
2 min 30s											
3 min											
3min 30s											
4 min											
4 min 30s											
5 min											
5 min 30s											
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9 min 30s											
10 min											
10min 30s											
11min											
11min 30s											
12min											
12min 30s											
13min											

Focal activity survey form 2 of 2

	Stand	Walk	Trot/run	Forage	Alert/ Stand	Nurse	Stressor start	Stressor end	Stressor Type	Other	Notes:
13min 30s											
14min											
14min 30s											
15min											
15min 30s											
16min											
16min 30s											
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29min 30s											
30min											

Focal foraging survey form

FOCAL ANIMAL – Feeding Intensity (multiple animals per datasheet)

Date:________________________ **Site number:**____________________

Observer:____________________

	Start time:	Focal caribou is: cow, cow w calf, yearling cow	Total time watching single animal forage (Stop Watch 1)	Total time animal spent eating -taking bites (Stop Watch 2)	Start Time of stressor	End Time of Stressor	Stressor (aircraft, vehicle, predator, blasting, etc.)	Notes (e.g. why survey was stopped early)
e.g.	12:05pm	Cow w calf	10	7min 44s	6min 33s	6min58s	Helicopter	
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Appendix B: Model Tables

What follows are the full results from the analyses of chapters 2 and 3. This includes the model rankings, according to AIC$_c$, coefficient values with standard errors (SE), and an assessment of predictive accuracy of models using the AUC of ROC tests or an assessment of the difference between model predictions and Leave One Out Cross Validation (LOOCV) model predictions (Fielding and Bell 1997, Pearce and Ferrier 2000). The tables of model rankings are followed by the model coefficients, starting with the behavioural analyses, then the hormone analyses, and finally the crossing analysis.

Table B.1 Ranking and assessment of fractional logistic regression models (with robust SEs) representing the mean proportion of caribou in groups engaged in foraging or lying near the Tibbitt to Contwoyto Winter Road, Northwest Territories, Canada. Leave-One-Out-Cross-Validation (LOOCV) results are the P from a Mann-Whitney U test contrasting the LOOCV predicted values with the model's predicted values.

Model	Model structure	K	AICc	ΔAIC$_c$	LOOCV P
Distance	Distance to road + year + observer upwind + survey duration + group size	6	42.856	0	0.608
Time of year	Day of year + year + observer upwind + survey duration + group size	6	45.378	2.522	0.585
Hunting pressure	In no-hunting zone + year + observer upwind + survey duration + group size	6	45.569	2.713	0.723
Weather	cloud cover + windchill + year + observer upwind + survey duration + group size	7	46.828	3.971	0.632
Null	1	1	48.394	5.538	0.226
Global	distance to road + in no-hunting zone + cloud cover + windchill + year + day of year + observer upwind + survey duration + group size	10	55.130	12.274	0.510

Note: Covariates are described in Table 2.1.

Table B.2 Model coefficients, SEs, Z, and P for the distance model of the mean proportion of caribou in groups engaged in foraging or lying near the Tibbitt to Contwoyto Winter Road, Northwest Territories, Canada.

Coefficient	Estimate	SE	Z	P
Intercept	0.581	0.465	1.249	0.212
Distance to road (km)	0.041	0.020	2.049	0.040
Year (2020)	0.828	0.607	1.365	0.172
Observer upwind	-1.38	0.439	-3.143	0.002
Group size	0.001	0.003	0.314	0.754
Survey duration	0.501	0.235	2.131	0.033

Table B.3 Model coefficients, SEs, Z, and P for the time of year model of the mean proportion of caribou in groups engaged in foraging or lying near the Tibbitt to Contwoyto Winter Road, Northwest Territories, Canada.

Coefficient	Estimate	SE	Z	P
Intercept	0.368	1.465	0.251	0.802
Day of year	0.008	0.022	0.372	0.710
Year (2020)	1.078	0.498	2.164	0.030
Observer upwind	-1.550	0.348	-4.455	<0.001
Group size	0.001	0.003	0.177	0.860
Survey duration	0.522	0.251	2.078	0.038

Table B.4 Model coefficients, SEs, Z, and P for the hunting pressure model of the mean proportion of caribou in groups engaged in foraging or lying near the Tibbitt to Contwoyto Winter Road, Northwest Territories, Canada.

Coefficient	Estimate	SE	Z	P
Intercept	1.109	0.443	2.502	0.012
In no-hunting zone	-0.390	0.464	-0.841	0.401
Year (2020)	1.076	0.541	1.989	0.047
Observer upwind	-1.671	0.401	-4.164	<0.001
Group size	0.001	0.003	0.200	0.841
Survey duration	0.549	0.266	2.062	0.039

Table B.5 Model coefficients, SEs, Z, and P for the weather model of the mean proportion of caribou in groups engaged in foraging or lying near the Tibbitt to Contwoyto Winter Road, Northwest Territories, Canada.

Coefficient	Estimate	SE	Z	P
Intercept	1.105	0.842	1.313	0.189
Cloud cover (true)	0.372	0.417	0.893	0.372
Windchill	0.014	0.029	0.487	0.626
Year (2020)	1.118	0.591	1.890	0.059
Observer upwind	-1.421	0.370	-3.838	<0.001
Group size	0.000	0.003	-0.046	0.963
Survey duration	0.515	0.260	1.979	0.0478

Table B.6 Model coefficients, SEs, Z, and P for the global model of the mean proportion of caribou in groups engaged in foraging or lying near the Tibbitt to Contwoyto Winter Road, Northwest Territories, Canada.

Coefficient	Estimate	SE	Z	P
Intercept	-2.282	4.912	-0.465	0.642
Distance to road (km)	0.041	0.025	1.631	0.103
In no-hunting zone	-0.341	0.655	-0.521	0.603
Cloud cover (true)	0.560	0.458	1.223	0.221
Windchill	-0.020	0.057	-0.348	0.728
Day of year	0.033	0.051	0.659	0.510
Year (2020)	0.932	0.893	1.043	0.297
Observer upwind	-1.388	0.500	-2.779	0.005
Group size	0.000	0.004	-0.046	0.964
Survey duration	0.517	0.313	1.654	0.098

Table B.7 Ranking and assessment of multinomial logistic regression models representing the relative dominant behaviour of caribou near the Tibbitt to Contwoyto Winter Road, Northwest Territories, Canada. AUC scores are from ROC curves and are based on predicted outputs from a leave-one-out cross-validation procedure. The SEs of the AUC scores are presented in brackets.

Model	Model structure	K	AIC_c	ΔAIC_c	AUC_{stand}	$AUC_{walk/trot}$
Distance	Distance to road + year + observer upwind	8	210.672	0	0.498 (0.065)	0.537 (0.064)
Null	NA	2	215.654	4.983	0 (0)	0.424 (0.061)
Hunting	In no-hunting zone + year + observer upwind	8	216.898	6.226	0.499 (0.065)	0.502 (0.063)
Time of year	Day of year + year + observer upwind	8	218.019	7.347	0.597 (0.065)	0.487 (0.063)
Global	Distance to road + in no-hunting zone + cloud cover + windchill + year + observer upwind	18	219.018	8.346	0.602 (0.065)	0.477 (0.063)
Weather	Cloud cover + windchill + year + observer upwind	14	222.433	11.762	0.632 (0.065)	0.481 (0.063)

Note: Covariates are described in Table 2.1.

Table B.8 Model coefficients, SEs, Z, and P for the distance model of the relative dominant behaviour of caribou near the Tibbitt to Contwoyto Winter Road, Northwest Territories, Canada.

Coefficient	Response	Estimate	SE	Z	P
Distance to road (km)	Stand	-0.048	0.033	-1.456	0.145
	Walk/trot	-0.119	0.040	-2.988	0.003
Observer upwind	Stand	1.273	0.755	1.686	0.092
	Walk/trot	0.401	0.713	0.563	0.574
Year (2020)	Stand	2.021	0.719	2.813	0.005
	Walk/trot	1.378	0.692	1.992	0.046

Table B.9 Model coefficients, SEs, Z, and P for the hunting pressure model of the relative dominant behaviour of caribou near the Tibbitt to Contwoyto Winter Road, Northwest Territories, Canada.

Coefficient	Response	Estimate	SE	Z	P
In no-hunting zone	Stand	0.920	0.033	-1.456	0.145
	Walk/trot	1.233	0.040	-2.988	0.003
Observer upwind	Stand	0.983	0.755	1.686	0.092
	Walk/trot	0.047	0.713	0.563	0.574
Year (2020)	Stand	1.505	0.719	2.813	0.005
	Walk/trot	0.290	0.692	1.992	0.046

Table B.10 Model coefficients, SEs, Z, and P for the time of year model of the relative dominant behaviour of caribou near the Tibbitt to Contwoyto Winter Road, Northwest Territories, Canada.

Coefficient	Response	Estimate	SE	Z	P
Day of year	Stand	-0.035	0.033	-1.079	0.281
	Walk/trot	0.033	0.033	1.005	0.315
Observer upwind	Stand	1.156	0.749	1.543	0.123
	Walk/trot	0.418	0.681	0.613	0.540
Year (2020)	Stand	1.143	0.676	1.691	0.091
	Walk/trot	0.658	0.674	0.976	0.329

Table B.11 Model coefficients, SEs, Z, and P for the global model of the relative dominant behaviour of caribou near the Tibbitt to Contwoyto Winter Road, Northwest Territories, Canada.

Coefficient	Response	Estimate	SE	Z	P
Distance to road (km)	Stand	-0.041	0.037	-1.147	0.252
	Walk/trot	-0.118	0.049	-2.387	0.017
In no-hunting zone	Stand	0.776	0.751	1.033	0.301
	Walk/trot	1.338	0.867	1.543	0.123
Cloud cover (clear)	Stand	-0.969	0.950	-1.020	0.308
	Walk/trot	-1.271	0.869	-1.463	0.143
Cloud cover (overcast)	Stand	-1.582	1.010	-1.566	0.117
	Walk/trot	-2.007	1.101	-1.824	0.068
Cloud cover (scattered)	Stand	-0.091	0.891	-0.102	0.919
	Walk/trot	-0.963	0.897	-1.074	0.283
Windchill	Stand	-0.067	0.041	-1.629	0.103
	Walk/trot	0.081	0.045	1.796	0.072
Observer upwind	Stand	1.679	0.891	1.884	0.060
	Walk/trot	0.746	0.885	0.843	0.399
Year (2020)	Stand	1.683	0.904	1.862	0.063
	Walk/trot	2.312	1.031	2.242	0.025

Table B.12 Model coefficients, SEs, Z, and P for the weather model of the relative dominant behaviour of caribou near the Tibbitt to Contwoyto Winter Road, Northwest Territories, Canada.

Coefficient	Response	Estimate	SE	Z	P
Cloud cover (clear)	Stand	-0.966	0.891	-1.084	0.279
	Walk/trot	-1.228	0.798	-1.539	0.124
Cloud cover (overcast)	Stand	-1.635	0.991	-1.649	0.099
	Walk/trot	-1.894	0.943	-2.010	0.044
Cloud cover (scattered)	Stand	-0.116	0.799	-0.146	0.884
	Walk/trot	-0.463	0.738	-0.627	0.530
Windchill	Stand	-0.075	0.040	-1.868	0.062
	Walk/trot	0.033	0.036	0.928	0.353
Observer upwind	Stand	1.871	0.887	2.108	0.035
	Walk/trot	1.178	0.815	1.445	0.148
Year (2020)	Stand	0.895	0.733	1.221	0.222
	Walk/trot	0.543	0.711	0.763	0.446

Table B.13 Ranking of fractional logistic regression models (with robust SEs) representing the mean proportion of time spent foraging by caribou near the Tibbitt to Contwoyto Winter Road, Northwest Territories, Canada.

Model	Model structure	*K*	AIC_c	ΔAIC_c
Null	NA	1	43.435	0
Hunting	In no-hunting zone + year + observer upwind	3	49.448	6.014
Time of year	Day of year + year + observer upwind	3	49.531	6.097
Distance	Distance to road + year + observer upwind	3	49.744	6.310
Weather	Cloud cover + windchill + year + observer upwind	4	52.213	8.779
Global	Distance to road + in no-hunting zone + cloud cover + windchill + year + observer upwind	6	56.119	12.684

Note: Covariates are described in Table 2.1.

Table B.14 Model coefficients, SEs, Z, and P for the hunting pressure model of the mean proportion of time spent foraging by caribou near the Tibbitt to Contwoyto Winter Road, Northwest Territories, Canada.

Coefficient	Estimate	SE	Z	P
Intercept	0.783	0.143	5.487	<0.001
In no-hunting zone	0.512	0.254	2.019	0.044
Observer upwind	0.268	0.188	1.420	0.156
Year (2020)	0.278	0.249	1.114	0.265

Table B.15 Model coefficients, SEs, Z, and P for the time of year model of the mean proportion of time spent foraging by caribou near the Tibbitt to Contwoyto Winter Road, Northwest Territories, Canada.

Coefficient	Estimate	SE	Z	P
Intercept	3.827	1.969	1.944	0.052
Day of year	-0.041	0.028	-1.465	0.143
Observer upwind	0.248	0.208	1.194	0.233
Year (2020)	-0.462	0.432	-1.069	0.285

Table B.16 Model coefficients, SEs, Z, and P for the distance model of the mean proportion of time spent foraging by caribou near the Tibbitt to Contwoyto Winter Road, Northwest Territories, Canada.

Coefficient	Estimate	SE	Z	P
Intercept	0.836	0.158	5.283	<0.001
Distance to road (km)	0.007	0.007	0.980	0.327
Observer upwind	0.185	0.182	1.017	0.309
Year (2020)	0.089	0.248	0.358	0.720

Table B.17 Model coefficients, SEs, Z, and P for the weather model of the mean proportion of time spent foraging by caribou near the Tibbitt to Contwoyto Winter Road, Northwest Territories, Canada.

Coefficient	Estimate	SE	Z	P
Intercept	0.623	0.617	1.011	0.312
Windchill	-0.012	0.024	-0.517	0.605
Cloud cover (true)	-0.043	0.183	-0.234	0.815
Observer upwind	0.202	0.211	0.959	0.337

Table B.18 Model coefficients, SEs, Z, and P for the global model of the mean proportion of time spent foraging by caribou near the Tibbitt to Contwoyto Winter Road, Northwest Territories, Canada.

Coefficient	Estimate	SE	Z	P
Intercept	1.008	0.791	1.275	0.203
Distance to road (km)	0.012	0.009	1.323	0.186
In no-hunting zone	0.768	0.383	2.004	0.045
Cloud cover (true)	-0.170	0.218	-0.777	0.437
Windchill	0.010	0.030	0.344	0.731
Observer upwind	0.340	0.218	1.559	0.119
Year (2020)	0.281	0.456	0.615	0.538

Table B.19 Ranking of regression models representing the level of cortisol and corticosterone in fecal pellets from caribou near the Tibbitt to Contwoyto Winter Road, Northwest Territories, Canada. Leave-One-Out-Cross-Validation (LOOCV) results are the P from a Mann-Whitney U test contrasting the LOOCV predicted values with the model's predicted values.

Model		*K*	Cortisol			Corticosterone		
			AIC$_c$	ΔAIC$_c$	LOOCV P	AIC$_c$	ΔAIC$_c$	LOOCV P
Time of year	Day of year + year + site id	3	4383.221	0	0.634	3565.689	5.552	0.102
Weather	Windchill + year + site id	3	4384.724	1.502	0.647	3560.137	0	0.106
Hunting	In no-hunting zone + year + site id	3	4386.112	2.890	0.637	3573.787	13.650	0.101
Distance	Distance to road + year + observer upwind	3	4386.520	3.299	0.637	3574.119	13.982	0.101
Global	Distance to road + in no-hunting zone + windchill + day of year + year + site id	6	4388.771	5.550	0.631	3564.312	4.175	0.113
Null	1	1	4486.125	102.904	0.718	3591.331	31.194	0.088

Note: Covariates are described in Table 2.1.

Table B.20 Model coefficients, SEs, Z, and P for the time of year model of the level of cortisol in fecal pellets from caribou near the Tibbitt to Contwoyto Winter Road, Northwest Territories, Canada.

Coefficient	Estimate	SE	Z	P
Intercept	278.734	22.324	12.486	<0.001
Day of year	0.697	0.337	2.066	0.039
Year (2020)	-107.785	7.326	-14.713	<0.001

Table B.21 Model coefficients, SEs, Z, and P for the weather model of the level of cortisol in fecal pellets from caribou near the Tibbitt to Contwoyto Winter Road, Northwest Territories, Canada.

Coefficient	Estimate	SE	Z	P
Intercept	359.981	22.430	16.049	<0.001
Windchill	0.883	0.539	1.639	0.101
Year (2020)	-96.997	9.787	-9.911	<0.001

Table B.22 Model coefficients, SEs, Z, and P for the hunting pressure model of the level of cortisol in fecal pellets from caribou near the Tibbitt to Contwoyto Winter Road, Northwest Territories, Canada.

Coefficient	Estimate	SE	Z	P
Intercept	327.876	5.694	57.600	<0.001
In no-hunting zone	-8.104	7.191	-1.130	0.260
Year (2020)	-107.640	7.464	-14.420	<0.001

Table B.23 Model coefficients, SEs, Z, and P for the distance model of the level of cortisol in fecal pellets from caribou near the Tibbitt to Contwoyto Winter Road, Northwest Territories, Canada.

Coefficient	Estimate	SE	Z	P
Intercept	323.412	4.556	71.000	<0.001
Distance to road (km)	0.078	0.084	0.920	0.355
Year (2020)	-112.249	9.084	-12.360	<0.001

Table B.24 Model coefficients, SEs, Z, and P for the global model of the level of cortisol in fecal pellets from caribou near the Tibbitt to Contwoyto Winter Road, Northwest Territories, Canada.

Coefficient	Estimate	SE	Z	P
Intercept	298.152	53.774	5.540	<0.001
Distance to road (km)	0.040	0.085	0.467	0.641
In no-hunting zone	-3.553	7.975	-0.446	0.656
Windchill	0.189	0.763	0.248	0.804
Day of year	0.539	0.454	1.187	0.235
Year (2020)	-107.969	12.357	-8.737	<0.001

Table B.25 Model coefficients, SEs, Z, and P for the weather model of the level of corticosterone in fecal pellets from caribou near the Tibbitt to Contwoyto Winter Road, Northwest Territories, Canada.

Coefficient	Estimate	SE	Z	P
Intercept	106.522	9.517	11.200	<0.001
Windchill	0.869	0.228	3.806	<0.001
Year (2020)	26.959	4.187	6.439	<0.001

Table B.26 Model coefficients, SEs, Z, and P for the global model of the level of corticosterone in fecal pellets from caribou near the Tibbitt to Contwoyto Winter Road, Northwest Territories, Canada.

Coefficient	Estimate	SE	Z	P
Intercept	95.270	22.771	4.180	<0.001
Distance to road (km)	-0.013	0.037	-0.350	0.726
In no-hunting zone	3.882	3.434	1.130	0.258
Windchill	0.861	0.322	2.677	0.007
Day of year	0.141	0.194	0.726	0.468
Year (2020)	27.656	5.280	5.238	<0.001

Table B.27 Model coefficients, SEs, Z, and P for the time of year model of the level of corticosterone in fecal pellets from caribou near the Tibbitt to Contwoyto Winter Road, Northwest Territories, Canada.

Coefficient	Estimate	SE	Z	P
Intercept	42.702	9.820	4.350	<0.001
Day of year	0.437	0.148	2.946	0.003
Year (2020)	16.435	3.242	5.069	<0.001

Table B.28 Model coefficients, SEs, Z, and P for the hunting pressure model of the level of corticosterone in fecal pellets from caribou near the Tibbitt to Contwoyto Winter Road, Northwest Territories, Canada.

Coefficient	Estimate	SE	Z	P
Intercept	71.954	2.566	28.000	<0.001
In no-hunting zone	-1.873	3.244	-0.577	0.564
Year (2020)	16.595	3.366	4.931	<0.001

Table B.29 Model coefficients, SEs, Z, and P for the distance model of the level of corticosterone in fecal pellets from caribou near the Tibbitt to Contwoyto Winter Road, Northwest Territories, Canada.

Coefficient	Estimate	SE	Z	P
Intercept	71.057	2.054	34.600	<0.001
Distance to road (km)	-0.001	0.038	-0.030	0.977
Year (2020)	16.693	4.092	4.080	<0.001

Table B.30 Ranking of regression models representing the selection of crossing events by barren-ground caribou across the Tibbitt to Contwoyto Winter Road, Northwest Territories, Canada. The SEs of the AUC scores are presented in brackets.

Model	Model structure	*K*	AIC$_c$	ΔAIC$_c$	AUC
Traffic count	traffic count + year	5	356.000	0	0.949 (0.892)
Global model	Traffic count + day of year + directionality coefficient (relative) + in no-hunting zone + windchill + year	9	357.284	1.670	0.951 (0.897)
Active road	active road + year	5	379.546	23.900	0.937 (0.871)
Open road	open road + year	5	422.356	66.742	0.916 (0.844)
Windchill	windchill + year	5	455.219	99.605	0.901 (0.812)
Movement combined	windchill + directionality coefficient + year	6	456.839	101.000	0.901 (0.809)
Day of year	day of year + year	5	457.796	102.182	0.902 (0.805)
Hunting	in no-hunting zone + year	5	458.224	102.610	0.898 (0.804)
Directional persistence	directionality coefficient + year	5	460.200	104.586	0.897 (0.800)
Null	1	1	542.680	187.066	0.500 (0.000)

Note: Covariates are described in Table 3.1.

Table B.31 Model coefficients, SEs, Z, and P for the traffic count model representing the selection of crossing events by barren-ground caribou across the Tibbitt to Contwoyto Winter Road, Northwest Territories, Canada.

Coefficient	Estimate	SE	Z	P
Intercept	0.064	0.471	0.135	0.893
Traffic count	-0.101	0.026	-3.818	<0.001
Year (2020)	-0.901	0.549	-1.641	0.101
Year (2020)	-2.210	0.695	-3.181	0.001

Table B.32 Model coefficients, SEs, Z, and P for the global model representing the selection of crossing events by barren-ground caribou across the Tibbitt to Contwoyto Winter Road, Northwest Territories, Canada.

Coefficient	Estimate	SE	Z	P
Intercept	1.703	1.341	1.270	0.204
Traffic count	-0.100	0.026	-3.839	<0.001
Windchill	0.017	0.019	0.932	0.351
In no-hunting zone	-1.140	0.515	-2.212	0.027
Directionality coefficient (relative)	0.515	0.868	0.593	0.553
Day of year	-0.005	0.010	-0.461	0.645
Year (2020)	-0.911	0.561	-1.623	0.105
Year (2020)	-2.228	0.746	-2.987	0.003

Table B.33 Model coefficients, SEs, Z, and P for the active road model representing the selection of crossing events by barren-ground caribou across the Tibbitt to Contwoyto Winter Road, Northwest Territories, Canada.

Coefficient	Estimate	SE	Z	P
Intercept	-0.077	0.561	-0.137	0.891
Active road	-3.008	0.400	-7.513	<0.001
Year (2020)	-0.339	0.591	-0.574	0.566
Year (2020)	-1.949	0.839	-2.323	0.020

Table B.34 Model coefficients, SEs, Z, and P for the open road model representing the selection of crossing events by barren-ground caribou across the Tibbitt to Contwoyto Winter Road, Northwest Territories, Canada.

Coefficient	Estimate	SE	Z	P
Intercept	-0.564	0.540	-1.040	0.296
Open road	-2.146	0.381	-5.633	<0.001
Year (2020)	-0.111	0.560	-0.199	0.843
Year (2020)	-2.131	0.800	-2.664	0.008

Table B.35 Model coefficients, SEs, Z, and P for the weather model representing the selection of crossing events by barren-ground caribou across the Tibbitt to Contwoyto Winter Road, Northwest Territories, Canada.

Coefficient	Estimate	SE	Z	P
Intercept	-0.524	0.684	-0.765	0.444
Windchill	0.032	0.014	2.268	0.023
Year (2020)	-0.447	0.547	-0.816	0.415
Year (2020)	-1.975	0.813	-2.429	0.015

Table B.36 Model coefficients, SEs, Z, and P for the movement combined model representing the selection of crossing events by barren-ground caribou across the Tibbitt to Contwoyto Winter Road, Northwest Territories, Canada.

Coefficient	Estimate	SE	Z	P
Intercept	-0.698	0.735	-0.950	0.342
Year (2020)	-0.467	0.549	-0.852	0.395
Year (2020)	-1.980	0.815	-2.430	0.015
Windchill	0.033	0.014	2.279	0.023
Directionality coefficient (relative)	0.491	0.756	0.650	0.516

Table B.37 Model coefficients, SEs, Z, and P for the time of year model representing the selection of crossing events by barren-ground caribou across the Tibbitt to Contwoyto Winter Road, Northwest Territories, Canada.

Coefficient	Estimate	SE	Z	P
Intercept	-2.453	0.747	-3.280	0.001
Day of year	0.014	0.008	1.642	0.101
Year (2020)	-0.383	0.545	-0.702	0.483
Year (2020)	-2.100	0.817	-2.572	0.010

Table B.38 Model coefficients, SEs, Z, and P for the hunting pressure model representing the selection of crossing events by barren-ground caribou across the Tibbitt to Contwoyto Winter Road, Northwest Territories, Canada.

Coefficient	Estimate	SE	Z	P
Intercept	-1.051	0.607	-1.730	0.084
In no-hunting zone	-0.612	0.393	-1.557	0.119
Year (2020)	-0.327	0.535	-0.611	0.541
Year (2020)	-1.869	0.803	-2.326	0.020

Table B.39 Model coefficients, SEs, Z, and P for the directional persistence model representing the selection of crossing events by barren-ground caribou across the Tibbitt to Contwoyto Winter Road, Northwest Territories, Canada.

Coefficient	Estimate	SE	Z	P
Intercept	-1.739	0.583	-2.980	<0.001
Directionality coefficient (relative)	0.456	0.749	0.608	0.543
Year (2020)	-0.336	0.537	-0.625	0.532
Year (2020)	-1.874	0.807	-2.323	0.020