Commentary

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Caribou and reindeer migrations in the changing Arctic

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Abstract: Caribou and reindeer, *Rangifer tarandus*, are the most numerous and socio-ecologically important terrestrial species in the Arctic. Their migrations are directly and indirectly affected by the seasonal nature of the northernmost regions, human development and population size; all of which are impacted by climate change. We review the most critical drivers of *Rangifer* migration and how a rapidly changing Arctic may affect them. In order to conserve large *Rangifer* populations, they must be allowed free passage along their migratory routes to reach seasonal ranges. We also provide some pragmatic ideas to help conserve *Rangifer* migrations into the future.

Keywords: Barrier effect, Climate change, Connectivity, Conservation, Development, Mitigation, *Rangifer*

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1 Introduction

Caribou and wild reindeer (Figure 1), both *Rangifer tarandus*, are the most numerous large mammals in the Arctic and are highly migratory and gregarious [1, 2]. Their seasonal migrations, defined as periodic movements between discrete seasonal ranges, are the longest (up to 1350 km round trip) terrestrial migrations not only in the Arctic, but in the world [2, 3]. For more than 10,000 years, these long-distance migrations have taken *Rangifer* within reach of northern subsistence hunters [4, 5, 6]. The importance of these influxes of *Rangifer* are woven into the culture and spirituality of northern people around the world, relationships that persist to this day [7, 8, 9]. Their migrations are also valued by sport hunters, tourists, and nature enthusiasts. *Rangifer*, through their migrations, play a pivotal role in arctic ecology as they directly impact vegetation through herbivory and trampling, transfer nutrients among tundra, boreal forest, and aquatic ecosystems (e.g., by utilizing lakes) and support arctic food webs that include predators, scavengers and parasites [1].

The impetuses for migration are manifold. The Arctic has pronounced summer and winter seasons, which is one key driver of ungulate migrations [10, 11, 12]. In spring, parturient *Rangifer* migrate from their wintering grounds to their traditional calving grounds. These calving grounds are a predictable destination where the females come together to access high-quality forage to meet the high energetic demands of lactation and they typically have lower predator densities, which helps increase neonatal survival [13, 14, 15, 16]. After calving, all members of the herd can form huge aggregations to reduce individual exposure to insect harassment, which can be fierce in the Arctic [17, 18]. Fall migration is more variable in its timing and destination than spring and can be triggered by snowfall, decreasing temperatures, and vegetative senescence [3, 19]. Fall migration brings *Rangifer* together for the rut and then to their winter ranges where lichen, which dominate winter diets [20], tend to be more plentiful and accessible [19, 21].

Figure 1: Caribou starting to cross the Kobuk River on their southward, fall migration in northwest Alaska, USA. Photo by Kyle Joly.

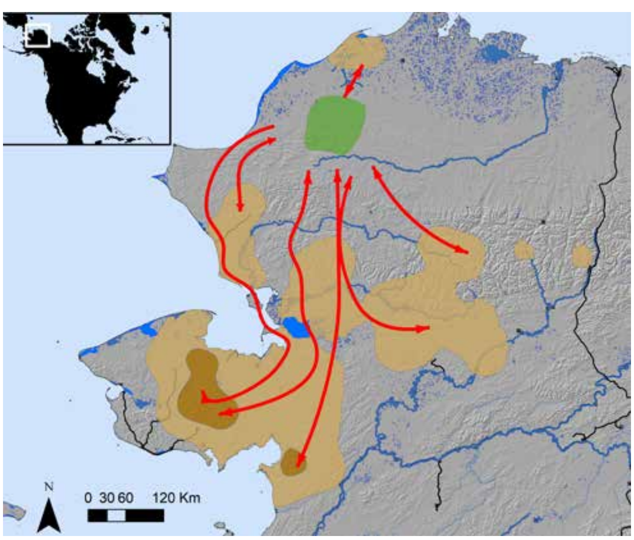

Figure 2: A map illustrating some of the different, general migratory routes (red arrows) used by Western Arctic Herd caribou in northwest Alaska, USA. The green polygon is the core calving area for the herd as identified by Cameron et al. [13] and the brown polygons are winter ranges as identified by Joly et al. [125]. Darker brown areas indicate areas of concentrated winter use.

The migratory movements of *Rangifer* are highly variable (Figure 2), with their distances and routes changing over time [2, 19, 21, 22]. In gregarious social ungulates like *Rangifer*, population abundance, along with collective and learned behavior, is an important impetus for migration that can facilitate information transfer among individuals and improve fitness [12, 23, 24, 25, 26]. While migration can lead to abundant ungulate populations [10], a threshold abundance may be needed to trigger long-distance migration in a population. Arctic *Rangifer* herd sizes fluctuate widely [27, 28, 29], with some numbering >500,000 individuals at their peak, but many have been in decline since the mid-1990s [30, 31]. When *Rangifer* abundance drops substantially, often, so does the length and even the persistence of seasonal migrations [12, 32]. In eastern Canada, as the Rivière-George Herd increased in abundance threefold from 1973 to 1984, migration distance increased fivefold [15], and with the recent 99% decline in population size, the migration distance greatly decreased [33]. On high arctic islands, Peary caribou halted seasonal migrations when their abundance declined [34].

In addition to changes in abundance, migration can also be limited when movements are constrained by human infrastructure, like mines or oil and gas fields, but are particularly affected by linear corridors like roads, pipelines and transmission lines [35]. In free-ranging mountain reindeer populations in Norway, for example, migratory movements are restricted because the landscape is highly structured topographically and infrastructure has largely left reindeer with few to no options. Here, many of the historical migration routes are no longer in use and few migration routes remain intact for wild Norwegian reindeer [36, 37]. Like other ungulates, *Rangifer* migrations are threatened in places and have been extirpated in others [36, 38, 39, 40].

Where migration is more prevalent, variability exists in more ways than changing routes. Herds can exhibit partial migration (where only a percentage of the herd migrates) and facultative migration (where individuals switch between migratory and non-migratory tactics depending on conditions) [12, 19]. Some *Rangifer* populations have already undergone changes in their migratory characteristics. For example, the percentage of collared Western Arctic Herd female caribou, in northwestern Alaska, migrating south during fall to reach their southern wintering grounds declined from 82% in 2010-2015 to 41% in 2016-2019 [41]. This has raised the question among stakeholders, including Indigenous peoples, rural residents, sport hunters, managers, conservationists, and wildlife biologists, whether climate change might be driving changes in migratory characteristics of *Rangifer*. The changes in Western Arctic Herd migration have also come during a population decline, but the nexus between population size and migration has not received as much attention.

The intent of our review is to highlight specific mechanisms influencing *Rangifer* migration that may be affected by a rapidly changing climate in the Arctic. *Rangifer* ecotypes display an incredible level of behavioral and physiological plasticity which allows them to survive in environments ranging from the wet temperate forests of British Columbia to the polar deserts of the High Arctic [30]. These traits have also provided *Rangifer* the resilience to persist through millennia of previous dramatic climatic changes and should help them survive the current era of climate change. We argue that climate change will induce both direct and indirect impacts that will alter caribou migrations into the future (Figure 3). Caribou may be more vulnerable due to the effects of climate change during migration, yet at the same time, their ability to migrate may increase their resilience to climate change as these movements are, in part, an adaptation to unfavorable weather, such as rain-on-snow (ROS) events.

Direct impacts include *Rangifer* rerouting paths around waterbodies that are no longer frozen [42] or delayed migration through deeper snow [3, 21]. Indirect impacts to *Rangifer* include how climate change may impact caribou abundance [43]. A potential major issue is how climate change may facilitate additional human development and that development may synergistically interact with other factors to accelerate habitat loss and fragmentation. The magnitude of these impacts will depend on the rate and intensity of climate change, the geography and demographics of the individual herds, the individual mechanism being affected, and whether impacts have an additive or synergistic effect [44, 45]. We close by suggesting some pragmatic mitigation measures and suggestions to conserve *Rangifer* migrations well into the future, despite the impacts of climate change.

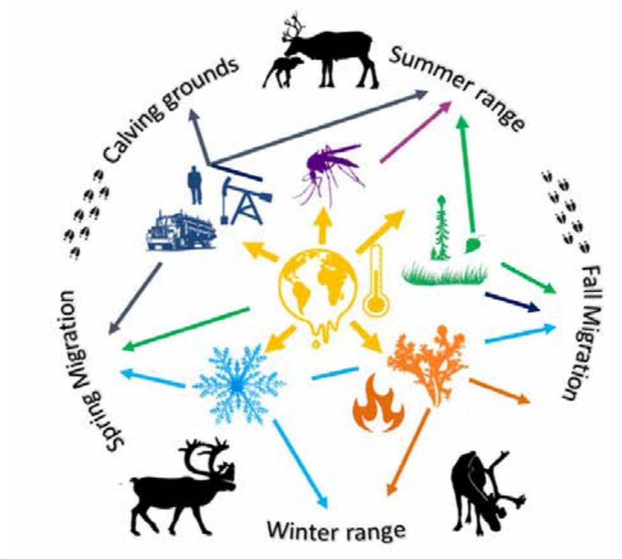

Figure 3: Schematic of hypothesized mechanisms by which climate change can influence caribou populations and distributions, arranged according to the caribou annual cycle (outer circle). These include: increased shrubification (green) changing forage quantity, quality, and availability in summer; more frequent and intense fires affecting lichen availability (orange), especially in winter; increased insect harassment (purple) worsening physical condition in summer; higher probability of rain-on-snow and icing events making forage unavailable in winter; extended period of deep soft snow slowing migration (light blue); and increased human developments obstructing migration routes and excluding caribou from prime habitats for calving and summering (dark blue).

2 The expanding human footprint in the Arctic and free passage for migrants

Free passage (the ability to move without restriction) is a key element to abundant arctic *Rangifer* herds, especially in a changing climate. Of all the *Rangifer* ecotypes, only migratory populations reach abundance numbering tens or hundreds of thousands (orders of magnitude more than non-migratory populations). While *Rangifer* may cross a single obstacle, like a road, there is a limit on how much human infrastructure can be placed before it acts as a barrier to migration. Even a single, isolated road can delay *Rangifer* migrations for days or weeks to more than a month [38, 46] and the amount of traffic on the road greatly influences the strength of a barrier effect. In Norway, where fjords and steep mountains shape reindeer movement options and infrastructure development is much denser and has proliferated especially along valley bottoms, virtually all free-ranging reindeer migrations have ceased and a once panmictic population has been isolated into 24 distinct herds [36, 37]. Barriers to migration can cause declines in affected populations by reducing and fragmenting available habitat [12, 47].

Human development is particularly important in relation to *Rangifer* accessing their winter ranges. *Rangifer* winter ranges can vary widely in location for a given population across years and are generally more widely dispersed than other seasonal ranges [19, 21, 48, 49]. Grazing and wildfire can reduce the abundance of lichens on winter ranges, which may be drivers of low winter range fidelity [50]. The extent and timing of snowfall during autumn is highly variable and *Rangifer* adapt their movements in response if they have free passage [3]. For example, freezing rain and heavy snowfall along the coast of Hudson Bay in 2005 [51] forced several herds to migrate hundreds of kilometers west of their typical winter ranges to find vegetation that was not locked in ground-fast ice [52]. Additionally, when herds decline and increase in size, their use of winter ranges contracts or expands, respectively, and can shift as well [19, 21, 32, 53, 54]. Whatever the root cause, the key consideration is that large *Rangifer* populations need access to vast multi-annual winter ranges to acquire sufficient resources and deal with annual extremes in climate. If human-made obstacles, such as roads, railroads, villages, hydroelectric lines, pipelines, mines, wind turbines, and oil and gas facilities, prevent caribou from migrating, large areas of key habitat can be isolated and functionally lost [36, 38, 45]. The impacts associated with these obstacles, such as noise, aircraft, and road dust, as well as human recreational activity, including hunting, snowmachining, skiing, and hiking, need to be considered as well [35, 55, 56, 57, 58]. Heavy harvest, facilitated by increased access provided by all-season and winter (ice) roads, can accelerate natural population declines in *Rangifer*, as was the case in the winters of 2007-2008 and 2008-2009 when winter roads enabled an annual harvest of several thousand caribou from the Bathurst Herd when it was already in decline [59].

Global human population growth will create increasing demands on natural resources and foster additional development and use of the Arctic [60]. There are multiple amplifying feedbacks related to increased human activity with, for example, increased fires and increased shipping both a consequence and cause of more rapid warming. To date, accommodating cumulative impacts has been slow despite available tools [45, 61, 62, 63]. *Rangifer* are known to be displaced by human infrastructure and activity under certain conditions, particularly females with neonates [45, 64, 65, 66]. These zones of influence vary but can exceed 15 km [45, 67, 68, 69]. As the human footprint expands in the changing Arctic, mitigations will be needed to ensure free passage of *Rangifer* so that their migrations are maintained, and their populations remain robust.

3 Direct effects of changing temperature and precipitation regimes on caribou migrations

Climate change will directly impact *Rangifer* migrations through changes in temperature and precipitation. One of the most obvious changes will be on the formation and loss of ice [70]. Loss of sea ice may extinguish migratory routes, as *Rangifer* tend to avoid swimming long distances in the ocean, increasing genetic isolation in some populations [71, 72, 73, 74, 75]. In extreme cases, such as in the Dolphin and Union Herd in Canada which calves on Victoria Island and winters on the Canadian mainland, delays in sea-ice formation can lead to increased mortality during fall migration [76]. Similarly, loss of freshwater ice may also cause *Rangifer* to divert around unfrozen lakes and rivers or swim across them, both adding to the energetic costs of migration [42]. Thin ice conditions may also be avoided or result in additional energy expenditures, injury, or even death if the animal breaks through [77]. Thin or moving ice on rivers can present a barrier to *Rangifer* migrations. *Rangifer* can either pause their migration to wait for the ice to thicken or disperse. We expect that *Rangifer* will encounter less and thinner ice conditions under almost all climate change scenarios, which will likely lead to longer routes and the loss of some migratory movement options, especially those associated with arctic islands.

Snow accumulation and characteristics are other factors that can affect the timing and duration of migration [3, 22, 78, 79]. During spring migration, deep, soft snow can impede *Rangifer* movements and delay migration [79]. In contrast, shallower or wind-hardened snow can facilitate movement. In fall, which is less studied than spring, accumulating snow can trigger migratory movements [80]. Under climate change scenarios, snow may come later in the fall, delaying migrations. In spring, snow melt may happen early, which may lead to earlier departures and earlier or later (if deep, wet, soft snow conditions develop) arrivals on the calving grounds [3, 78] with subsequent shifts in distribution to take advantage of optimal forage and calving locations [16]. While many northern areas may see less snow [81], with less sea ice extent, the amount of available moisture in the Arctic may greatly increase, which could lead to increased spring snow loads in some regions [82, 83]. This could delay migration and/or require additional energy expenditure to traverse it [84]. Precise information on the energetic costs of real-world locomotion through snow and sinking depths in various snow conditions across large landscapes would be beneficial for a more accurate understanding of the impacts of a changing snow regime.

Climate change is expected to bring about more ROS events in the Arctic, which are known to affect caribou movements and the free passage of *Rangifer* [85, 86, 87]. The formation of ice crusts on the snow's surface can prevent *Rangifer* from accessing their primary winter forage, terricolous lichens, and cause them to abandon affected areas. However, if the ice layer is thick enough, it can support the weight of *Rangifer* and improve mobility [42]. Similarly, if enough rain falls, it can melt the entire snowpack, exposing bare ground and lichens that could improve travel and foraging. Thus, whether climate change negatively or positively impacts *Rangifer* is a matter of degree and timing. It has been suggested that colder temperatures in fall may trigger migratory movements [88, 89] and, therefore, warmer temperatures associated with climate change might dampen migratory cues for *Rangifer* in fall. Warmer temperatures are also associated with permafrost degradation [90]. Loss of permafrost can lead to catastrophic lake draining and the development of thermokarst features. In some cases, such as thaw slumps and slides, these features will hinder *Rangifer* migratory movements, but in others, like lake draining, they may facilitate them. The direct impacts of climate change on *Rangifer* migration will be diverse and highly varied across regions and populations. The question as to whether long-distance migrants, like *Rangifer,* are more or less resilient to climate change, or other perturbations, than non-migrants depends on local conditions, the intensity of the perturbations, and the particularities of a given population's migration portfolio. Populations that display greater migratory plasticity will likely have greater resiliency.

4 Vegetation and diminishing seasonality

Forage quality and quantity, which is impacted by seasonality, are critical to *Rangifer*. Changes in vegetative phenology, including timing of green up and length of the growing season, have been relatively well studied [91]. Vegetative green up is occurring sooner and the growing season lasting longer, and both trends are expected to continue as the Arctic warms [16, 92, 93]. Earlier and longer access to green vegetation could reduce seasonal differences in the Arctic, improve individual body condition of *Rangifer* [94], and, we posit, lead to a lower prevalence of migration or shorter migratory movements. Alternatively, if improvements in body condition lead to greater abundance, this could trigger more and longer migratory movements. However, the length of the growing season in the Arctic is also impacted by day length, which will not be affected by climate change, so there are likely limits to how much seasonality will change in the Arctic. Further, one key driver of *Rangifer* movements in spring is the need to fully utilize the highest quality forage, which is typically newly emergent green growth [13, 16, 95]. A longer, warmer growing season on the Arctic is associated with greater plant growth and productivity, but forage quality will not necessarily improve and may actually decline [96]. As selective feeders, *Rangifer* access forage that emerges over a wide spatio-temporal matrix that is influenced by snow melt, topography, soils, and habitat types. *Rangifer* living in mountainous regions, for example, have access to a wide window of emergent vegetation due to topography and therefore may not have to migrate (other than vertically). If climate change reduces the spatio-temporal availability of emergent vegetation [97], by condensing the temporal window of availability, this could have proximate impacts on body condition and ultimately affect *Rangifer* migrations.

Concerns over a potential trophic mismatch, where the timing of green up does not coincide with calving, have been raised, but also questioned [78, 92, 98, 99]. Arctic *Rangifer* arrive on the calving grounds before vegetative green up and rely on bodily stores at the end of winter before high-quality forage is available [22, 100, 101]. Thus, we expect any effects of a trophic mismatch to be subtle at first, but they could be amplified as climate warming and earlier greening progress. Changes in pre-calving migration timing are likely, as *Rangifer* are adaptable in when they arrive on their calving grounds [3, 22, 78, 102].

Rangifer tend to avoid dense vegetation during migration, perhaps to avoid predators and the snow it traps, and/or to reduce energy expenditures associated with getting through it [21, 79, 103]. Climate change is predicted to increase the extent of woody vegetation across the Arctic [104]. Expanded shrubland and forest may extend current migratory routes, as *Rangifer* move around these areas, or shorten them, as the distance between tundra calving areas and taiga wintering areas is reduced. In either case, the vulnerability of some *Rangifer* herds to predation during migratory periods may increase [105]. These habitat types may also increase the abundance of other ungulate species like moose, *Alces alces*, and deer, *Odocoileus* spp., which in turn could increase predators of *Rangifer* like wolves, *Canis lupus*, and bears, *Ursus* spp. In a process known as apparent competition, these increases in predators could lead to more predation and fewer *Rangifer* on the landscape [106]. The impact of this process would likely be limited to the boreal forest-tundra ecotone. This highlights the importance of vast expanses of tundra habitat for large populations of *Rangifer* [19, 107].

Wildfires are projected to increase under climate warming scenarios [108, 109]. Large burned areas may alter *Rangifer* migrations, especially if they result in a tangle of downed trees that are difficult to traverse or deterioration of winter ranges through reduced lichen abundance [50, 110, 111, 112]. In the vast, largely undisturbed northern *Rangifer* ranges, wildfire has not been shown to affect population sizes, however, with an expanding human footprint and other stressors, increases in wildfires driven by climate change could ultimately have population-level effects [110]. Overall, we predict that climate change-induced impacts on vegetation will be substantial, with increased shrubs, a northward moving treeline, and less lichens on the landscape. These changes will likely impact *Rangifer* populations and their migratory routes.

5 Changing impacts of biting insects, parasites, diseases, and invasive species

Biting insects, parasites, diseases, and invasive species can strongly impact *Rangifer* and their migrations. While *Rangifer* migration is most closely associated with the spring movements of parturient females to the calving grounds and the herd moving to their wintering grounds in fall, movements to insect relief habitats is another characteristic of many arctic *Rangifer* populations. The importance of biting insects, including mosquitoes, *Aedes* spp., warble flies, *Hypoderma tarandi*, nasal bot, *Cephenemyia trompe*, and black flies, Simuliidae family, on the ecology of *Rangifer* is pervasive and hard to overstate [18].

Warmer summers will likely expedite parasite development times, raising the possibility of phenological changes in this cycle. Avoidance of gastro-intestinal nematode parasites has been proposed as a rationale to why *Rangifer* females and calves migrate away from calving grounds [113]. Predicting how different parasite species will respond to climate change and the implications for their *Rangifer* hosts is complex [114,115]. Climate change also has the potential to affect the location and extent of insect relief areas, as well as the duration and intensity of the insect harassment period. *Rangifer* aggregate at remnant snow patches, in habitats with little vegetation, including gravel bars, lakes and even shallow ocean waters, and areas with greater wind speeds to reduce insect harassment [17, 18, 116]. Climate change will likely substantially reduce the available snow patches that *Rangifer* use for insect relief. While shrubland is are predicted to increase, reducing insect relief habitat, edaphic conditions will likely attenuate these increases in certain habitats like mountainous regions. How winds will be impacted by climate change is uncertain, especially because of how the progressive loss of summer sea ice will modify coastal winds for many herds that move to the coast for mosquito relief. Temperature, which is a key factor in the duration and intensity of insect harassment [17], is much more certain to increase, and with it, so will insect harassment. Thus, we predict that climate change will lead to earlier and more intense insect harassment, with less overall insect relief habitat. In turn, this could lead to further migration distances and/or negatively impact individual body condition.

We expect that disease prevalence will increase with changes in the Arctic. The vector for many new diseases will be invasive species. These may include white-tailed deer, *Odocoileus virginianus*, and black-tailed deer, *Odocoileus hemionus*. Aside from negative impacts associated with apparent competition (see above), these species carry and can transmit pathogens, such as brainworm, *Parelaphostrongylus tenuis*, that are very harmful to *Rangifer*. We expect that climate change will increasingly bring deer into proximity to northern *Rangifer* populations, which could have negative impacts on *Rangifer* populations and migrations. The prion-based Chronic Wasting Disease (CWD) is spreading in several northern cervid species whose distribution overlaps with *Rangifer* populations. Prion disease can also occur spontaneously which led to the eradication of a Norwegian reindeer population in which it was found [117, 118]. Exposure of migratory *Rangifer* to this disease, for which there is no treatment and a high mortality rate, is one of several possible increased pathogen risks that may increase with a warming climate.

6 Next Steps

Climate change is going to affect a wide array of factors that influence *Rangifer* migrations in complex and interrelated ways, making it very difficult to precisely predict how a changing Arctic will impact *Rangifer* populations and their migrations. While *Rangifer* have persisted through previous climatic changes and have inherent resiliency to change, we posit that maintaining free passage of *Rangifer* movements is critical for maintaining migrations and therefore supporting large populations [12]. They need to be able to make choices about how they use the landscape, both in the long term (e.g., reaching seasonal ranges) and in the short term (e.g., escaping food shortage due to ROS or reducing exposure to human disturbance or avalanche risk). In addition, we need to consider the variability in the location of calving areas through time [13, 102] or predictable shifts that will occur as optimal conditions are modified by changes in phenology [16].

Development in the Arctic is going to continue. Given the incalculable value of *Rangifer* to the North, we recommend finding ways to ensure that large *Rangifer* populations have enough space to roam by implementing effective mitigation measures on potential barriers that allow them free passage using "green" infrastructure. Some lessons have already been learned. From Norway, we know what amounts of infrastructure have led to the cessation of migrations and how *Rangifer* respond to traffic frequency during pre-calving as compared to fall migration [36, 37, 119]. In the Arctic, mining companies attempt to mitigate the effects of ore hauling on caribou migration through speed restrictions and partial road closures [120]. In Canada, pre-calving migration was delayed 2-4 days by a haul road and almost ¾ of the crossings were when roads were closed to non-essential traffic [121]. In Alaska, we have learned that either burying or elevating pipelines high enough that *Rangifer* can cross under them even with snow on the ground can improve permeability [35]. Throughout their range, we also know that calving *Rangifer* and females with neonates are the most sensitive to disturbance [64, 65].

While this is a good start, additional knowledge is urgently needed. Specifically, 1) identifying thresholds at which permeable barriers become impermeable to migrants, 2) determining cumulative impacts of different types of human disturbance, including climatic changes [45], 3) determining effectiveness of mitigation measures for roads to make them more permeable (e.g., seasonal use restrictions, use of convoys, vehicle trip limits, speed limits, noise and/or dust reduction measures, separating responses to hunting from roads, etc.), 4) identifying and mapping migratory routes by integrating all sources of information, including Indigenous, local and palaeoecological knowledge, so they can be conserved [40], 5) conducting modelling and manipulative experimental work to better understand the potential impacts of climate change on vegetation, insects, and icing events [97], and 6) identifying ecological and social tipping points. Additionally, researchers must improve information transfer to and from all involved stakeholders (i.e., the general public, local communities, land managers, and politicians that make decisions) in a digestible format. While it has become standard for impact analyses to include an assessment of cumulative impacts, the problem of translating these assessments into regional planning and policies remains [29, 61]. The importance of *Rangifer* to Indigenous peoples, whom have co-existed for thousands of years with migratory herds and identified the effects of mines and roads on *Rangifer* movements and persistence, has made them key advocates for large-scale conservation of *Rangifer* habitat [e.g. 122]. The maintenance of Indigenous rights will likely become a key mechanism for *Rangifer* conservation [e.g. 123].

7 Conclusion

The climate in the Arctic is changing faster than anywhere else in the world and perhaps at an unprecedented pace [109]. The key question is: can *Rangifer*, particularly in the face of significant changes in land use and development, keep up with these changes? *Rangifer* migration is highly plastic, has persisted through previous large changes in the climate (including multiple ice ages), and can be resilient to future changes so long as it is set in a relatively undisturbed, open landscape. Caribou need access to ranges even used occasionally [102] to respond to highly variable environmental conditions. Thus, we recommend that large areas of undeveloped critical habitat, like calving grounds, be protected to conserve *Rangifer*. Where barriers exist, or will exist, migrations will be altered or lost. This will have disproportional impacts on (often Indigenous) residents of remote arctic regions, including on their subsistence harvests, culture, economies, and well-being [5, 6, 124]. As awareness of ecological justice grows, our global society must acknowledge these effects upon the Arctic and its inhabitants.

Rangifer migration is shaped by collective behavior and memory. These two factors are key to how *Rangifer* migrate across landscapes and their adaptability to weather and climate variability. However, we are only just beginning to use contemporary tools of telemetry, biologging and genomics to understand how memory and collective behavior impart resilience to *Rangifer* [24]. Similarly, Indigenous knowledge on these topics is only now becoming prevalent in publications, public forums, and in government-led processes. We suggest that collective behavior and memory are likely underestimated drivers of individual fitness in social ungulates.

If piecemeal development of the Arctic continues without concertedly, conscientiously, and effectively conserving *Rangifer* migrations, we predict that this global spectacle will be greatly reduced, severely impacting arctic peoples, ecological services, and *Rangifer* themselves. While management and ecology are complex and possibilities are limited in the Arctic, we believe that there is another future: one where large populations of *Rangifer* continue to undertake long-distance migrations that support arctic peoples and ecosystems. This future relies upon developing and implementing science- and local/Indigenous knowledge-based best practices to mitigate barrier effects, understanding cumulative impacts, respect for the Arctic and its peoples, and restraint. While this requires a substantial amount of work and trade-offs, the vision of large *Rangifer* herds streaming across the vast northern tundra 100 years from now is certainly worth the effort.

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