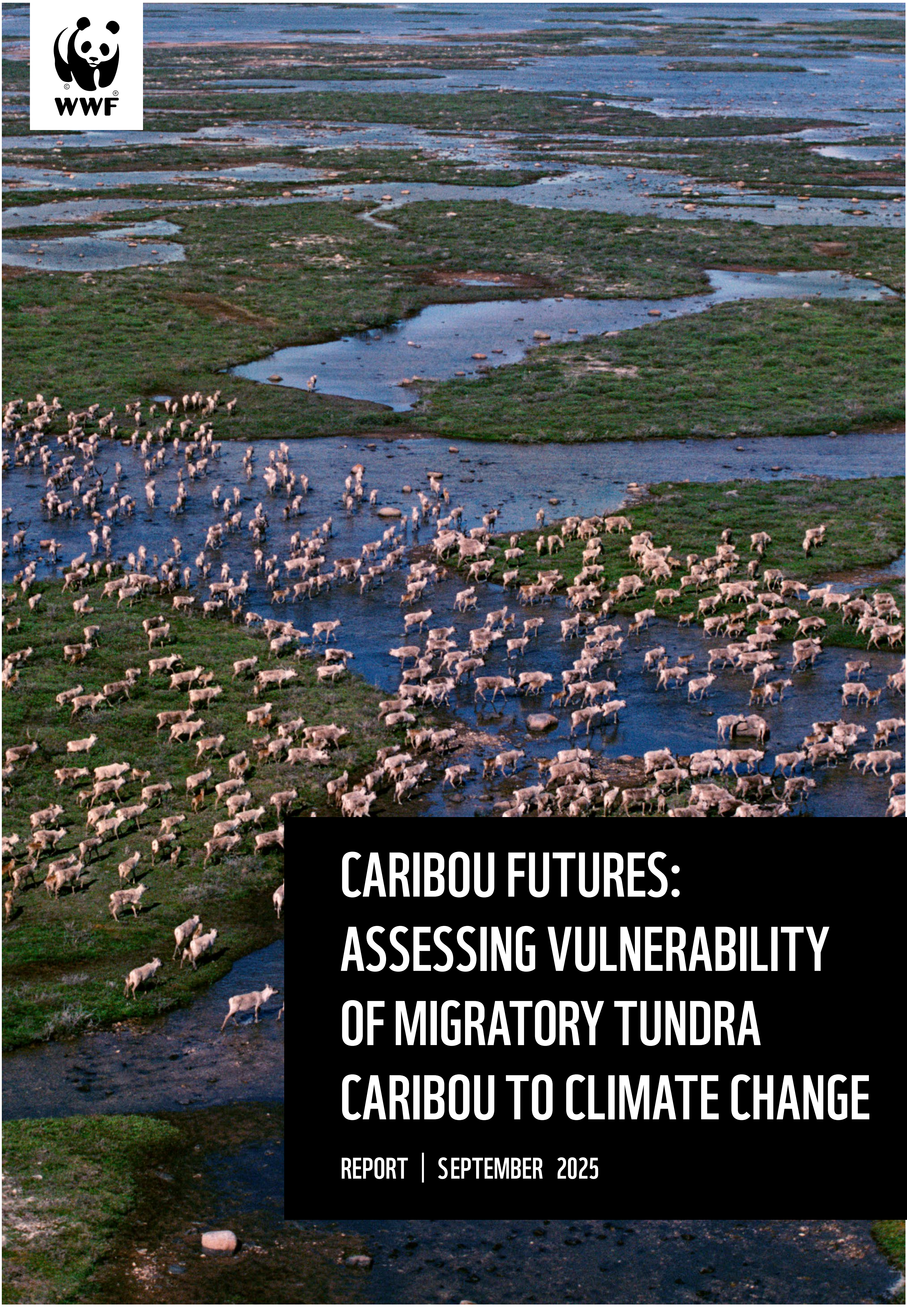

# CARIBOU FUTURES: ASSESSING VULNERABILITY OF MIGRATORY TUNDRA CARIBOU TO CLIMATE CHANGE

REPORT | SEPTEMBER 2025

# CARIBOU FUTURES: ASSESSING VULNERABILITY OF MIGRATORY TUNDRA CARIBOU TO CLIMATE CHANGE

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# 1. INTRODUCTION

The Arctic is rapidly warming with far-reaching changes in temperatures, sea ice, snow, and permafrost, accelerating impacts to all aspects of Arctic life. Recent estimates suggest an average warming of 4°C (Rantanen et al. 2020, 2023). In turn, we urgently need to understand impacts and their implications for guiding proactive Arctic conservation, adaptation and sustainable development investments. WWF's Global Arctic Programme has initiated the Arctic Conservation Forecast Project[1] (ARCON4) using climate forecasts and interdisciplinary expert deliberations to describe Arctic ecological changes across the 21st century under different warming scenarios. ARCON4 uses a bracketing approach to assess the range of changes that are likely under climate scenarios of "best-case" (low warming) and "worst-case" (high warming).

We applied WWF's approach to assess the vulnerability of representative migratory caribou herds to answer the question of how migratory tundra caribou herds might fare under climate change. Caribou (*Rangifer tarandus)* are highly important for Arctic terrestrial ecosystems and Indigenous peoples. Concerns for the fate of large migratory tundra caribou herds are already high at a time when most migratory tundra herds are declining (CARMA 2023; Figure 1). For 27 tundra migratory herds in the last 40 years the maximum number of *Rangifer* known to exist was 3.92 million in 1994. The latest estimate is 1.84 million, a 53 per cent reduction and a halving rate of 20 years. But those figures conceal some collapses in formerly large herds (Gunn et al. 2024). Protecting and connecting current and future habitats of caribou and working towards management that accounts for and is informed by climate change effects, is a priority for the WWF Global Arctic Programme and other rights- and stakeholders.

The climate scenarios are derived from the Coupled Model Intercomparison Project Phase 6 (CMIP6) global climate models, which are those scenarios used in the Intergovernmental Panel on Climate Change Assessment Report. Consistent with the ARCON4 project, we projected potential impacts of changing temperatures for a best-case (optimistic) and a worst-case (pessimistic) scenario for two periods: mid-century (2050) and end-century (2100). The optimistic (low emissions) scenario, SSP1-1.9 (referred to in this report as 119) is based on the possibility of global warming staying below 1.5°C in 2100 while SSP5-85 (585 in this report) is the most pessimistic (high emissions) scenario.

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[1] https://www.arcticwwf.org/our-priorities/biodiversity-and-nature/arctic-conservation-forecast-initiative/. For further information on this initiative, please contact info@arcticwwf.org.

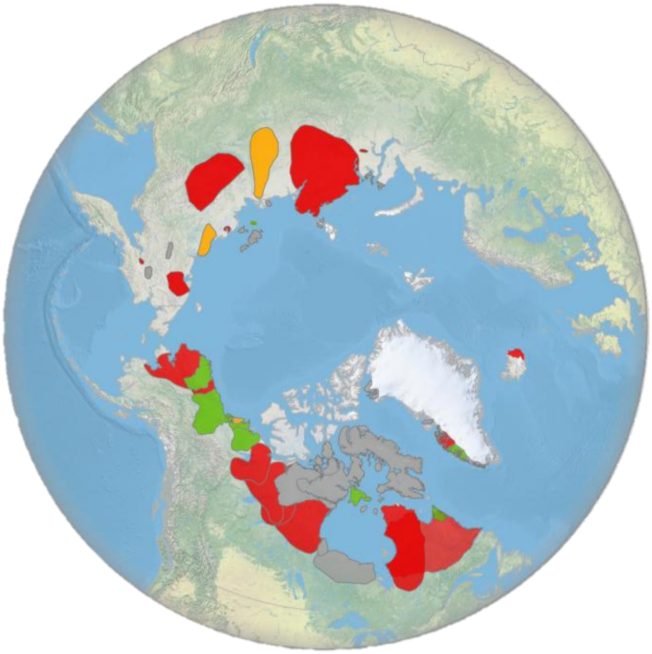


Figure 1. Current trends in global migratory tundra caribou herds: red is declining, orange is stable, green is increasing and grey is unknown status.

To assess caribou vulnerability, we adopted the International Panel on Climate Change's (IPCC 2007) approach for assessing vulnerability to climate impacts which is a widely accepted approach. Singer and Lee (2021), for example, describe rating the vulnerability for species at risk in the Northwest Territories, including caribou. Vulnerability is a measure of risk or potential harm and combines potential impacts of climate change with the capability to adapt to, or cope with, these changes. Vulnerability is typically defined by exposure, sensitivity and adaptive capacity (Figure 2).

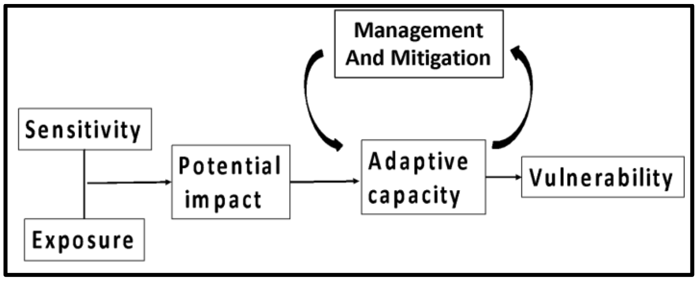


Figure 2. Flowchart for a vulnerability assessment (IPCC 2007).

To predict the vulnerability of circum-arctic migratory tundra caribou herds, we selected three representative herds that have evolved under regional climates, which allowed us to describe where, when, why and to what degree they are vulnerable (Glick et al., 2011). By sampling regional climates, we also reduce uncertainties in projected caribou impacts.

Climate influences almost every aspect of caribou ecology. While reviewing impacts of a warmer climate, Mallory and Boyce (2018) concluded, “The predicted consequences of climate change on *Rangifer* populations are complex and varied. How these environmental changes might interact remains unclear.” Consequently, to integrate climate impacts, we use modelling, an increasingly well-accepted approach (Johnston et al. 2019), to project individual responses to climate at the population (herd) level. While there are models linking forage intake to population output (Stratmann et al. 2023), we relied on an integrative model which incorporates how a cow allocates energy and protein from forage to her maintenance and her calf’s survival and linking to herd productivity and trends in herd size (White et al. 2014, Russell et al. 2021). We included both adult and calf caribou as mature and young life history stages can differ in their responses to climate (for example, Kissel et al. 2024).

For the vulnerability assessment, our quantitative caribou model integrates herd-specific climate, plant response, foraging dynamics, nutrient allocation and activity budgets to herd productivity. The resulting model projections allow caribou managers to ask “what if” questions across multiple scales. None of these attributes would be possible with a simple qualitative review of caribou and climate.

Given the importance of Arctic caribou, a sense of urgency is growing about their vulnerability to a warmer climate. Caribou are a cold-adapted widely distributed Arctic species with, for example, specific genes associated with brown fat for non-shivering heat production in calves, regulating capillary flow for restricting nasal heat loss and heat loss from the legs (Li et al. 2023). As caribou are herbivorous, many impacts of climate change are indirectly mediated through effects on plants (Appendix A). The caribou annual cycle (birth, lactation and conception) is tightly coupled to the timing of summer’s pulse of plant growth starting as snow cover recedes. Forage is high in nitrogen at the beginning of summer and as the plants mature, nitrogen declines while energy and biomass remain stable further into the summer. By late summer, plants senesce, nutrient quality declines and by late fall, snow cover increases the energy costs of foraging. While these relationships between caribou life cycle and plant growth were initially described for the Porcupine and Central Arctic herds (White 1983, Russell et al. 1993, Johnson et al. 2021, 2022), they are applicable to all herds although timing of phenological changes varies regionally relative to caribou protein and energy demands.

Our Caribou Cumulative Effects (CCE) model (Figure 3) tracks changes in diet quality and quantity to estimate nutrient intake under different climate scenarios. The model allocates nutrient intake to body maintenance, fat and protein reserves, gestation and milk production to project cow and calf/fetal body weights, and how these weights impact probability of pregnancy and cow survival. Those potential impacts are then assessed through a population model to project potential trends in herd size.

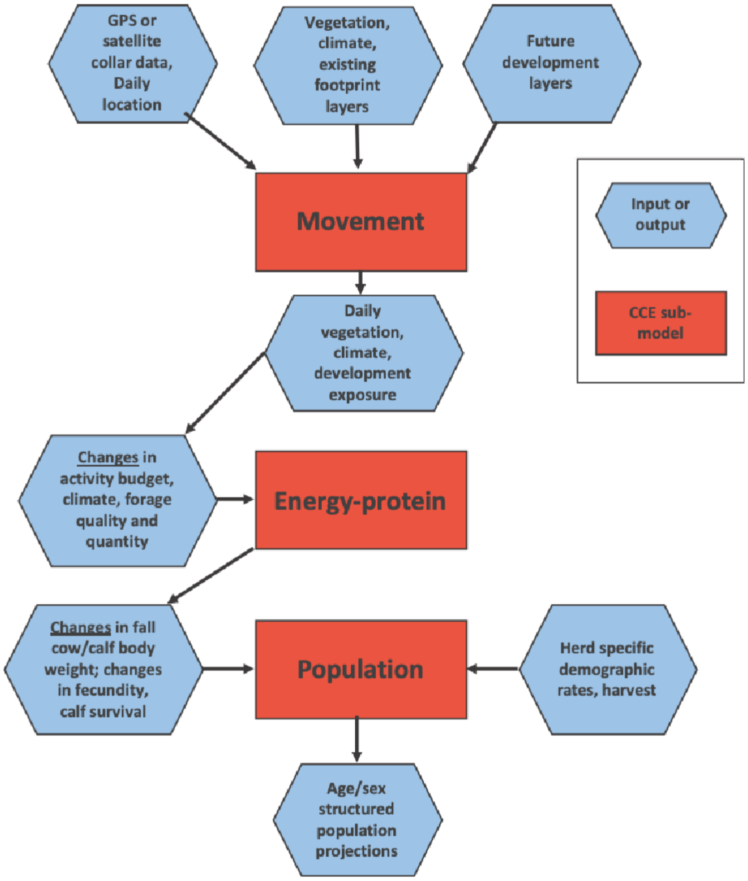


Figure 3. Schematic of the caribou cumulative effects (CCE) model showing sub-model components in red and various sub-model inputs/outputs in blue.

# 2. OBJECTIVES

To develop a scientific basis for guiding WWF's future conservation efforts and emerging priorities, as well as informing decision makers on Arctic development by:

1. Identifying climate variables that can be meaningfully connected and projected into the future for selected migratory tundra herds (Central Arctic, Bathurst and Taimyr).
2. Developing a vulnerability assessment of select migratory tundra herds by employing cumulative effects modelling that derive linkages between climate variables and herd productivity.
3. Projecting identified vulnerabilities into the 21st century by using the outputs from the latest generation of global climate models (Coupled Model Intercomparison Project Phase 6; CMIP6) for 2050 and 2100 for best-case and worst-case scenarios.

# 3. METHODS

Applying the CCE model requires building data sets for climate scenarios from the global climate models by, for example, converting CMIP6 temperature projections data to plant growing degree days. Studies on herd/climate integration for the three herds are unevenly available which required us to generalize existing relationships among climate variables, plant growth and caribou forage intake.

## 3.1. STUDY HERDS

We selected three migratory tundra herds to sample the Arctic's bioclimatic zones which reflect how geography (coastal or continental; lowland or upland climates) and underlying geology (sedimentary vs Precambrian Shield) all contribute regional differences to migratory caribou ecology. To sample the regional variability, we selected the Central Arctic (CAH), Bathurst (BAH) and Taimyr (TAI) caribou herds (Figure 4). The three herds also currently vary in whether they are increasing, decreasing or stable at extreme low numbers: those demographic trends influence their vulnerability and resilience. Management regimes are based on monitoring demographic rates and trends in herd size with management actions largely being restricted to changes in hunting regulations and on occasion, reducing wolf numbers.

### 3.1.1 Central Arctic herd (CAH)

The herd's calving and summer ranges on the Alaskan northern coastal plains are low-lying, flat, lake or pond rich landscape with an intensive cover of calcium-rich tundra. The calcium-rich tundra has fewer shrubs and a higher forb diversity than tussock tundra (Walker et al. 2001). The herd winters south into the tundra of the Brooks Range. Caribou continue to respond to traffic on the Prudhoe Bay oilfield all-weather roads and reduce their use within 2-5km of the roads and structures even after 40 years during calving, post-calving and summer ranges (Johnson et al. 2020, Severson et al. 2023).

The coast modifies the calving and summer climate and this is changing as the extent of open water is increasing (Dial et al. 2024). Significant climate trends (1989-2016) are more plant growing degree days in June and July, more precipitation in July, an increasing mushroom index and warmer temperatures in October. Severe events were exceptionally late spring in 2013 resulting in adult female deaths with as high as 25 per cent of collared females dead in May.

The herd increased during the 1990s and peaked at 70,000 caribou by 2010 before declining to 22,630 caribou (range: 20,074–25,186) in 2016 (ADF&G 2017). Subsequently, numbers started to increase and by 2022, the herd numbered 34,000.

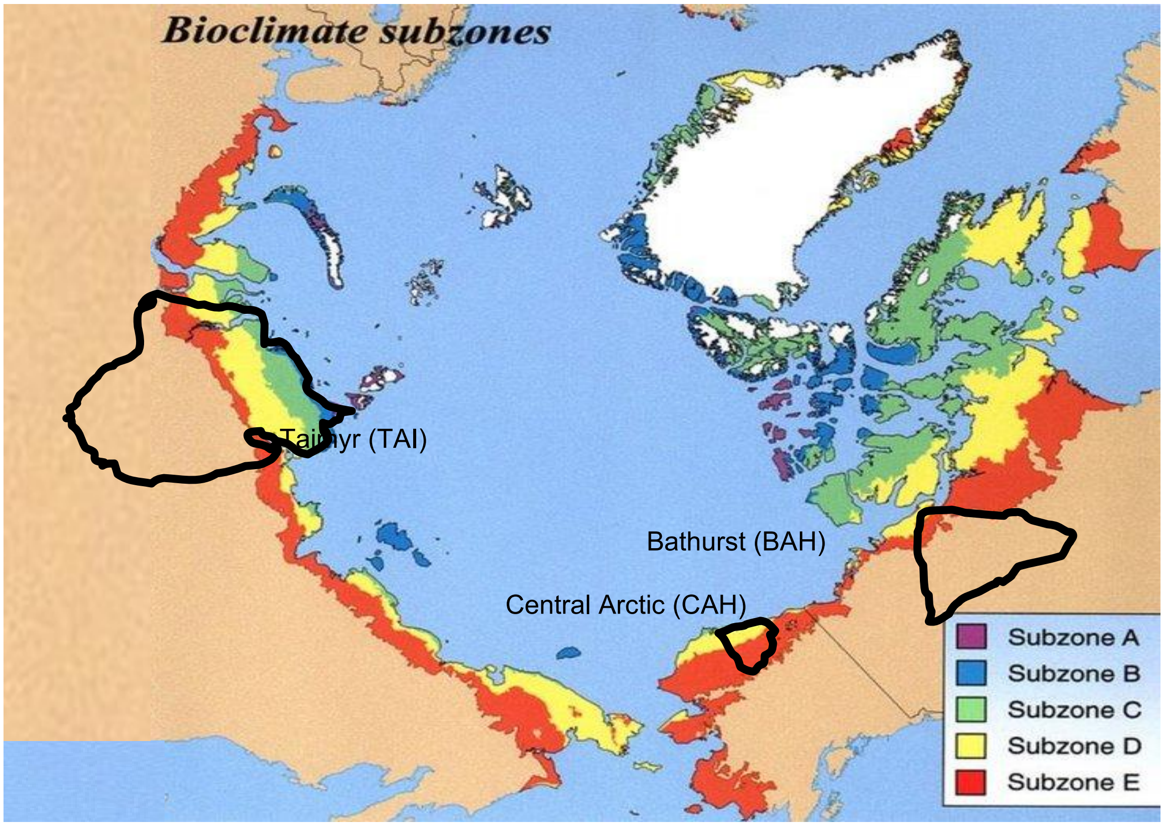


Figure 4. The Circumpolar Arctic vegetation map showing approximate summer ranges of the three representative migratory tundra *Rangifer* herds.

### 3.1.2 Bathurst herd (BAH)

The annual ranges are located on the Precambrian Shield characterized by rock outcrops, glacial deposits, many lakes and sparse acidic tundra vegetation. The herd's summer range lies inland with a continental climate with warmer summers: July precipitation is higher than the neighboring herds which reduces the drought index despite the warm July temperatures. The BAH has higher parasitic warble fly (oestrid) index and colder drier winters than its neighboring herds to the west. Severe events include high drought indices in 2012 and 2014. The number of days with freezing rain, July precipitation and the mushroom index have declined while rain-on-snow and October temperatures have increased.

Mining exploration and development is a landscape feature with abandoned and three active open pit and underground mines (Bathurst Caribou Range Plan 2017). The cumulative impacts of industrial development remain largely unmeasured. A seasonal ice road links the mines to Yellowknife and the high frequency of traffic influences caribou movements (Smith et al. 2023). As warmer winters contract the ice road season, the ice road is likely to be replaced by an all-season road (Russell et al. 2022).

Herd abundance peaked at 472,000 in 1986, slowly declined until between 2006 and 2009, the rate of decline accelerated as the herd dropped from 128,000 to 32,000 caribou, equivalent to a halving time of ca. 1.7 years (Boulanger et al. 2015). Subsequently, the herd has continued to decline and has stabilized at about 6,000 caribou in 2022 (Adamczewski et al. 2023).

### 3.1.3 Taimyr herd (TAI)

The TAI is a continental herd and the annual ranges do not extend to the coast (Kolpaschikov et al. 2015) but the Taimyr Peninsula does protrude into the Kara and Laptev Seas which have a cooling impact. TAI summers on the Taimyr Peninsula, with a harsh continental climate, low lying topography, silty soils, rare rocky outcrops, without large wet depressions or mountains (Matveyeva 1994). As a consequence, the TAI spring and summer ranges are cooler than the BAH and CAH. As peak of calving in migratory tundra herds is related to timing of spring green-up, the TAI calves the latest among the three migratory tundra herds (~24 June) compared to ~June 8 for BAH and ~June 3 for CAH.

The TAI peaked in 2000 with some 1 million wild reindeer. Since 2000 the herd has declined to 420,000 in 2017 and 242,500 by 2021 and initial results of a 2022 survey indicated around 100,000 (Kolpaschikov pers. comm. 2023).

## 3.2 VULNERABILITY ASSESSMENT

We initiate the vulnerability assessment by assessing to which climate variables the caribou are sensitive. Then we estimate caribou exposure to those variables as the basis for estimating the diet, forage amount, nutrients and foraging time for the CCE model to project potential impacts (Figure 5). The model output is the potential impacts of the climate as measured by pregnancy rates, calf survival and ultimately, rate of change in herd size.

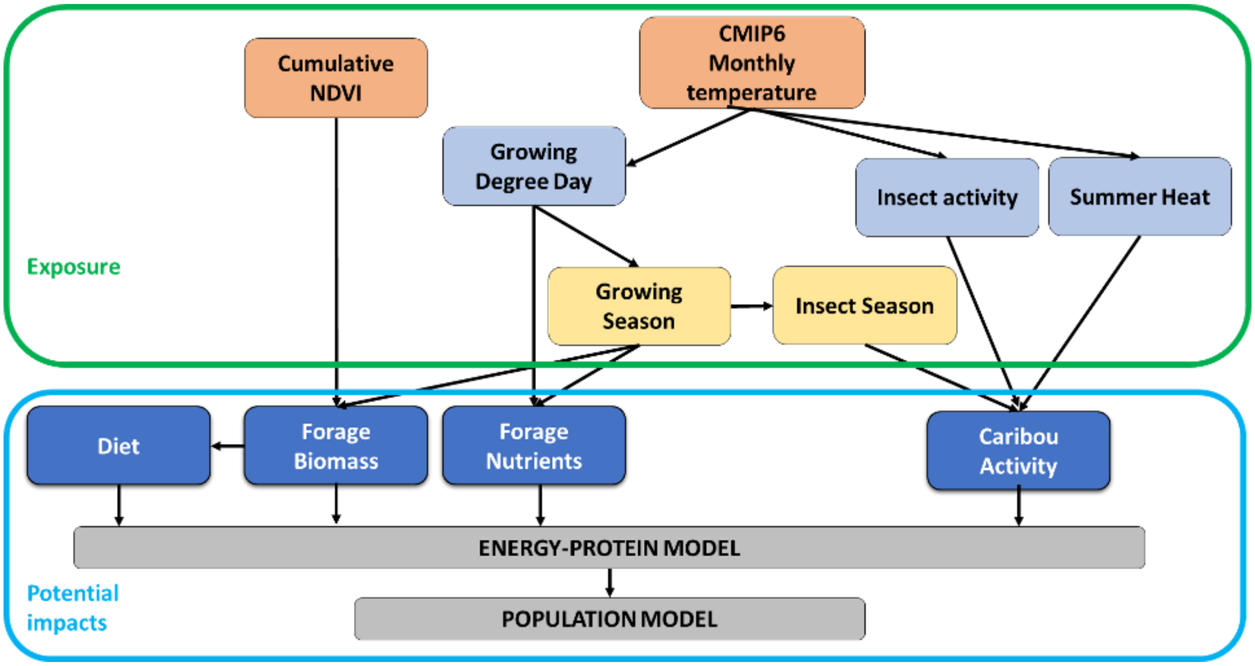


Figure 5. Modelling summer foraging ecology of caribou by basing climate inputs on projected mean monthly temperature to assess exposure and potential impacts.

### 3.2.1 Sensitivity to climate variables

Across the Arctic, warming is greater in the winter (relative to mean of 1981-2010), projected to reach about 4°C and 15°C by the end of the 21st century under SSP1-1.9 and SSP5-8.5, respectively. In contrast, summer warming is projected to reach about 1.5°C and 7°C under SSP1-1.9 and SSP5-8.5, respectively (IPCC, 2021). Although summer temperatures increase at a lower rate than winter, we focused on the caribou sensitivity to summer temperatures. Functional responses of caribou to colder or warmer winters are primarily related to icing conditions due to rain-on-snow, freeze-thaw events and freezing rain. However, icing conditions are poorly predicted by temperature alone, and uncertainty was high for precipitation forecasts. Therefore, our focus is on summer warming, a reliable indicator of plant dynamics, length of growing season and level of insect harassment. Further we understand how pregnancy rates and cow and calf survival are impacted by what happens in the summer through temperature effects on forage, insect harassment and direct effects of high temperatures on caribou internal body temperature.

For the this project, we used the mean monthly temperature data obtained from the CMIP6 global climate initiative. We projected potential impacts of changing temperatures for two periods: mid-century (2050; based on average monthly temperatures projected 2046-2050) and end-century (2100; based on average monthly temperatures projected 2096-2100). We summarized the CMIP6 data for two distinct future greenhouse gas emissions pathways temperatures for two scenarios (SSP1-1.9 and SSP5-8.5 referred to in this report as 119, 585, respectively) in each of the two time periods, 2050 and 2100. SSP1-1.9 is our optimistic scenario as includes the possibility of global warming staying below 1.5°C in 2100 while SSP5-85 is the most pessimistic scenario.

We identified the climate variables to which the CAH and BAH are most sensitive from an earlier analysis of vital rates and climate (Russell et al. 2024). We had used climate data from the Modern Era Retrospective Analysis for Research and Applications (MERRA) climate database to quantify the linkages between vital rates, such as adult and calf survival with climate variables. We examined the relationships with direct climate variables, such as temperature and derived variables such as a mosquito index derived from temperature and wind speed to describe the sensitivity of the caribou herds to climate.

### 3.2.2 Exposure to climate variables

For estimating exposure, we also used satellite-based green-up data (Normalized Difference Vegetation Index, NDVI) to adjust relative available green vegetation (shrubs, graminoids, forbs, for example) among the three representative herds. Mean monthly temperature was used to create the intermediate indicators to represent the exposure faced by caribou under future scenarios.

i) <u>Summer temperature: Monthly temperature and Growing Degree Days (GDD)</u>

We downloaded mean monthly temperatures for all five project scenarios (current, 2050 and 2100, optimistic [119] and pessimistic [585]). As most of our previous analysis and modelling regarding climate was based on MERRA climate data (Russell et al. 2013), while the current “historical” climate data for the project is ERA5 reanalysis data, we verified that these two datasets were correlated ($r^2 > 0.88$) and thus use MERRA in replace of ERA5 historical data throughout this analysis. To visualize how projected temperatures will depart from current conditions, we plotted mean, maximum and minimum of current temperatures and compared to mean monthly temperature for all three reference herds (see Figure 10).

The next step was using our MERRA dataset to perform a multiple regression predicting GDD in late spring and summer from mean monthly temperatures. As our MERRA database contains daily cumulative GDD, we generated herd-specific equations at approximate 10-day intervals between 26 May and 27 July. Then, by interpolating between these 10-day intervals, we produced a daily profile of GDD for each herd, scenario and time period.

ii) <u>Summer temperature: Insect activity</u>

Caribou reduce their exposure to mosquitos at the expense of foraging by moving to windier, less vegetated areas to escape the insect impacts of irritation, blood loss and parasite transmission (Russell et al. 1993). Mosquito harassment leads to reduced body reserves, reproduction and over-winter survival for adult caribou females (Johnson et al. 2018). Caribou also reduce their foraging time in response to oestrid (warble and nose bot) flies as they try to avoid them. The trend to early springs as well as changing the peak of plant nitrogen will also advance peak mosquito harassment (Gustine et al. 2017) and extend the oestrid harassment season.

We converted mean monthly temperature to insect harassment indices, separately for mosquitoes and oestrids. CARMA's MERRA climate database contains an annual cumulative insect index from 1980-2019 (Russell et al. 2013) for our three representative herds .Russell et al. (1993) generated the reduction in percent of day spent foraging based on level of insect harassment, used as input into the CCE model.

iii) Summer temperature: Hot days

In warm summers, caribou can suffer from over-heating partly because of the thermal mass of their large rumen. For large mammals in general, there are significant knowledge gaps in how they deal with heat (Fuller et al. 2016). Caribou (and reindeer) seek cooler slopes and snow patches and reduce their activity including forage intake. We applied Trondrud et al.'s (2023) documentation that, at 20°C, reindeer spent 9 per cent less time foraging compared to cooler days. First, we regressed our MERRA data to mean monthly temperature to estimate the number of days >19°C for each herd and future scenario. Then, to simulate reduced foraging, we reduced eating intensity (proportion of foraging time spent feeding), thus reducing food intake while leaving foraging, standing, walking, running and lying unchanged.

### 3.2.3 Potential Impacts

The potential impacts are projected through the CCE model which allocates forage quality and quantity to body weight which, in turn, relate to pregnancy rates and survival. The population model then projects those pregnancy and survival rates to herd size and trends.

i) Linking Growing degree day to forage nutrients

A major component of our CCE model is the rumen sub-model which simulates food intake and digestion producing daily metabolizable energy and nitrogen to be allocated to the caribou for growth, reproduction and mounting an immune response (Figure 6).

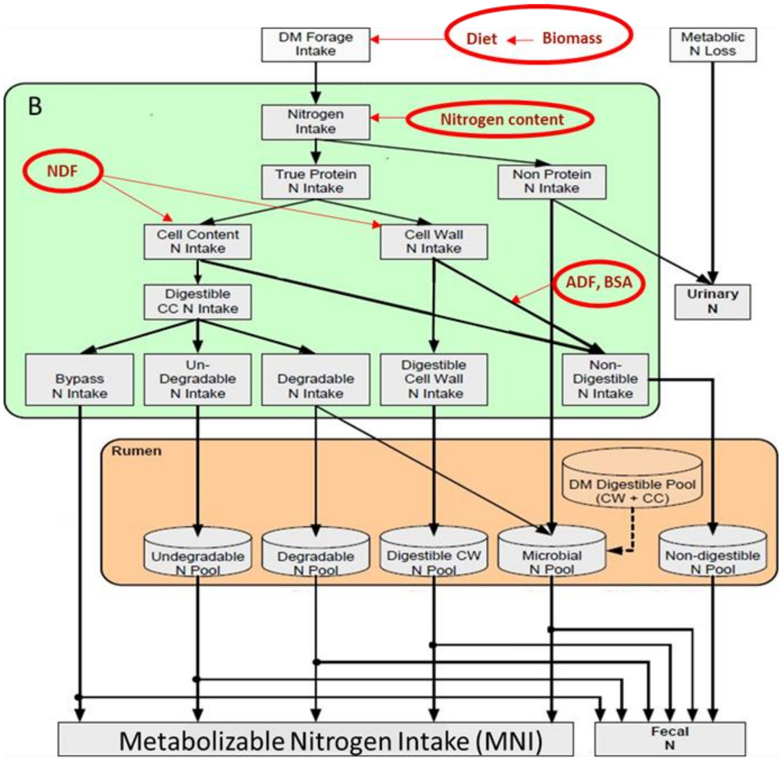


Figure 6. Nutrient pathways for nitrogen in the Rumen-Sub model. Acronyms in red depict where nutrient components entered the pathways.

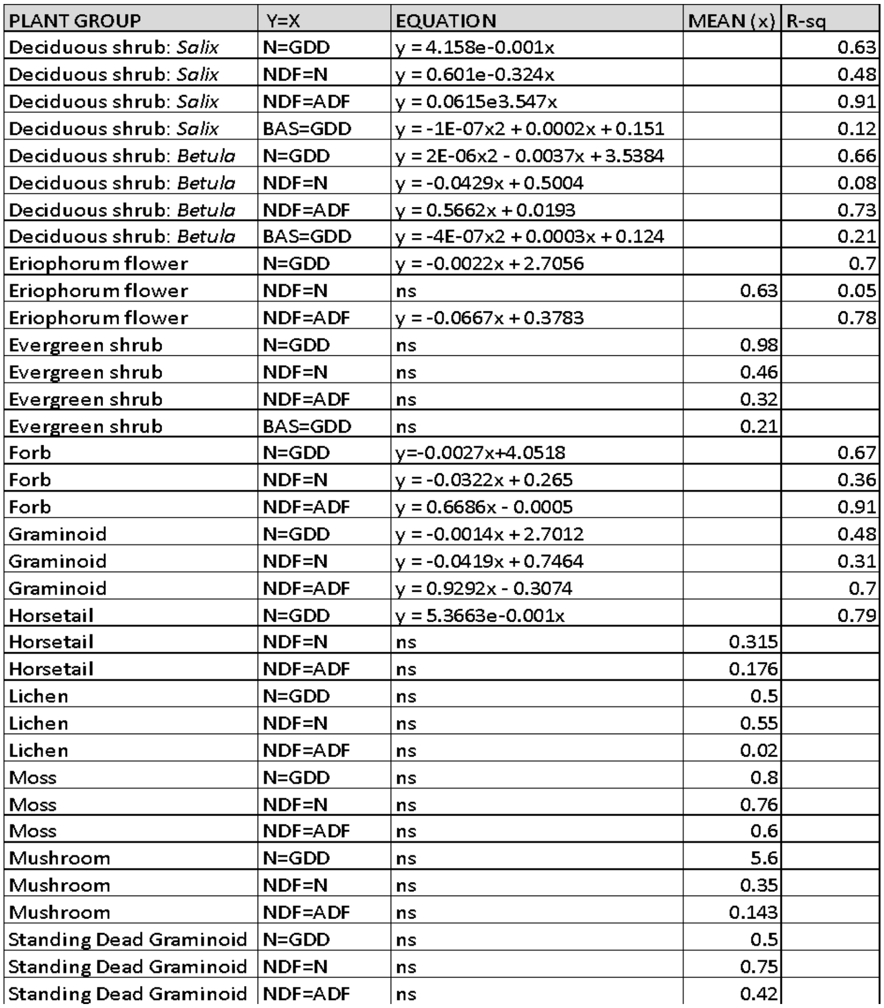
Warmer temperatures will impact the quality and timing of nutrient availability. To link growing degree days to nutrient quality, we used three plant nutrient datasets from northern Alaska that sampled plant species throughout the late spring, summer and early fall. Finstad (1998) sampled on the Seward peninsula from 1996-1998; Adams et al. (2018) sampled the summer range of the CAH from 2011-2014 and Leffler et al. (2022) sampled the summer range of the CAH from 2016-2018.

Integrating our MERRA climate database with the plant nutrient collections, we are able to link Growing Degree Days (GDD) with changes in plant nutrient contents. Predictive equations were developed from the datasets to generate nutrient input into the model in relation to GDD. For key plant groups in the diet of caribou, we generated their amount of energy, protein and digestibility from:

1. Percent nitrogen and Bovine Serum Albumen (BSA) by applying polynomial regression equation between GDD and percent nitrogen and BSA,
2. Neutral detergent fibre (NDF) from relationship between estimated percent nitrogen (from step 1) and NDF.
3. Acid detergent fibre (ADF) generated from relationship between ADF and NDF (from Step 3)

Thus, all components were updated automatically from the GDD profile for any climate scenario. Predictive equations were attempted on all 10 plant groups tracked in the model, however where relationships were not significant (p>0.05), mean values were substituted (Table 1).

Table 1: Predictive equations used to construct a profile of seasonal phenological change in plant nutrients among plant groups.



| PLANT GROUP | Y=X | EQUATION | MEAN (x) | R-sq |
|---|---|---|---|---|
| Deciduous shrub: *Salix* | N=GDD | y = 4.158e-0.001x | | 0.63 |
| Deciduous shrub: *Salix* | NDF=N | y = 0.601e-0.324x | | 0.48 |
| Deciduous shrub: *Salix* | NDF=ADF | y = 0.0615e3.547x | | 0.91 |
| Deciduous shrub: *Salix* | BAS=GDD | y = -1E-07x2 + 0.0002x + 0.151 | | 0.12 |
| Deciduous shrub: *Betula* | N=GDD | y = 2E-06x2 - 0.0037x + 3.5384 | | 0.66 |
| Deciduous shrub: *Betula* | NDF=N | y = -0.0429x + 0.5004 | | 0.08 |
| Deciduous shrub: *Betula* | NDF=ADF | y = 0.5662x + 0.0193 | | 0.73 |
| Deciduous shrub: *Betula* | BAS=GDD | y = -4E-07x2 + 0.0003x + 0.124 | | 0.21 |
| Eriophorum flower | N=GDD | y = -0.0022x + 2.7056 | | 0.7 |
| Eriophorum flower | NDF=N | ns | 0.63 | 0.05 |
| Eriophorum flower | NDF=ADF | y = -0.0667x + 0.3783 | | 0.78 |
| Evergreen shrub | N=GDD | ns | 0.98 | |
| Evergreen shrub | NDF=N | ns | 0.46 | |
| Evergreen shrub | NDF=ADF | ns | 0.32 | |
| Evergreen shrub | BAS=GDD | ns | 0.21 | |
| Forb | N=GDD | y=-0.0027x+4.0518 | | 0.67 |
| Forb | NDF=N | y = -0.0322x + 0.265 | | 0.36 |
| Forb | NDF=ADF | y = 0.6686x - 0.0005 | | 0.91 |
| Graminoid | N=GDD | y = -0.0014x + 2.7012 | | 0.48 |
| Graminoid | NDF=N | y = -0.0419x + 0.7464 | | 0.31 |
| Graminoid | NDF=ADF | y = 0.9292x - 0.3074 | | 0.7 |
| Horsetail | N=GDD | y = 5.3663e-0.001x | | 0.79 |
| Horsetail | NDF=N | ns | 0.315 | |
| Horsetail | NDF=ADF | ns | 0.176 | |
| Lichen | N=GDD | ns | 0.5 | |
| Lichen | NDF=N | ns | 0.55 | |
| Lichen | NDF=ADF | ns | 0.02 | |
| Moss | N=GDD | ns | 0.8 | |
| Moss | NDF=N | ns | 0.76 | |
| Moss | NDF=ADF | ns | 0.6 | |
| Mushroom | N=GDD | ns | 5.6 | |
| Mushroom | NDF=N | ns | 0.35 | |
| Mushroom | NDF=ADF | ns | 0.143 | |
| Standing Dead Graminoid | N=GDD | ns | 0.5 | |
| Standing Dead Graminoid | NDF=N | ns | 0.75 | |
| Standing Dead Graminoid | NDF=ADF | ns | 0.42 | |

### ii) Forage biomass

Our approach to providing biomass to the CCE model was to develop four representative vegetation types within the range of the Central Arctic Herd (coastal, tussock tundra, non-tussock graminoids and shrub herb) by collapsing types mapped from Raynolds et al. (2019). Species composition and biomass among the four vegetation types were approximated from representative sites (Epstein et al. 2004, Walker et al. 2003). These authors worked on the Circumpolar Arctic Vegetation map (CAVM; Figure 4) and types are generalizable across the Arctic. After developing the biomass dataset for the CAH, we applied the same vegetation types and adjusted among herds based on analysis done by Qin Yu (2016) who showed that the BAH and TAI had lower green biomass (Figure 7), compared to the CAH. The modifier (Figure 7) was applied to all green vegetation, while non-vascular plants remained the same (although lichen biomass was elevated in the summer range of the BAH, reflecting its unique location on the Canadian Shield).

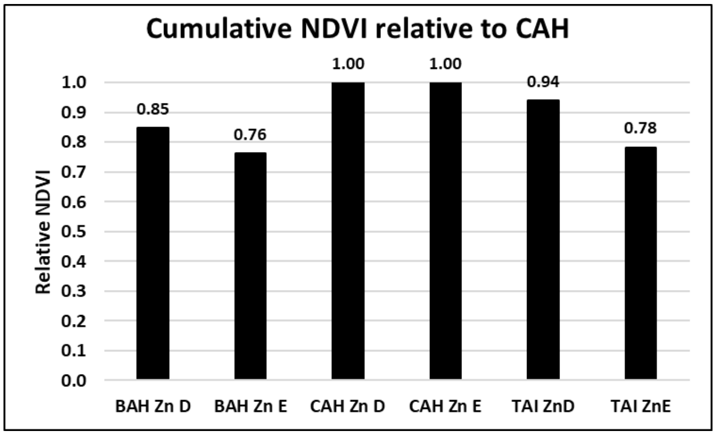


Figure 7. Biomass modifier based on cumulative NDVI relative to the CAH in coastal (Zn D) and interior (Zn E) ranges (Qin et al. 2016).

iii) Diet

Diet can be either empirically-derived or generated from plant biomass using an algorithm (White et al. 2009). Although there are empirical data on diets in the CAH (White et al. 1999), we applied the diet algorithm so that the diet is sensitive to changes in timing and magnitude of plant biomass in the climate-mediated scenarios. Our diet algorithm is based on seasonal selectivity indices for major plant groups, constrained by plant group biomass.

### 3.2.4 Adaptive capacity

Adaptive capacity is what can or needs to be done to mitigate potential impacts. Adaptive capacity includes the plasticity and resilience of the caribou themselves which includes genetic and behavioral plasticity. However, adaptive capacity also includes caribou and landscape management to reduce additive disturbances and to ensure a permeable landscape for caribou to move through unhindered (Appendix B). A large part of the adaptability of caribou is through their seasonal migrations and movements and their spatial memories of their landscapes. Caribou accommodate the seasonal and annual environmental variations through adapting their movements. To maintain this adaptive capacity, it becomes increasingly necessary to maintain permeability of landscapes for caribou movements. To describe how herd and landscape management can increase the herd's adaptive capacity, we used the CCE model projections of survival and trends in herd size to gauge the possible extent changes required from herd and range management actions.

For this report, we limited application of the CCE model to the date of calving which is an example of plasticity, both behavioral and also likely a trait under selection (Bonnet et al. 2019). We applied the CCE model to explore whether caribou can adapt the timing of calving to earlier plant green up as the climate warms (trophic mismatch). We used government reports to describe peak calving dates from the rate of movement during calving of collared caribou for the BAH and CAH. For the TAI, we used CARMA's database for caribou condition to regress fetal weights to determine the peak of calving. For the four climate scenarios, we examined the effects of shift of the calving date to a week earlier. We recognize that a week earlier may be the limit unless the timing of the rut is flexible which has typically been considered unlikely as it reflects changes in daylight (photoperiod).

### 3.2.5 Vulnerability

We compared the projected potential impacts to possible adaptive capacity to rank the potential for vulnerability to be increased or decreased. Although management actions have the potential to reduce vulnerability by, for example, increasing adult survival, it is not straightforward. Caribou management is often a trade-off between competing values and opinions and the available actions are relatively few, being focused on adult and calf survival through hunting regulations or predator management. The CAH and BAH current management actions are specified through co-management plans which are arrived at after consultation and collaboration (Lenart 2021, BCAT 2021).

### 3.2.6 Extrapolating to other herds

To extrapolate results from our analysis of the three representative herds to other circum-arctic migratory tundra caribou is not straightforward. Using our MERRA climate database, we summarize key summer climate indicators (temperature, precipitation, drought, insect harassment) for 15 global migratory tundra herds to quantify the range of variability among herds. We also apply a previous Principal Components Analysis (Oksanen et al. 2019) to categorize 13 North America herds into three clusters based on climate (Russell et al. unpubl.).

# 4. RESULTS

## 4.1. SENSITIVITY (IDENTIFYING CLIMATE VARIABLES)

Previously, Russell et al. (2024) analyzed key climate indicators that correlated with vital rates for seven North American herds which included the Central Arctic and the Bathurst herds. We did not include the Taimyr herd, as annual vital rate data (not generated from population models) were not available on an annual basis. This analysis quantifies the current sensitivity of the BAH and CAH herds to climate.

### 4.1.1 Central Arctic herd

The climate factors that had the most impact on vital rates were at the end and beginning of winter – May and November snow depth (Figure 8). Additionally, June drought explained half the variation in cow survival and the 15 July cumulative mosquito index affected the June calf:cow ratio.

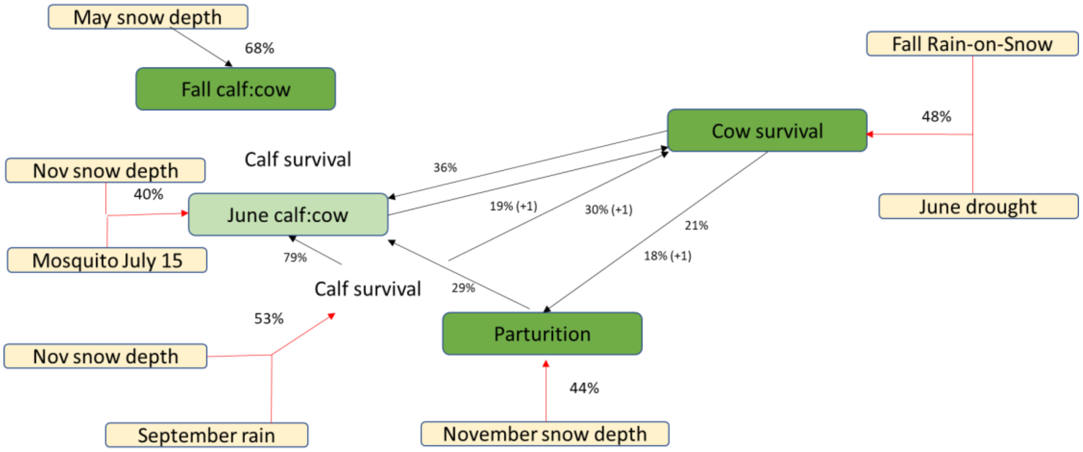


Figure 8. Linkages among vital rates for the Central Arctic herd (red – negative trend; black - positive trend; +1 is a one-year lag).

### 4.1.2 Bathurst herd

Similar to CAH, fall snow depth was influential as October snow depth was negatively related to parturition rate and the next year’s recruitment (Figure 9). Cooler fall temperature (average September and October) and higher June rainfall the previous June accounted for 43 per cent of the variation in cow survival. March temperature positively influenced the fall calf:cow ratio.

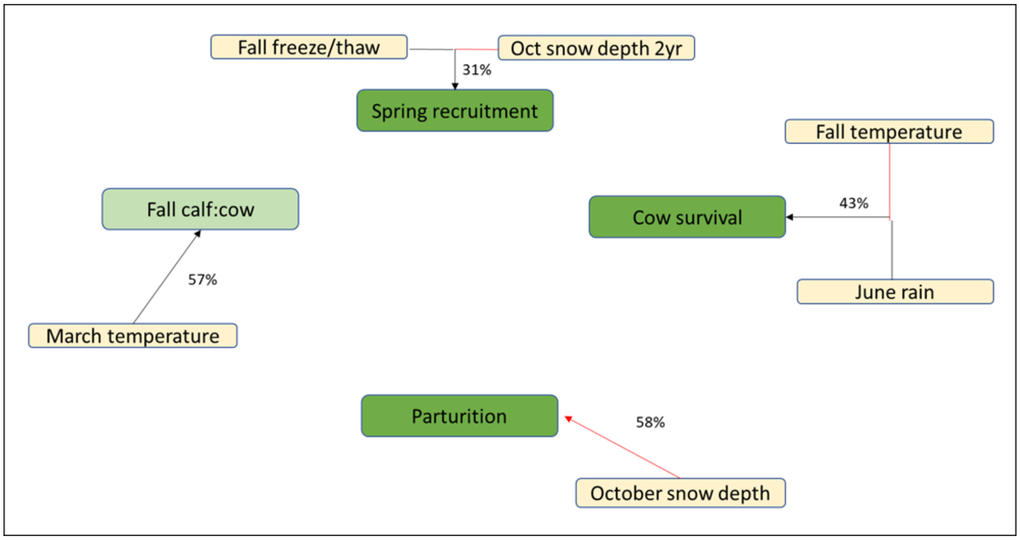


Figure 9. Linkages among vital rates for the Bathurst herd (red – negative trend; black – positive trend; +1 is a one-year lag).

For both the CAH and BAH, spring (44 per cent) and fall (29 per cent) accounted for the relationships among climate indicators and vital rates. Thus, spring and fall are when the reproductive and survival strategies of caribou cows apparently buffer variability in winter and summer, respectively. But, possibly, the importance of summer and winter climate is underestimated in our regression equations as it is the dynamics and variability in spring and fall that ultimately dictate vital rates. Spring is the period of 1) low post-winter reserves, 2) migration energetics, 3) timing of green-up, 3) birth, 4) milk production, 5) calf viability. Similarly, cows entering fall after poor summer conditions must “decide” to 1) wean calf early, 2) wean normally during rut, 3) extend lactation into winter, 4) ovulate, 5) resorb embryo early.

## 4.2 EXPOSURE (HERD-SPECIFIC CLIMATES)

### 4.2.1 Summer monthly temperatures and GDD

The BAH has the warmest summer range compared to the CAH and TAI. Summers for both the optimistic and pessimistic scenarios on the BAH’s range will be hotter as they will exceed the current maximum. The pessimistic-2100 projection will be as much as 10°C hotter (Figure 10A). In contrast, the coastal summer ranges for the CAH will be warmer but within the current maximum except the 2100 year-projection for the pessimistic scenario, which will be about 6°C hotter than current. Under the optimistic scenario, temperatures in the summer ranges of the TAI will be lower than the current maximum (Figure 10) but the pessimistic scenario predicts about a 10°C increase over current mean temperatures.

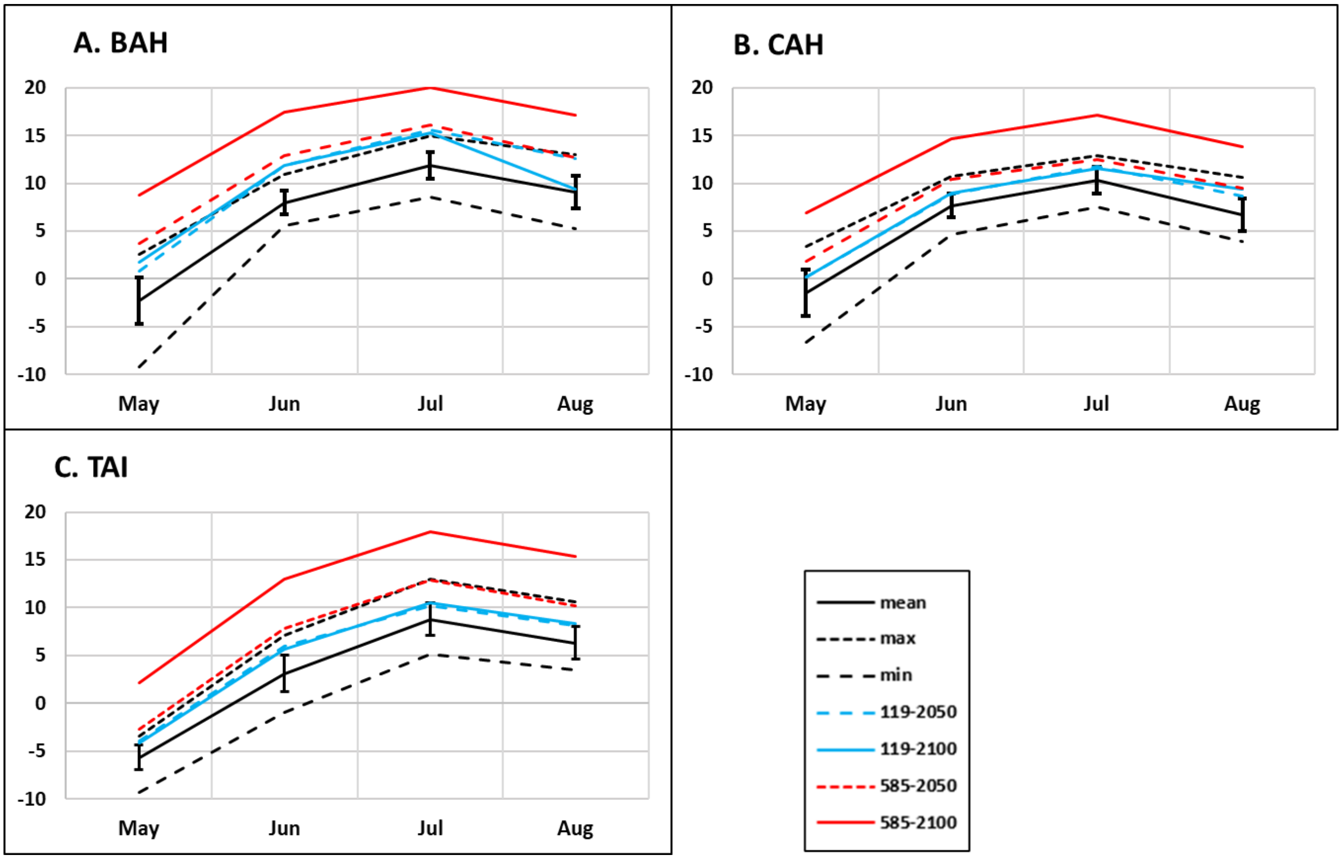


Figure 10. Mean, maximum and minimum of current temperatures compared to mean monthly temperature for Bathurst, Central Arctic and Taimyr herds.

The current GDD for the end of May-August reveals marked monthly and herd differences to be incorporated in the CCE model (Figure 11). The BAH’s consistently warmer summer range is reflected in its higher mid-and late summer totals of plant growing degree days. But, in early summer, the CAH’s western and coastal location brings its plant growing degree days to similar levels as for the Bathurst herd. The Taimyr summer GDD profile lags behind both the CAH and BAH throughout the summer (Figure 11).

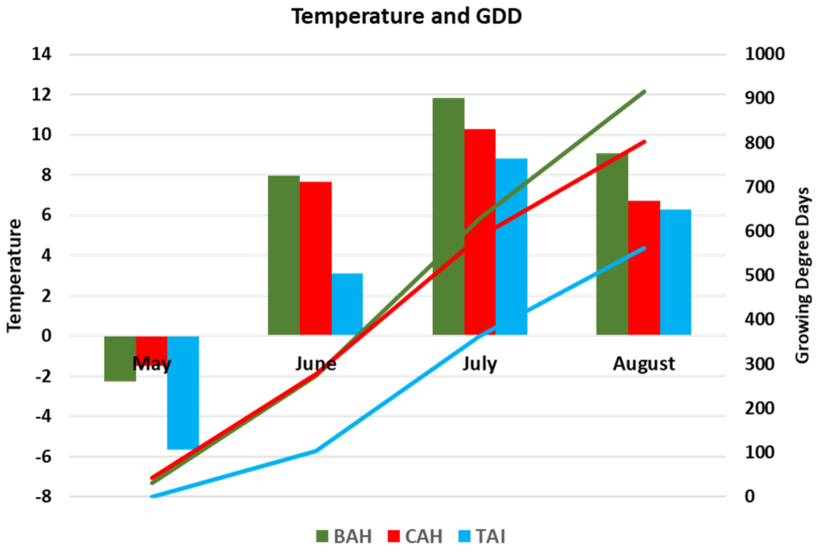


Figure 11. Current average monthly temperature and corresponding GDD (at end of month) for our representative herds.

The differences between the three herds, especially early in the plant growing season, is also evident between scenarios (Table 2). The increase in plant growing degree days for the optimistic scenario compared to current was high for early summer especially for the BAH but varied relatively little between the 2050 and 2100 timeframe (Table 2). The magnitude of changes for late May included a tripling of the GDD for the BAH while the CAH, already with a higher GDD, changes relatively little and the TAI being cooler also changes relatively little in May. Under the pessimistic (585) scenario and the 75-year timeframe, late May GDD jumps from 19 to 252 for the BAH, 27 to 187 for the CAH and 0 for 70 GDD for the TAI (Table 2) showing the effects of an earlier spring. However, by late July, the current conditions compared to the pessimistic (585) 2100-time frame are less marked than in late May for all three herds, ending up being roughly doubled since additional increase over current conditions is less severe in the later part of summer.

Table 2: Growing Degree Days projected for three herds and five scenarios during summer

| Scenario | ERA | Herd | 26-May | 05-Jun | 16-Jun | 26-Jun | 09-Jul | 27-Jul |
|---|---|---|---|---|---|---|---|---|
| **Current** | | BAH | 19 | 57 | 134 | 227 | 376 | 595 |
| 119 | **2050** | BAH | 62 | 111 | 248 | 376 | 554 | 769 |
| 119 | 2100 | BAH | 47 | 93 | 233 | 355 | 539 | 754 |
| 585 | **2050** | BAH | 100 | 152 | 298 | 449 | 615 | 834 |
| 585 | 2100 | BAH | 252 | 301 | 499 | 753 | 832 | 1066 |
| **Current** | | CAH | 27 | 68 | 145 | 237 | 374 | 560 |
| 119 | **2050** | CAH | 38 | 83 | 180 | 283 | 438 | 645 |
| 119 | 2100 | CAH | 37 | 82 | 178 | 280 | 438 | 646 |
| 585 | **2050** | CAH | 64 | 113 | 227 | 347 | 504 | 716 |
| 585 | 2100 | CAH | 187 | 239 | 396 | 595 | 716 | 942 |
| **Current** | | TAI | 0 | 2 | 22 | 76 | 176 | 344 |
| 119 | **2050** | TAI | 4 | 31 | 95 | 176 | 301 | 500 |
| 119 | 2100 | TAI | 3 | 29 | 86 | 167 | 279 | 476 |
| 585 | **2050** | TAI | 9 | 43 | 128 | 215 | 375 | 579 |
| 585 | 2100 | TAI | 70 | 120 | 274 | 415 | 607 | 826 |

### 4.2.2 Summer temperature: Insect activity

The potential exposure of caribou to biting and parasitic insects as indexed for mosquitos shows a relatively modest change in magnitude from current for the optimistic 2050 scenarios (Figure 12) for the CAH (28 per cent) and TAI (20 per cent), while the BAH is projected to have a 62 per cent increase in insect harassment. The index for all three herds remains unchanged by 2100. However, for the pessimistic scenario, the three herds have an index 45-75 per cent higher by 2050 and 220-300 per cent higher by 2100.

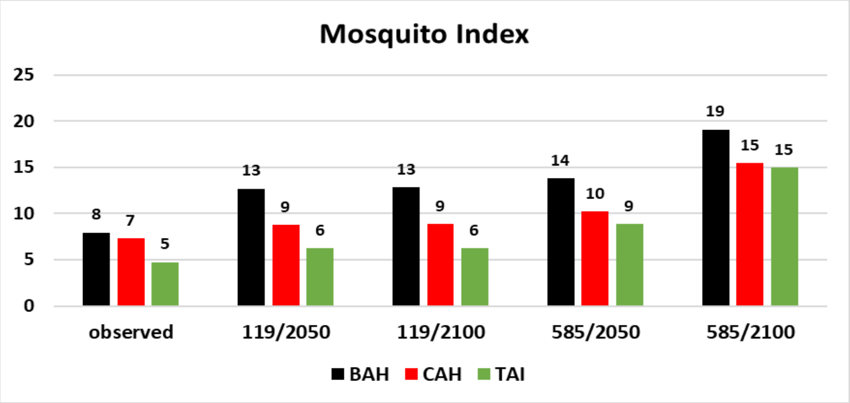


Figure 12. Current and projected mosquito harassment index.

The insect activity and resulting level of insect harassment reduces the percentage of the day spent foraging. By 2100 under the pessimistic scenario, daily foraging is reduced by 5 to 10 percent compared to the present (Figure 13).

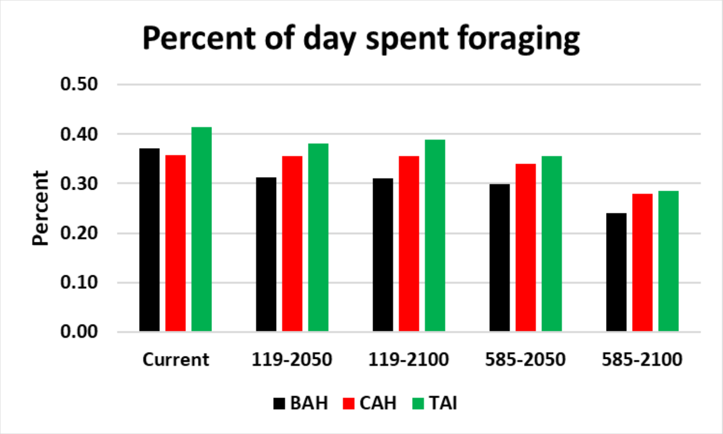


Figure 13. The percentage of the day spent foraging based on level of insect harassment for the three herds and four scenarios.

### 4.2.3 Summer temperature: Heat

The likely impact of heat stress on the caribou based on the number of days >10°C (Figure 14) is strongly noticeable for the Bathurst herd. The number of days above 19°C jumps fourfold from current to the optimistic and 2050 pessimistic scenarios before almost doubling again for the 2100 pessimistic scenario (Figure 14). The combined effect of heat and increasing insect harassment result in even stronger decreases in eating time than insect harassment on its own (Figure 15).

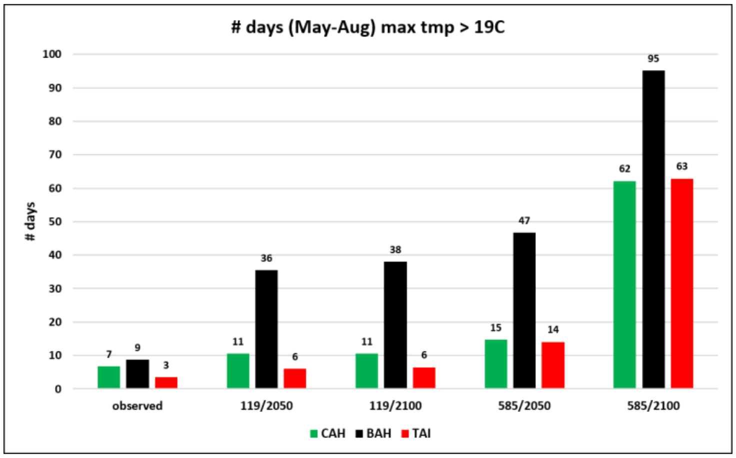


Figure 14. The number of days > 19°C in each scenario.

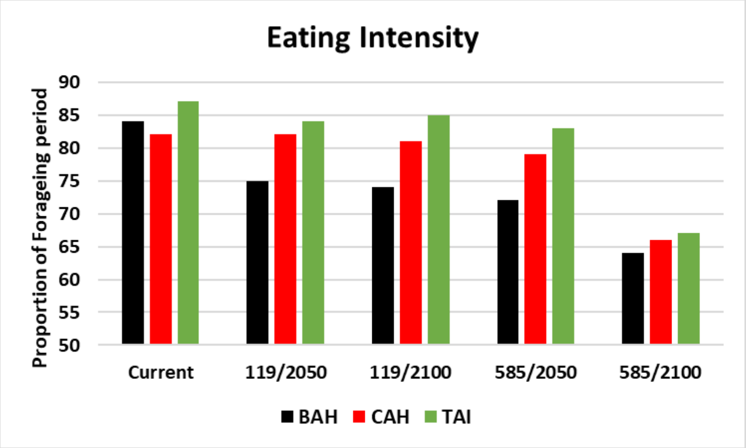


Figure 15. July reduction on eating intensity due to insect harassment and the number of days > 19°C for each scenario.

## 4.3 POTENTIAL IMPACTS

### 4.3.1 Cow and calf body weights

Modelled cow and calf body weights for the three herds differed among the climate scenarios partly because the initial body weights differed (Figure 16). For the BAH and the TAI herds, their lower body size than the CAH herd is partly attributed to their current low abundance. The cows from the CAH are currently the heaviest and lost most weight but by the pessimistic scenario were a similar weight to the BAH cows. The BAH cows maintained relatively stable body weights across the scenarios in contrast to their calves, which lost weight under the 2050 pessimistic and the 2050 and 2100 optimistic scenarios, and lost 11 kg for the 2100 pessimistic scenario. The TAI cows and calves initially lost weight for the 2050 optimistic scenario but their weights remained relatively stable until the 2100 pessimistic scenario.

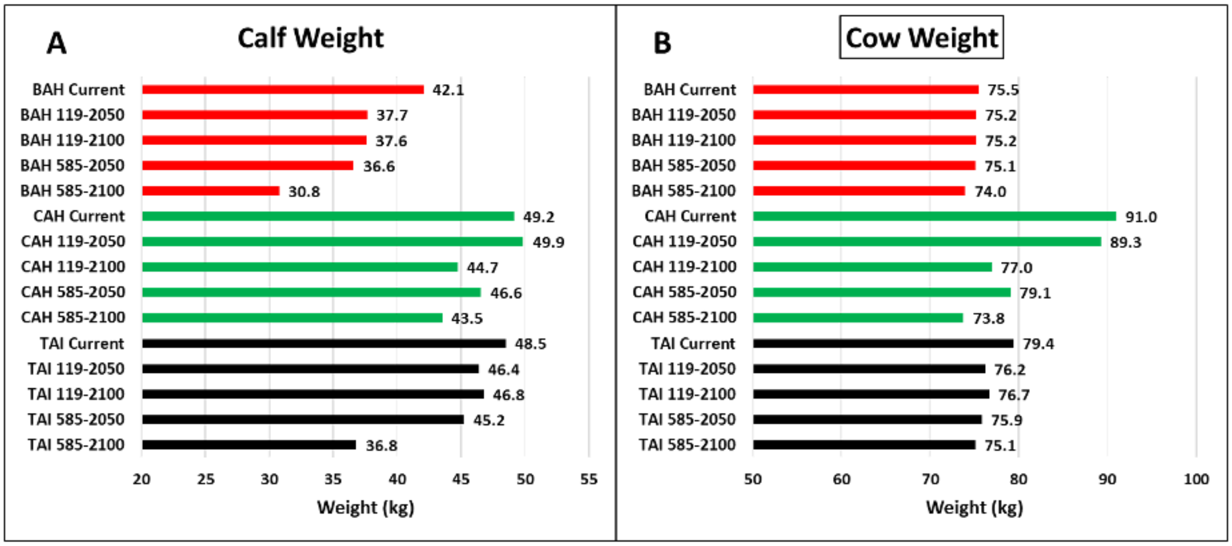


Figure 16. Model projected calf (A) and cow (B) body weights for three representative herds by climate scenario.

### 4.3.2 Population model

For the cows, body weight determines the likelihood of pregnancy and for the calves, body weight influences their survival – small calves fare less well. The changes in pregnancy rates were highest for the Taimyr herd during each scenario (Figure 17). By comparison the percentage reductions in pregnancy rates for the CAH and BAH were negligible or absent for the optimistic scenario. For the 2100 pessimistic scenario, the rates decreased especially for the CAH herd. Calf mortality for the TAI herd contrasted with the pregnancy rates as they were relatively low until 2100 in the pessimistic scenario. The calf mortality rates for the CAH, similar to the pregnancy rates, were lower than the other two herds while the BAH calf mortality was higher than the other herds and like for the TAI, the projected calf mortality for the 2100 scenario was about 50 per cent.

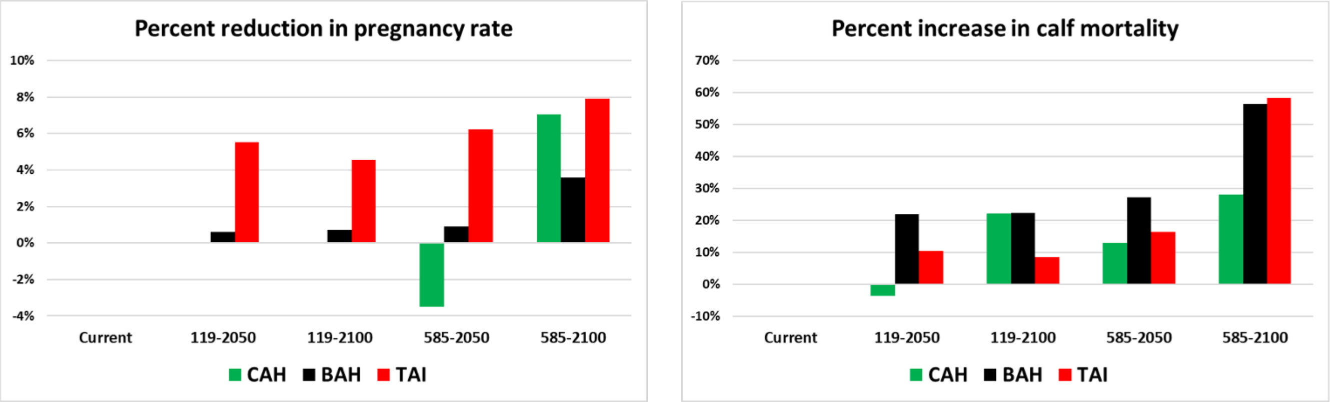


Figure 17. Model projections for reduction in pregnancy rate and increase in calf mortality for three herds by period and optimistic or pessimistic scenarios.

We used two approaches to demonstrate potential impacts at the population level. First to show the relative impacts of warmer summers, we assumed a current herd size of 100,000 caribou for all three herds and then applied the herd-specific vital rate changes (Figure 17) based on our projected future scenarios. The three herds changed relatively little during the first 50 years of an optimistic scenario (Figure 18) although the continental BAH was declining at a slightly higher rate. By 2100 for the optimistic scenario or 2050 of the pessimistic scenario, all three herds were declining at a rate <5 per cent/year. But then by 2100 of the pessimistic scenario, possibly as adaptive capacity of the caribou is exceeded, the rate of decline for the Bathurst and Taimyr herds doubled and the herds declined by more than half. In contrast, the CAH declined by the lower rate of 5 per cent and the herd size by about 40 per cent.

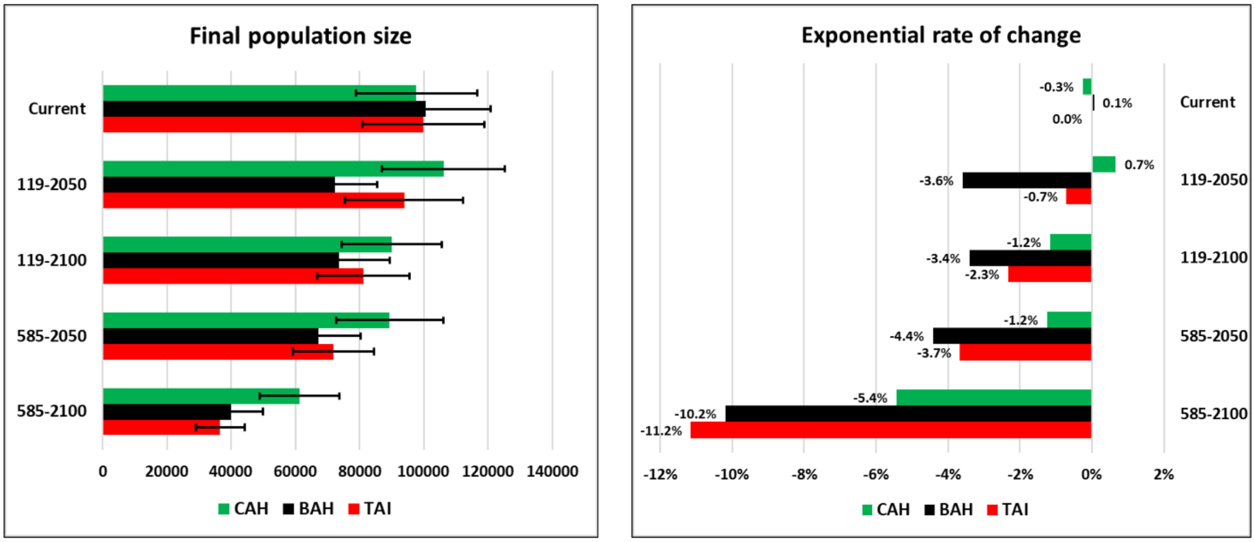


Figure 18. Model projections for population size and exponential rate of change for three herds by period and optimistic or pessimistic scenario. Error bars (+ 1 sd) reflect results of 100 model iterations, selecting

random pregnancy rates and adult mortality from mean and standard deviation unique to each herd and scenario.

Our second approach was to model a 10-year population protection based on the current herd sizes and trends (Table 3). This approach thus incorporates the unique current trends for each herd and asks the question: what would have been the added cost of climate impacts to current trends on herd population size? All herds have declined since 2012 and population estimates and the BAH and TAI continue to decline, while the CAH has recently increased by ~30 per cent from 2016-2019 (Table 3) although there is significant variability around these estimates. Using the actual estimates, we modelled population size for 10 years (2012-2022 for the BAH, 2016-2026 for the CAH and 2016-2026 for the TAI). Note that the 10-year estimate for the BAH did not involve extrapolation.

Table 3: Recent population estimates of three representative herds.

| Year | BAH | CAH | TAI |
|---|---|---|---|
| **2012** | 34690 | | |
| **2013** | | 50753 | |
| **2014** | | | |
| **2015** | 20000 | | |
| **2016** | | 22630 | 384000 |
| **2017** | | 28051 | 370000 |
| **2018** | 8200 | | |
| **2019** | | 30000 | |
| **2020** | | | |
| **2021** | 6240 | | 241000 |
| **2022** | 6851 | | |
| **2023** | | | 100000 |

We ran the most pessimistic and optimistic scenario for each herd, assuming impacts on vital rates (calf survival and pregnancy rates) from Figure 17. These three scenarios are shown in Figure 19 assuming 1) current trends continue, 2) optimistic conditions (119-2050) and 3) pessimistic conditions (585-2100). For comparative purposes in Figure 19, we plotted the relative population size assuming the year 10 projection for current conditions is 1.0. Based on relative population size, the optimistic projection for the BAH and TAI were 71 per cent and 67 per cent of current levels. For the CAH our assessment is that the CAH would do better with modest warming (4 per cent higher). All three herds declined significantly under the pessimistic scenario, estimated by 2100 to be 64 per cent, 32 per cent and 9 per cent of current levels for the CAH, BAH and TAI, respectively, compared to current trends continuing. The reason that the BAH did slightly better than the TAI even though projected impacts on vital rates are higher for the BAH (Figure 17), relates to the current rate of decline (significantly higher for the TAI).

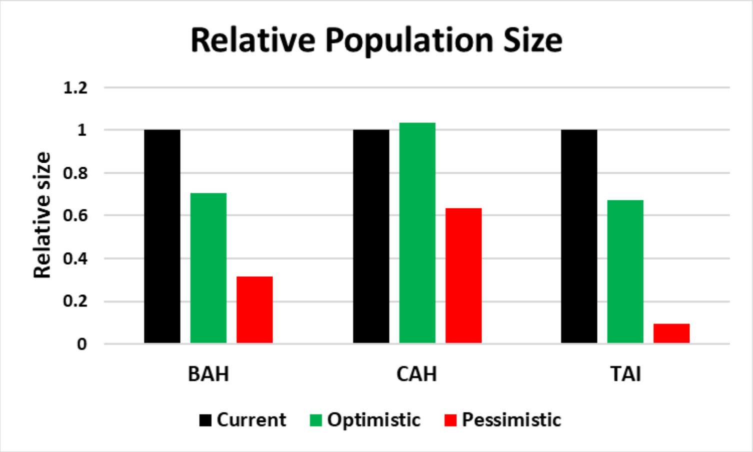


Figure 19. The relative population size of representative herds assuming current population size trends continues under current conditions, under 2050 optimistic projections or under 2100 pessimistic conditions.

## 4.4 ADAPTIVE CAPACITY

Adaptive capacity can mitigate potential impacts which in turn reduces vulnerability. We report the results on adaptive capacity first for the CCE model projections for earlier calving. Then, we summarize available management actions which could potentially modify herd trends.

### 4.4.1 Earlier peak calving

Russell (unpublished data) has shown that the herd-specific mean peak of calving coincides with approximately 65 cumulative growing degree days. The peak of calving was 3-9 June for North American herds but not until 24 June for the Taimyr herd (Figure 20).

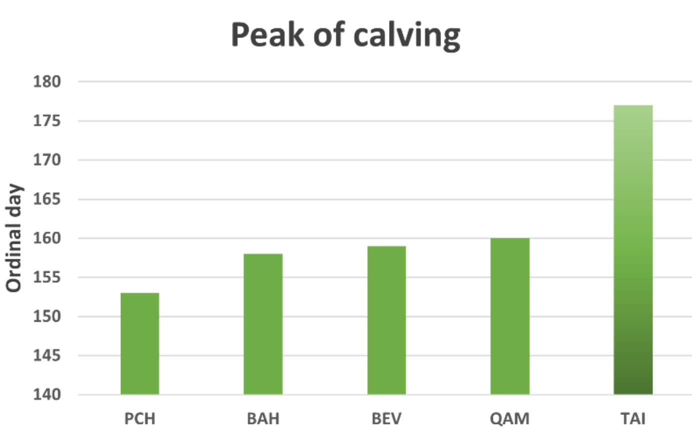


Figure 20. Timing of calving for North American caribou herds and the Taimyr herd.

Annual variability in the timing of peak of calving among migratory tundra herds has been associated with timing of green-up in the spring and or habitat conditions the previous spring and summer (Rowell and Shipka 2009; Chen et al. 2018; Adams and Dale 1998; Post and Forchhammer 2008). Warming climate, as projected by CMIP6, offers an opportunity to assess the degree of physiological adaptive capacity by quantifying if calving earlier in the future might mitigate changes in available nutrients. Figure 21 shows the modelling projections when we advanced the calving date by one week in response to warming climate scenarios. Earlier calving for the CAH was not a benefit as the cow's body weight declined for the optimistic scenarios and was relatively stable for the pessimistic scenarios (Figure 21). Calving a week earlier increased cow weight in the TAI for all the optimistic scenarios, but made little difference for the pessimistic scenario. Calves did not appear to benefit from the earlier calving as their body weight changed little except for close to a 1kg increase in the optimistic 2100 scenario. Earlier calving for the BAH had almost no projected impact on either the cow or calf body weights, although greater than a 1kg benefit is noted for the 585-2100 scenario for calves.

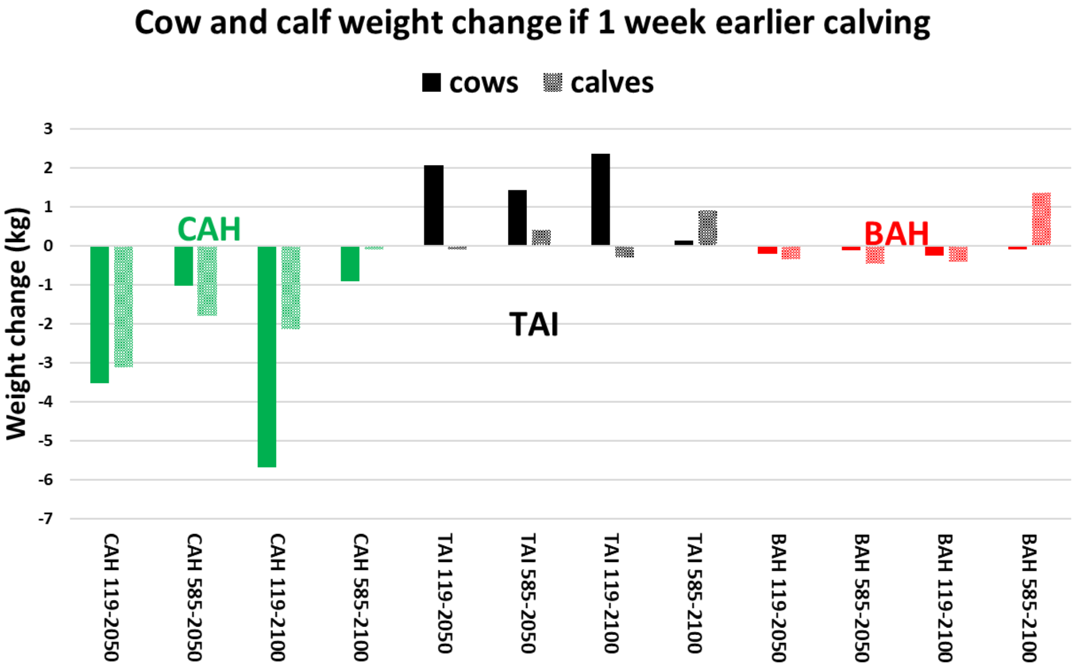


Figure 21. Change in cow and calf body weight at the rut by advancing calving date one week for three herds and four climate futures.

### 4.4.2 Available management options

The role of caribou management in adaptive capacity is mostly focused on survival rates which can be modified through changes in hunting regulation or imposing predator removal. This approach is possible for the CAH but the BAH's adaptive capacity is low as the harvest has been almost totally closed and wolf removal is underway. For the TAI, reducing harvests is countered by illegal harvesting (Kolpaschikov et al.

2015). Management to counter a 30-50 per cent increase in calf survival and 5-10 per cent annual rates of decline for the long-term pessimistic scenario are unlikely even if caribou harvesting was reduced for the CAH and TAI.

The role of caribou management relative to the potential impacts on the rate of change in herd size varied by herd for the optimistic scenarios. The CAH harvesting could be reduced to accelerate the low rate of increase or offset the low rate of decline for the . However, management actions to increase the adaptive capacity of the BAH are unlikely given the current level of management actions. But for the 2100 of the pessimistic scenarios, adaptive capacity of the caribou management is likely exceeded for the three herds.

## 4.5 VULNERABILITY

The adaptive capacity from earlier calving would not have reduced vulnerability of the CAH as the cows and calves lost weight. The TAI might have reduced vulnerability as they gained weight in the optimistic scenario as the BAH showed relatively little change.

## 4.6 EXTRAPOLATING TO OTHER HERDS

Through CARMA, we track trends in 15 migratory tundra herds. We summarized the MERRA summer (June-August) data to compare and contrast 14 North American herds as well as the Taimyr herd (Figure 22) for key summer climate variables (temperature, precipitation, drought and mosquito index). Across migratory tundra herd ranges, there is a 6-degree variation in mean summer temperatures; an 80 mm difference in mean summer precipitation; greater than a three-fold range in mosquito index and a four-fold range in drought index.

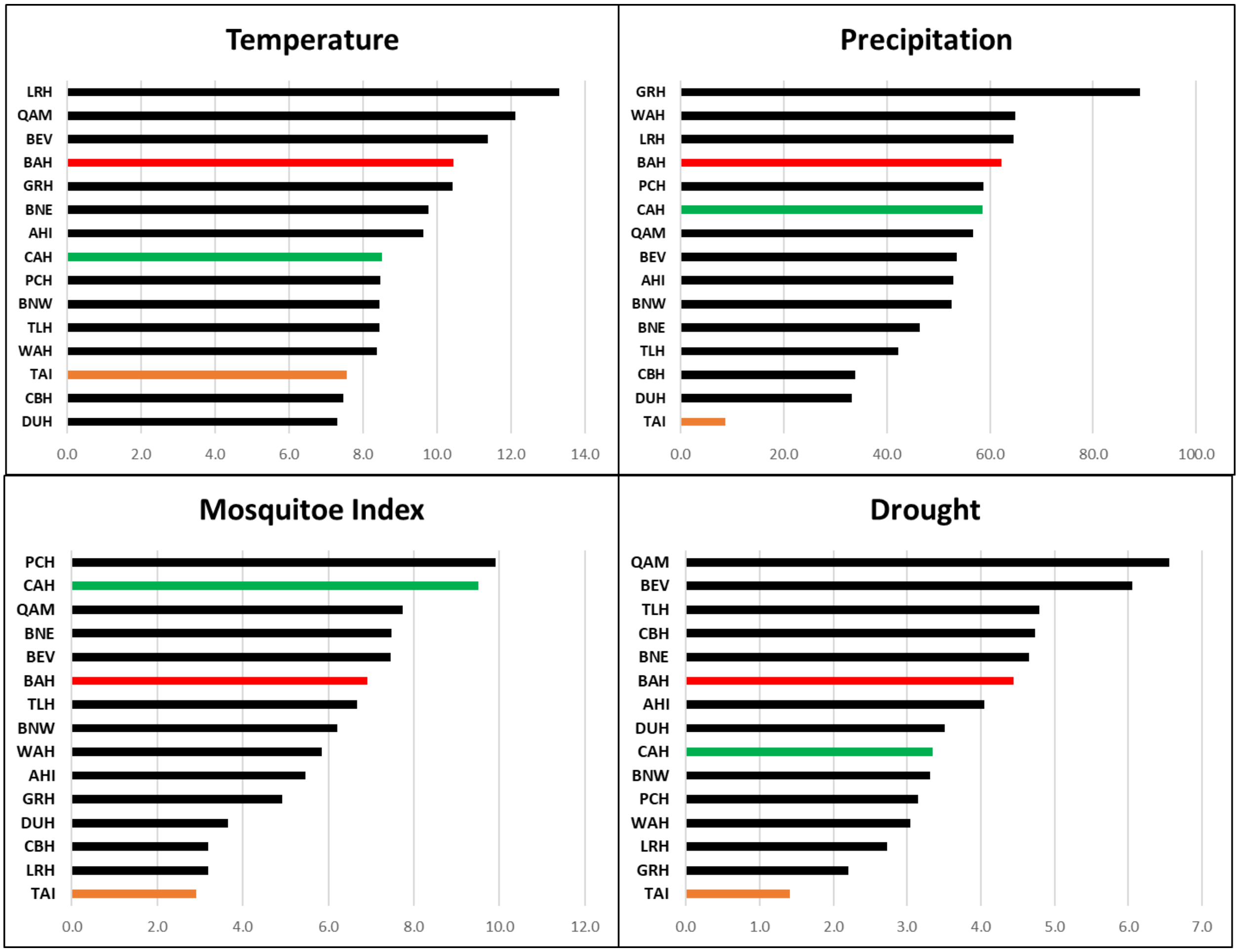


Figure 22. Mean temperature, precipitation, drought and cumulative mosquito index (to 15 July) for 15 migratory tundra herds (the three reference herds are highlighted).

The Taimyr herd has the lowest temperature, precipitation, drought and mosquito index compared to all other regions. Western herds (Western Arctic (WAH), Teshekpuk Lake (TLH), Central Arctic (CAH), Porcupine (PCH)) had the highest insect levels, even though herds east of the Mackenzie (Cape Bathurst (CBH), Blue Nose West (BNW), Blue Nose East (BNE) are cool compared to central and Eastern herds (Figure 23).

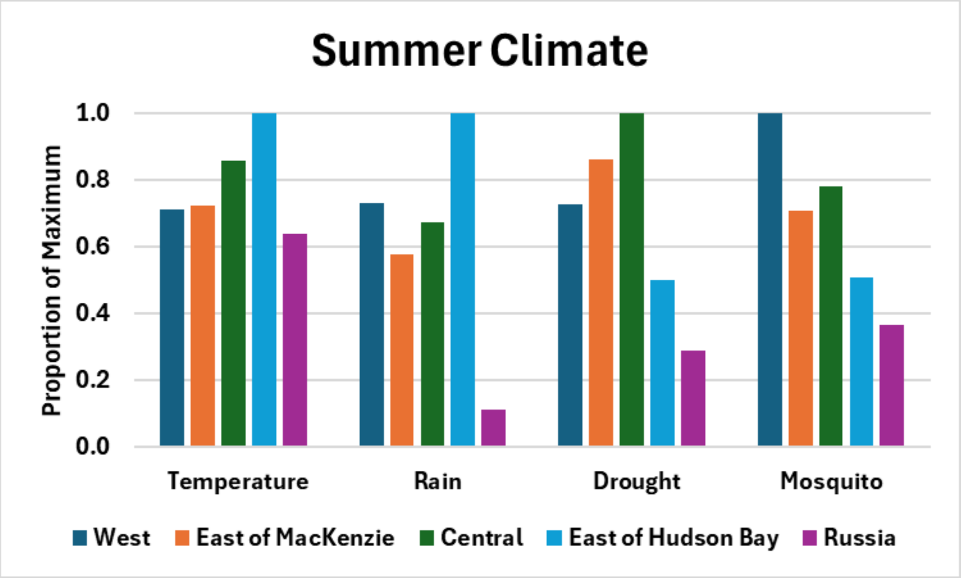


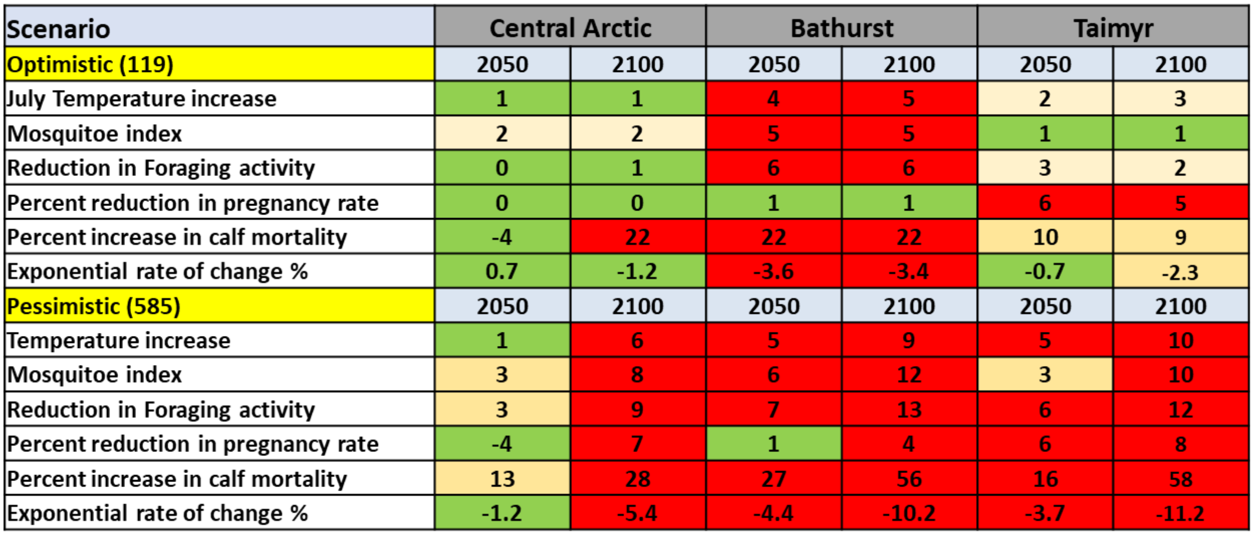
Figure 23. Regional patterns in summer climate. The proportion of the region with maximum values are displayed.

# 5. DISCUSSION

## 5.1 POTENTIAL IMPACTS

We quantified potential impacts of a warming climate for three caribou herds in different geographic regions with current herd sizes increasing and decreasing. We compared impacts among indicators of caribou health (Table 4) for 2050 and 2100 optimistic and pessimistic scenarios. The Bathurst herd's continental range is projected to see the most summer warmth, number of hot days and the highest rate of decline in numbers. The Central Arctic herd on its cooler coastal range is projected to be the least affected but even so during the 2100 pessimistic scenario it will decline to about 40 per cent of its starting herd size. The Taimyr and Bathurst herds will be reduced to 60 per cent of their starting herd size with rates of decline that double those projected for the Central Arctic herd.

Table 4: Summary of Potential Impacts. We have subjectively colored the cells to highlight the degree of impacts from low (green), moderate (orange) and high (red). Cell colours subjectively represent degree of impact.



| Scenario | Central Arctic | | Bathurst | | Taimyr | |
|---|---|---|---|---|---|---|
| **Optimistic (119)** | 2050 | 2100 | 2050 | 2100 | 2050 | 2100 |
| July Temperature increase | 1 | 1 | 4 | 5 | 2 | 3 |
| Mosquitoe index | 2 | 2 | 5 | 5 | 1 | 1 |
| Reduction in Foraging activity | 0 | 1 | 6 | 6 | 3 | 2 |
| Percent reduction in pregnancy rate | 0 | 0 | 1 | 1 | 6 | 5 |
| Percent increase in calf mortality | -4 | 22 | 22 | 22 | 10 | 9 |
| Exponential rate of change % | 0.7 | -1.2 | -3.6 | -3.4 | -0.7 | -2.3 |
| **Pessimistic (585)** | 2050 | 2100 | 2050 | 2100 | 2050 | 2100 |
| Temperature increase | 1 | 6 | 5 | 9 | 5 | 10 |
| Mosquitoe index | 3 | 8 | 6 | 12 | 3 | 10 |
| Reduction in Foraging activity | 3 | 9 | 7 | 13 | 6 | 12 |
| Percent reduction in pregnancy rate | -4 | 7 | 1 | 4 | 6 | 8 |
| Percent increase in calf mortality | 13 | 28 | 27 | 56 | 16 | 58 |
| Exponential rate of change % | -1.2 | -5.4 | -4.4 | -10.2 | -3.7 | -11.2 |

At this stage, our modeling does not include discrete recurrent events/hazards (such as an exceptional drought year) or abrupt climate system switches such as a phase change in the Arctic Oscillation (Appendix A). While our focus was on continuous hazards (increasing summer temperatures), how warmer temperatures impact the timing of the snowfall and melt, snow depth and freezing rain or rain-on-snow (ROS) will also be imposed on those summer changes. For example, warmer summers have improved forage biomass for Svalbard reindeer (Hansen et al. 2019), but winter ROS events periodically reduce numbers. However, behavioral plasticity has mitigated the impacts of the ROS as the wild reindeer have shifted their diet to grasses available above the ground-fast ice (Hiltunen et al. 2022).

Our assessment was restricted to summer foraging ecology, which assumes that autumn and winter conditions will play a neutral role in herd productivity. We know this is not true. Here we discuss two examples of how increasing temperatures can impact 1) autumn by delaying the snow season, particularly end of October snow depth, and 2) increase in fire weather Index on winter ranges.

Based on additional analyses of the relationship between October snow depth and parturition rate in the following spring and energetic costs of icing conditions (Appendix A), we expect that projections may underestimate the decline. Furthermore, while we expect an increase in forest fire activity with a warming climate overall (Appendix A), the role of spring and summer precipitation are probably more important and therefore difficult to predict based on CMIP6 data.

## 5.2 ADAPTIVE CAPACITY

Having identified the potential impact of warming temperature on migratory tundra caribou, we asked the question: how likely is it that potential impacts can be mitigated either physiologically and behaviorally by the animals themselves or by management actions?

First, we have already described physiological plasticity: whether caribou could advance the date of calving to better align nutritional needs with phenological changes in plant chemistry (Figures 20 and 21). Our conclusions were mixed, with a week earlier calving adversely impacting calves and cows in the Central Arctic Herd, marginally improving calf weight in the 2100 pessimistic scenarios but marginally worsening calf and cow weights in the other scenarios.

For the Taimyr herd, on the other hand, advancing calving by one week had a mitigating effect on cow weights for all scenarios (except 2100 pessimistic), while not having much of an effect on calf weights on the optimistic scenario in both time periods, but benefitting calves during both time periods for the pessimistic scenario (Figure 21). In the last decade, the peak of calving has advanced about one-week from the historic 24-26 June to 18-20 June (Kolpashikov pers. comm. 2024) and June temperatures have a significant warming trend (Figure 27), especially after 1997.

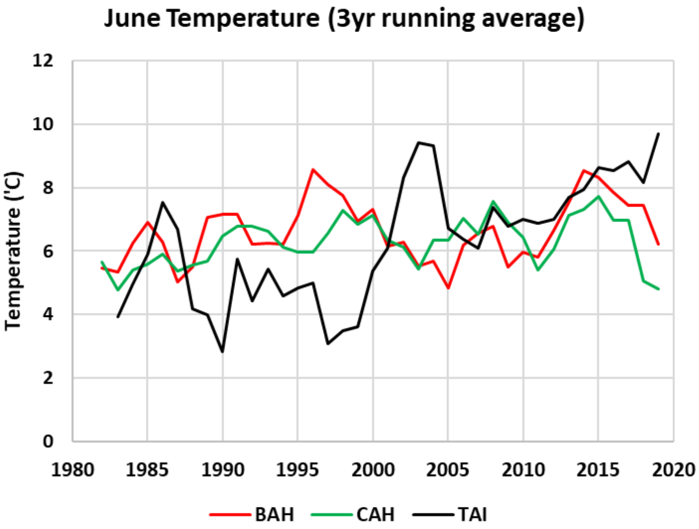


Figure 24. Mean June (three-year running average; 1980-2019) for three representative herds.

Although behavioral plasticity will contribute to caribou adaptive capacity, less is currently known about if and how caribou will adapt through natural selection favoring alleles that confer a fitness advantage. Migratory tundra caribou are genetically variable and already are found in regionally diverse climates which may suggest an increased likelihood of evolving adaptive variation (https://www.caribougenome.ca/). However, it will not likely be simple to describe local adaptations to climate. In bird species historically adapted to variable climates, the local adaptations to climates are genetically complex with selection at many different genes likely driven by different climatic variables (Stonehouse et al. 2024). There are, however, actions that can be taken to maintain levels of genetic variation occurring in caribou herds, such as those that ensure continued gene flow and maintain herd abundance well above minimum effective population sizes.

A second pathway to increasing adaptive capacity is already relatively well understood. Adaptive capacity can be increased through caribou management and range action although caribou herd management has a mixed track record in slowing or reversing declines. Landscape (range) planning has a greater potential to increase adaptive capacity. Of the three herds, only the Bathurst herd currently has an advisory range plan to manage disturbances including roads across the landscape. Roads and traffic can delay or deflect caribou during seasonal migrations (Boulanger et al. 2024, Boulanger and D'Eon-Eggertson 2023, Smith and Johnson 2023), but especially important during warmer summers, is that caribou, as they respond to vehicles, reduce their forage intake and those costs can accumulate (Russell et al.2021). Thus, minimizing or avoiding caribou responses to traffic and roads as part landscape planning will potentially increase the adaptive capacity of caribou. Through local knowledge and innovative approaches to mitigation such as traffic management, at least industrial roads can be modified to create smaller avoidance reactions by caribou (Agnico Eagle Ltd 2025).

## 5.3 VULNERABILITY

The vulnerability of the Bathurst herd is high as management actions are already underway and thus unavailable to build its adaptive capacity; it is already facing the strongest signal of hotter summers and its continental ranges are projected to be the hottest of the three herds. The vulnerability of the Taimyr herd is moderate with a slow annual rate of decline despite management actions (harvest restrictions, although illegal harvesting is a problem also requiring action) to increase its adaptive capacity. In comparison, the vulnerability of the Central Arctic Herd is low as the projected impacts are minimal until the second half of the century under the pessimistic scenario (Table 4).

## 5.4 EXTRAPOLATING TO OTHER HERDS

The herd-specific climate summaries (Figure 22) highlight the regionally variable summer ranges (Figure 23). Below (Table 5) we also summarize herds based on use of coastal and interior ecoregions and geological differences. Our analyses suggest that herds which calve and summer on the coast and that calve on tussock tundra and especially calcium-rich tundra are the least vulnerable to optimistic climate scenarios but less so for pessimistic scenarios.

Table 5: Trend, geography and geology of migratory tundra caribou herds calving and summer ranges. (herd names = red - declining; green - increasing; column entries red unfavorable, green favorable and yellow somewhat favorable).

| Herd | Coastal | | Interior | | Precambrian Shield | Sedimentary | |
|---|---|---|---|---|---|---|---|
| | Calving | Summer | Calving | Summer | | Ca tussock | Tussock |
| Western Arctic | | | X | x | | | x |
| Teshekpuk | x | x | | | | x | |
| Central Arctic | x | x | | | | x | |
| Porcupine | x | x | | | | x | |
| Cape Bathurst | x | x | | | | | x |
| Bluenose West | x | | | x | | | x |
| Bluenose East | | x | X | x | x | | x |
| Bathurst | | | X | x | x | | x |
| Beverly | x | | | x | x | | x |
| Qamanirjuaq | | | X | x | x | | x |
| Leaf River | | x | X | | x | | x |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| George River | x | | | x | x | | x |
| Taimyr | | | X | x | x | | x |

Understanding mechanisms for how a warmer climate is driving ecological changes helps refine extrapolating the risk for other herds. The accelerating loss of sea-ice (Jahn et al. 2024, Dail et al. 2024) is a case in point as it strengthens our understanding of regional climates faced by caribou. (Appendix A) The Taimyr herd range has pockets of both advancing treeline and stable treelines, and although treeline plots are sparse, all other Russian herd ranges adjacent the east Siberian Seas are not associated with an advancing treeline. All western North American herds, including the CAH, except the Porcupine Herd are associated with advancing treelines. For herds east of the Mackenzie, such as the BAH, treelines have generally remained stable; however, the closer ranges are to Hudson Bay, the higher the probability of advancing treelines.

# 6. LIMITATIONS OF THE APPROACH

Our projections for how migratory tundra caribou may respond over a 25- and 75-year period to a warming climate are conservative. The projections are focused on calving and summer seasons which risks that we underestimated potential impacts. When we consider uncertainties, firstly, looking forward over 75 years is a step into uncertainty itself. By 2050, under the worst-case scenario (pessimistic future), the mean temperature from May to August will be similar to the historic maximum temperature in those months for the three representative herds. But by 2100, the Taimyr herd and the Bathurst herd will be on average 5°C higher than the historic maximum while the Central Arctic Herd will be 4°C higher. The significance of those values means that any functional response between temperature and, for example, nutrient quality, make assumptions on the shape of the response curve beyond the limit of current data or assume relationships derived in different (perhaps warmer) regions generally apply.

Secondly, relying on global climate models has introduced uncertainties as precipitation is not well tracked in the CMIP6 models. Warmer temperatures will likely mean higher incidence of forest fires. Although we track a Drought Index and are confident that forest fire frequency will increase, our Drought Index is more sensitive to precipitation than it is to temperature which introduces uncertainties. The uncertainties about precipitation limited how we could include impacts of changing winter conditions. Additionally, there are limits to our knowledge about caribou relationships with snow and ice. Warmer temperatures will result in more severe icing, which, for the BAH and CAH, increases with increasing October temperature. We are uncertain how variability in icing is quantifiably linked to caribou energetics despite correlations between icing and vital rates. Additionally, we do not know if under a warmer fall, October snow depth will remain an accurate indicator of winter severity although we model implications of earlier calving on cow and calf fall weight.

All of our future climate projections are based on mean temperature increases. However, current scientific predictions indicate that rising temperatures will likely be accompanied by greater climate variability, which is not fully captured in these models. When the mean values are already higher than the current maximum temperature in all herds, we can’t predict impacts of extremely high temperatures.

Limits to our predictions and the conservatism of our projections increase any likelihood of ecological surprises and tipping points. First, ecological surprises are when human expectations or predictions of ecosystem behaviour deviate from observed ecosystem behaviour (Filbee-Dexter et al. 2017). We suggest that the BAH’s collapse to about 2 per cent of its peak size despite management actions over 10 years, was unexpected – an ecological surprise. A tipping point is a non-linear response such that “a relatively small perturbation can cause a large, qualitative change in the future state of a system” (Cumming and

Peterson 2017). An example is how the cumulative effects of a warmer climate, landscape changes, including mining, roads and railways, and increasing predation are driving reindeer herding in Finland toward tipping points when adaptive mechanisms reach their limits (Landauer et al. 2021).

# 7. CONCLUSIONS: RISKS AND UNCERTAINTIES FOR THE CENTRAL ARCTIC, BATHURST AND TAIMYR HERDS AND OTHER MIGRATORY TUNDRA HERDS

We assessed that of the three herds, the Central Arctic herd would be impacted the least. In fact, under the optimistic scenario, the CAH would slightly benefit from modest warming, with productivity increasing +0.7 per cent per year compared to current conditions by 2050. Even by 2100, under the optimistic scenario the CAH is projected to decline the least among the herds, decreasing 1 per cent more per year than stable conditions. However, assuming emission targets are not met and no future restrictions in $CO_2$ occur, the CAH is expected to decline 1 per cent per year more than currently by 2050, and by 2100 would decline 5 per cent per year compared to the current conditions. From our analysis herds that share similar current summer climatic environments include the TLH, PCH, CBH, BNE, all herds with coastal calving and sedimentary substrates. We expect these herds would be impacted by a similar magnitude as the CAH.

Among the three herds the Bathurst herd is projected to be the most impacted by future warming, declining 4 per cent and 3 per cent greater than stable conditions by 2050 and 2100 assuming emission targets are met. If no targets are met and it is the pessimistic scenario, the BAH would annually decline by 4 per cent (2050) and 10 per cent (2100). The BAH ranges are continental and on the Precambrian Shield which is similar to the ranges for the BNE, BEV, AHI and QAM. Continental and bedrock dominated ranges are characterized by warmer summer temperatures and frequent drought conditions.

The Taimyr has evolved under a cooler climate than the CAH and BAH: it has a cooler May and June temperature with later green-up, fewer growing degree days, lower insect harassment index, lower precipitation and drought conditions and an almost three week later peak of calving date. These attributes both positively and negatively impact cow and calf growth. Projected temperature increases are moderate between CAH (low) and BAH (high). Our model projected that by 2050, temperature increases will result in modest declines (-0.7 per cent optimistic and -1.2 per cent pessimistic) and by 2100 the rate of decline increases by 3.7 per cent (optimistic) and -11.2 per cent (pessimistic).

The CAH, BAH and TAI herds are representative for all but three of the migratory tundra herds. However, the Western Arctic (WAH), Leaf River (LRH) and George River (GRH) herds are strongly affected by maritime climate influences, resulting in wetter summer ranges characterized by low insect levels and low drought conditions. The closest counterpart would be the Taimyr herd.

Currently, most migratory tundra herds are declining, which in itself is not alarming as herds cycle from abundance to scarcity a couple of times a century. That said, with many herds at all-time lows, herds are more vulnerable when it comes to rebuilding at low numbers in an ever-change arctic environment – climate and development – is a step into the unknown. The uncertainty is amplified by a constraint on how we projected impacts as we did not include the cumulative impacts of industrial development including roads and traffic.

From our analysis, we conclude that, at best, the impacts of the optimistic scenario by 2050 and 2100 could be mitigated assuming concrete mitigation plans are developed proactively rather than reactively. The exception is the BAH which already has strong mitigation measures (severe harvest restrictions and wolf management) and is not recovering. The lack of recovery means that a warming climate will have higher potential impacts on the BAH than the CAH and TAI. However, for all three herds, our evidence is that adaptive capacity as we currently understand it will not be enough to mitigate the pessimistic scenario. Migratory tundra herds risk either dwindling to small remnant herds or disappearing altogether. This conclusion comes back to the fact that the most effective way to reduce vulnerability is to limit greenhouse gas emissions: the optimistic versus pessimistic scenario is an assessment of how meeting our emissions target compares with not meeting our targets.

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# APPENDIX A. LITERATURE SUMMARY ON A WARMER CLIMATE

## 1. IMPACTS ON CARIBOU FORAGE

Caribou as a ruminant spend about three-quarters their day foraging and digesting which emphasises how climate interacts with forage quality and quantity as it will affect individual fitness. A warmer greener Arctic with a longer and earlier plant growth season and enhanced plant growth has caught many people's attention (Callaghan et al. 2022). But as measured by remote sensing, much of the Arctic is not greening: for example, Berner et al. (2020) showed that from 1985 to 2016, 37 per cent of the Arctic greened, while 5 per cent browned and 58 per cent did not change. Graminoids and shrubs are the most likely to increase while many plant groups are relatively resilient to at least moderate climate changes (Callaghan et al. 2022, Bjorkmann et al. 2019). Shrub increases are mostly in regions with mesic or wet soils rather than colder and dry tundra sites (Bjorkmann et al. 2019). Why so many Arctic plants are stable despite a warmer climate is uncertain but may include physiological plasticity, intolerance to high temperatures and pre-adaptation for widely distributed species (Callaghan et al. 2022).

The warmer temperatures will increase rain during the summer months and the rain in spring will be up to a month earlier (Dou et al. 2022). During winters, snowfall, as indexed by snow water equivalent, has increased in coastal Alaska (Stueffer et al. 2020). Snow depth is often seen in terms of its effects on the energy costs of caribou moving and digging craters to reach forage. However, snow also is a driver of many vegetation changes largely through its effects on soil temperature (Richert et al. 2021).

How a greener and wetter Arctic benefits caribou is complicated as warming occurs alongside herbivory (Yu et al. 2017). When plants renew their annual growth in spring, their newly flushed leaves and flower buds are high in nitrogen and essential minerals, such as phosphorus, potassium and copper (Oster et al. 2018). As the plants grow during the summer, the new tissue dilutes the concentration of nitrogen, phosphorus, potassium and copper. As the proportion of fiber and other structural components increase, the amount of plant tissue (biomass) and energy value increases along with calcium, iron and zinc (Oster et al. 2018). The quality of forage declines as measured by nitrogen while quantity increases. The seasonal reduction in phosphorus is a potential limitation for caribou as it is essential for lactation and antler growth (Oster et al. 2018). Although the relationships of minerals, plant growth and caribou needs are complex, mineral shortages, especially phosphorus, sodium, calcium and copper, are more likely as the Arctic summers become warmer and longer (Oster et al. 2018, Kaspari 2021).

The change during the summer from caribou forage quality to quantity is especially well-described for the Alaskan coastal herds. Johnson et al. (2018) associated an earlier-green up with lower predicted forage nitrogen levels measured over the summer which is a concern given that forage nitrogen levels are already a nutritional constraint for caribou (Barboza et al. 2018). Gustine et al. (2017) reported the trend, for example, the Central Arctic herd ranges is warmer summers (42 per cent warmer in 2011±13 than 1977) that start earlier (4±17 days earlier than in the 1980s) and last longer (almost 4 days/decade). The advance of spring green-up (forage quality based on digestible nitrogen) is still about 10 days later than the time from peak of calving to peak lactation (Johnson et al. 2018: Figure 2) which is a critical time for the calf and cow. For at least the Central Arctic herd, trophic mismatch (earlier green-up shifts peak forage quality away from peak nutritional demand leading to lower productivity) has not occurred yet (Gustine et al. 2017, Johnson et al. 2018).

Among the impacts of warmer climate on Arctic plant communities are more shrubs, such as willow and dwarf birch. The increase is through complex changes mediated partly through deeper snow captured by the taller shrubs which, in turn, increases thaw depth, alters soil nitrogen and increases shrub biomass (Leffler et al. 2022). Caribou browsing on shrubs varies with caribou abundance but can offset some impacts of warming on shrub growth (Zamin and Grogan 2013, Zamin et al. 2017).

Longer-term experimental studies reveal that warm spells during winter may be detrimental to evergreen shrub growth if rain and icing diminish or remove the snowpack. In contrast, deciduous shrubs compensated for icing with increased summer leaf growth at the expense of reproduction (Le Moullec et al. 2021). Although there is confidence that the beginning and end of the annual snow pattern is changing, there is uncertainty about the timing of impacts on caribou forage quality and quantity depending on a shorter winter or a longer winter with deeper snow. Earlier springs due to warmer temperatures shift peak forage quality and biomass earlier into the growing season (Figure 23 B), but deeper snow mitigates these shifts somewhat and increases the duration of forage with sufficient protein content into an extended autumn (Figure 23C). This creates a matrix of low- and high-quality forage across the landscape (see: Figure 5 in Richert et al. 2021). After winters with experimental deep snow which buffered soil temperatures, forage quality (leaf nitrogen) in deciduous shrubs and graminoids increased and the peak shifted to late summer and into the fall (Richert et al. 2021).

While flowering and leaf emergence are mostly earlier, the evidence is less clear for fall senescence (Bjorkmann et al. 2019). Loe et al. (2020) noted that the timing of plant senescence is complex with the interplay of daytime and nighttime temperatures. They reported that in any case, at least on Svalbard, it is the timing of snow-onset season rather than the timing of plant senescence that allowed wild reindeer to gain additional body mass. Loe et al. (2020) predicted a 10 per cent increase in late winter body mass from the observed six-week variation in snow-onset which in turn could lead to 0.20 growth rate (r).

## 2. THE WARMER CLIMATE, FORAGE AND CARIBOU DEMOGRAPHY

How the warming climate and its impacts on caribou forage relate to caribou demography is riddled with knowledge gaps and regional differences. As herbivores (caribou/reindeer and lemmings/voles) reduce greening through their foraging. However, their current declines in abundance may, conversely, have increased greening (Olofsson et al., 2009, 2018). Meanwhile Fauchald et al. (2017) suggested that the greening caused caribou declines as the increased shrub growth was less palatable due to secondary toxins and the shrubs shaded preferred forage plants, such as lichens. However, modelling indicates that while caribou and reindeer impact their forage, especially deciduous shrubs, a warmer climate had a stronger impact. On average, herbivory decreased biomass approximately 12 per cent, while warming increased biomass to about 25 per cent (Yu et al. 2021). However, in some areas, such as the Urals and southwestern Greenland, herbivory had a greater impact than warming.

Analyses to link a warmer climate impact to caribou demography first depend on establishing relationships between climate variables and demographic rates. Johnson et al. (2022) reported that higher forage digestible nitrogen contributed to late June calving success the following year for the Central Arctic herd. They also found that higher forage biomass increased adult female survival over the subsequent winter but did not discern an impact on the herd’s rate of change. Albon et al. (2017), however, linked how climate impacts body mass and then how body mass is related to demographic rates using individually marked and monitored female wild reindeer on Svalbard (no predators or biting insects). Rain-on-snow restricts forage intake leading to reduced April body mass, adult survival and recruitment (recruitment was reduced by intra-uterine deaths). Summer weather and forage growth enabled body mass to recover to allow fall conceptions although fall body mass did not impact April body mass (Albon et al. 2017). An uncertainty is how the frequency of the rain-on-snow events changes relative to further summer warming and whether forage continues to positively respond to the warming.

## 3. EFFECTS OF A MORE UNPREDICTABLE CLIMATE

Previously, we linked October snow depth with the following spring parturition rate (Russell et al in prep; Figure 24); the deeper the snow, the lower the parturition rate. Given late October snow depths should not be energetically stressful for cows, our conclusion was that if October snow depths were a strong indicator of overall winter severity, cows in poor or marginally poor shape could resorb embryos and thus increase their chances of surviving the winter. We have previously shown that there is a significant relationship between body condition and early embryotic loss in the Porcupine caribou Herd (Russell et al. 1998). Females could conceive a calf in October, yet "reevaluate" in November and either wean the current calf and maintain the pregnancy or allocate nutrients preferentially into either the growth and survival of their current calf (extending lactation) or into their own survival (both resorbing the fetus and weaning the current calf). Russell et al. (1998) speculated at the time that the "decision" might be related to nutrient availability during late autumn and early winter. We now think that trigger is related to fall snow depth (Russell et al. 2024) as October and November snow depth predicts overall winter snow depth.

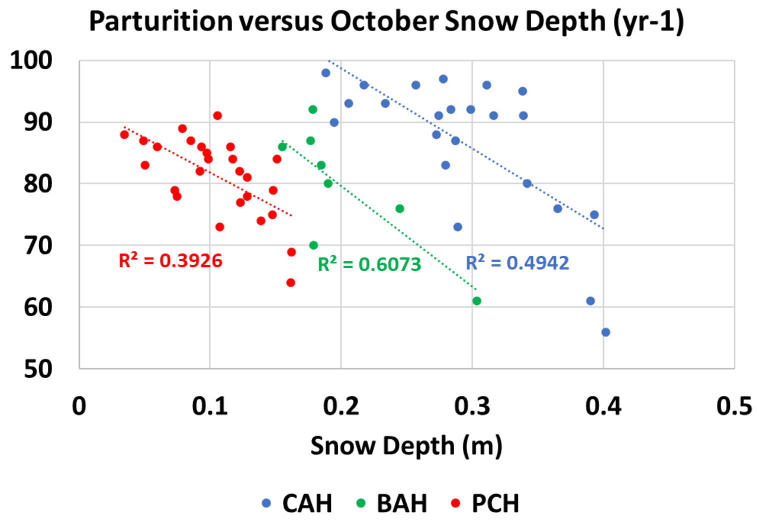


Figure 25. Relationship between October snow depth and following spring parturition rate.

Based on global climate CMIP6 projections, October snow depth is predicted to sharply decline for the three herds (Figure 25). Given the timing of the rut is related to day length and is not likely to change regardless of autumn climate, snow depths in late October/early November may not remain a reliable indicator of winter severity. Further as we have shown in our modelling, average fall body weight of cows would be lower and thus a larger proportion of newly pregnant cows would fall into the” marginal” category.

# 4. EXTREME EVENTS

Trends in climate warming are also punctuated by infrequent and extreme events – those events that lie outside the statistical distribution (van Beest et al. 2022). The frequency of extreme weather events is increasing, especially in the Arctic (van Beest et al. 2022). Most extreme events are rain-on-snow with subsequent icing causing unusual movements and die-offs but extremes in summer temperatures and rainfall also put caribou at risk.

## 4.1 Rain-on-snow

Although warmer temperatures increase the ratio of rain to snow (ROS) events, the same warmer temperatures reduce snow cover and consequently ROS events may be fewer but patterns are complex (Cohen et al. 2015). The ROS events are associated with atmospheric patterns, such as Arctic Oscillation and North Atlantic Oscillation. The positive Arctic Oscillation phase increases the frequency of ROS across northwest Eurasia (Cohen et al. 2015) where ROS have had devastating impacts. Recent models project a wetter Arctic climate with rainfall replacing snowfall especially in the fall (McCrystal et al. 2021).

Widespread ROS impedes *Rangifer* from digging through the snow to reach their forage (Hansen et al. 2014). Although wild reindeer may move to more favourable areas and survive (Loe et al. 2016), this is not always possible and die-offs have drastic although relatively transitory impacts on trends in abundance (Miller and Gunn 2003, Forbes et al. 2016). On the Western Arctic herd's ranges in Alaska, a midwinter thaw with rain meant that by spring 2006, many caribou were in poor body condition and adult female mortality was 32 per cent (Dau 2011).

We did not include potential increase in icing conditions in the winter in our modelling as we do not have estimates of energetic costs of accessing forage under variable icing conditions. Using our climate database (Figure 8 and Figure 9), we note that October temperature was a good predictor of overall winter icing conditions (rain-on-snow, freezing rain, and freeze/thaw events). For the BAH, higher mean October temperature had the highest predictive value (among other months) for most icing conditions, although the correlation was low compared to the CAH. October temperature was not a good predictor of icing conditions in the TAI herd. We would thus expect higher frequency of icing with warmer October temperatures in the future for the CAH and BAH, although we are uncertain about similar increases in icing conditions for the TAI herd.

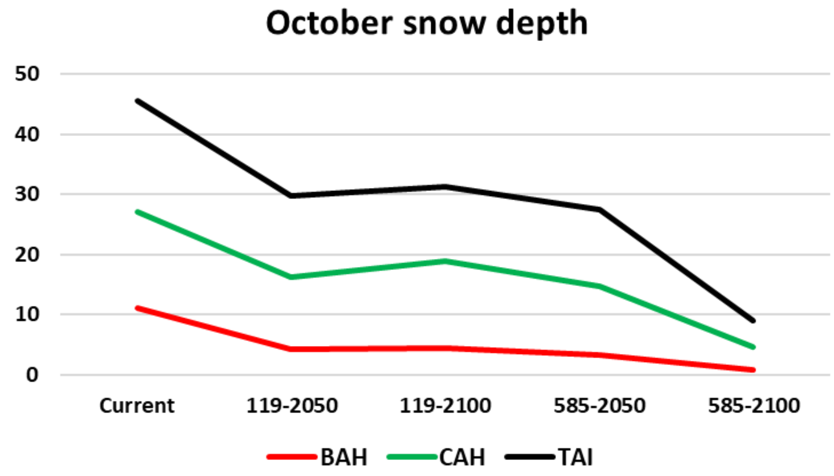


Figure 26. Projected CMIP6 October snow depths for three representative herds.

## 4.2 Heat waves

Heat waves in the Arctic are less likely than at lower latitudes and their occurrence is highly regional. However, the frequency has significantly increased since 2002 for the central and northeast Canadian Arctic mainland, the northeastern Arctic islands and northeast Greenland (Dobricic et al. 2020). In contrast, possibly under an ocean influence, the 1951-2021 trend for heat waves for coastal Alaska was not significant (Rantanen et al. 2023). Caribou are cold-adapted and dissipating heat gain from high ambient temperatures is physiologically stressful. Behavioural responses to heat include seeking residual snow patches or cooler slopes and delaying activities until later in the day (Trondrud et al. 2023). But if heat gain continues when external temperatures are >25°C and because ruminants digest forage in a large rumen producing body heat, they will reduce forage intake which can limit body reserves and reproduction.

During the 2018 heat wave in northern Finland, mean ambient temperatures were at least 5°C higher than the climate normal (14.0°C) on 14 days compared to two days on average (Trondrud et al. 2023). Above 20°C, the domesticated reindeer had lower heart rates and decreased food intake which contributed to exceptionally low fall body mass (Trondrud et al. 2023). The lower body mass was not just from the response to reduced forage intake from the high temperatures: additionally, the hot dry conditions reduced forage quality and increased insect harassment (Trondrud et al. 2023). It is difficult even with animals fitted with heart rate and activity monitors to single out responses to any one factor, such as temperature. This may mean impacts of heat waves are underestimated. For example, on the summer range of the Bathurst herd on the central Canadian Arctic mainland, high drought indices in 2014 occurred with 12 days >25°C and an exceptionally severe oestrid index: adult female and calf survival were below average (Russell et al. in Press; unpubl. data).

Higher than normal temperatures can also co-occur with reduced rainfall (drought) or above average rainfall. Outbreaks of disease, such as necrobacillosis, during unusually hot rainy summer can sharply reduce juvenile survival (Mysterud et al. 2023). Typically, variations in juvenile survival contribute less to trends in abundance than adult female survival (Boulanger et al. 2011). Trends to hotter and wetter summers may increase the frequency of disease outbreaks raising the risk of declines in herd size.

## 4.2 Forest fires

Warmer summer temperatures have the potential to increase the incidence and intensity of forest fires on the winter range of migratory tundra caribou herds. Our climate data base (Russell et al. 2013) calculates a daily drought index, KBDI, as described by Keetch and Byram (1968). The KBDI is defined as ‘‘a number representing the net effect of evapotranspiration and precipitation in producing cumulative moisture deficiency in deep duff or upper soil layers’’ (Keetch and Byram, 1968) and is used as a Fire Weather Index by forest managers. The index is dependent on temperature and precipitation and the KBDI index from the previous day, thus it is a cumulative index that tracks moisture deficits through the fire season.

Using our climate database (1980-2019) for our three representative herds, we determined the mean July KBDI on the winter range and, with simple regression, the correlation coefficient between KBDI and temperature or rainfall (Figure 26).

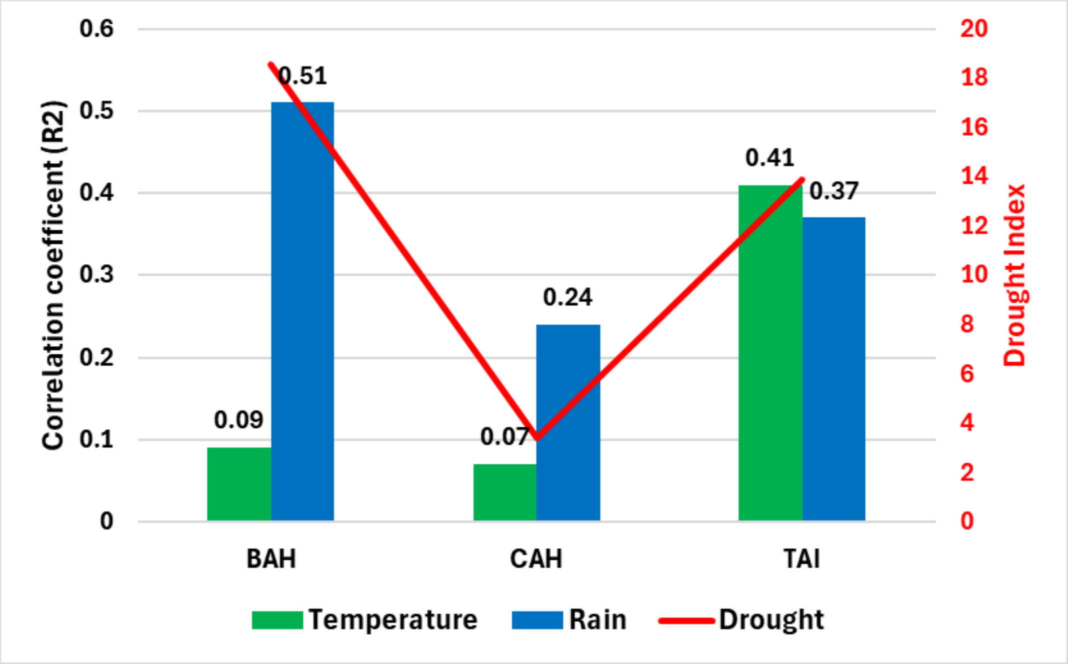
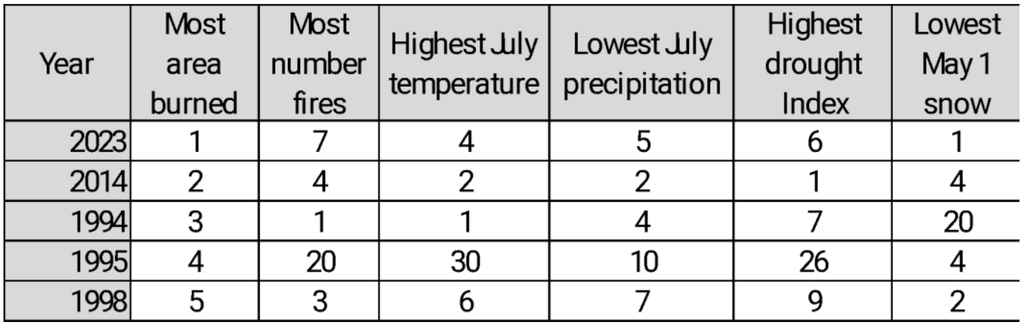


Figure 27. Correlation between July temperature or July rain versus drought index. Red line is the mean July drought index.

Currently the BAH has the highest drought index and rainfall appears to be the driver of annual variability. Because BAH has the highest temperatures among the three herds, we assume that temperatures are normally high enough to cause elevated drought conditions and the variability depends on summer rainfall. Although the drought index is low for the CAH, a similar pattern between temperature and rainfall emerges, precipitation is a better predictor of drought. Annual drought variability for the TAI herd is equally driven by temperature and rainfall. Thus, for our application, given we are only working with temperature predictions, it is not easy to project future forest fire conditions with any level of certainty.

We do have a long record of forest fire frequency (number of fires) and intensity (area burned) for Northwest Territories, much of it on historic BAH winter range. To examine the characteristics of high fire years we looked at the worst five years (area burned> 1M ha) in a 33-year forest fire record (1990-2023) in relation to climate conditions (**Error! Reference source not found.**).

Table 6: Ranks of climate conditions over 33 years (1990-2023) associated with the five worst years (area burned) in the Northwest Territory. Climate variables are from the winter range of the Bathurst caribou herd.



| Year | Most area burned | Most number fires | Highest July temperature | Lowest July precipitation | Highest drought Index | Lowest May 1 snow |
|---|---|---|---|---|---|---|
| 2023 | 1 | 7 | 4 | 5 | 6 | 1 |
| 2014 | 2 | 4 | 2 | 2 | 1 | 4 |
| 1994 | 3 | 1 | 1 | 4 | 7 | 20 |
| 1995 | 4 | 20 | 30 | 10 | 26 | 4 |
| 1998 | 5 | 3 | 6 | 7 | 9 | 2 |

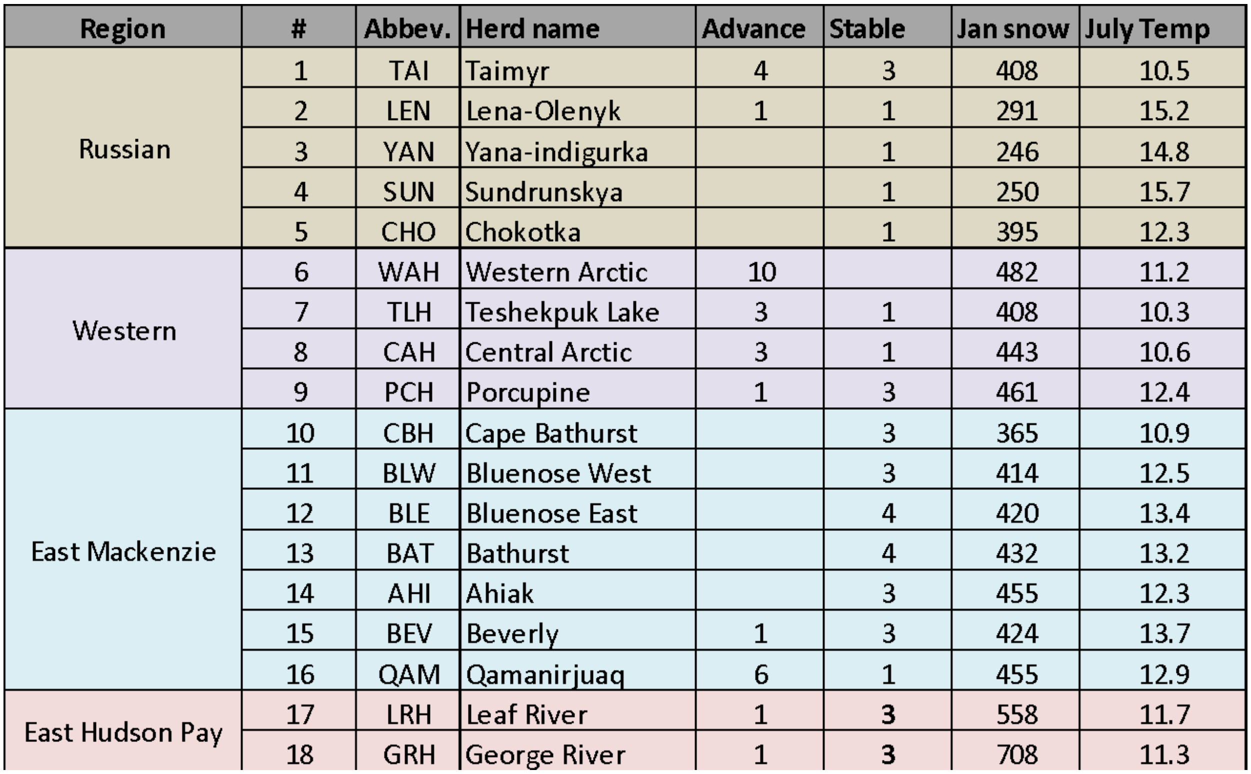
**Error! Reference source not found.** reveals that with the possible exception of 1995, several climate conditions have to coincide to result in a severe forest fire year. 1995 is an anomaly in that the only factor that might be linked to a severe forest fire year was May 1 snow depth. There wasn't even an above average number of fires. The simple analysis suggests that although we would expect an increase in forest fire activity with a warming climate, the role of spring and summer precipitation are probably more important, certainly for the BAH.

## 4.2 Sea ice change

Understanding mechanisms for how a warmer climate is driving ecological changes helps refine extrapolating the risk for other herds. The accelerating loss of sea-ice (Jahn et al. 2024, Dail et al. 2024) is a case in point as it strengthens our understanding of regional climates faced by caribou. For example, the ice-free season in the Laptev, East Siberian, Chukchi and Beaufort Sea will jump to seven to eight months under SSP5-8.5; nine months in the Kara Sea; the Barents Sea will be ice free year-round (Jahn et al. 2024). Change of Arctic sea-ice signals terrestrial ecological changes, such as proportionally more circumarctic tree line advances as sea ice loss increases (Dial et al. 2024). Tree ring growth responds more to sea ice retreat than to growing season temperatures while forest advance has a threshold response to snowpack depth. The modelled forest advance was 6.6 ±1.4 m/decade in more maritime watersheds) which was nearly twice that found in more continental watersheds (Dial et al. 2024).

There are regional generalizations when we superimposed herd ranges on Dial et al.'s (2024) circumpolar map to see where the treeline is advancing or stable (**Error! Reference source not found.**). The Taimyr herd range has pockets of both advancing treeline and stable treelines, and although treeline plots are sparse, all other Russian herd ranges adjacent the east Siberian Seas are not associated with an advancing treeline. All western North American herds, except the Porcupine Herd are associated with advancing treelines. For the PCH, the portion of range in Alaska has an advancing treeline, while ranges in Canada experienced stable treeline. East of the Mackenzie treelines have generally remained stable; however, the closer ranges are to Hudson Bay, the higher the probability of advancing treelines. The Qamanirjuaq Herd had 6 of 7 treeline plots recording treeline advance.

Table 7: Number of treeline plots within the ranges of migratory tundra caribou that were either advancing or stable based on Dial et al. (2024).



| Region | # | Abbev. | Herd name | Advance | Stable | Jan snow | July Temp |
|---|---|---|---|---|---|---|---|
| Russian | 1 | TAI | Taimyr | 4 | 3 | 408 | 10.5 |
| | 2 | LEN | Lena-Olenyk | 1 | 1 | 291 | 15.2 |
| | 3 | YAN | Yana-indigurka | | 1 | 246 | 14.8 |
| | 4 | SUN | Sundrunskya | | 1 | 250 | 15.7 |
| | 5 | CHO | Chokotka | | 1 | 395 | 12.3 |
| Western | 6 | WAH | Western Arctic | 10 | | 482 | 11.2 |
| | 7 | TLH | Teshekpuk Lake | 3 | 1 | 408 | 10.3 |
| | 8 | CAH | Central Arctic | 3 | 1 | 443 | 10.6 |
| | 9 | PCH | Porcupine | 1 | 3 | 461 | 12.4 |
| East Mackenzie | 10 | CBH | Cape Bathurst | | 3 | 365 | 10.9 |
| | 11 | BLW | Bluenose West | | 3 | 414 | 12.5 |
| | 12 | BLE | Bluenose East | | 4 | 420 | 13.4 |
| | 13 | BAT | Bathurst | | 4 | 432 | 13.2 |
| | 14 | AHI | Ahiak | | 3 | 455 | 12.3 |
| | 15 | BEV | Beverly | 1 | 3 | 424 | 13.7 |
| | 16 | QAM | Qamanirjuaq | 6 | 1 | 455 | 12.9 |
| East Hudson Pay | 17 | LRH | Leaf River | 1 | **3** | 558 | 11.7 |
| | 18 | GRH | George River | 1 | **3** | 708 | 11.3 |

# APPENDIX B. ADAPTIVE CAPACITY

Adaptive capacity is what needs to be done to mitigate potential impacts of a warmer climate. Adaptive capacity reflects the ability to evolve, dispersal and distribution and behavioral plasticity. Thurman et al. (2021) recently catalogued how adaptive capacity attributes can be linked to potential conservation actions. Singer and Lee (2021) applied adaptive capacity for rating NWT species vulnerability. Singer and Lee (2021) commented that uncertainty limited their completed vulnerability assessment but they rated barren-ground caribou as having moderate adaptive capacity; moderate sensitivity to climate change and a high score for forest fires, harvesting and cumulative impacts.

The caribou's life history is already adapted to annual variations in climate as they are capital breeders – it supports the cost of reproduction from their body reserves and they can curtail reproductive costs to favor their own survival when forage is restricted (Apollonio and Chirichella 2023). Evolutionary adaptive capacity (i.e. the ability to evolve) is apparent in the wide global range and diversity of *Rangifer*. *Rangifer* typically is genetically variable and selection for individual traits will be part of adaptive capacity. Although evolution is thought to occur over generations; it may be more rapid in those *Rangifer* genetically diverse populations which are under selective pressure for specific traits. For example, genes of the major histocompatibility complex (MHC) are an essential component of the immune system. It is energetically costly maintaining the immune system and in the George River caribou herd, the functional MHC diversity was negatively related to survival suggesting that individuals with higher MHC diversity suffer higher costs of immunity (Gagnon et al. 2020). This finding may link evolutionary and phenotypic plasticity through selection of individual traits relative to the costs of immune function, increased exposure to parasites in a warmer climate and plasticity in the allocation of costs to survival and reproduction. Recent advances in *Rangifer* genome analyses will transform our understanding of evolutionary adaptive capacity.

Caribou through their movements and migrations have a marked capacity to change their distribution to maintain their access for energetically-efficient foraging. For example, caribou can shift winter ranges in response to Rain-on-Snow events. The corollary of this is the vital need to maintain landscapes permeable to caribou movements – a combination of land use planning and effective mitigation. The likely impacts of a road are, for example, relatively predictable which means that the degree of landscape management to offset the impacts is predictable (Russell et al. 2022).

Phenotypic plasticity is the ability of an organism to change (behavior or physiologically) as response to its environment. Phenotypic plasticity allows individuals or genotypes to adjust their phenotypes so that they can track the varying environmental optimums (Beever et al. 2015, 2017). An example is caribou seeking cooler slopes, wet areas or residual snowbanks in hot weather: Svalbard reindeer select cool, wetter bed sites on warmer days (Williamson 2018). Another example is plasticity in diets. Caribou select a remarkably wide variety of forage plants (Ehler et al. 2021) which should enable plasticity in feeding behavior as the composition of plant communities' changes with respect to a warmer climate. Svalbard reindeer have increased their intake of grasses during the increasingly frequent winters with ROS events. The ice coats the mosses which were previously a larger part of the diet (Hiltunen et al. 2022).

A frequently cited example of plasticity is adjusting calving dates in response to trends in earlier plant green-up (LaForge et al. 2023). A caribou cow supports early lactation from her body reserves rather than forage intake as peak calving is timed to precede beginning green-up by three to four days. Calf growth rate (150-500g/day) depends on milk production up until about three weeks when the calf is eating more vegetation. Thus, nutritional demands for females increase from calf birth to peak lactation (1-2 liters/day), which occurs approximately three weeks after parturition. Potentially, an earlier green-up will shift peak nutrient availability away from peak nutritional demand (peak lactation) leading to reduced calf growth and lower calf survival. To date, evidence has not detected this potential mismatch (Mallory et al. 2020, Gustine et al. 2017, Veiberg et al. 2016, Tveraa et al. 2013, Griffith et al. 2002). Daylength partly sets the timing of rut timing and conception as well as body condition and as such, was considered to be relatively inflexible. In the Qamanirjuaq caribou herd, advancing green-up coincided with earlier migration and calving (Mallory et al. 2022) and by 2023, the calving ground rapidly shifted possibly to adjust to green-up timing. However, most calving grounds are already coastal so shifting calving grounds will not be an option.

An increasing part of adaptive capacity to reduce vulnerability to potential impacts of a warmer climate is the role of caribou management and landscape management. Conventional wildlife management practices, such as harvest management, can be used to buffer environmental changes. An example was reducing the harvest of caribou cows to offset the costs of, in this case, oilfield development on the Central Arctic herd's calving and summer ranges (Russell and Gunn 2019).