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Title: Merging indigenous and scientific knowledge links climate with the growth of a large migratory caribou population

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Abstract

1. Climate change in the Arctic is two to three times faster than anywhere else in the world. It is therefore crucial to understand the effects of weather on keystone arctic species, particularly those such as caribou (*Rangifer tarandus*) that sustain northern communities. Bridging long-term scientific and indigenous knowledge offers a promising path to achieve this goal, as both types of knowledge can complement one another.

2. We assessed the influence of environmental variables on the spring and fall body condition of caribou from the Porcupine Caribou Herd. This herd ranges in the Yukon and Northwest Territories (Canada) and Alaska (USA), and is the only large North American herd that has not declined since the 2000s. Using observations recorded through an indigenous community-based monitoring programme between 2000-2010, we analyzed temporal trends in caribou condition and quantified the effects of weather and critical weather-dependent variables (insect harassment and vegetation growth), on spring (n = 617 individuals) and fall (n =711) caribou condition.

3. Both spring and fall body condition improved from 2000 to 2010, despite a continuous population increase of ca. 3.6% per year. Spring and fall caribou condition were influenced by weather on the winter and spring ranges, particularly snow conditions and spring temperatures. Both snow conditions and spring temperatures improved during our study period, likely contributing to the observed caribou population increase. Insect harassment during the previous summer and the frequency of icing events also influenced caribou condition.

4. *Synthesis and applications.* Our study shows how untangling the relative influences of seasonal weather variables allows a much better understanding of variation in seasonal body condition of caribou. It indicates that a large migratory caribou population can grow and improve

condition in a global context of caribou decline and climate warming, thereby warning against generalizations about the influence of climate on all caribou populations. Finally, it testifies how data from indigenous community-based monitoring can remarkably improve ecological understanding of wildlife sustaining human communities. Were possible, we recommend management practices that respectfully engage with indigenous community-based monitoring, as this can enhance knowledge and relationships with communities, both prerequisites of successful resources management.

Keywords: body condition, demography, icing events, indigenous knowledge, caribou, snow, seasonal, community-based monitoring

1. INTRODUCTION

Climate change has occurred at an unprecedented rate in the circumpolar North (IPCC, 2013). Ecologists and members of northern indigenous communities have thus been increasingly interested in assessing how climate and weather affect the dynamics of arctic animal populations, which are adapted to cold and short growing seasons (Berteaux, Réale, McAdam, & Boutin, 2004). Climate change is expected to greatly affect their population dynamics, but spatial and temporal variations in climate and weather could affect species differently (Mysterud, Yoccoz, Langvatn, Pettorelli, & Stenseth, 2008).

The highly abundant pan-Arctic *Rangifer tarandus* (L., 1758; including caribou and reindeer) is a keystone tundra species (COSEWIC, 2016) at the heart of the cultures and livelihoods of many arctic Indigenous Peoples (Kofinas et al., 2003). In North America, migratory caribou herds undergo large-scale population fluctuations (Gunn, 2003). However, the accelerated declines observed in most herds since 2000s (CARMA, 2017) raise serious concerns (Festa-Bianchet, Ray, Boutin, Côté, & Gunn, 2011). Climate change could explain this quasi general decline via a trophic mismatch between plant phenology and caribou needs (Post & Forchhammer, 2008), an increased occurrence of ice-locked winter pastures (Hansen, Aanes, Herfindal, Kohler, & Sæther, 2011), or decreased pasture quality (Fauchald, Park, Tømmervik, Myneni, & Hausner, 2017).

Owing to the ecological and cultural importance of caribou, a detailed understanding of how environmental conditions affect their population dynamics is urgently needed. Body condition is a key variable to understand this link in large herbivores (Barboza, Parker, & Hume, 2009) because it represents the energy reserves that an animal possesses to sustain daily and seasonal activities (Barboza et al., 2009; Schulte-Hostedde, Zinner, Millar, & Hickling, 2005). Therefore, body condition correlates with over-winter survival (Parker, Barboza, & Gillingham, 2009), age at first reproduction (Festa-Bianchet, Gaillard, & Jorgenson, 1998), and pregnancy probability (Russell, Gerhart, White, & Van De Wetering, 1998). Although different measurements are used to assess ungulates' body condition, including body mass, body size and body reserves (e.g. fat and protein; Barboza & Parker, 2008), body mass is best to describe caribou condition (Taillon, Brodeur, Festa-Bianchet, & Côté, 2011).

Environmental impacts of climate change can affect caribou condition in various ways. During winter and spring, snow depth increases costs of locomotion and reduces access to forage (Adams, 2005; Fancy & White, 1987). Likewise, events such as freeze-thaw, freezing rain and rain-on-snow create ice layers and ground ice that impede access to forage (Hansen et al., 2011;

Solberg et al., 2001). During summer, low winds and warm temperatures promote insect harassment, leading caribou to expend energy avoiding insects, thus reducing feeding time (Mörschel, 1999; Weladji, Holand, & Almoy, 2003). Yet high temperatures can enhance plant productivity and quality, improving forage conditions (Lenart, Bowyer, Hoef, & Ruess, 2002). Environmental variables affecting body condition are thus likely to differ across seasons, with different consequences on demography (Albon et al., 2017; Figure 1).

Investigating the effects of seasonal meteorological variables on caribou condition over different seasons requires long-term datasets. In the North American Arctic, long-term and uninterrupted scientific data about migratory caribou are mostly lacking (Festa-Bianchet et al., 2011). Monitoring programmes involving observations from northern indigenous hunters, however, hold remarkable potential for mobilizing indigenous knowledge about caribou. Hunters have been looking at the body condition of caribou for their entire life, and for generations. They often live year-round in caribou habitat, spend months in direct contact with the herds, and have access to many harvested carcasses. Hunters therefore own a thorough expertise in evaluating the condition of animals. This expertise is exemplified by the indicators of body condition that hunters have developed for evaluating caribou health before and after harvest (Kofinas et al., 2003; Lyver & Lutsël K'é Dene First Nation, 2005).

Here, we worked with a unique long-term dataset from an indigenous community-based monitoring programme that has documented spring and fall body condition annually since 2000 for the Porcupine Caribou Herd (PCH; see Appendix S1 in Supporting Information). The PCH (Alaska, Yukon, and Northwest Territories; *Rangifer tarandus granti*) is one of the largest migratory caribou populations in the world (CARMA, 2017). It occupies a region experiencing amongst the most dramatic climatic changes on Earth (IPCC, 2013). Paradoxically, it is the only migratory caribou herd in North America that increased in size over the last two decades (CARMA, 2017). To understand this exceptional case, our aim was first to analyse temporal variations in the annual spring and fall condition of PCH caribou between 2000-2010, and then to quantify the influence of local seasonal environmental variables and large-scale climate proxies on spring and fall caribou condition over the same period. We anticipated that spring and fall condition would decrease over time as a response to increase in caribou density (Bonenfant et al., 2009). We also expected spring body condition to be mostly influenced by winter precipitation (Fancy & White, 1987; Hansen et al., 2011) and fall body condition by summer temperature (van der Wal & Stien, 2014).

2. MATERIALS AND METHODS

2.1 Study area and caribou population

The PCH ranges over ca. 250,000 km^2 in the northern Yukon and Northwest Territories (Canada) and Alaska (USA; Figure 1). During winter, the herd uses the southern part of its range, where snow is shallower, thus facilitating locomotion and access to lichens, their primary winter forage (Russell, Martell, & Nixon, 1993). During spring, the herd migrates north to reach the calving grounds on the arctic coastal plain of Alaska and northern Yukon (Russell et al., 1993). Common forage plants during spring, calving and summer include mosses, graminoids (especially *Eriophorum* spp.) and deciduous shrubs (Russell et al., 1993). Indigenous communities belonging to the Inupiat, Inuvialuit and Gwich'in cultures are located within or close to the PCH range. These include the communities of Kaktovik and Arctic Village (Alaska), Old Crow (Yukon), and Aklavik, Fort McPherson, Inuvik, Tsiigehtchic and Tuktoyaktuk (Northwest Territories). The PCH has been a central component of the culture and diet of these communities during thousands of years (Pilon, 2017). According to aerial censuses, the size of this herd has fluctuated over time (Figure 1), with an increase since 2001 and spring became earlier and warmer between 2000 and 2010 (see Figure S1).

2.2 Hunters' monitoring of caribou condition

Seasonal body condition of PCH caribou was monitored through the annual community-based monitoring programme of the Arctic Borderlands Ecological Knowledge Society (ABEKS; (ABEKS, 2014). Since 1998, ABEKS has conducted its monitoring programme through a survey questionnaire covering topics such as caribou, berries, birds, weather and fish. This programme involves annually 10 PCH user communities and is conducted by local indigenous monitors trained by experienced community monitors and the ABEKS' coordinator (Appendix S1). Monitors identify annually 15-20 local experts from their community who are active on the land (ABEKS, 2014). Each expert is given a personal identity number allowing anonymous tracking of answers.

We analyzed answers to a question asking local experts to report their general impression regarding the average body condition of caribou harvested and/or observed during fall and spring. Respondents chose between "Poor/skinny", "Fair/mix of poor and fat", "Good/excellent", and "Don't know". These qualitative categories were developed based on discussions with Porcupine caribou hunters who use several criteria to assess caribou condition (Supplementary Information Appendix S1) In the following, we refer to these categories as poor (1), average (2) and excellent (3), respectively ("Don't know" answers were ignored). During our study, ABEKS data were available for the 2000-2010 period, yielding 711 answers for the fall and 617 answers for the spring, including 10 communities in both seasons. Hunter evaluations were positively correlated with scientific measurements (Appendix S2).

2.3 Large-scale climate

We used the Arctic Oscillation index (AO; National Weather Service, 2017) to describe broad-scale climate. In our study area, the "positive" phase of AO corresponds to warmer and wetter winters, with increased snow, whereas the "negative" phase corresponds to colder, drier, and less snowy winters (Thompson & Wallace, 1998). We averaged monthly AO anomalies to obtain an annual AO index for 2000-2010. Because the AO index is most variable during winter (Zhou, Miller, Wang, & Angell, 2001), we also calculated annual winter (January-March) averages (hereafter identified as AOw) using daily AO anomalies for 2000-2010.

2.4 Local weather over the winter and spring caribou ranges

Weather data from meteorological stations were sparse in our study area. We thus used the CircumArctic *Rangifer* Monitoring and Assessment (CARMA) network's caribou range climate database (https://carma.caff.is/; Russell et al., 2013). The CARMA database was developed using NASA's MERRA database (NASA, 2017), containing remotely sensed daily averaged climate data with a spatial resolution of 0.50° Lat. x 0.66° Long. To construct the CARMA caribou range database, shapefiles of seasonal PCH ranges, estimated through satellite collared animals, were overlapped with MERRA' s gridded climate variables using ArcGIS version 10 (ESRI, 2010; Russell et al., 2013). This allowed calculating daily weather variables specific to the range used by the PCH during the fall (16 August-30 November), winter (1 December-31 March), spring (1 April-31 May), calving (1 June-21June) and summer (22 June-15 August; Cai, Russell, & Whitfield, 2011; Table S1). From the CARMA database, we calculated 19 seasonal weather variables describing snow, temperature and icing conditions susceptible to impact caribou condition (Tables S2, S3).

The calculated variables were numerous and often correlated. To reduce the number of variables to below the number of years recorded (n=11), we eliminated variables that were highly correlated ($r > 0.7$, Table S2), retaining only one representative variable. We log-transformed the variable “freezing-rain falling on the ground on the winter range” to meet assumptions of normality and homogeneity of variance. We then pooled remaining variables according to two categories: 1) variables pertaining to snow and temperature, 2) variables pertaining to icing events. We then performed a separate Principal Component Analysis (PCA; Jolliffe, 2005) to transform correlated variables into uncorrelated Principal Components (PCs) for each category. We determined the number of PCs to be used as final variables in each model based on the scree-test method (relying on the sharp decline in consecutive eigenvalues (Cattel, 1966) and eigenvalues > 1.0 (Jolliffe, 2005)). This resulted in two PCs describing snow/temperature conditions (“PCsnow1” and “PCsnow2”) and one PC describing icing events (“PCice1”; see Table 1 for interpretation of each PC).

2.5 Proxies of vegetation and insect conditions on the calving and summer ranges

Temperature is a strong driver of plant growth in the Arctic. We used effective growing degree-days (GDD; cumulative values above 5°C, available from CARMA; Table S1) as a proxy to capture variability in vegetation productivity and phenology (e.g. Albon et al., 2017; Gamon, Huemmrich, Stone, & Tweedie, 2013). To reflect differential forage availability across periods, we used cumulative GDD from 1 January to 31 May (when caribou leave the spring range; “GDDMay”), from 1 January-21 June (plant productivity on the calving range; “GDDJune”), and from 1 January-15 August (plant productivity over the entire summer; “GDDAugust”). GGDJune and GDDAugust were strongly positively correlated (*r*= 0.86), thus we only retained GDDMay and GDDJune in further analyses. To measure the level of insect harassment during calving and summer, we used the daily oestrid harassment index from 1 June to 15 August (available from CARMA; Table S1). This insect harassment index (IHI) is a proxy of insect harassment calculated from temperature and wind data (Mörschel, 1999; Weladji et al., 2003).

Since IHI was positively correlated with GDDJune (*r*= 0.77), we never used both variables in the same model. Both GDD and IHI were measured in the summer prior to measures of body condition, meaning that both variables were measured at *t-1* for the spring condition (see Table S4). Both GDD and IHI were standardized to be comparable with the PCs scores (Schielzeth, 2010).

2.6 Statistical analyses

We used R software version 3.4.2 (R Development Core Team, 2017). To investigate temporal trends in the spring and fall caribou condition, we used Pearson’s product moment correlations for normally distributed samples (cor.test function) to test for association between years and both spring and fall annual average body condition. To assess the effects of large-scale climate, local weather, vegetation productivity and insect harassment on spring and fall caribou condition, we used cumulative link mixed models (function clmm2, ordinal package; Christensen, 2015a). CLMMs, also known as “ordinal regression models”, allow for analysis of ordered categorical response variables. They calculate the probability of an observation to fall into a certain category according to variations in explanatory variables, while considering the effects of random factors (Christensen, 2015b). We included “community” as a random intercept to control for repeated observations within a community each year. A CLMM assumes proportional odds or equal slopes, meaning that the slope estimate representing the probability of passing from one category to another with changes in an explanatory variable is held constant (Christensen, 2015b). We used the “nominal” option to relaxes this assumption when it was violated, allowing slope estimates to vary according to response categories (Christensen, 2015b). Thus, the model estimated two slopes instead of one, one for the probability of changing from condition “1” to “2” and one for changing from “2” to “3”.

Because we were dealing with numerous explanatory variables, we developed candidate models using a distinctive step approach using four steps for both spring and fall. In all steps, we excluded variable combinations with correlations of $r > 0.50$. In step I, we built candidate models assessing the effect of large-scale climate on body condition (Tables S4, S5). In step II, we built models assessing the influence of locomotion and thermoregulation costs during winter/spring season on body condition (PCsnow1, PCsnow2, and PCice1). In step III, we built models assessing impacts of environmental conditions reflecting vegetation productivity and insect harassment during calving/summer season on body condition (GDDMay, GDDJune, and IHI). For these three steps, we used an Akaike Information Criterion approach, considering models with $\Delta AIC \leq 2$ as equivalently supported (Burnham & Anderson, 2002). In step IV, we built final candidate models with variables from all the supported models in steps I to III, and again considered final models with $\Delta AIC \leq 2$ as supported. Parameter estimates and 95% confidence intervals (CI) for the final equivalent models are in Tables S6, S7.

3. RESULTS

3.1 Variation in caribou condition over time

Despite the increase in population size with time, spring and fall caribou condition increased significantly during the study period (Pearson's r [95% CI]: spring= 0.86 [0.54; 0.96], n= 11; fall= 0.84 [0.48; 0.96], n= 11; Figure 2).

3.2 Spring body condition

According to the most parsimonious model selected (#2, Table 2), spring body condition was correlated to the insect harassment index during the previous summer (IHI_{yr-1}) and winter severity (PCsnow1 and PCsnow2). When IHI_{yr-1} more than tripled, the probability of caribous' being rated in "excellent" condition declined by 44% (0.45 to 0.25), "average" increased by 44% (0.45 to 0.65), and "poor" remained constant at about 0.10 (Figure 3a). High PCsnow1 scores also reduced the probability of caribou being rated in good condition. When cumulated snow doubled, average temperature in spring dropped from -2^{o}C to -10^{o}C, and spring was delayed by 28 days, the probability of caribous' being rated in "excellent" condition decreased by 64% (0.55 to 0.20), "average" increased by 40% (0.43 to 0.60), and "poor" rose by a factor 10 (0.02 to 0.20; Figure 3b). High PCsnow2 scores also reduced the probability of caribous' being rated in good condition, but to a lesser extent than insect harassment and harsh winters (Figure 3). When the coefficient of variation in winter snow depth almost tripled, the probability of caribou's being rated "excellent" declined by 25% (0.40 to 0.30), "poor" tripled (ca. 0.05 to 0.15), and "average" remained relatively constant at 0.55 (Figure 3c). Equivalent but less parsimonious models identified icing events occurring during winter and spring (PCice1) and the AO has having a potential influence on spring body condition (Table 2), but estimates for these variables were small and imprecise, with their 95% CI overlapping 0 (Table S6).

3.3 Fall body condition

According to the most parsimonious model selected (Table 3), fall body condition was also influenced by winter severity. The probability of caribous' being rated in good condition was affected by PCice1, PCsnow1, and PCsnow2 (Figure 4, Table S7). When the number of days with freeze-thaw events recorded on the winter range increased from 12 to 34, the probability of caribous' being rated "excellent" declined by 25% (0.73 to 0.55), "average" increased by 60% (0.25 to 0.40) and "poor" increased by 150% (0.02 to 0.05; Figure 4a). When cumulated snow doubled on the spring range, average temperatures in the spring dropped from -2ºC to -10ºC, and spring was delayed by 28 days, the probability of caribous' being rated "excellent" declined by 25% (0.73 to 0.55), "average" increased by 60% (0.25 to 0.40) and "poor" increased by 150% (0.02 to 0.05; Figure 4b). Finally, when the coefficient of variability in snow depth tripled over the previous winter, the probability of caribous' being rated "excellent" decreased by 31% (0.75 to 0.52), "average" increased by 54% (0.24 to 0.37) and "poor" increased by a factor of 10 (0.01 to 0.11; Figure 4c).

Two equivalent models also presented support to the data, with model 1 having almost twice greater support than model 2 (Table 3). Model 1 differed by including GDDMay instead of PCsnow1, and was less parsimonious simply because GDDMay had a nominal effect, increasing by 1 the number of parameters estimated. GDDMay and PCsnow1 were highly negatively correlated with (r= -0.90), suggesting these two variables have a similar influence on fall condition. Indeed, GDDMay had a strong influence (Table S7): with an increase of 58 growing degree-days in May, the probability of caribous' being rated "excellent" increased by 55% (0.55 to 0.85), "average" decreased by 70% (0.43 to 0.13) and "poor" remained relatively constant (0.02; Figure 4d).

4. DISCUSSION

Our findings show that bridging long-term indigenous observations about caribou condition with climate data can considerably improve our understanding of the ecology of a growing migratory caribou herd. Two results are of particular interest. First, though we expect body condition to decrease with increasing density (Bonenfant et al., 2009), spring and fall caribou condition improved over time despite population growth. Second, both spring and fall caribou condition were influenced by weather on the winter and spring ranges, particularly snow conditions and spring temperatures. Most importantly, our results reiterate how indigenous knowledge can provide reliable data on caribou at temporal and spatial scales that are not easily monitored by scientists. In northern Canada, numerous studies have documented traditional knowledge about caribou that contributed to a wealth of detailed descriptions about caribou distribution, movement and population fluctuations (e.g. Ferguson, Williamson & Messier, 1998; Parlee, Manseau & Lutsël K'é Dene First Nation, 2005). Our study takes a different approach that is less descriptive, but nevertheless based on one important strength of indigenous knowledge: repeated observations and evaluation of the surrounding environment. This approach allowed us to merges two very different long-term datasets using novel analytical tools.

Earlier studies of the PCH showed that parturition rate, calving rate and net calf production were not affected by population size (Griffith et al., 2002). Our results also suggest that density-dependence might not be the main driving factor of body condition, at least for population sizes encountered during the decade studied. Because the PCH inhabits one of the northernmost ranges occupied by migratory caribou herds (CARMA, 2017), this finding supports the suggestion that negative density-dependence declines with latitude (Bjørnstad, Falck, & Stenseth, 1995; Post, 2005). Nevertheless, we observed strong temporal trends during that decade towards warmer springs, earlier snow melt, and shallower snow depths (see Figure S1).

These weather trends are likely responsible for the improvement in spring and fall caribou condition in the PCH during that time period, and perhaps its population growth, and thereby could have compensated for density-dependence (Albon et al., 2017).

Our results suggest that snow depth and its variation, temperature, and melt date are fundamental drivers of spring and fall caribou condition in the PCH. Early calf survival and recruitment correlate with female caribou condition in late winter (Veiberg et al., 2017). By increasing by as much as 10 times the probability of caribou being in poor condition in spring, harsh snow conditions likely have large impacts on the PCH, as reported in other northern ungulates (Post & Stenseth, 1999; Solberg et al., 2001). The negative effects of a long snow season with deep snow during spring also had a carry-over effect on the subsequent fall. This supports previous evidence that PCH females could not compensate during summer for poor spring condition (Russell & McNeil, 2005), affecting fecundity rates in the fall (Russell et al. 1993). Furthermore, our study indicated that greater growing degree-days in May increased the probability that caribou were in excellent fall condition. GDDMay was highly negatively correlated with the principal component representing snow depth, spring melting date and spring temperatures. Together, the influence of these two variables demonstrates that spring weather is a crucial determinant of fall caribou condition in the PCH, as shown in other ungulates (Couturier, Côté, Otto, Weladji, & Huot, 2009; Mysterud et al., 2008; Pettorelli et al., 2005) .

While snow depth is a major determinant of caribou winter survival (Weladji, Klein, Holland, & Mysterud, 2002), the density, layering and hardness of snow can also affect forage availability by impeding digging and changing diet composition (Tyler, 2010). In our study, variability in snow depth was inversely correlated with cumulative snow depth and was one of the main variables negatively affecting caribou condition. Caribou overwinter in areas with shallower snow (Russell et al., 1993), but select habitat based on both snow depth and hardness (LaPerriere & Lent, 1977). We thus hypothesize that years with high snow variability represent years with hardest snow and perhaps greater snow density, resulting in a more difficult access to forage.

Icy conditions reducing or impeding access to forage will increase winter mortality and reduce fecundity (Hansen et al., 2013; Solberg et al., 2001). In the PCH, icing events affected fall body condition, with condition being reduced mostly by an increase in the number of freeze-thaw events occurring on the winter and spring ranges and in the amount of ground ice before snow arrival. Icing was included as a variable influencing spring condition in an equivalent but less parsimonious models, but this effect was weak and imprecise compared with winter severity and insect harassment (Tables S1, S7). It is possible that the strong influence of these variables overrode the weaker influence of icing events, or that the power to detect this effect was reduced in the spring models because it included more parameters.

A combination of early spring and cool summer temperatures are optimal for reindeer juveniles as this increase vegetation quality and reduce insect harassment (Finstad & Prichard, 2000). Increased insect harassment due to climate warming was suggested as a cause of the PCH decline in the 1990s (Griffith et al., 2002). We found that summer insect harassment did not reduce the proportion of caribou found in excellent condition in the fall, but did so the following spring. This may seem surprising but could be explained by methodology. Our study focused on adult condition whereas insect harassment mostly reduces fall condition in reindeer calves (Weladji et al., 2003). While calves were unlikely to be included in the fall data, we hypothesize that some soon-to-be yearlings might have been considered in hunters' evaluation in spring, as they are very similar to adults in size and appearance.

5. CONCLUSIONS

Much remains to be understood about the direct and indirect effects of climate and weather on the dynamics of migratory caribou populations. Our study demonstrates how body condition at a seasonal scale provides a mechanistic link between weather and demography (Albon et al., 2017; Veiberg et al., 2017). While climate change was shown to have detrimental effects on *Rangifer* populations (Hansen et al., 2013), our results suggest these detrimental impacts are not ubiquitous (Uboni et al., 2016). Given that human disturbances can impact *Rangifer* populations more heavily than climate (Parlee, Sandlos, & Natcher, 2018; Uboni et al., 2016), population models including the cumulative impacts of weather and human development are much needed. This is very challenging considering that data on North American migratory caribou are riddled with gaps (Kofinas et al., 2003, Festa-Bianchet et al., 2011).

We hope our study will trigger broader interest in community-based monitoring of caribou. Engaging with indigenous resource-users has broader implications than just additional data collection. This underlines the differences between scientific and traditional knowledge systems, and the persistent power dynamics in the natural resource management sector, where indigenous knowledge is prone to be co-opted (Nadasdy, 1999). These challenges, however, must not lead resource managers and communities to isolate themselves from each other. In this regard, community-based monitoring programmes, if truly inclusive of indigenous communities, offer opportunities to move forward. They can act as venues for scientists and land users to co-produce knowledge and to build long-term relationships based on trust and respect, the latter being a prerequisite for successful caribou conservation in northern Canada (Parlee et al., 2018).

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AUTHORS' CONTRIBUTIONS

C.A.G., S.H., D.B. and D.E.R. conceived the ideas; C.A.G. and S.H. designed and performed the analysis, with access to databases and new analytical ideas being provided by M.Y.S., D.E.R., T.P. and J.A.; C.A.G., S.H. and D.B. led the writing of the manuscript. All authors contributed critically to drafts and approved the final manuscript for publication.

DATA AVAILABILITY STATEMENT

All climate and climate related environmental data are available via the Dryad Digital Repository https://doi.org/10.5061/dryad.wpzgmsbh4 (Gagnon et al., 2019). Authors were not allowed to publicly archive survey data from the ABEKS due to its sensitive nature relating to endangered species and human identity. Access to ABEKS data requires consent from indigenous communities involved in the project and the completion of a data request form which can be accessed via https://www.arcticborderlands.org/services. If you have any question please contact the corresponding author at catherinealexandra.gagnon@erebia.ca

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Table 1. Description of the principal components (PCs) used as climate indices.

Variable	Description	Meaning of component	% of variance explained	Cumul. % of variance explained
PCsnow1	Temperature and early melt	Greater scores represent years with a longer snow season (late melting date), deeper snow in winter and spring, and colder temperatures	61.5	61.5
PCsnow2	Variability in snow depth	Greater scores represent years with more variability in snow depth during winter, as well as shallower snow on the winter range	24.5	86.0
PCice1	Icing events	Greater scores represent years with more icing events in general, and especially more freeze-thaw events on the winter range	48.0	48.0

Table 2. Model selection to explain variation in spring body condition of the Porcupine Caribou Herd (2000-2010).

	Models	K	AIC	ΔAIC	AICweight
_1_	_PCsnow1* + PCsnow2 + PCice1 + IHI$_{yr-1}$*_	_9_	_1096.91_	_0.00_	_0.32_
2	**PCsnow1* + PCsnow2 + IHI$_{yr-1}$***	**8**	**1096.98**	**0.07**	**0.31**
_3_	_AO + PCsnow1* + PCsnow2 + PCice1 + IHI$_{yr-1}$*_	_10_	_1098.63_	_1.72_	_0.14_
4	AO + PCsnow1* + PCsnow2 + IHI$_{yr-1}$*	9	1098.96	2.05	0.12
5	AO + GDDMay$_{yr-1}$ + PCsnow2 + PCice1 + IHI$_{yr-1}$*	9	1100.47	3.56	0.05
6	AO + GDDMay$_{yr-1}$ + PCsnow2 + IHI$_{yr-1}$*	8	1101.46	4.55	0.03
7	GDDMay$_{yr-1}$ + PCsnow2 + PCice1 + IHI$_{yr-1}$*	8	1103.70	6.79	0.02
8	AO + GDDMay$_{yr-1}$ + IHI$_{yr-1}$*	7	1104.19	7.27	0.01
9	GDDMay$_{yr-1}$ + PCsnow2 + IHI$_{yr-1}$*	7	1105.79	8.88	0.00
10	GDDMay$_{yr-1}$ + IHI$_{yr-1}$*	6	1109.10	12.18	0.00
11	PCsnow1* + PCsnow2 + PCice1	7	1112.21	15.30	0.00
12	PCsnow1* + PCsnow2	6	1112.44	15.53	0.00
13	AO + PCsnow1* + PCsnow2 + PCice1	8	1114.21	17.29	0.00
14	AO + PCsnow1* + PCsnow2	7	1114.28	17.37	0.00
15	AO	4	1144.53	47.62	0.00
16	Null	3	1149.47	52.56	0.00

Notes: The selected model is indicated in bold; equivalently supported but less parsimonious models are in italic (based on difference in Akaike Information Criterion AIC). AO: annual Arctic Oscillation index; GDDMay: cumulative growing degree-days on 31 May; GDDJune: cumulative growing degree-days on 21 June; IHI: insect harassment index; PCsnow1, PCsnow2, PCice1: see Table 1; yr-1: variable measured the previous year; *: variables with a nominal effect (see Materials and methods).

Table 3. Model selection to explain variation in fall body condition of the Porcupine Caribou Herd (2000-2010).

	Models	**K**	**AIC**	**ΔAIC**	**AICweight**
1	*GDDMay* + PCsnow2* + PCice1*	*8*	*1020.30*	*0.00*	*0.40*
2	**PCsnow1 + PCsnow2* + PCice1**	**7**	**1021.27**	**0.97**	**0.24**
3	*AO + GDDMay* + PCsnow2* + PCice1*	*9*	*1021.70*	*1.40*	*0.20*
4	AO + PCsnow1 + PCsnow2* + PCice1	8	1023.17	2.87	0.09
5	AO + GDDMay* + PCsnow2* + GDDJune	9	1025.69	5.39	0.03
6	GDDMay* + PCsnow2* + GDDJune	8	1025.85	5.55	0.03
7	PCsnow1 + PCsnow2* + GDDJune	7	1027.91	7.61	0.01
8	AO + PCsnow1 + PCsnow2* + GDDJune	8	1029.81	9.52	0
9	GDDMay* + GDDJune	6	1033.79	13.49	0
10	AO + GDDMay* + GDDJune	7	1035.43	15.14	0
11	AO	4	1048.86	28.56	0
12	Null model	3	1050.71	30.42	0

Notes: See Table 2 for notations.

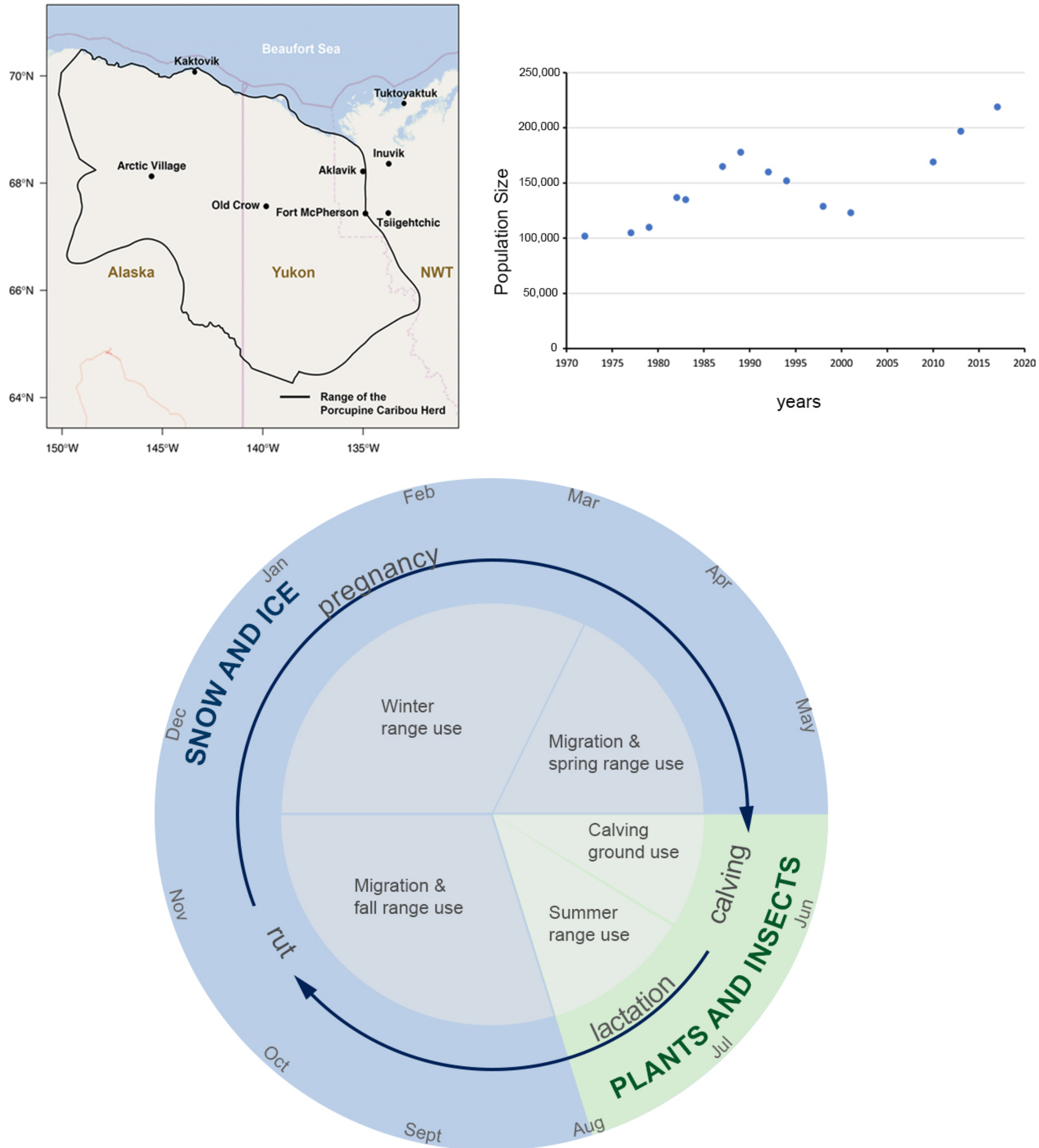


Figure 1. Range and population size of the Porcupine Caribou Herd (top), and annual range use, reproductive cycle, and environmental factors affecting body condition of migratory caribou (bottom). During fall, winter, and early spring (blue), ice and snow impact body condition through their effects on thermoregulation, locomotion, and access to forage. During late spring and summer (green), vegetation productivity and insect harassment impact body condition through energy availability and expenditures, respectively.

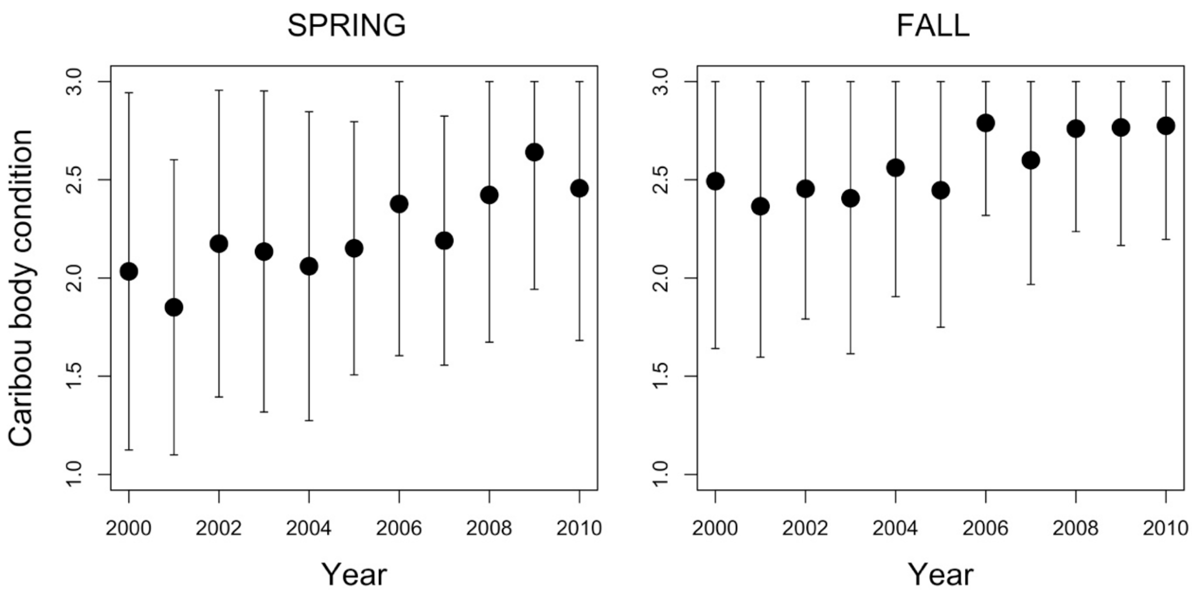


Figure 2. Changes in the average spring and fall caribou condition of the Porcupine Caribou Herd between 2000-2010.

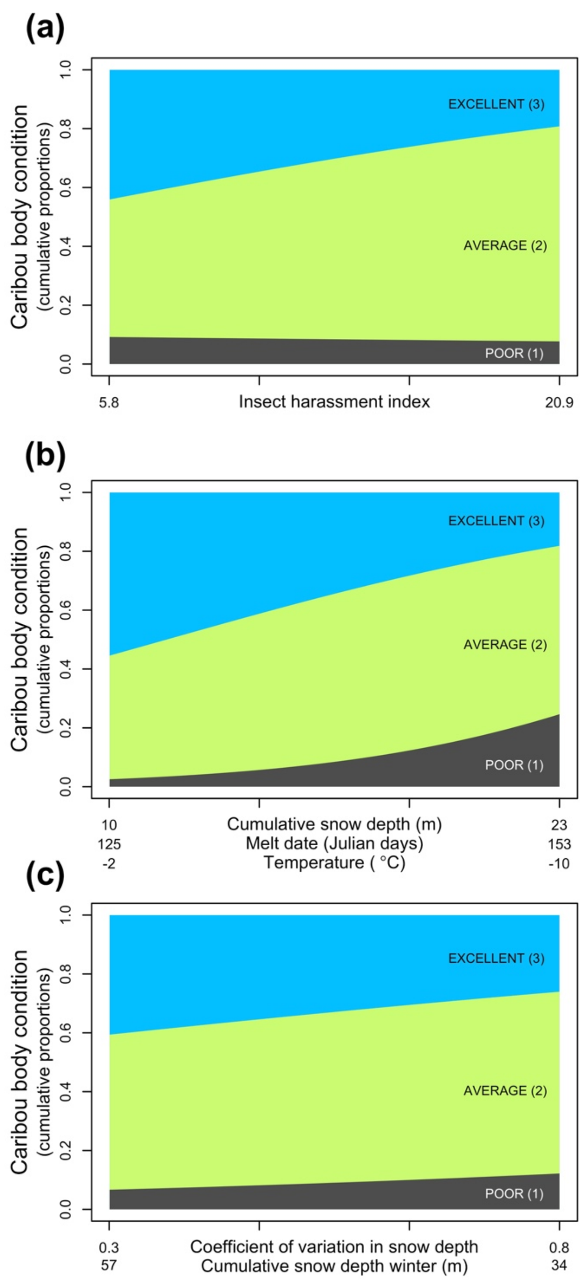


Figure 3. Relationship between weather conditions occurring on the range of the Porcupine Caribou Herd, and local experts' body condition assessment during spring, 2000-2010. Panels show the cumulative probabilities (proportion) of experts rating caribou as being in excellent, average, or poor condition in relation to a proxy of insect harassment index (**a**), cumulative snow depth on the spring range, melt date and temperature (**b**) and variation in snow depth and cumulative snow depth on the winter range (**c**).

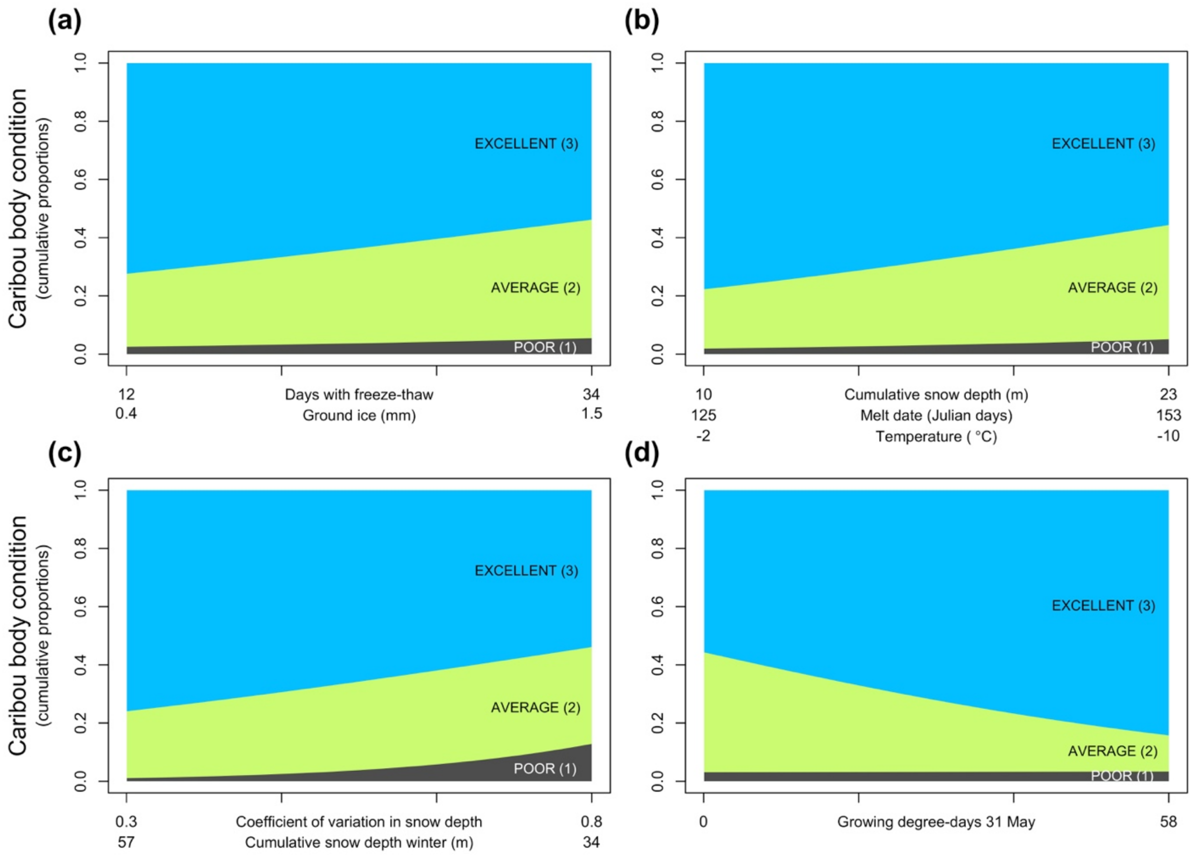


Figure 4. Relationship between weather conditions occurring on the range of the Porcupine Caribou Herd, and local experts' body condition assessment during fall, 2000-2010. Panels show the cumulative probabilities (proportion) of experts rating caribou as being in excellent, average or poor condition in relation to number of days with freeze-thaw events on the winter range and quantity of ground ice (**a**), cumulative snow depth on the spring range, melt date and temperature (**b**), variation in snow depth and cumulative snow depth on the winter range (**c**) and cumulative growing degree-days in May (**d**).

Table S1. Climate variables from the CircumArctic *Rangifer* Monitoring and Assessment Network (CARMA).

CARMA climate variable	Unit	Calculation algorithm*
Mean daily snow depth	m	No algorithm. Equals to MERRA variable named as snow depth (snodp)
Mean daily temperature at 2 m above displacement	^{o}C	No algorithm. Equals to MERRA variable named as daily mean temperature at 2 m above displacement (t2m)
Mean daily fractional snow-covered area	fraction	No algorithm. Equals to MERRA variable named as fractional snow-covered area (frsno)
Number of days of freeze/thaw events	days	Cumulative days when t2m_max is above 0^{o}C and t2m_min is below 0^{o}C
Mean daily cumulative rain on snow	mm	Uses MERRA variables named as surface snowfall rate (precsno) and total surface precipitation rate (prectot). Is calculated as cumulative rainfall$_{(mm/s)}$*24*60*60 if (prectot-precsno)>0 & snodp >0.01
Number of days of rain on snow	days	Cumulative days with rain on snow events.
Mean daily cumulative freezing rain	mm	Uses MERRA variables named as surface snowfall rate (precsno) and total surface precipitation rate (prectot). Is calculated as cumulative rainfall$_{(mm/s)}$*24*60*60 if (prectot-precsno)>0 & t2m <0
Number of days of freezing rain	days	Cumulative days with freezing rain.
Mean daily cumulative growing degree days (above 5 ◦C)	GDD	Accumulate daily averaged values of t2m if t2m > 5◦C.
Mean daily oestrid harassment index		Correspond to =T×W, where: T = 1 if [t2m > 18^{o}C], T = 0 if [t2m < 13^{o}C], and T = 1− 18−t2m/10 if [13 ^{o}C < t2m > 18 ^{o}C] W = 0 if wind speed > 9m/s and W = 9−wind speed/ 9 if wind speed < 9m/s

*Calculation algorithms describe how CARMA variables were calculated from the Modern Era Retrospective analysis for Research and Applications (MERRA) daily averaged values.

Table S2. Climate variables describing temperature, snow conditions and icing events likely to affect the body condition of caribou, calculated from the CARMA database (Supporting Information Table S1).

Climate variable	Unit	Calculation	Season of analysis	PCH range*	Included in PCA†
Average temperature–spring range	ºC	Mean temperature for the spring season	Spring	Spring	Yes
Cumulative snow depth–winter range	m	Daily snow depth added over the winter season	Spring	Winter‡	Yes
Cumulative snow depth–spring range	m	Daily snow depth added over the spring season	Spring	Spring	Yes
Coefficient of variation in snow depth–spring range		Coefficient of variation in snow depth for the spring season	Spring	Spring	Yes
Coefficient of variation in snow depth–winter range		Coefficient of variation in snow depth for the winter season	Spring	Winter‡	Yes
Melting date-spring range	Julian day	Julian day when snow cover reaches less than 20% on the spring range and never increase over 20% again	Spring	Spring	Yes
Average snow depth–spring range	m	Mean daily snow depth for the spring season	Spring	Spring	No, correlated with cum. snow depth–spring range†
Maximum snow depth–spring range	m	Highest daily snow depth recorded during the spring season	Spring	Spring	No, correlated with cum. snow depth–spring range†

Average snow depth–winter range	m	Mean daily snow depth for the winter season	Spring	Winter‡	No, correlated with cum. snow depth–winter range†
Maximum snow depth–winter range	m	Highest daily snow depth recorded during winter	Spring	Winter‡	No, correlated with cum. snow depth–winter range†
Number of days with freeze–thaw–spring range extended§	days	Number of days when freeze-thaw events occurred on the spring range from 16 August to 31 May	Spring	Fall, winter and spring‡	Yes
Number of days with freeze–thaw–winter range extended§	days	Number of days when freeze-thaw events occurred on the winter range from 16 August to 31 Mars	Spring	Fall and winter‡	Yes
Freezing rain falling on the ground–fall range	mm	Daily freezing rain when fraction of snow cover is less than 0.2, added over the fall season	Spring	Fall‡	Yes
Freezing rain falling on the ground–spring range	mm	Daily freezing rain when fraction of snow cover is less than 0.2, added over the spring season	Spring	Spring	Yes
Freezing rain falling on the ground–winter range	mm	Daily freezing rain when fraction of snow cover is less than 0.2, added over the winter season	Spring	Winter‡	Yes
Cumulative rain on snow–winter range extended§	mm	Daily rain on snow falling on the winter range from 16 August to 31 March	Spring	Fall and winter‡	Yes
Cumulative freezing rain–winter range extended§	mm	Daily freezing rain falling on the winter range from 16 August to 31 Marc.	Spring	Fall and winter‡	No, correlated with rain on snow–winter range expanded†

Cumulative rain on snow–spring range	mm	Daily rain on snow added over the spring season	Spring	Spring	No, correlated with rain on snow–winter range extended†
Cumulative freezing rain–spring range	mm	Daily freezing rain added over the spring season	Spring	Spring	No, correlated with rain on snow–winter range extended†

*Variables were calculated with reference to the Porcupine Caribou Herd (PCH) seasonal range use. For the PCH, fall range is considered to be used from around 16 August to 30 November, the winter range is used from around 1 December to 31 March, and the spring range is used from around 1 April to 31 May. †Variables highly correlated (r > 0.7) with another variable providing similar information were excluded from the principal component analysis (PCA) to ensure stability (see Materials and methods ‡Climate variables describing conditions on the winter and fall ranges were included in spring analysis considering that caribou arriving on the spring range have been affected by climate conditions previously encountered. § Extended range: signifies that the variables were calculated (e.g. number of days with freeze-thaw) starting from the fall season. This was done under the logic that caribou arriving on their winter range may have meet ice layers that were formed on the winter range during previous fall.

Table S3. Principal components (PC) scores (eigenvectors) from principal component analyses (PCA) including snow and temperature conditions, and the PCA including icing events, between 2000-2010. These PCA included weather conditions occurring during the winter and spring and likely affecting the body condition of Porcupine caribou.

Climate variables	**Snow and temperature**		**Icing events**
	PC1	**PC2**	**PC1**
Average temperature – spring range (°C)	-0.46	-0.29	
Cumulative snow depth – winter range (m)	0.37	-0.42	
Cumulative snow depth – spring range (m)	0.47	-0.28	
Coefficient of variation in snow depth – spring range	-0.41	0.00	
Coefficient of variation in snow depth – winter range	0.11	0.79	
Melting date (Julian days)	0.49	0.18	
Number of days with freeze-thaw – spring range extended‡			0.49
Number of days with freeze-thaw – winter range extended‡			0.53
Freezing rain falling on the ground – fall range (mm)			0.46
Freezing rain falling on the ground – the spring range (mm)			0.28
Freezing rain falling on the ground – the winter range (mm)			0.43
Cumulative rain on snow – winter range extended (mm)			0.00

‡Extended range means that the number of days of freeze-thaw or rain on snow events occurring on the spring or winter ranges were computed starting from the fall season. This was done under the logic that caribou arriving on their winter range may have encountered ice layers that were formed on the winter range during previous fall.

Table S4. Complete list of potential competitive models evaluated for the influence of environmental conditions on the spring body condition of caribou from the Porcupine migratory caribou herd between 2000-2010 (n=617 observations in 10 communities).

Models	NP	AIC	ΔAIC	AIC weight
Step I) Large-scale climatic variables				
AO	**4**	**1144.53**	**0.00**	**0.89**
AOW	4	1150.84	6.30	0.04
Null model	3	1149.47	4.94	0.07
Step II) Local weather variables over winter and spring – variables affecting costs of locomotion and thermoregulation				
PCsnow1*	5	1114.83	2.62	0.12
PCsnow2	4	1147.05	34.84	0.00
PCice1	4	1151.04	38.83	0.00
PCsnow1* + PCsnow2	**6**	**1112.44**	**0.23**	**0.38**
PCsnow1* + PCice1	6	1115.83	3.62	0.07
PCsnow2 + PCice1	5	1147.68	35.47	0.00
PCsnow1* + PCsnow2 + PCice1	**7**	**1112.21**	**0.00**	**0.43**
Null model	3	1149.47	37.26	0.00
Step III) Proxies of vegetation productivity and insect harassment on the summer range				
$GDDMay_{yr-1}$	4	1120.59	11.49	0.00
$GDDJune_{yr-1}$*	5	1147.60	38.50	0.00
$GDDMay_{yr-1}$ + $GDDJune_{yr-1}$*	6	1117.60	8.50	0.02
IHI_{yr-1}*	5	1137.84	28.75	0.00
$GDDMay_{yr-1}$ + IHI_{yr-1}*	**6**	**1109.10**	**0.00**	**0.98**
Null model	3	1149.47	40.38	0.00
Step IV) Comparison of candidate models				
AO	4	1144.53	47.62	0.00
PCsnow1* + PCsnow2	6	1112.44	15.53	0.00
PCsnow1* + PCsnow2 + PCice1	7	1112.21	15.30	0.00
$GDDMay_{yr-1}$ + IHI_{yr-1}*	6	1109.10	12.18	0.00
AO + PCsnow1* + PCsnow2	7	1114.28	17.37	0.00
AO + PCsnow1* + PCsnow2 + PCice1	8	1114.21	17.29	0.00
AO + $GDDMay_{yr-1}$ + IHI_{yr-1}*	7	1104.19	7.27	0.01
PCsnow1* + PCsnow2 + IHI_{yr-1}*	**8**	**1096.98**	**0.07**	**0.31**
AO + PCsnow1* + PCsnow2 + IHI_{yr-1}*	9	1098.96	2.05	0.12
$GDDMay_{yr-1}$ + PCsnow2 + IHI_{yr-1}*	7	1105.79	8.88	0.00
AO + $GDDMay_{yr-1}$ + PCsnow2 + IHI_{yr-1}*	8	1101.46	4.55	0.03
PCsnow1* + PCsnow2 + PCice1 + IHI_{yr-1}*	**9**	**1096.91**	**0.00**	**0.32**
AO + PCsnow1* + PCsnow2 + PCice1 + IHI_{yr-1}*	**10**	**1098.63**	**1.72**	**0.14**
$GDDMay_{yr-1}$ + PCsnow2 + PCice1 + IHI_{yr-1}*	8	1103.70	6.79	0.02
AO + $GDDMay_{yr-1}$ + PCsnow2 + PCice1 + IHI_{yr-1}*	9	1100.47	3.56	0.05
Null model	3	1149.47	52.56	0.00

Notes: models in boldface were selected based on ΔAIC (difference in Akaike Information Criterion; see Materials and methods). AO: annual Arctic Oscillation index; AOw: Arctic Oscillation index for the winter months (January to March); PCsnow1: first principal component on snow and temperature variables, contrasting years with a longer snow season (late melting date), deeper snow in winter and spring, and colder temperatures and years with warmer springs, short snow season and shallower snow conditions (see Materials and methods and Supporting Information Tables 1 and S3); PCsnow2: second principal component on snow and temperature variables, contrasting winters with high and low variability in the snow depth; PCice1: first principal component on icing variables contrasting years with high and low frequencies of icing events; $GDDMay_{yr-1}$: cumulative growing degree-days (above 5°C) on May 31 the previous year; $GDDJune_{yr-1}$: cumulative growing degree-days (above 5°C) on June 21 the previous years; IHI_{yr-1}: insect harassment index the previous years (see Materials and methods). Variables marked with an asterisk (*) have a nominal effect. For these variables, the probability of caribou passing from the poor to average category (1 to 2) is not the same as the probability to pass from the average to good/excellent category (2 to 3). In these cases, two parameter estimates are calculated instead of one regression slope coefficient, which increases K (see Statistical analyses).

Table S5. Complete list of potential competitive models evaluated for the influence of environmental conditions on the fall body condition of caribou from the Porcupine migratory caribou herd between 2000-2010 (n=711 observations in 10 communities).

Models	NP	AIC	ΔAIC	AIC weight
Step I) Large-scale climatic variables				
AO	**4**	**1048.86**	**0.00**	**0.59**
AOW	4	1051.21	2.36	0.18
Null model	**3**	**1050.71**	**1.86**	**0.23**
Step II) Local environmental variables over winter, spring and fall – variables affecting costs of locomotion and thermoregulation				
PCsnow1	4	1040.30	19.04	0.00
PCsnow2*	5	1038.51	17.24	0.00
PCice1	4	1047.74	26.47	0.00
PCsnow1 + PCsnow2*	6	1029.66	8.39	0.01
PCsnow1 + PCice1	5	1035.92	14.65	0.00
PCsnow2* + PCice1	6	1030.91	9.65	0.01
PCsnow1 + PCsnow2* + PCice1	**7**	**1021.27**	**0.00**	**0.98**
Null model	3	1050.71	29.45	0.00
Step III) Proxies of vegetation productivity and insect harassment on the summer range				
GDDMay*	5	1040.67	6.88	0.03
GDD_21June	4	1039.32	5.53	0.05
IHI	4	1050.23	16.44	0.00
GDDMay* + GDDJune	**6**	**1033.79**	**0.00**	**0.87**
GDDMay* + IHI	6	1039.68	5.89	0.05
Null model	3	1050.71	16.93	0.00
Step IV) Comparison of candidate models				
AO	4	1048.86	28.56	0.00
PCsnow1 + PCsnow2* + PCice1	**7**	**1021.27**	**0.97**	**0.24**
GDDMay* + GDDJune	6	1033.79	13.49	0.00
PCsnow1 + PCsnow2* + GDDJune	7	1027.91	7.61	0.01
GDDMay* + PCsnow2 + PCice1	**8**	**1020.30**	**0.00**	**0.40**
GDDMay* + PCsnow2* + GDDJune	8	1025.85	5.55	0.03
AO + PCsnow1 + PCsnow2* + PCice1	8	1023.17	2.87	0.09
AO + GDDMay* + GDDJune	7	1035.43	15.14	0.00
AO + PCsnow1 + PCsnow2* + GDDJune	8	1029.81	9.52	0.00
AO **+ GDDMay* + PCsnow2* + PCice1**	**9**	**1021.70**	**1.40**	**0.20**
AO + GDDMay* + PCsnow2* + GDDJune	9	1025.69	5.39	0.03
Null model	3	1050.71	30.42	0.00

Notes: models in boldface were selected based on ΔAIC (difference in Akaike Information Criterion; see Materials and methods). AO: annual Arctic Oscillation index; AOw: Arctic Oscillation index for the winter months (January to March); PCsnow1: first principal component on snow and temperature variables, contrasting years with a longer snow season (late melting date), deeper snow in winter and spring, and colder temperatures and years with warmer springs, short snow season and shallower snow conditions (see Materials and methods and Supporting Information Tables 1 and S3); PCsnow2: second principal component on snow and temperature variables, contrasting winters with high and low variability in the snow depth; PCice1: first principal component on icing variables contrasting years with high and low frequencies of icing events; GDDMay: cumulative growing degree-days (above 5°C) on the 31 of May; GDDJune: cumulative growing degree-days (above 5°C) on the 21 of June; IHI: insect harassment index (see Materials and methods). Variables marked with an asterisk (*) have a nominal effect. For these variables, the probability of caribou passing from the poor to average category (1 to 2) is not the same as the probability to pass from the average to good/excellent category (2 to 3). For these variables, two parameter estimates are calculated instead of one regression coefficient, which increases K (see Materials and methods).

Table S6. Parameter estimates for the variables included in the most parsimonious of the supported models (Supporting Information Table S4, Table 2) describing variation in spring body condition of the Porcupine caribou herd, between 2000-2010. Estimates for additional variables included in equivalent models are also listed below. Variables for which 95% CI exclude 0 are indicated in bold.

Variable category	**Variable**	**Estimate [95 % CI]**
Fixed intercepts	**1|2**	**-2.36 [-2.69; -2.02]**
	2|3	**0.66 [0.44; 0.88]**
Local environment winter and spring	**PCsnow2**	**-0.14 [-0.27; -0.01]**
	1|2 PCsnow1*	**0.38 [0.23; 0.52]**
	2|3 PCsnow1*	**0.26 [0.16; 0.36]**
Local environment spring and summer	1|2 IHI_{yr-1}*	-0.06 [-0.38; 0.26]
	2|3 IHI_{yr-1}*	**0.37 [0.20; 0.55]**
Additional variables included in equivalent models:		
Local environment winter and spring	PCice1	0.08 [-0.03; 0.20]
Large-scale climate	AO	0.06 [-0.14; 0.25]
Variance of random intercept	community	0.03

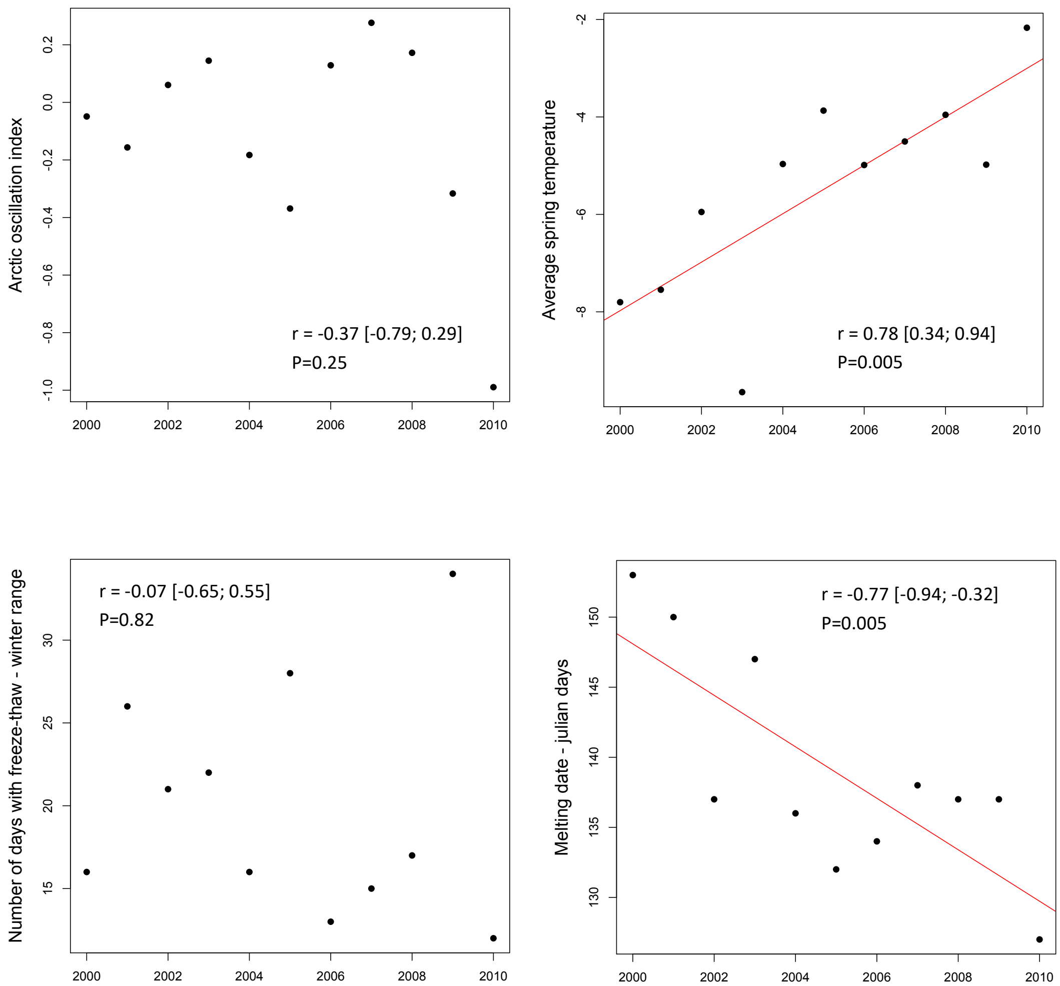
Notes: Parameters estimates for variables in models within ΔAIC ≤ 2 are presented. Abbreviations are: AO: annual Arctic Oscillation index; PCsnow1: first principal component on snow and temperature variables, contrasting years with a longer snow season (late melting date), deeper snow in winter and spring, and colder temperatures and years with warmer springs, short snow season and shallower snow conditions (see Materials and methods and Supporting Information Tables 1 and S3); PCsnow2: second principal component on snow and temperature variables, contrasting winters with high and low variability in the snow depth; PCice1: first principal component on icing variables contrasting years with high and low frequencies of icing events; IHI_{yr-1}: insect harassment index the previous years. Variables marked with an asterisk (*) have a nominal effect. For these variables, the probability of caribou passing from the poor to average category (1 to 2) is not the same as the probability to pass from the average to good/excellent category (2 to 3). For these variables, two parameter estimates are calculated instead of one regression coefficient, which increases K (see Materials and methods).

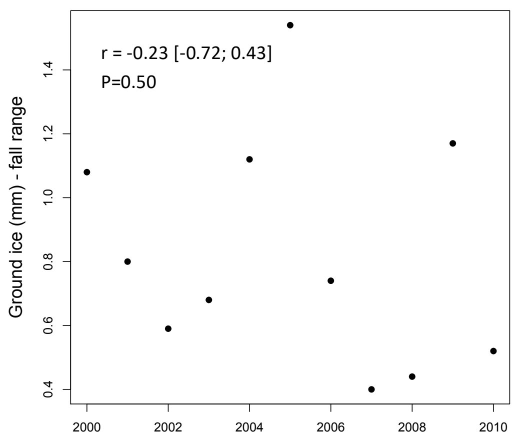
Table S7. Parameter estimates for the variables included in the most parsimonious of the supported models (Supporting Information Table S5, Table 3) describing variation in fall body condition of the Porcupine caribou herd, between 2000-2010. Estimates for additional variables included in equivalent models are also listed below. Variables for which 95% CI exclude 0 are indicated in bold.

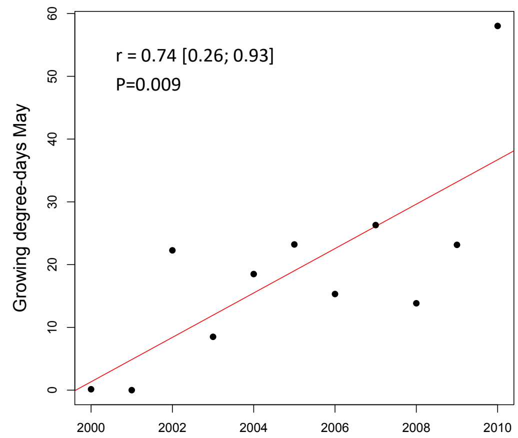
Variable category	**Variable**	**Estimate [95 % CI]**
Fixed intercepts	**1|2**	**-3.43 [-3.93; -2.92]**
	2|3	**-0.73 [-1.05; -0.41]**
Local environment winter and spring	**PCsnow1**	**-0.15 [-0.24; -0.06]**
	PCice1	**-0.15 [-0.24; -0.06]**
	1|2 PCsnow2*	**0.56 [0.29; 0.82]**
	2|3 PCsnow2*	**0.21 [0.07; 0.35]**
Additional variables included in equivalent models:		
Local environment spring and summer	1|2 GDDMay*	0.10 [-0.28; 0.48]
	2|3 GDDMay*	**-0.32 [-0.50; -0.13]**
Large-scale climate	AO	0.12 [-0.18; 0.41]
Variance of random intercept	community	0.16

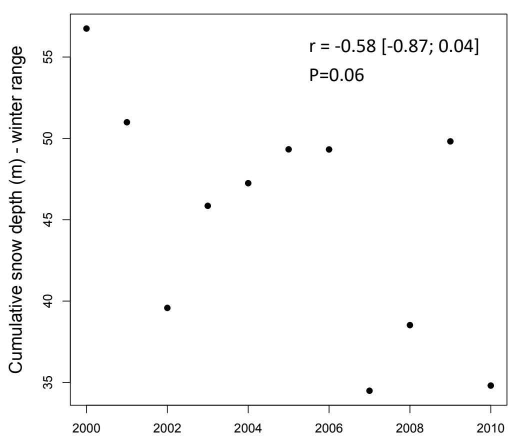
Notes: Parameters estimates for variables in models within ΔAIC ≤ 2 are presented. Abbreviations are: AO: annual Arctic Oscillation index; PCsnow1: first principal component on snow and temperature variables, contrasting years with a longer snow season (late melting date), deeper snow in winter and spring, and colder temperatures and years with warmer springs, short snow season and shallower snow conditions (see Materials and methods and Supporting Information Tables 1 and S3); PCsnow2: second principal component on snow and temperature variables, contrasting winters with high and low variability in the snow depth; PCice1: first principal component on icing variables contrasting years with high and low frequencies of icing events; GDDMay: cumulative growing degree-days (above 5°C) on the 31 of May. Variables marked with an asterisk (*) have a nominal effect. For these variables, the probability of caribou passing from the poor to average category (1 to 2) is not the same as the probability to pass from the average to good/ excellent category (2 to 3). For these variables, two parameter estimates are calculated instead of one regression coefficient, which increases K (see Materials and methods).

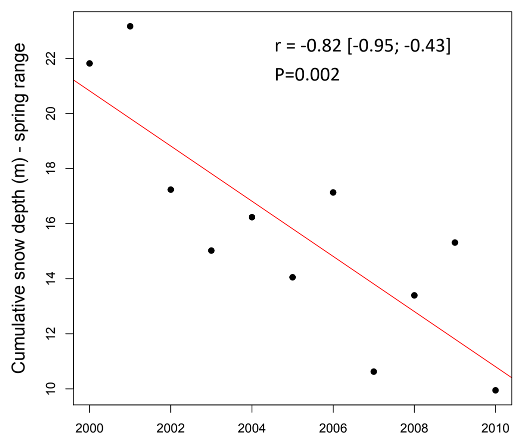
Figure S1. Time series of environmental variables evaluated in the analyses on the spring and fall body condition Porcupine caribou herd and their correlation with time (r [95% confidence interval]) between 2000-2010.

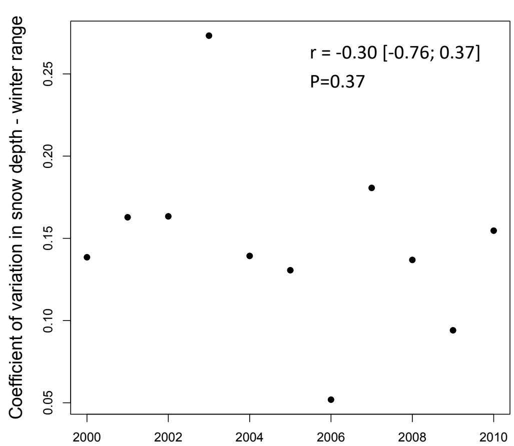


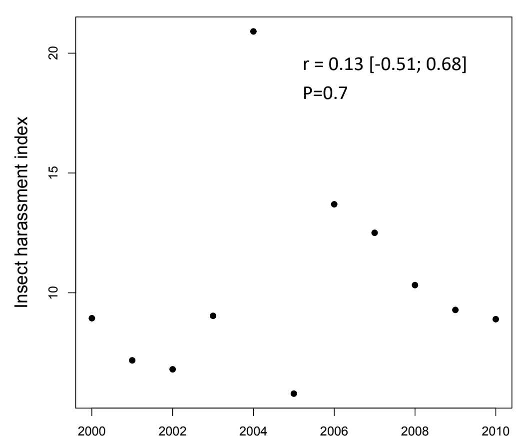

r = -0.23 [-0.72; 0.43]
P=0.50
Ground ice (mm) - fall range
0.4 0.6 0.8 1.0 1.2 1.4
2000 2002 2004 2006 2008 2010


r = 0.74 [0.26; 0.93]
P=0.009
Growing degree-days May
0 10 20 30 40 50 60
2000 2002 2004 2006 2008 2010


r = -0.58 [-0.87; 0.04]
P=0.06
Cumulative snow depth (m) - winter range
35 40 45 50 55
2000 2002 2004 2006 2008 2010


r = -0.82 [-0.95; -0.43]
P=0.002
Cumulative snow depth (m) - spring range
10 12 14 16 18 20 22
2000 2002 2004 2006 2008 2010


r = -0.30 [-0.76; 0.37]
P=0.37
Coefficient of variation in snow depth - winter range
0.05 0.10 0.15 0.20 0.25
2000 2002 2004 2006 2008 2010


r = 0.13 [-0.51; 0.68]
P=0.7
Insect harassment index
10 15 20
2000 2002 2004 2006 2008 2010

Appendix S1. The Community-based monitoring program of the Arctic Borderlands Ecological Knowledge Society.

Context

The Arctic Borderlands Ecological Knowledge Society (ABEKS) is a non-profit organization that was established in 1996 to monitor ecological changes within the range of the Porcupine Caribou Herd (PCH). The creation and implementation of the ABEKS are described in Eamer (2006) and Kofinas (2002). In short, the ABEKS was born out of a meeting held in the Yukon in 1994 between community representatives, government managers, scientists and indigenous leaders (Arctic Borderlands Ecological Knowledge Society, 2014; Eamer, 2006). The aim of the meeting was to find a way to improve ecological monitoring in the range of the PCH, given various concerns about climate change and potential developments in the region. From the onset of the program, collaboration between scientists and community members was at the core of the ABEKS. In the mid-1990s, most environmental management in the North American Arctic drew on scientific information only. People creating the ABEKS wanted to overcome the gap between scientists and community members by developing a monitoring program incorporating scientific research, local observations and traditional ecological knowledge. The ABEKS was established as a non-profit organization running cooperatively by its members, including community residents, government agencies, representatives of management boards and academic researchers. The communities of Aklavik, Old Crow and Fort McPherson were involved in the ABEKS since its beginning and were later joined by Kaktovik, Arctic Village, Tsiigehtchic, Inuvik and Tuktoyaktuk.

Since 1998, ABEKS has decided to conduct a community-based ecological monitoring program that would allow monitoring the PCH range through the eyes of active community land users. It was then decided, by community members, researchers and government agencies altogether, that the monitoring program would take the form of a survey questionnaire covering topics such as caribou, berries, birds, weather and fish. The questionnaire was developed with inputs from local hunters and included close and open-ended questions. Over the years, the questionnaire was evaluated and modified to take into consideration new community concerns, or comments from local monitors on how to formulate questions. Nonetheless, most of the original questions remained unchanged.

This ABEKS community-based monitoring program is still ongoing in 2019. It involves annually the 10 PCH user communities and is conducted by local indigenous monitors who have been trained by ABEKS staff and experienced local monitors, some of them having worked for the ABEKS for over 15 years. During training, monitors discuss the importance of selecting the most active land users for the interviews. This list of land users is elaborated by the monitors, with help from local organizations. During training, monitors also discuss the meaning of all the questions within the context of local cultures (Gwich'in, Inuvialuit or Inupiat). It is during this important training that monitors become able to refine the questionnaire, making suggestions and providing input to ensure that questions are relevant and comprehensible to younger and older interviewees, and address issues relevant to land users. Finally, and following their demand soon after ABEKS was created, monitors are also trained in data entry and reporting.

Indigenous monitoring of caribou condition

During the annual community-based monitoring of ABEKS, hunters are asked:

"Compared with other spring seasons, how were the caribou this past spring?".

Respondents can choose between the following responses: "Poor/skinny", "Fair/mix of poor and fat", "Good/excellent", and "Don't know". The same question is also asked for the fall season. This question and the response categories were elaborated from discussions and suggestions by indigenous hunters involved in the development of the questionnaire. Similar categories were developed by Denésoline hunters in another community-based monitoring context (Lyver & Lutsël K'é Dene First Nation, 2005). Questions and answers are given in English. Active hunters targeted by the community-based monitoring are English speakers, as they have lost their Native language through the residential school process.

To evaluate the body condition and overall health of caribou, Porcupine caribou hunters use several different indicators that were reported by Kofinas et al. (2003). To summarize, caribou hunters evaluate caribou condition prior to harvest by looking at indicators such as the size of the rump, the size, symmetry and overall shape of the rack, and the posture of the animal when moving. Post-mortem, hunters evaluate caribou condition by looking at body fat (back fat, stomach fat, marrow), color of kidney and liver, and presence of parasites.

References

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Kofinas, G., Lyver, P. O., Russell, D., White, R. G., Nelson, A., & FLanders, N. (2003). Towards a protocol for community monitoring of caribou body condition. *Rangifer, 14*, 43-52.

Lyver, P. O. B., & Lutsël K'é Dene First Nation. (2005). Monitoring barren-ground caribou body condition with Denesoline traditional knowledge. *Arctic, 58*(1), 44-54.

Appendix S2. Comparison between hunter's evaluation of caribou condition and scientific measurements for the Porcupine Caribou Herd.

The Porcupine Caribou Technical Committee (Porcupine Caribou Technical Committee, 2016) has conducted a body condition survey of hunted caribou since the 2000's that included sporadic measures of back fat thickness (cm) and kidney fat (g). Although more precise than the qualitative evaluations of hunters, these scientific measures were about 10 times less frequent and extremely unbalanced across time and seasons. Nonetheless, we found a positive correlation between the qualitative hunter assessment on a given animal and the scientific measurement taken on the same animal afterwards (Spearman's r [95% CI]: back fat= 0.45 [0.32; 0.55], n=152; kidney fat= 0.42 [0.25; 0.57], n= 88), providing further evidence that hunters' evaluations offer a reliable index of caribou condition.

Reference

Porcupine Caribou Technical Committee. (2016). *Porcupine Caribou anual summary report 2016*. Porcupine Caribou Technical Committee, Whitehorse, Canada.