Habitat indicators for migratory tundra caribou under a changing climate: winter and pre-calving migration ranges

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Abstract: In this paper, we defined and developed winter range and pre-calving migration habitat indicators for the Bathurst caribou herd. Several observations showed that during the winter caribou usually avoid recent burned areas where lichens (i.e., the main caribou winter diet) are less abundant than in mature forestland. We found there was a significant decrease in mature forested area during recent decades due to increase in burned area, which in turn was positively correlated with summer temperature. In addition to the decreased winter forage availability, we also found there was deterioration in the winter forage accessibility. We used two indicators of the winter forage accessibility: annual maximum snow depth and mean ice content in snow (ICIS). There was a significant increasing trend in ICIS during 1963-2006, but no trend in maximum snow depth. Both indicators showed large inter-annual variations. The percent of years in which ICIS > 10 mm water equivalent increased from 14, 20, 20, 30, to 43%, respectively, during 1963-69, 70s, 80s, 90s, and 2000-06. Thaw-freeze cycles contributed ~90% of ICIS, while rain on snow events contributed ~10%. During the pre-calving migration, the percent snow cover along the migration routes showed no significant trend. Together with the companion paper that reports results of calving ground and summer range habitat indicators, for the first time we have a comprehensive dataset of caribou habitat indicators for this migratory tundra caribou herd. By integrating these datasets with information relevant to caribou distribution, abundance and productivity, researchers, managers and community members will be able to interpret and assess the overall effects and implied impacts of climate change on caribou and thus may better manage this caribou resource.

Key words: Habitat indicator, migratory tundra caribou, remote sensing, climate change, Bathurst caribou herd, forage availability, snow depth, ice content in snow, snow fraction

1 Introduction

The decline of many migratory tundra caribou (*Rangifer tarandus*) herds in arctic Northern America worries many aboriginal communities that have used caribou for thousands years (http://www.carmanetwork.com; Klein 1989; Kofinas et al. 2000; Bergerud et al., 2008). For example, the population of the Bathurst caribou herd was 472,000 ± 72,900 in 1986, and has since declined to 128,000 ± 27,300 in 2006, a ~73% reduction in abundance (http://www.enr.gov.nt.ca/_live/pages/wpPages /caribou_information.aspx). The Bathurst caribou herd exists mainly in Northwest Territories and Nunavut and winters occasionally in Saskatchewan (Fig. 1). The herd is used by 10 northern communities (i.e., Behchokö, Gamètì, Whatì, Wekweètì, Dettah, N'Dilo, Lutsel, Yellowknife, K'eKugluktuk, and Cambridge Bay).

Many factors (e.g., habitat, harvest, predators, diseases/parasites, extreme weather events, and climate) may contribute to the decline in the abundance of migratory tundra caribou (Klein et al. 2005; Bergerud et al. 2008). To understand how these factors interact and impact caribou abundance under a changing climate, we need to develop a comprehensive dataset of these factors in addition to measures of caribou productivity. In a companion paper (Chen et al. 2009a), we developed five habitat indicators for the calving ground and the summer range of the Bathurst caribou herd. The objective of this paper is to define and develop habitat indicators on the winter range and along the pre-calving migration route. Specifically, we will (1) define four habitat indicators for the winter range and pre-calving migration of the Bathurst caribou herd (i.e., the winter range forage availability, forage quality, and forage accessibility; and pre-calving migration snow condition); (2) develop historical datasets of these habitat indicators for the Bathurst caribou herd using field measurements, satellite remote sensing imagery, and climate records; and (3) analyze the relationships between climate variables and these habitat indicators for the Bathurst caribou herd.

2 Definition, calculation methods, and data sources

2.1 Winter range forage availability indicator

Satellite collared cow data during 1996-2003 indicate that the winter range of the Bathurst caribou herd lies in south of tree-line, in Northwest Territories and northern Saskatchewan (http://www.nwtwildlife.com/nwtwildlife/caribou/bathurstpop.htm). Lichens, which are the dominate caribou winter diet, are common in mature forests but largely absent in recent burns (Thomas and Killian 1998b; Joly et al. 2003; Rupp et al. 2006). Once lichen mats are destroyed by wildfires, their replacement may take > 50 years. Thomas and Killian (1998b), working in the adjacent winter range of the Beverly herd, found that forests became productive in terms of caribou forage as early as 40 – 60 years, but that “use of forest under 50 years old was negligible”. Caribou will move through recent burns but spend little time feeding in them. Larger burns were avoided, with movement deflected around them in the NWT range of the Beverly herd (Thomas and Killian 1998a). A reduction in mature forest area can thus be detrimental to caribou, resulting in overuse of unburned areas, occupation of regions with adverse snow conditions, and reduced foraging time – all impacting the energy balance of overwintering caribou (Fancy and White 1985; Russell et al. 1993). Under adverse conditions therefore this can lead to increased over winter weight loss, lower birth weight calves and reduced survival rate (Adams 2005). Therefore, we chose forest area as one indicator of winter forage availability.

We determined the forest area in the winter range in 2000, the baseline year, on the basis of land cover classification using circa 2000 Landsat-7/ETM+ images. As with the calving ground and the summer range (Chen et al. 2009a), the Landsat images are first merged in a seamless mosaic, and then classified and aggregated into 3 land cover classes following the Classification by Progressive Generalization (CPG) method (Cihlar et al., 1998): mature forest (>50 years old), water, and other non-treed areas (recent burns, shrub/grass, > 5% lichen cover, and barren).

The > 50 year old forest area in year *i*, $A_{w,wr}(i)$, during 1959-2006 was estimated from the 2000 baseline value and burned areas from 1898 to 2006, given by:

$$A_{w,wr}(i) = A_{w,wr}(i-1) - A_{b,wr}(i) + A_{b,wr}(i-50), \tag{1}$$

where $A_{b,wr}(i)$ is the burned area in year *i* in the winter range. Note here that we assume all burned areas were forest, which is a reasonable approximation as most burned areas are coincident with treed areas. To test the accuracy of this approximation, we compare the estimated change in forest area between 1990 and 2000 using equation (1) with remote sensing post-classification comparison change detection using circa 1990 and circa 2000 Landsat images and temporal signature extension similar to Fraser et al. (2009).

2.2 Winter range forage quality indicator

Easily digestible carbohydrates are the main nutrient value in lichen used by caribou (White et al. 1980; Person et al. 1980; Svihus and Holand 2000). There are some differences in the rumen fermentation capacity among lichen species: e.g., *Cetraria*s and *Alectoria*s exceeding *Cladinas* and *Stereocaulon* (Svihus and Holand 2000). Thus the overall diet digestibility depends on the dietary mix of lichens and more importantly the extent to which graminoids, woody browse and mosses are consumed. Nevertheless, because graminoids are not preferred and mosses are avoided, such selective feeding can result in the dominance of lichens as winter diet (White et al. 1980). Therefore, we may reasonably assume there is little change in forage quality on the winter range.

2.3 Winter range forage accessibility indicators (1): annual maximum snow depth

Deep and dense snow with a hard icy crust is known to restrict caribou's access to winter forage, and increase energy consumption for digging through snow to find forage (Fancy and White 1985; Adamczewski et al. 1988; Russell et al 1993). A deep winter snow pack may also make caribou more vulnerable to wolf predation since lighter wolves can travel on snow crusts that caribou would sink through (Bergerud et al. 2008). Therefore, we used two measures to quantify the winter forage accessibility: the annual maximum snow depth and weighed ice content in snow on the winter range.

Data of annual maximum snow depth are available at climate stations within or near the Bathurst caribou winter range (Fig. 1). One way to estimate the annual maximum snow depth on the winter range is to use data from a climate station that has the longest continuous snow depth records. However, a single climate station may not be a good representation of the entire winter range's snow conditions because precipitation events are often highly localized. To circumvent this problem, we examined four alternative methods of quantifying the annual maximum snow depth of the winter range.

(1) The first alternative method is to use annual maximum snow depth averaged over 4 climate stations located in the east, south, west, and north directions of the winter range.

(2) The second alternative method is to use the maximum snow depth spatially averaged over the 0.5^{o} latitude/longitude grid snow depth data, which were simulated using a northern ecosystem soil temperature model (Zhang et al. 2003). Zhang et al. (2009) simulated snow depth at a 0.5^{o} latitude/longitude spatial resolution over Canada's landmass from 1901 to 2002. Snow depth is determined on the basis of snow density and the amount of snow on the ground. The profile of snow density and its change with time were simulated by considering compaction and destructive metamorphism, following Kongoli and Bland (2000). Precipitation was designated as rainfall or snowfall based on air temperature. Since the spatial resolution of 0.5° latitude/longitude was much coarser than the fetch scale of blowing snow, wind effects on snow redistribution were not considered.

(3) The third alternative method is to correct the spatial bias in the maximum snow depth from the climate station that has the longest records using the 0.5^{o} latitude/longitude spatial distribution of maximum snow depth. The spatial bias correction coefficient for station i in year j, $C_{sb}(i,j)$, is given by

$$C_{sb}(i, j) = \frac{\overline{\text{MSD}}\,(\text{winter range}, j)}{\text{MSD}\,(i,j)}, \quad (2)$$

where $\overline{\text{MSD}}(\text{winter range}, j)$ is the maximum snow depth averaged over the winter range in year *j* calculated using the 0.5° latitude/longitude grid data, and MSD (*i*,*j*) is the maximum snow depth in year *j* at the 0.5° latitude/longitude grid within which the climate station *i* is located. The corrected value = original value × C_{sb}.

(4) The fourth alternative method is to correct the spatial bias in the 4-station averaged maximum snow depth using the 0.5° latitude/longitude spatial distribution of maximum snow depth. The spatial bias correction coefficient for the 4-station averaged maximum snow depth in year *j*, C_{sb}(4-station,*j*), is given by

$$C_{sb}(4\text{-station}, j) = \frac{\overline{\text{MSD}}(\text{winter range}, j)}{\sum_{i=1}^{4} \text{MSD}(i, j)/4}. \quad (3)$$

2.4 Winter range forage accessibility indicators (2): ice content in snow

Putkonen et al (2009) called rain-on-snow (ROS) events as a little understood killer in the North, as exemplified by the severe ROS event that killed ~20,000 musk-oxen in October 2003 on Banks Island, Canada. If the amount of ROS is large enough (e.g., > 10 mm), the rain may wet the snow surface, percolate well into snow, and even pool at the soil surface. The resultant ice-rich snow park and icy layers by these ROS events, and icy layers formed by freeze-thaw cycles can restrict access by caribou to lichens, and force them to expend more energy on activities associated with feeding, and into putative negative energy balance (Griffith et al. 2002; Putkonen and Roe 2003; Grenfell and Putkonen 2008; Rennert et al 2009; Putkonen et al 2009). In extreme cases, the icy layers can make feeding impossible and lead to starvation and death, or cause animals to move away from affected areas. The analyses by Russell et al (2005) suggested that even a small ROS event can add animals' stress, reducing their productivity both in terms of number of animals and survival of calves. Since the ices in the snowpack are likely distributed throughout the snow depth as the ROS and thaw-freeze cycles alternating with snowfall events, observations of the total ice content are theoretically possible at a site, but no such data are available at present. Nevertheless, the mean ice content in snow (ICIS) can be estimated by summing ICIS caused by ROS events ($\mathrm{ICIS}_{\mathrm{rain}}$) and that caused by thaw-freeze events ($\mathrm{ICIS}_{\mathrm{thaw}}$), with all three items in units of mm of water equivalent:

$$\mathrm{ICIS} = \mathrm{ICIS}_{\mathrm{rain}} + \mathrm{ICIS}_{\mathrm{thaw}} . \tag{4}$$

$\mathrm{ICIS}_{\mathrm{rain}}$ is then further defined as

$$\mathrm{ICIS}_{\mathrm{rain}} = \sum_{i=1}^{243} [\mathrm{if}(\text{ice forming conditions met},1,0) \times \mathrm{ROS}(i) \times \frac{243 - i}{243}] , \tag{5}$$

where if(ice forming conditions met,1,0) is a logical operation that gives the value of 1 when the following ice formation conditions are met and 0 otherwise: (a) rain on the day i followed by a night with minimum air temperature < 0 ^{o}C, where i = 1 on October 1 and 243 on May 30; and (b) snow depth > 5 cm for day i and next 6 days to ensure there is snow for rains to fall on and to discount isolated snow events in early fall and during the last snow melting days in late spring. ROS (i) is the rainfall (mm) in day i. The weighing factor [243 – i]/243 is introduced to account for the fact that icing layers formed in late fall and early winter last much longer than those in late winter and early spring and thus have a more prolonged and larger impact on accessibility by caribou to winter forage. The resultant $\mathrm{ICIS}_{\mathrm{rain}}$ is the temporal mean of ice content in snow caused by ROS. Finally, it is possible that some of rains may be leaked into soil. Unfortunately, we have no data to quantify the proportion of water leaked into the soil, although the majority of winter rainfalls are small and thus likely stay in the snowpack. The estimated $ICIS_{rain}$ with equation (5) is likely the upper-limit of mean ICIS caused by ROS.

The estimation of $ICIS_{thaw}$ is less straight forward. To quantify the amount of ice may be formed by thaw-freeze cycles, we examined the relationship between daily snow depth reduction and daily maximum air temperature. As shown in Figure 2, there is a significant linear relationship between daily snow depth reduction and daily maximum air temperature on the Bathurst caribou winter range. To avoid the influence of other factors, we only included data points that meet the following ice formation conditions: (a) maximum air temperature > 0 ^{o}C on the day *i* followed by a night with minimum air temperature < 0 ^{o}C; and (b) snow depth > 5 cm for day *i* and next 6 days to ensure there is snow to be melt and to discount isolated snow events in early fall and the last snow melting days in late spring. We also excluded days with ROS so that the effect of ROS events on snow depth reduction can be eliminated from the relationship between snow depth reduction and maximum air temperature. When all eligible data points are used, we found that the relationship between daily snow depth reduction and daily maximum air temperature on the Bathurst caribou winter range is significant, with *P* value = 1.5×10^{-65}, (Fig. 2). Nevertheless, some data points appear to be abnormal: e.g., the snow depth increase from 20 to 30 cm at the Yellowknife station on May 2, 1972, when there was no snowfall and the maximum air temperature was 2.8 ^{o}C. We suspect that if the measurements were correct, then redistribution due to wind may be responsible for the abnormal change in snow depth. Of course, wind may also cause abnormal reduction in snow depth, as some data points showed. To minimize these non-temperature effects, we pooled data points into 0.5 ^{o}C maximum air temperature bins. One exception is for data points with daily maximum air temperature > 12 ^{o}C. Since there were only 22 data points with daily maximum air temperature > 12 ^{o}C, we pooled all of them into one bin. For the pooled data, the statistics for the relationship between daily snow depth reduction and daily maximum air temperature is y = 0.2887x + 0.41, $R^2 = 0.77$, $F = 76.2$, $P = 9.3\times10^{-9}$, and $n = 24$. We assume the daily 0.41 cm snow depth reduction when daily maximum air temperature = 0 ^{o}C is the result of snow sublimation, gravitational settling, wind packing, and evaporation. Lemmela and Kuusisto (1974) found evaporation from snow cover is mainly controlled by the vapour pressure difference between snow surface and air, and it is not significantly correlated with air temperature. Therefore, although effects of snow sublimation, gravitational settling, wind packing, and evaporation on reduction in snow depth may be variable, they may not change systematically with air temperature. Consequently, we may rationally assume that the linear reduction in snow depth by 0.2887 cm per 1 ^{o}C maximum air temperature is mainly caused by snow melting. $\mathrm{ICIS}_{\mathrm{thaw}}$ thus can be estimated by

$$\mathrm{ICIS}_{\mathrm{thaw}} = \sum_{i=1}^{243}[\mathrm{if(ice\ forming\ conditions\ met,1,0)} \times 0.2887 T_{a,\max}(i) d_{snow} \frac{243-i}{243}], \quad (6)$$

where the ice forming conditions are for thaw-freeze events as aforementioned, $T_{a,\mathrm{max}}(i)$ is the maximum air temperature on day i, and d_{snow} is the bulk density of snowpack. One of the main sources of snow density information in Canada is bi-weekly snow course measurements, compiled in the Canadian SNOW CD (MSC, 2000). These measurements were not evenly distributed in space and time, and the bulk of the currently available historical observations came from the twenty-year period 1966-1985. Seasonal and spatial variations in snow density can be approximated by simple interpolation of available snow course observations. For winter range of the Bathurst caribou herd in December, snow density is mostly between 175-200 kg m^3, with a small fraction of area between 200-250 kg m^3. Snow density increases with time to between 200-275 kg m^3 by April. In this study we use d_{snow} = 200 kg m^3, or 2 mm of water equivalent per 1 cm snow depth reduction. Considering the possibility of water leaking into the soil, we suggested that the $ICIS_{thaw}$ value calculated using equation (6) is likely an upper-limit of mean ICIS caused by thaw-freeze events on the winter range.

Again, concern about spatial representation of data from one climate station for the entire winter range must be addressed in estimating ICIS. Similar to the annual maximum snow depth indicator, we investigated the alternative method using 4-station mean values. Alternative methods 2 to 4 used for maximum snow depth cannot be used here because spatial distribution data of ICIS are not available.

2.5 Spring migration snow condition indicator

Deep snow and/or delayed melting may hinder caribou spring migration from the winter range to the calving ground, and could result in calving before reaching the calving grounds (Griffith et al 2002). In addition, movement through deep snow increases energy costs with reduced feeding time during late migration (Fancy and White 1987). Such increased costs appear to reduce calf birth mass and delayed calving, and in the Porcupine caribou herd delayed calving resulted in an increase in calf mortality (Griffith et al. 2002). Based on data from satellite collared females during 1996-2003, pre-calving migration usually occurs during April 16-June 15 over the entire Bathurst caribou habitat, although the routes, starting and end dates, and the duration of caribou pre-calving migration may vary from year to year. Therefore, ideally we would use the average snow depths over the entire caribou habitat during April 16-June 15 as the indicator of snow condition during pre-calving migration.

Many efforts have been made to estimate the snow depth or its snow water equivalent (SWE) from satellite passive microwave measurements (Kunzi et al 1982; Chang et al. 1987; Goodison and Walker 1995; Foster et al. 1997; Derksen et al., 2002; Goita et al. 2003; Kongoli et al. 2004). Unfortunately, the accuracy of these snow depth or SWE data is usually low. The reported accuracy of microwave-based retrievals of SWE ranges within 5 mm to 45 mm over non-forested areas and increases to 10-55 mm over forests (e.g., Derksen et al. 2003; Pulliainen et al. 1999; Singh and Gan 2000; Tait 1998; Kelly et al. 2003). This corresponds to 40–100% if the error is expressed as a percentage error of the total SWE. Much of uncertainty associated with SWE and snow depth retrievals from satellite observations in the microwave is due to a strong dependence of the surface-emitted microwave radiation on other physical properties of the snow pack, besides its depth, particularly on the snow grain size, density and stratification (Rosenfeld and Grody 2000). Other deficiencies of the microwave technique include difficulty or inability to identify shallow, wet, melting snow and difficulty in distinguishing between snow and cold snow-free rocky surfaces. In addition, the spatial resolution of current satellite measurements in the microwave and hence the resolution of derived products is 25–50 km, which may be too coarse if spatial details are important considerations in assessment models of caribou spring migration. Finally, although efforts are being made to derive SWE coverage over Canada's Arctic as a part of

Canadian International Polar Year initiative, SWE data are presently not available for most habitats of migratory tundra caribou in North America (http://www.ec.gc.ca/api-ipy).

During the spring snow melting period, good relationships between percent snow cover and snow depth have been observed (Romanov and Tarpley 2007). Therefore, we can use the snow cover data developed by Zhao and Fernandes (2009) as an alternative to the snow depth. Zhao and Fernandes (2009) developed daily 5-km resolution data of snow presence/absence from 1982 to 2004 over Canada's Arctic, using AVHRR Polar Pathfinder (APP) data over Northern Hemisphere land surfaces. The APP snow cover maps showed an >80% agreement rate at 95% of climate stations that have long-term snow depth measurements over Canada and the northern Eurasia. In this, we define the pre-calving migration snow condition indicator $I_{sc,sm}$ as the percent snow cover averaged from April 16 to June 15 over the entire caribou habitat, using the 5-km spatial distribution data of snow presence (= 1) or absence (= 0), and extend the data period to 1982-2006.

2.6 Data sources

To estimate forest area on winter range in 2000, we used a total of 33 Landsat-7/ETM+ scenes during 1999 and 2002. An additional 29 nearly clear-sky circa 1990 Landsat-5 TM scenes were used for detecting change in the forest area on winter range between 1990 and 2000. Most of these images were acquired in July and August supplemented by some June or September scenes. A mosaic procedure was applied to create the seamless winter range Landsat imagery coverage. As most Landsat scenes used in the study were acquired under different atmospheric conditions and at different times, radiometric normalization is needed to generate a consistent mosaic. Normalization was achieved in a recursive manner, in which a normalized scene becomes the reference for the subsequent overlapping scene entering into the mosaic. In order to minimize error propagation across the mosaic (Guindon, 1997), the centre scene was chosen as the initial reference for each mosaic. Radiometric normalization equations were developed based on inter-scene overlap using a Scattergram Controlled Regression method (Elvidge et al. 1995; Yuan and Elvidge 1996).

The burned area in the winter range was based on the large fire database during 1959-1999 (Stocks et al. 2002), estimated from Canada-wide coarse resolution satellite burned maps during 1995-2006 (Fraser et al. 2004), and derived using the relationship between climate variables and burned area for the period 1909-1958. During 1995-1999 in which we have data from both the large fire database and the Canada-wide coarse resolution satellite burned maps. We found excellent consistency in burned areas, with burned areas from the large fire database = 1.0732×burned area from the Canada-wide coarse resolution satellite burned maps, $R^2 = 0.99$, $F = 2278$, $P = 2\times10^{-5}$, and $n = 5$..

Climate data used in this study were from the Canadian Daily Climate Database (ftp://arcdm20.tor.ec.gc.ca/pub/dist/CDCD). For the Bathurst caribou winter range, we use data from 4 climate stations within or near the winter range boundary: Yellowknife (62°28'N, 114°26'W), Reliance (62°43'N, 109°10'W), Rae Lakes (64°7'N, 117°19'W), and Uranium City (59°34'N, 108°29'W), respectively, in the west, east, north, and south directions of the winter range. The Yellowknife climate station has the longest climate record; daily maximum air temperature, daily minimum air temperature, daily mean air temperature, and daily precipitation since July 1, 1942, and daily snow depth since January 1, 1955. The Reliance climate station has snow depth and temperature and precipitation data during 1956-91 and 2003-06, while the Rae Lakes climate station has data from 2000 to 06. The Uranium City climate station, which is located in northern Saskatchewan, has snow depth and temperature and precipitation data during 1962-86 and 2004-06. Examination of snow depth data reveals that they are abnormal at the Yellowknife station during winters of 1955/56-1958/59 and at the Reliance station during winters of 1956/57-1964/65, because in these years the snow depth was nearly equaling that accumulation of snowfall before the snow depth reach annual maximum. In later years, the ratio of snow depth to the accumulated snowfall is about 0.4-0.6, corresponding to a snow density of 200 kg m^{-3}. Consequently, snow data for these early years at the Yellowknife and Reliance stations were not included in the calculation of winter forage accessibility indicators. The data gaps in annual maximum snow depth and snow-icing days for a station without complete data coverage during 1956-2006 are filled by relationship between observed values from the station and that from the 4-station mean. Since the relationships are implicit in which the 4-sttation mean values are computed from these observations, an iteration procedure is needed and performed until the relationships vary less than 0.1% in an iteration step. The monthly 0.5° latitude/longitude grid climate input data for simulating maximum snow depth during 1901 to 2002 were from Mitchell and Jones (2005).

The June-September mean air temperature, which was used for estimating burned area, was further extended back to 1909 using data from the Hay River climate station

(60°51'N, 115°57'W). For the spring migration snow condition indicator that covers the entire habitat of the Bathurst caribou herd, we also used climate data from station T23026HN (Lupin at 65°46'N, 111°15'W) located at the boundary between summer range and calving ground. Within the summer range and calving ground, this climate station has the longest climate record: daily maximum air temperature, daily minimum air temperature, daily mean air temperature, and daily precipitation since January 1, 1982.

3 Results and discussions

3.1 Winter range forage availability indicator

As shown in Fig. 3, we estimated the forest area to be 32324 km^2 in 2000 for the Bathurst caribou winter range, using circa 2000 Landsat-based land classification. Combining the baseline 2000 forest area value with burned area data from 1909-2006 (Fig. 4), we estimated the annual forest areas between 1959 and 2006. There was a significant decline in forest area in the winter range from 1959 to 2006, with large periodic changes caused by years of extreme high burned areas (Fig. 5). For example, the steep decline from ~47,000 km^2 during 1959-1976 to ~38,000 km^2 during 1980-1987 was largely caused by the large burned area of 3675 km^2 in 1976 and of 5551 km^2 in 1979. On the other hand, the re-growth of the large burned area of 8393 km^2 in 1938 resulted in the forest recovering to ~46,000 km^2 during 1988-1994. The smallest forest area in the winter range, ~32,000 km^2 during 1999-2003, was caused by large burned areas in 1994 at 11599 km^2 and in 1998 at 5629 km^2. Rupp et al. (2006) also demonstrated a negative effect of fire frequency on vegetation change and caribou winter habitat in interior Alaska.

We emphasize that the annual burned area in the Bathurst caribou winter range from 1909 to 1958 was estimated using a burned area-climate relationship (Fig. 6) and thus is less accurate than the burned area data during 1959-2006 based on the large fire database and coarse resolution remote sensing data. Fig. 6 shows a statistically significant relationship between burned area and mean air temperature from June 1-Septmber 30 over the winter range of the Bathurst caribou herd during 1959-2006, with $R^2 = 0.29$, $F = 19$, $P = 7.2\times10^{-5}$, and $n = 48$. Flannigan et al. (2005) reported a similar relationship for Canada's ecozone 5 that covers most of Canada's forests in the forest-tundra transitional zones. In the Arctic, climate change has been recognized as the most dominant factor influencing the changes in ecosystems, given that land use change over Canada's North has been found to be minimal (Chen et al. 2009b).

As a test of the above results, we also detected the change in forest area within winter range between 1990 and 2000 using the circa 1990 and the circa 2000 Landsat mosaics. Fig. 3 indicates that there was a significant reduction in forest area from 1990 to 2000, especially in regions south of the Great Slave Lake. The remote sensing change detection method estimated a 35% reduction in forest area during 1990 and 2000, whereas the burned area-based method estimated a 30% decline for the same period (Fig. 5). This good agreement indicates the burned area-based method is valid, although a longer Landsat time series (e.g., circa 1985 and circa 2005) when available should be used to test the method.

3.2 Winter range forage quality indicator

Without measures of winter diet that indicate an increase in components of low digestibility such as graminoids and mosses we cannot definitively deduce major changes in diet quality. Winter range forage quality could change somewhat based on diversity of available lichen species. In the absence of definitive data, we assumed winter diet quality changed little because preferred lichen species are highly digestible (Person et al. 1980; Svihus and Holand 2000).

3.3 Annual maximum snow depth over the winter range

Annual maximum snow depth varied widely between stations, including Yellowknife during 1963-2006, Reliance during 1966-91 and 2003-06, Rae Lakes during 2000-06, and Uranium City during 1963-86 and 2004-06 (Fig. 7). Correlation of annual maximum snow depth between climate stations was not significant: e.g., $R^2 = 0.07$, $P = 0.15$, for $n = 29$ between Yellowknife and Reliance during 1963-2006. Therefore, use of maximum snow depth data from a singe climate station to represent the entire winter range of the Bathurst caribou herd is not recommended.

A comparison of the average annual maximum snow depth for the 4 climate stations, during 1963-2006, with the 0.5° latitude/longitude spatial average of the maximum snow depth, for the entire winter range, during 1963-2002 suggested no trend in maximum snow depth (Fig. 7). Although individual years show correspondences between the two datasets ($R^2 = 0.23$, $P = 0.001$, and $n = 40$), year-to-year differences are apparent and spatial average exceeds that for the 4-station mean. Several reasons may contribute to these differences: (1) measurement errors in the 4-station mean values; (2) estimation error in the spatial average values due to uncertainties in input data and model assumptions and parameterizations; (3) spatial bias when using the 4-station mean to represent the entire winter range.

As a general rule, station measurements are much more accurate and reliable than simulation results and should be preferred, although the errors caused by their spatial bias need to be quantified and corrected. Fortunately, data for the 0.5^{o} latitude/longitude spatial distribution of maximum snow depth over the winter range can be used to correct the spatial bias (Fig. 8). As shown in Fig. 8 for the 30-year normal during 1970-1999, there were two peaks in the northwest and southeast parts of the caribou winter range, whereas low values typified the mid-range coinciding with Great Slave Lake. Within these generalities, large inter-annual variations in spatial distribution of maximum snow depth are exemplified by results for 1970, 1980, and 1990. The finding of low snow-depth data around Great Slave Lake is consistent with the finding of Romanov and Tarpley (2007) who report that smooth non-vegetated areas usually have lower snow accumulation than rough vegetated areas. Both the Yellowknife and Reliance climate stations are near the Great Slave Lake, therefore using these data to represent the winter range would likely result in an underestimation of snow depth. Using the spatial bias correction coefficients calculated using equations (2) and (3), we obtained a corrected maximum snow depth from the 4-station mean as well as a corrected snow depth for the Yellowknife climate station (Fig. 9). Agreement between the corrected 4-station mean and the spatially averaged maximum snow depth was improved (R^2 = 0.4, P = 1.8×10^{-5}, and n = 40 during 1963-2002), as was agreement between the spatial bias-corrected maximum snow depth from the Yellowknife and the spatially averaged maximum snow depth (R^2 = 0.46, P = 1.6×10^{-6}, and n = 40 during 1963-2002). From these results, we conclude that all three alternative methods (i.e., spatial bias-corrected 4-station mean, spatial bias-corrected data from a single climate station, and spatially explicit average) are acceptable measures of maximum snow depth. The spatial bias-corrected 4-station mean should be preferred as it combines the strength of both station measurements and spatial distribution, and requires a smaller correction than the single station method (Fig. 9). Because spatial average is a simulated result, rather than direct observations, we suggest it is the least preferred method to use, in the case of no long term climate record exists within a caribou winter range.

Fancy and White (1985) found that, in harsh winter conditions with an unusually thick snow pack averaging of 50-80 cm, animals cratered only in highland areas where the snow was 10-20 cm thick. As a result, we may reasonably use 50 cm snow depth as evaluation criteria. Fig. 10 shows there is a strong relationship between maximum snow depth and days with snow depth > 50 cm. For example, when the maximum snow depth increases 50 cm to 55, the days with snow depth > 50 cm increases from 0 to 19. An annual maximum snow depth of 85 cm corresponds to 100 days of >50 cm snow depth. These values of days with snow depth > 50 cm may be more meaningful when assessing the impact of snow conditions on caribou. On the other hand, the days with > 50 cm snow depth index ignores the effect of days with snow depth somewhat less than 50 cm, e.g., snow depth 49 cm. It's hard to be certain that a maximum snow depth = 51 cm has a significant impact while a maximum snow depth = 49 cm has no impact at all. To avoid this, we may also calculate effective snow depth days, ESDD:

$$ESDD = \sum_{i=1}^{243}(SD(i) - 20), \tag{7}$$

where i = 1 corresponding to October 1 and 243 to May 31, and $SD(i)$ is the snow depth in day i. ESSD was significantly related to annual maximum snow depth over the range of 20 – 115 cm (Fig.10).

We calculated a significant negative relationship between spatial bias-corrected annual maximum snow depth and the averaged October and April air temperature from the 4 stations (Fig. 11). Because of the high correlations of temperature between climate stations, spatial bias between the 4-station-mean temperatures are negligible. For the Yellowknife climate station during 1963-2006 we report a significant negative relationship between snow depth on October 31 and the mean air temperature for October (R^2 = 0.41). As a result, a warmer October generally reduced the snow depth at the end of October, which contributes to a decrease in annual maximum snow depth. A warmer April is associated with a decrease in snow depth in April, and thus a reduced annual maximum snow depth.

3.4 Ice content in snow (ICIS) on the winter range

In comparison with the effect of deep snow, icing in snow may have a much more severe impact on access to lichens by caribou. A relative thin layer of high ice content, constituting “hard” snow, can increase the energy cost of cratering through snow for lichens (Fancy and White 1985; Russell et al 1993). Results in Fig. 12 show that during

1963-2006, the 4-station-mean ICIS displayed large inter-annual variation. Similar to results for annual maximum snow depth, we found that ICIS also was not well correlated between climate stations. For example, the R^2 = 0.03, P = 0.39, and n = 28 between Yellowknife and Reliance during 1963-2006. Therefore, the 4-station-mean was the preferred ICIS estimate used in this study.

Thaw-freeze cycles made up ~90% of the total ICIS, whereas the remaining contribution by ROS events was ~10%. Within the large inter-annual variations in ICIS, from 1963 to 2006, $ICIS_{rain}$ tended to increase (Fig. 13). However, major ROS events, defined by Putkonen et al (2009) as > 10 mm rainfall on snowpack, were rare. The only major ROS for the 4 climate stations was recorded at the Uranium City station: 13.4 mm rainfall on November 10, 2006. This major ROS event, and the subsequent 7.4 mm rainfall on November 19, 2006, was mainly responsible for the significant increase trend on $ICIS_{rain}$ during 1963-2006. While the temporal trend for $ICIS_{thaw}$ was not significant, the total ICIS did have a significant increasing trend (Fig. 13). Following Putkonen et al (2009), we set the 10 mm water equivalent of ICIS as criteria of major impact. From the results in Fig. 13 we estimated that ICIS > 10 mm water equivalent occurred 14% of years 1963-69, 20% of years 1970-79, 20% of years 1980-89, 30% of years 1990-99, and 43% of years 2000-06. Coincidently, the deep snow year of 2001 with maximum snow depth = 82 cm incurred a high ICIS at 13 5.4 mm water equivalent, suggesting that accessibility to lichens by caribou in 2001 may have been impeded. Overall, however, annual maximum snow depth was not correlated with the ICIS within the winter range of the Bathurst caribou herd during 1963-2006 (R^2 = 0.04 for n = 44).

Air temperature was again correlated with ICIS. The 4-station-mean ICIS was significantly correlated with 4-station-mean April – October air temperature during 1963-2006 (Fig. 14). The relation was apparently due to an increase in April mean air temperature enhancing the chance of thaw-freeze cycle, while colder October increased the chance 7 days with > 5 cm snow depth. No significant relationship was found between temperature and rain-freeze days. These results suggest that under a warming climate, there is a greater frequency of “hard” snow years that will have negative energetic effects for caribou attempting to forage on lichens. Many aboriginal elders have told the authors about their observations of increase in “hard” snow in recent years. In northern Alaska and Yukon Griffith et al (2002) report a doubling in the number of freeze/thaw days during spring migration for the Porcupine Caribou Herd in the period of their studies. On the basis of results from global climate models, Putkonen et al (2009) suggest that much of northwestern North America will experience an increase in ROS events over the next 40 years.

3.5 Pre-calving migration habitat indicator

The difference in spatial distribution of snow presence/absence on May 31 over the Bathurst caribou habitat in an early spring year (2003), and a late spring year (2004) can be extreme (Fig.15). In 2004 a larger proportion of Bathurst caribou habitat area was covered by snow on May 31. This between year effect also is reflected in snow condition during pre-calving migration (April 16-June 15) as indicated by AVHRR imagery of average of snow presence/absence (see 2003 and 2004, Fig. 16). Although we found no significant temporal trend in percent snow cover from 1982-2006, year to year variability was high and documentation of extreme years have import for timing of migration and can account for variability in calving location.

Because of these large inter-annual variations Fig. 17 shows the strong negative correlation between the snow condition indicator for spring migration and the April 16-June 15 mean air temperature. The relation suggests improving conditions for spring migration under a warming climate. However, the existence of large inter-annual variations means that even under a warming climate, it is still possible that some years may have substantial snow cover during the spring migration period, as exemplified by 2004, which can delay the onset of calving and increase calf mortality rate.

4 Conclusions

We defined the >50 years old forest area as one forage availability indicator on the winter range. During 1959-2006, the increase in the mean June-September air temperature resulted in a higher value of annual burned area within the winter range, which reduced the forested area and thus the winter range forage (lichen) availability. The remote sensing change detection method using Landsat images circa 1990 and circa 2000 further confirmed this result. However, we realize that the annual change in unburned area will not immediately be reflected in body condition or vital rates. Vors et al. (2007) documented a 20 year lag between forest removal and population response in woodland caribou in Ontario.

Unless lichens are unavailable, caribou prefer and use lichens that are highly digestible, and so we assumed range forage quality was high and changed little.

We indexed the winter range forage accessibility to two indicators: annual maximum snow depth and ice content in snow. Five different methods for quantifying the maximum snow depth were investigated. We suggest that the preferred method is based on data from 4 climate stations located in west, south, east, and north directions of the winter range, and corrects its spatial bias by using the 0.5^{o} latitude/longitude spatial distribution data of annual maximum snow depth. There were large inter-annual variations in annual maximum snow depth but no significant trend over the winter range of the Bathurst caribou herd during 1963-2006. However, annual maximum snow depth was significantly negatively correlated with the average October and April air temperature, suggesting a decrease in maximum snow depth under a warming climate.

The mean ice content in snow indicator (ICIS), which represents the hardness of snow and the thickness of icy crust, may be caused by thaw-freeze events and rain on snow events. From 1963 to 2006, we found significant temporal trends for the ICIS as well as its rain-on-snow component $ICIS_{rain}$. Thaw-freeze events contributed ~90% of ICIS, while $ICIS_{rain}$ contributed ~10%. The percent of years in which ICIS > 10 mm water equivalent increased from 14, 20, 20, 30, to 43%, respectively, during 1963-69, 70s, 80s, 90s, and 2000-06. Overall, ICIS had a significant positive relationship with April - October air temperature, indicating an increase in “hard” snow or icy crust in the snowpack under a warming climate, which corroborates well with local traditional knowledge as well as results reported for the Porcupine caribou herd in northern Alaska and Yukon and global climate model prediction.

Using daily 1-km snow presence/absence data derived from AVHRR Polar Pathfinder data, we defined the pre-calving migration snow condition indicator as the tempo-spatial ensemble average over the entire caribou habitat from April 16 to June 15. Correlation analysis with climate variables indicate that there was a strong negative correlation between the spring migration snow condition indicator and April 16-June15 mean air temperature during 1982-2006, suggesting improved (less snow cover) pre-calving migration condition under a warming climate.

Together with results from the companion paper (Chen et al. 2009a), we may concluded that under a warming climate, (1) on calving ground, there was more vascular foliage available and better quality, but less lichen; (2) on the summer range, there was more vascular foliage available, but poorer quality and more severe insect harassment; (3) on the winter range, there was reduced lichen availability and accessibility, possibly with little change in lichen diet quality; and (4) during the spring migration, snow cover was reduced. However, all these habitat indicators had large inter-annual variations, and so conditions opposite with these trends are still possible in some years.

Finally, for the first time we have a comprehensive dataset of habitat indicators for migratory tundra caribou herd. Using the dataset, we can further analyze the direct linkages between habitat indicators and changes in caribou body conditions, health conditions, and population dynamics. By integrating the dataset with information about harvest, predators, diseases/parasites, extreme weather events, and industrial developments, caribou researchers, managers and community members will be able to assess the overall impact of climate change on caribou abundance, to better understand the decline in the Bathurst caribou herd, and thus to better manage the caribou resource.

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Figure list

Fig 1. Locations of the winter range, summer range, and calving ground of the Bathurst caribou herd, based on satellite collared cows from 1996 to 2003. The background is land cover map derived from circa 2000 Landsat-TM/ETM+ images, including 6 classes: sparsely treed woodland, recent burns, shrub/grass dominated, lichen cover > 5%, barren, and water. Treeline is used to separate the winter range from the summer range. Also shown are a distribution map of major migratory tundra caribou and wild reindeer herds around the Arctic, locations of four climate stations from which climate records are used in this study: Yellowknife (62^{o}28'N, 114^{o}26'W), Reliance (62^{o}43'N, 109^{o}10'W), Rae Lakes (64^{o}7'N, 117^{o}19'W), and Uranium City (59^{o}34'N, 108^{o}29'W), respectively, in the west, east, north, and south directions of the winter range, as well as Lupin (65^{o}46'N, 111^{o}15'W) on the summer range and calving ground

Fig. 2 Relationships between daily snow depth reduction (cm) and daily maximum air temperature: (a) using all eligible data points from Yellowknife, Reliance, Rae Lakes, and Uranium City, respectively, in the west, east, north, and south directions of the Bathurst caribou winter range during 1963-2006, with $y = 0.3096x + 0.3162$, $R^2 = 0.15$, $F = 317.8$, $P = 1.5\times10^{-65}$, and $n = 1794$; (b) for pooled data in 0.5 ^{o}C maximum air temperature bins, with $y = 0.2887x + 0.4093$, $R^2 = 0.77$, $F = 76.2$, $P = 9.3\times10^{-9}$, and $n = 24$. The error bars show one standard deviation. Data eligibility is described in the text

Fig. 3 Land cover maps circa 1990 and circa 2000 derived from Landsat images, including 3 aggregated classes: forest/woodland (>50 years old), water, and other non-treed areas (recent burns, shrub/grass, > 5% lichen cover, and barren)

Fig. 4 Annual burned area in the winter range of the Bathurst caribou herd during 1898 and 2006: based on the large fire database for period 1959-1999, estimated using coarse resolution remote sensing data (AVHRR, MODIS, or VGT) for period 1995-2006, and derived using the relationship between climate variables and burned area for period 1898-1958

Fig. 5 Forest area, the winter range forage availability indicator of the Bathurst caribou herd during 1959-2006. The straight line represents the temporal trend of the forest area in the winter range, with $R^2 = 0.51$, $F = 47$, $P = 1.4\times10^{-8}$, and $n = 48$

Fig. 6 Relationship between burned area and June 1-Septmber 30 mean air temperature on the winter range of the Bathurst caribou herd during 1959-2006, with $y = 1.0261x - 7.4213$, $R^2 = 0.29$, $F = 19$, $P = 7.2\times10^{-5}$, and $n = 48$

Fig. 7 Annul maximum snow depth at Yellowknife (1963-2006), Reliance (1966-91, 2003-06), Rae Lakes (2000-06), and Uranium City (1963-86, 2004-06) climate stations, as well as averaged over the four stations (1963-2006). Also shown is the spatial average of the maximum snow depth over the entire winter range of the Bathurst caribou herd during 1963-2002, simulated using 0.5^{o} latitude/longitude grid climate inputs

Fig. 8 Spatial distribution of maximum snow depth over the winter range of the Bathurst caribou herd in 1970, 1980, 1990, and averaged over the period of 1970-99, displayed as 3-D surfaces at 0.5^{o} latitude/longitude grid resolution

Fig. 9 Comparison of the spatial bias-corrected maximum snow depth from the 4-station mean the bias-corrected snow depth at the Yellowknife climate station during 1963-2006. Also shown are corresponding correction coefficients applied to the 4-station mean and the Yellowknife maximum snow depth during 1963-2002. The straight lines represent temporal trends of the annual maximum snow depth: for the spatial bias-corrected 4-station mean $y = 0.2134x - 363.58$, $R^2 = 0.08$, $F = 3.8$, $P = 0.08$, and $n = 44$; for the spatial average $y = 0.0567x - 54.794$, $R^2 = 0.00$, $F = 0.1$, $P = 0.72$, and $n = 40$

Fig. 10 Correspondence between maximum snow depth and days with snow depth > 50 cm at Yellowknife (1963-2006), Reliance (1966-91, 2003-06), Rae Lakes (2000-06), and Uranium City (1963-86, 2004-06) climate stations. The fitted line is given by $y = 186.31\mathrm{Ln}(x) - 728.05$ for years with maximum snow depth > 50 cm and $y = 0$ otherwise, $R^2 = 0.77$, $F = 667$, $P = 4.6\times10^{-51}$, and $n = 110$. Also shown is a plot between maximum snow depth and effective snow depth days, with fitted line given by $y = 93.439x - 2406.1$, $R^2 = 0.86$, $F = 715$, $P = 1.3\times10^{-52}$, and $n = 110$. Because of no systematic difference among stations, we combined all data points from the 4 stations into one equation.

Fig. 11 Relationship between spatial bias-corrected annul maximum snow depth and October and April mean air temperature averaged over the 4 stations from 1963 to 2006, with y = 52.63exp(-0.0343x), R^2 = 0.13, F = 5.9, P = 0.02, and n = 51

Fig. 12 Winter range ice content in snow (ICIS) at Yellowknife (1963-2006), Reliance (1966-91, 2003-06), Rae Lakes (2000-06), and Uranium City (1963-86, 2004-06) climate stations, as well as averaged over the four stations

Fig. 13 Components of the 4-station-mean ice content in snow (ICIS) for the winter range of the Bathurst Caribou herd from 1963 to 2006, averaged over Yellowknife, Reliance, Rae Lakes, and Uranium City climate stations: $ICIS_{rain}$ and $ICIS_{thaw}$. The straight lines represent temporal trends: for $ICIS_{rain}$ y = 0.0225x - 44.065, R^2 = 0.06, F = 2.86, P = 0.1, and n = 44; for $ICIS_{thaw}$ y = 0.0544x - 100.4, R^2 = 0.06, F = 2.59, P = 0.12, and n = 44; and for ICIS y = 0.0769x - 144.48, R^2 = 0.08, F = 3.7, P = 0.06, and n = 44

Fig. 14 Relationship between snow-icing days and the air temperature difference between April and October, both averaged over the 4 stations, with y = 0.3723x + 9.7895, R^2 = 0.18, F = 9.2, P = 0.004, and n = 44

Fig. 15 Snow cover map on May 31 over the Bathurst caribou habitat in 2003, an early spring year, and in 2004, a late spring year.

Fig. 16 Percent snow cover averaged over the Bathurst caribou habitat during April 16-June 15 from 1982 to 2006, derived from AVHRR Polar Pathfinder data. The straight line represents the temporal trend: $R^2 = 0.05$, $F = 1.1$, $P = 0.3$, and $n = 25$

Fig. 17 Relationship between pre-calving migration snow condition indicator and April 16-June 15 mean air temperature, calculated as the average at the Yellowknife and Lupin climate stations during 1982-2006, with $y = -4.4832x + 65.283$, $R^2 = 0.56$, $F = 28.8$, $P = 1.91\times10^{-5}$, and $n = 25$