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Original article

Can Landsat data detect variations in snow cover within habitats of arctic ungulates?

Andrew I. Maher, Paul M. Treitz & Michael A.D. Ferguson

With climate change, modelling has suggested that increased inaccessibility of forage through snow may endanger some populations of arctic ungulates; however, contemporaneous data on snow-cover conditions, other ecological factors and ungulate responses are lacking at the landscape scale. Researchers have increasingly used remote sensing to map snow cover with higher accuracy, but such tools have not been utilized in research and management of arctic ungulate populations. We estimated field-measured percent snow-covered area (F-SCA) in wintering areas of endangered Peary caribou *Rangifer tarandus pearyi* in the Bathurst Island complex (BIC) and developed a threshold for a normalized difference snow index (NDSI) using Landsat data. We used our NDSI threshold and another threshold to estimate snow-covered area (SCA) in Peary caribou habitats in the BIC during 1993-2003, compared these estimates with snow data from the nearest weather station and assessed the adequacy of Landsat data for arctic ungulate research. Our calculated NDSI threshold of 0.70 reflected field observations better than the published threshold, and our estimated SCAs showed greater variation between study areas, between years and during snow melt. Estimated SCAs were not correlated with total snowfall or snow depth at the nearest weather station. We conclude that SCA using remotely-sensed data for ungulate habitats would be more useful than weather-station data. Our methods could detect winters with relatively mild snow-cover conditions, but not those with very severe conditions; therefore, we recommend development of NDSI thresholds corresponding to $\geq$ 75% F-SCA, instead of $\geq$ 50%. NDSI-derived SCA methods should prove more useful for southerly arctic regions where sun angles would be less limiting than in the BIC. Higher resolution imagery may be more suited than Landsat for the assessment of snow cover in arctic ungulate ecology. With climate change, further development of remotely-sensed indices of snow cover, such as NDSI and SCA, should enhance our understanding of how arctic ungulates may or may not adapt.

Key words: Bathurst Island, Canada, endangered species, muskoxen, NDSI, normalized difference snow index, Nunavut, Ovibos moschatus, Peary caribou, Rangifer tarandus pearyi, remote sensing, snow covered area

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Snow cover plays a dominant role in the high arctic by influencing the ecology of both plants and animals (Gray & Male 1981). It has been suggested that snow cover is an important factor affecting mortality, reproduction and distribution of caribou and reindeer *Rangifer tarandus* and muskoxen *Ovibos moschatus* on arctic tundra (Klein 1968, Reimers 1983, Schaefer & Messier 1995, Ferguson 1996, Larter & Nagy 2001, Tyler 2010). Severe snow and icing reportedly were responsible for major declines of the endangered Peary caribou *R. t. pearyi* and muskoxen during the winter of 1973/74 and the three winters of 1994-1997 on the high arctic islands of Canada (Miller et al. 1977, Gunn & Dragon 2002, Miller & Gunn 2003). Miller & Gunn (2003) suggested that higher than average accumulations of snow, possibly in combination with wind compaction or icing, caused catastrophic die-offs of Peary caribou between 1994 and 1997 in the Bathurst Island complex (BIC). Lacking data from occupied caribou winter habitats, Miller & Gunn (2003) analyzed total snowfall from 1947 to 2002 at the Resolute Bay weather station (74.43°N, 94.59°W), Cornwallis Island, Nunavut, Canada, which is 100-300 km from winter habitats of caribou on the BIC. They found that total snowfalls were greatest at Resolute Bay during the four winters when severe declines of the BIC caribou population were documented.

It may be hypothesized that unusually severe snow-cover conditions made a larger than usual proportion of winter forage inaccessible to these grazing herbivores, leading to malnutrition, starvation, mortality and emigration. Despite the increasingly broad acceptance of such hypotheses, there is a dearth of contemporaneous quantitative data on the population trends of arctic ungulates, snow-cover conditions within occupied habitats, and other ecological factors that may cause such population declines (Tyler 2010). Such data are needed to understand the complex population ecology of arctic ungulates. This need is made more apparent when we consider that a drainage basin < 10 km from Resolute Bay contained 130 - $>$ 300% more snow than was indicated by Resolute Bay snowfall records over seven years, while at the same time, some terrain features (e.g. hilltops and flats) were less variable and accumulated less snow (Woo et al. 1983).

Following the 1973/74 population declines, Miller et al. (1977) stated that they had no measures of range conditions, and after the 1994-1997 declines, Miller (1998) stated that detailed information on snow cover and icing was not available from within the winter ranges of the populations. Despite the lack of such information from within occupied ungulate habitats, the above hypothesis may be valid at least in some circumstances.

The Arctic Climate Impact Assessment (ACIA 2005) concluded that with future climate change, the amount and types of precipitation are expected to change in arctic terrestrial regions. Such changes have the potential to make winter forage less accessible to ungulates living on arctic tundra. Tews et al. (2007) developed a spatially-explicit model, parametrized for Peary caribou on the BIC. They concluded that arctic tundra caribou populations may be negatively affected if forage inaccessibility in poor winters increases by $>$ 30% over the next 100 years. Increases in the frequency of such winters did not have as great an impact.

This prediction, coupled with our current imprecise understanding of the impacts of snow cover on arctic ungulates (Tyler 2010), makes it imperative to find tools that could rectify the scarcity of data about snow-cover conditions within the winter ranges of arctic tundra ungulates. Such tools would need to be both effective and efficient in estimating parameters (or surrogate variables) that might impact ungulate populations (e.g. relative proportions of winter habitats with inaccessible forage). In addition, any such tools must be sufficiently flexible and robust to accommodate variations in ungulate distributions between years and over decades, which can occur in the absence of major changes in snow cover conditions (e.g. Ferguson et al. 1998, 2001). Additionally, the tools should also accommodate unpredictable short-term shifts in animal distributions that may occur in response to disturbance events (e.g. emigration from usual winter habitats; Tyler 2010).

Woo (1998) suggested that regional mapping of snow cover, using ground data alone, poses insurmountable difficulties, and that remote sensing offers viable surrogates for characterizing snow cover when the data and signals are properly validated. Over the past 25 years, snow-cover studies have increasingly relied on remote sensing of snow cover for applications related to monitoring of global climate change (Jin & Simpson 2001) and water management for hydropower and irrigation of watersheds (Swamy & Brivio 1997, Winther & Hall 1999).

Remote sensing of snow cover should be an attractive tool for landscape ecologists as well, because it could allow researchers to study snow cover over a range of spatial and temporal scales, while minimizing the need for extensive *in situ* data collection. Multi-spectral satellites that have been used over the last two decades for snow-cover mapping include Landsat (Lichtenegger et al. 1981, Swamy & Brivio 1997, Turpin et al. 1999, Li et al. 2002, Vogel 2002), Indian Remote Sensing System (IRS; Baral & Gupta 1997) and Système Pour l'Observation de la Terre (SPOT; Xiao et al. 2001). Of the techniques developed for multi-spectral data (Lichtenegger et al.

1981, Hall et al. 1995, Baral & Gupta 1997), the Normalized Difference Snow Index (NDSI) has been the most widely applied (Hall et al. 1995).

The NDSI provides several technical advantages for mapping snow cover (Hall et al. 1995, Winther & Hall 1999, Xiao et al. 2001, Salomonson & Appel 2004). These are based on the principle that snow and ice are highly reflective in the visible green portion of the electromagnetic spectrum (0.4-0.65 μm), while exhibiting very low reflectance in the mid-infrared portion (1.4-1.7 μm; Choudhury & Chang 1979, Rees 2006). By creating a ratio of the reflectance values from the Landsat Thematic Mapper band 2 (TM2; 0.52-0.60 μm) and band 5 (TM5; 1.55-1.75 μm), the NDSI highlights areas of snow cover and detects differences among snow types, while at the same time separating snow cover from cloud cover, using the equation: (TM2-TM5)/(TM2+TM5). The NDSI produces a value between -1.0 and 1.0 for each pixel in the data set. Hall et al. (1995) found that NDSI values $>$ +0.40 were indicative of pixels that exhibited $>$ 50% snow cover in Montana, USA. As a result, every pixel could be classified as either snow-covered (i.e. $>$ 50% snow) or not. Although a majority of NDSI studies have adopted +0.40 as a threshold value, some studies have adjusted the threshold to achieve a more accurate snow-cover map for specific locations or environmental conditions. In Abisko, Sweden, Vogel (2002) found that the NDSI threshold had to be adjusted to 0.48 for summer imagery and 0.60 for fall imagery.

Although local and regional distribution patterns of snow cover may be relatively consistent from year to year (i.e. prevailing snow conditions) because prevailing storm winds, topography, air temperature regimes and other factors tend to be similar (Sturm et al. 1995, Liston & Sturm 2002), snow cover can change through both episodic or stochastic disturbances (e.g. severe winters) and longer-term climatic trends. The NDSI allows mapping of SCA over large regions, and can be expressed as the percentage of a static study area or as a total area across a variable winter range of an ungulate population. We believe that temporal changes in SCA within occupied winter ranges of Peary caribou and muskoxen could allow assessment and monitoring of potential impacts of future disturbances and trends in snow cover patterns. Monitoring of SCA using data from satellites that regularly image the Earth's surface could provide the contemporaneous indices that Tyler (2010) identified as being required, but currently lacking, to scientifically examine hypotheses about weather-mediated declines of arctic reindeer, caribou and muskoxen. Nevertheless, we do acknowledge that SCA would not provide data on variations of snow hardness and the presence of basal ice which would probably still require *in situ* measurements. Despite this limitation, monitoring SCA derived from remotely-sensed data could prove to be a useful and efficient tool for assessing snow cover conditions that may impact arctic ungulates during specific winters, as well as to assess long-term trends in arctic climate.

The objective of our research was to assess the feasibility of using Landsat data as a tool for monitoring both short- and long-term changes in SCA within potential habitats of ungulates overwintering on remote arctic tundra. Our assessment involved: 1) collection of ground data within historically used winter caribou habitats on the BIC during May 2003, calibration of an NDSI threshold and estimation of SCA from usable Landsat scenes; 2) assessment of variation in estimated SCA between study areas, between years and during snow melt; 3) comparison of snow data from Resolute Bay (*sensu* Miller & Gunn 2003) with our estimates of Landsat-derived SCA; and 4) a review of Landsat data during April and May from 1993 to 2003 to assess the availability of useful scenes every year or two. This research has important implications for the long-term feasibility of monitoring snow-cover conditions within the winter habitats of arctic ungulates in the face of future climate change.

Methods

Study areas

The Bathurst Island complex (BIC) is located north of 75°N within the Queen Elizabeth Islands (QEI), Nunavut, Canada (Fig. 1). The BIC is a diverse area comprised of seven major islands, including Bathurst Island ($\approx$ 16,040 km^2), Île Vanier ($\approx$ 1,130 km^2), Cameron Island ($\approx$ 1,050 km^2), Alexander Island ($\approx$ 500 km^2), Massey Island ($\approx$ 430 km^2), Helena Island ($\approx$ 340 km^2) and Île Marc ($\approx$ 60 km^2), plus smaller islands. The BIC has been home to a disproportionately high density of Peary caribou as compared to other parts of the QEI (Miller & Gunn 2003), when the BIC population has been at or near its maximum known size. Despite increases since a major decline in the mid-1990s (M.A.D. Ferguson & Resolute Bay Hunters and Trappers Association (RHTA), unpubl. data), the BIC currently holds a

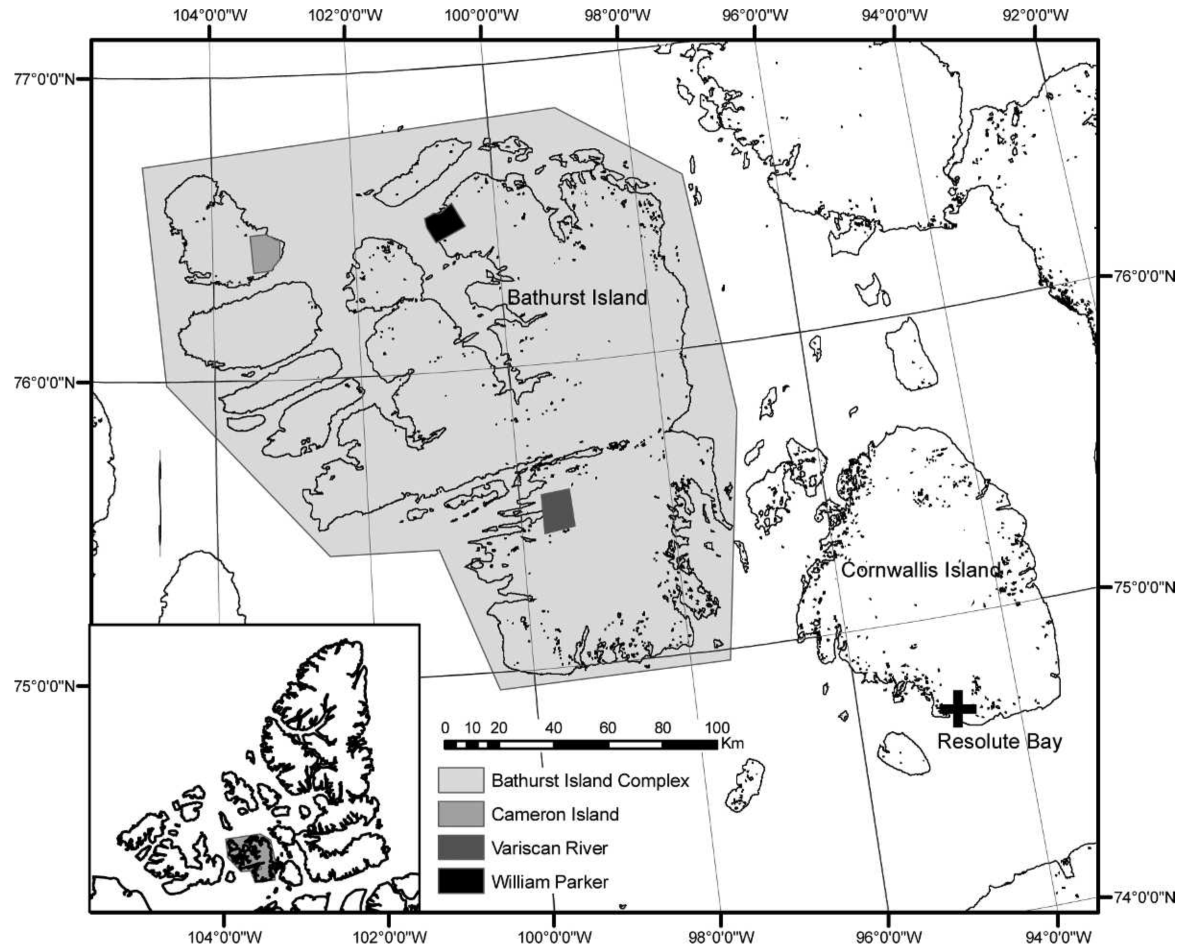

Figure 1. Bathurst Island complex (BIC; light grey), showing Cameron Island (grey), Variscan River (dark-grey) and William Parker Strait (black) study areas, and Resolute Bay on Cornwallis Island.

relatively small proportion of all Peary caribou. The population of Peary caribou on the BIC is an important nutritional and cultural part of the lives of Inuit in Resolute Bay (Freeman 1975, Taylor 2005). Peary caribou on the QEI were declared endangered by the Canadian government in February 2011 (Government of Canada 2011). The declaration recognized past efforts of Inuit in the high arctic to conserve the subspecies, as well as their continuing need for subsistence use.

Most of the BIC receives < 11 cm of precipitation annually (Parks Canada Agency 1997). Despite limited precipitation, the vegetation communities on the BIC are relatively diverse with three bioclimatic zones being represented (Edlund & Alt 1989). The herbaceous zone occurs mainly in northern parts of the BIC, where vascular plants are sparse and limited to herbaceous species. The prostrate shrub zone is limited mainly to major valley systems that have a roughly east-west orientation, and the southeastern coast of Bathurst Island. Within this zone, prostate shrubs dominate mesic sites, while sedges dominate wet areas. The herbaceous-shrub transition zone is relatively common on the southern two-thirds of Bathurst Island and on the northwestern islands. This zone is similar to the herbaceous zone in that vascular plant communities are dominated by herbs. Although prostrate shrubs and sedges do occur locally in the transition zone, they never dominate.

Our study focuses on three areas within the BIC that were selected because of the expected presence of caribou based on late winter-spring population surveys and Inuit qaujimajatuqangit (i.e. traditional and recent knowledge of Inuit; Miller et al. 1977, M.A.D. Ferguson & RHTA, unpubl. data, Taylor 2005). These study areas include: 1) 127 km^2 on southeastern Cameron Island (CI; 76°25'N, 103°20'W); 2) 155 km^2 surrounding the Variscan

Table 1. Climatic and vegetation characteristics of the Cameron Island (CI), Variscan River (VR) and William Parker Strait (WPS) study areas in the Bathurst Island complex, and Resolute Bay (RB) on Cornwallis Island (Edlund & Alt 1989).

Selected characteristics	CI	VR	WPS	RB
Bioclimatic zone	Herb-shrub transition	Herb-shrub transition	Herbaceous	Prostrate shrub
Mean June temperatures	Below freezing	Below freezing	Below freezing	Above freezing
Snow-melt completion	Late June - early July	Late June - early July	Early July	Mid-June
Snow-free period	7-9 weeks	7-9 weeks	6-7 weeks	> 9 weeks

River (VR) in central Bathurst Island (75°30'N, 99°30'W); and 3) 115 km^2 south of William Parker Strait (WPS) on northern Bathurst Island (76°30'N, 100°35'W; see Fig. 1). WPS lies within the herbaceous bioclimatic zone, while CI and VR lie within the herb-shrub transition zone (Table 1). Climatically, these areas are characterized by colder temperatures in June, later snow melt and shorter snow-free periods than areas within the prostrate shrub zone, which occurs at Resolute Bay (Edlund & Alt 1989).

Field data

We collected field data at VR during 7-14 May 2003 and on CI during 14-21 May 2003. Snow melt had not yet started during data collection at either of these study areas. Field data could not be gathered in WPS due to adverse conditions that prevented access to the area. We selected 15 and eight calibration sites to represent the diversity of snow cover and substrate characteristics at the CI and VR study areas, respectively. Each calibration site had to be large enough so that a 50 × 50-m plot could be placed within the site, while both the snow-cover pattern and the under-snow substrate had to be consistent across the entire plot. The location of the plot centre was determined using a Trimble hand-held GPS, which recorded positional data every second for 300 seconds. Subsequently, plot-centre positions were differentially corrected using data from a base station (Polar Continental Shelf Program, Natural Resources Canada) at Resolute Bay, the closest source of such data. Each set of 300 differential-GPS positions was then averaged to create a single centre point for each plot using Trimble Pathfinder GPS software version 2.9 (Trimble Navigation Ltd., Sunnyvale, California, USA). The centre points were expected to have a horizontal positional accuracy to within 1 m (Trimble 2002); however, positional accuracy may have been lower because of the distance from the study areas to the Resolute Bay base station (i.e. 155-305 km).

While the Trimble GPS was downloading positional data at the centre of each plot, the corners of the plot were determined using a Garmin GPS unit, averaging positions recorded every second for 100 seconds. Simultaneous use of two GPS units prevented depletion of the batteries that could have resulted from extended use at the cold ambient temperatures. The corner positions were used later only to rotate and orient each plot correctly on the imagery. The Garmin GPS data could not be differentially corrected, and the averaged positions should have an accuracy of about 15 m (Garmin 2002).

Once each calibration plot was identified and reference photos were taken, a grid of 50 red and 50 black points was established within each plot, and either the black or red sample points were selected by flipping a coin. At each selected point, the presence or absence (i.e. bare-ground or vegetation) of wind-hardened snow (i.e. snow that had hardened in place by wind action, as opposed to fresh snow and frost crystals that could be brushed away) was recorded. The results from the 50 points in each calibration plot were then used to estimate the percentage of the calibration plot that was covered by wind-hardened snow; i.e. the field-measured percent snow-covered area (F-SCA).

Calibration plots were recreated as polygon layers in ArcInfo version 8.3 (ESRI Inc., Redlands, California, USA). Each plot was georeferenced using the differentially corrected centre position and rotated to align the plot relative to the GPS data for the corners of the plot. Centre points, corner points and calibration plots were then exported into ENVI version 4.1 (Research Systems Inc., Boulder, Colorado, USA) for image analysis.

Remotely-sensed data

Five Landsat Thematic Mapper (TM; 3 May 1993 and 28 May 1993) and Enhanced Thematic Mapper+ (ETM+; 21 April 2000, 8 April 2001 and 30 April 2003) cloud-free images were selected from archived data available from Natural Resources Canada. Each sensor recorded similar visible and infrared channels at a spatial resolution of 30 m.

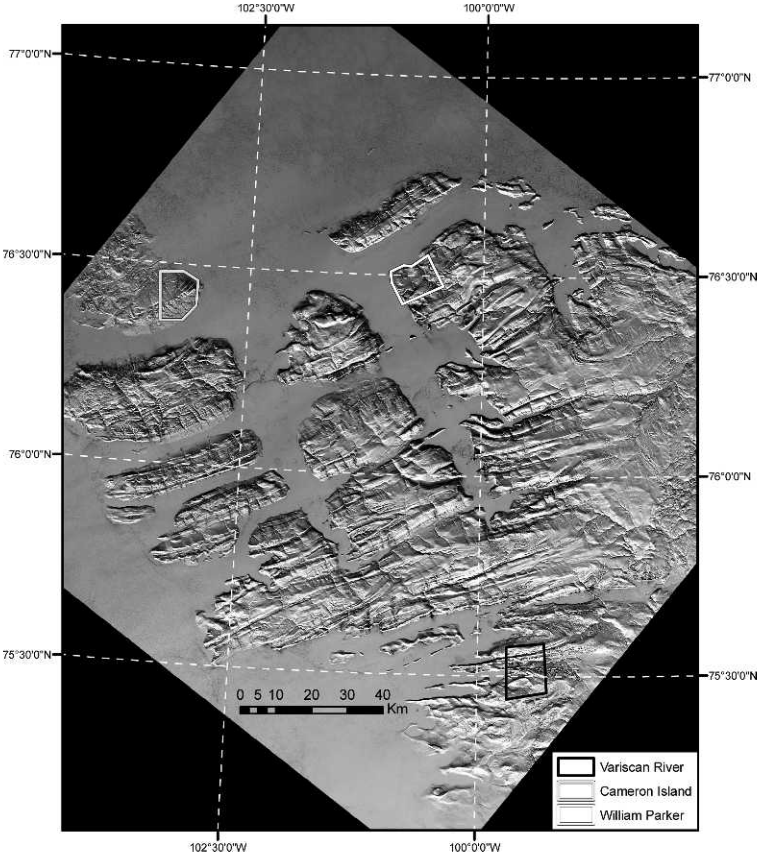

Figure 2. Composite image of Landsat ETM+ data (i.e. bands TM3 (red), TM2 (green) and TM1 (blue)) for 30 April 2003 for a large portion of the Bathurst Island complex including the Variscan River (black polygon), Cameron Island (grey polygon) and William Parker Strait (white polygon) study areas. Data have been georeferenced with a 1:50,000 NTDB map and has a spatial resolution of 30 m.

Landsat data for 30 April 2003 were georeferenced using 1:50,000 National Topographic Database (NTDB) maps (Fig. 2). A first-order polynomial transformation based on 15 ground control points (GCPs; i.e. points selected throughout the Landsat images for which map coordinates could be accurately determined from the 1:50,000 maps) was applied to produce a georeferenced image with a root-mean-square-error (RMSE) of less than 0.25 pixels. Each of the remaining Landsat images was registered to the image for 30 April 2003. All image-to-image registrations used a minimum of 15 GCPs and a first-order transformation to achieve a RMSE of less than 0.25 pixels. All images were converted to top-of-atmosphere reflectance using the Landsat TM calibration utility in ENVI version 4.1 (Research Systems Inc., Boulder, Colorado, USA) and published post-launch gain and offset values for each sensor (ENVI 2004, NASA 2004).

To detect snow cover, a NDSI was derived for each reflectance image using Landsat bands 2 (i.e. green) and 5 (i.e. mid-infrared; Hall et al. 1995). To determine an appropriate threshold value that distinguished classes of SCA, field plots were grouped into two classes: 1) $>$ 50% SCA and 2) $<$ 50% SCA and compared with image data from 30 April 2003 for the VR study area. Based on this comparison, pixels with $>$ 50% SCA had an NDSI $\geq$ 0.70. Since all images were acquired in April or May, this threshold was assumed to apply to all images examined in our study; however, direct testing of this assumption could not be performed due to the lack of historical field data. To partially address this issue, we estimated SCAs using both our 0.70 threshold and Hall et al.'s (1995) threshold of 0.40, based on the hypothesis that the better threshold would be more sensitive to variations in snow-cover patterns between study areas, between years and during snow melt.

Statistical analyses

NDSI validation and SCA

To assess the extent to which NDSI data represent actual snow conditions, we calculated the mean NDSI values for the calibration plots in the CI and VR areas using Landsat data from 30 April 2003. This was the cloud-free imagery that was the closest to the dates of our field data (e.g. 7-14 May at VR and

14-21 May on CI). We determined linear regressions for the mean NDSI values (i.e. the dependent variable) and percent snow cover (i.e. the independent variable) for each study area. All regressions were assessed for significance using the t-statistic, and for goodness-of-fit using the coefficient of determination (r^2).

To assess differences in SCA between the five NDSI images, we created a polygon delineating each of the CI, VR and WPS study areas, resulting in 15 NDSI data sets. Of these, one VR data set was discarded because the entire VR study area was not included in the Landsat scene. We created two snow-cover classifications for each of the 14 remaining data sets using Hall et al.'s (1995) 0.40- and our 0.70-threshold values, each creating two classes of SCA (i.e. greater than and less than 50% SCA). The SCA for each data set was then calculated as a percentage.

Snow data from Resolute Bay

Total snowfall (i.e. sum of total daily snowfall) and total snow depth (i.e. depth of snow on the ground at the end of the month) was obtained for all winter months (September-June) for the years from 1992 to 2003 from the Environment Canada National Climate Data and Information Archive (Environment Canada 2005), as per Miller & Gunn (2003). These data were used to compare SCA with snowfall and snow depth measurements at the Resolute Bay weather station. Total snowfall for September-June and for September-April was compared with SCA using a non-parametric Spearman rank-order correlation to determine if either of these were correlated with the variation in SCA estimated from Landsat data using our 0.70 threshold.

Results

NDSI validation

For the VR study area, mean NDSI values from the satellite imagery for 30 April 2003 were related ($r^2 = 0.485$, $P = 0.055$, $df = 7$) to F-SCA observed on the ground in late winter 2003 (Regression: mean NDSI = 0.632 + 0.0025 F-SCA). However, such a relationship was not evident ($r^2 = 0.002$, $P = 0.885$) for the CI area, suggesting a problem with the CI image data. Careful visual reinspection of the image for CI revealed that high-altitude cloud, which was not discriminated by the NDSI, obscured some areas of partial snow cover, causing poor correspondence between NDSI values and field measurements. As a result, the CI image of 30 April 2003 was removed from further analyses. Reinspection of other images did not reveal similar problems related to cloud cover.

Variations in estimates of SCA

Compared to our threshold of 0.70, Hall et al.'s (1995) threshold of 0.40 revealed little variation between the WPS, CI and VR study areas on dates of image acquisition (e.g. Fig. 3). The 0.40 threshold suggested that 98-100% of the study areas were covered with > 50% snow in all images acquired in April and early May (Table 2). On the other hand, employing our threshold of 0.70 to classify the three data sets suggested more variation (83-100%) between years (Table 3). Neither threshold suggested that there were major differences in SCA between the three study areas in April or early May. Our 0.70 threshold did suggest that snow-cover was less extensive on 3 May 1993 in the WPS and CI study areas than in April of 2000, 2001 and 2003 (see Table 3). This difference was not detected using Hall et al.'s 0.40 threshold.

During the snow-melt period of 1993, both thresholds for NDSI estimates of SCA detected decreases in the extent of snow cover in the CI and WPS study areas (see Tables 2 and 3). From 3 May to 28 May 1993, our 0.70 threshold was apparently more sensitive in detecting snow melt, registering declines of 18 and 12% in SCA within these study areas, respectively, compared to declines of 6 and 9% using a 0.40 threshold.

Comparisons of snow data with estimated SCA

Total snowfall (September-June and September-April) from the Resolute Bay weather station for the years corresponding to image acquisition (Table 4) did not correlate ($P \geq 0.20$) with SCA in images using our 0.70 threshold for any study area (see Table 3). In 1993, SCA estimates from our study areas and snow depth measurements at Resolute Bay indicated that snow melt began in May; however, the relative amount of snow melt differed between data sources. SCA decreased 12-18% during May 3-28 (see Table 3), while snow depth at Resolute Bay decreased by 54% between April 30 and May 31 in 1993 (see Table 4), suggesting different magnitudes of change, potentially due to spatial and climatic differences between the data sources, as well as differences between point- and area-based data.

Snow depth at the end of April at Resolute Bay was not correlated ($P \geq 0.20$) with our estimates of SCA within our selected caribou winter habitats. We

Figure 3. Images of the Normalized Difference Snow Index (NDSI) derived from Landsat ETM+ data from 30 April 2003 for the Cameron Island and Variscan River study areas (A and B, respectively). The NSDI data from Cameron Island and Variscan River were classified as areas having > 50% snow cover (white) and having < 50% snow cover (grey) using NDSI threshold values of 0.40 (C and D, respectively) and of 0.70 (E and F, respectively).

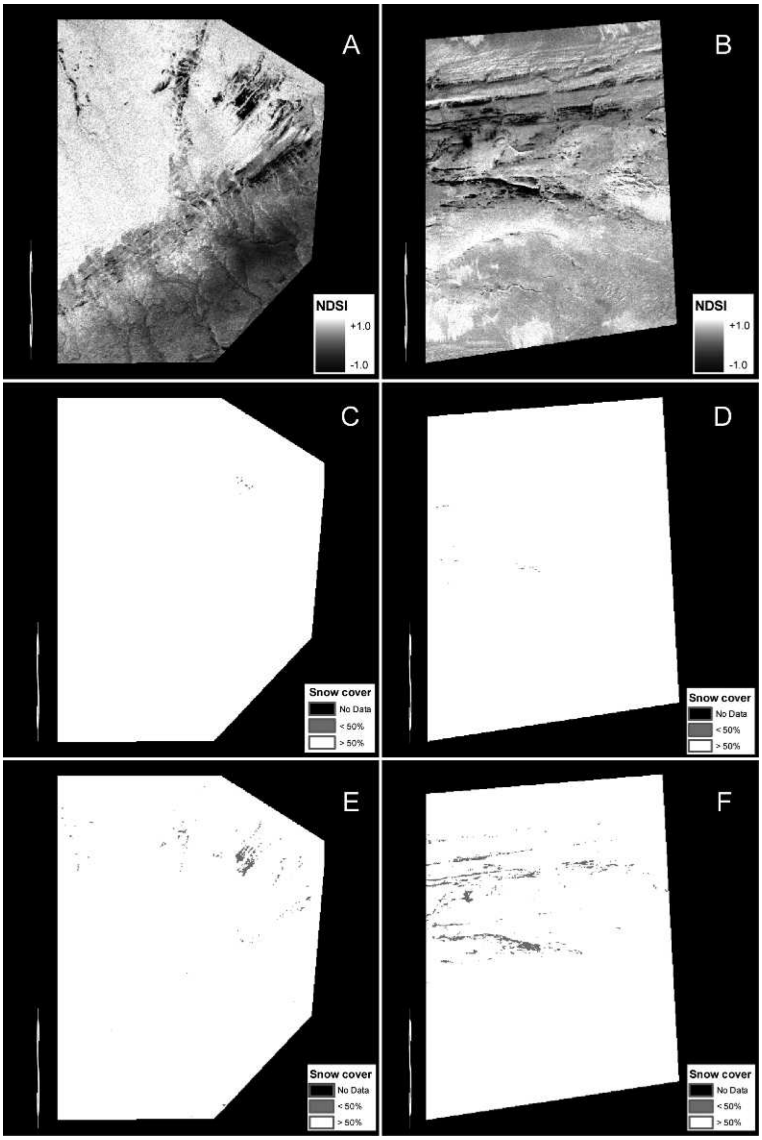

Table 2. Estimated total snow-covered area with > 50% snow cover using Landsat-derived NDSI data from the Cameron Island (CI), Variscan River (VR) and William Parker Strait (WPS) study areas on the Bathurst Island complex. Percentages are based on a NDSI threshold value of 0.40. For VR, ILC indicates inadequate Landsat coverage.

	Snow-covered area (%)				
Study area	3 May 1993	28 May 1993	21 April 2000	8 April 2001	30 April 2003
WPS	100	94	100	100	100
VR	ILC	91	100	100	100
CI	98	89	100	100	100

Table 3. Estimated total snow-covered area with > 50% snow cover using Landsat-derived NDSI data from the Cameron Island (CI), Variscan River (VR) and William Parker Strait (WPS) study areas on the Bathurst Island complex. Percentages are based on a NDSI threshold value of 0.70. For VR, ILC indicates inadequate Landsat coverage.

	Snow-covered area (%)				
Study area	3 May 1993	28 May 1993	21 April 2000	8 April 2001	30 April 2003
WPS	88	70	97	98	98
VR	ILC	70	96	96	98
CI	83	71	94	100	100

Table 4. Snow data gathered at the Resolute Bay weather station, Cornwallis Island, Nunavut, Canada, during 1993-2003. For June 1993, T indicates trace amount.

Year	Month	Total snowfall from September to month end (cm)	Snow depth at month end (cm)
1992/93	April	81.6	13
	May	99.6	6
	June	102	T
1999/2000	April	68.8	21
	May	90.4	25
	June	91.6	0
2000/01	April	71.2	21
	May	87.9	17
	June	93.9	1
2002/03	April	71.4	12
	May	81	15
	June	89.2	1

found the greatest differences in estimated SCA between 3 May 1993 and 30 April 2003 (see Table 3); however, snow depth at Resolute Bay at the end of April was similar in both years (see Table 4). April snow depth at Resolute Bay in 2003 was the shallowest among these four years, but SCA was at its maximums in our study areas. Snow depths at Resolute Bay in late April were similar in 2000 and 2001, and 162-175% of that in 2003, while our estimated SCAs in our study areas were similar in all three years.

Miller & Gunn (2003) used total snowfall at Resolute Bay summed from September through June as an index of the severity of each winter in assessing potential impacts of snow cover on caribou in the BIC. Using similar extrapolations from point data at Resolute Bay to the snow cover conditions within caribou habitats on the BIC, the 1992/93 winter would have been somewhat more severe for BIC caribou (with 102 cm of total snowfall in Resolute Bay) than the winters of 1999/2000, 2000/01 and 2002/03 (with 89-94 cm total snowfall in Resolute Bay; see Table 4). When we shortened the total snowfall period to September-April to coincide with the approximate timing of our satellite data, the relative severity of these winters did not change based on total snowfall at Resolute Bay (i.e. 82 vs 69-71 cm, respectively).

In contrast to Miller & Gunn's (2003) type of extrapolation of total snowfall data from a point 155-305 km away, our estimated SCAs indicated that the winter of 1992/93 was actually the least severe of the four years within the caribou wintering areas (i.e. 70-88% vs 94-100%, respectively; see Table 3). It is also notable that although total snowfall at the end of April 1993 at Resolute Bay suggested that it was the severest of these four years, snow depth at the same time at Resolute Bay would suggest that it was one of the two mildest of the four winters (see Table 4).

Discussion

Within any given region, estimates of SCA based on a given NDSI threshold may be affected by variations in atmospheric conditions (e.g. water vapour content and cloud cover) both within and between images (Hall et al. 1995). We addressed these factors by: first, eliminating all obviously cloud-covered images; second, reexamining and eliminating all candidate images showing evidence of more subtle atmospheric problems; and finally, calculating a threshold value based on thorough field validation for late-winter imagery for the high arctic. Careful reexamination led to elimination of the Landsat image for the CI in April 2003, but acceptance of the image for the VR area for the same day, allowing us to calculate a threshold value for our study region. We assume that our comparisons of SCA using this threshold value were valid for all images used in our study.

There are several possible reasons why a specific NDSI threshold value may not be applicable between regions (e.g. temperate forested mountains and high arctic tundra). NDSI thresholds can be sensitive to regional differences in snow structure and water content (e.g. light crystalline, moist snow in temperate zones vs wind-hardened, dry snow cover in the high arctic; Winther et al. 1999). Solar illumination differences due to solar elevation angles at high vs lower latitudes may also affect NDSI threshold values (Vogel 2002). As well, NDSI values may be influenced by regional differences in underlying ground cover or surface vegetation (e.g. temperate forested areas vs high arctic tundra; Hall et al. 1995).

Hall et al. (1995) developed a NDSI threshold value (i.e. 0.40) for hydrological snow-melt studies in temperate forested mountains (at about 48.5°N). By comparing our field data with a snow-cover map for 30 April 2003 based on Hall et al.'s (1995) threshold, none of the plots were identified as having $< 50\%$ snow cover, disagreeing with our field observations. Hall et al.'s (1995) threshold value was not adequate to differentiate between areas covered by more or less than 50% snow during late winter on high arctic tundra (at 75.5°-76.5°N), probably due to the combination of distinctive forms of snow cover and poor surface illumination due to low spring solar elevation in the high arctic. If we had used Hall et al.'s (1995) threshold, we would have estimated that all of our study areas in all years were nearly completely covered with $>$ 50% snow (i.e. 98-100%; see Table 2) prior to snow melt. Although a high percentage of the land is usually covered by snow in the high arctic during late winter, we observed comparatively greater variability in the proportions of the selected caribou wintering areas that were snow covered both within and between the study areas during our fieldwork in 2003. Based on our field observations, the observed variability appeared to depend largely on the proportions of exposed windward topographic features that were usually partially or completely snow free.

Our NDSI threshold (i.e. 0.70) detected greater variability between the study areas and between years; thereby appearing more realistic. Although our threshold did not estimate great levels of pre-snow-melt variability between most years (i.e. 94-100% in 2000, 2001 and 2003; see Table 3), we were able to detect comparatively little snow cover in 1993 (i.e. 83-88%; see Table 3) before snow melt started. Our threshold of 0.70 appears to be more suitable for assessing snow cover during late winter on high arctic tundra, based on stronger correspondence between our field data and snow-cover maps, and the detection of greater variability in snow cover between some years. We conclude that well-calibrated NDSI thresholds could potentially monitor snow cover variation in time and space in the Arctic if adequately field validated, but a threshold calculated for one region (e.g. the BIC) may not be applicable across the Arctic. Unfortunately, a lack of historical validation data from more areas limited further tests of our 0.70 threshold in this study.

The proportion of potential foraging habitat over which caribou might gain access to forage is likely to increase during snow melt, and we suggest that SCA may serve as a surrogate measure or index by which to monitor both the extent and timing of such changes within occupied caribou winter habitats. In 1993, decreases in snow depth at Resolute Bay (i.e. 54%) and SCA within our study areas (i.e. 12-18%) suggested that the initial period of snow-melt in the region occurred during May. However, the differing magnitudes of the decreases in the two measures suggested that snow-depth data at Resolute Bay may have overestimated the potential change in the proportion of area over which caribou might access forage during May 1993, if used for that purpose. Such differences would be expected given that Resolute Bay lies within a different bioclimatic zone than our study areas on the BIC (see Table 1 and Edlund & Alt 1989).

We also detected several inconsistencies between point data for snow depth at Resolute Bay and our estimates of SCA when comparing different years. These included: the greatest inter-annual differences in estimated SCA when snow depths at Resolute Bay were similar; similar SCAs in three years when late April snow depths at Resolute Bay differed by 75%; and similar SCAs when late April snow depths at Resolute Bay were also similar in some years.

Across years, we found no significant correlation between SCA within caribou wintering areas and measurements of total snowfall at Resolute Bay, which Miller & Gunn (2003) used to assess severity of snowfall during winter. Using Miller & Gunn's (2003) measure of winter severity, the winter of 1992/93 would have appeared to be the most severe of the four for which we estimated SCAs, while the SCAs from potential caribou wintering areas suggested the opposite. Snow cover patterns on the ground are governed by several variables, including but not limited to: amount of snowfall, timing of snowfall relative to wind speed, direction and variability, air and ground temperatures, terrain ruggedness and others (Sturm 2003). We did not have measures of these other variables; however, site-specific estimates of SCA are probably indicative of the net effects of these factors on snow cover. Thus, we conclude that estimated SCA may be a better indicator of the impact that snow cover may have on the ability of caribou and muskoxen to access forage in the late winter, compared to either late winter snow depth or total winter snowfall at distant weather stations.

Use of point-source data has been recognized by snow hydrologists as having limited applicability across large areas, even when collected relatively close to a given study area (Jacobs 1989, Woo et al. 1999, Yang & Woo 1999, Hinkler et al. 2002). Our results raise similar concerns about applying such measures in regional wildlife ecology research and management, especially when mobile wildlife populations may over-winter considerable distances from available weather stations. SCA could be of use in understanding the impacts of changing snow cover on the population ecology of these animals. Such information could be coupled with caribou animal telemetry over a period of years to enhance understanding of the timing of inter-annual and seasonal migration patterns, as well as the impacts of long-term climate change.

Unfortunately, the NDSI's sensitivity to extensive high-altitude cloud cover may cause a problem for reliable application of this index in arctic environments where this cloud cover may exist through much of the late winter (Marshall et al. 1994, Hope & Stow 1996). This, coupled with low sun angles during April-May at high latitudes, made it impossible for us to meet our objective to obtain at least one usable Landsat image every year or two from 1993 to 2003. We had initially planned to examine changes in SCA during this period when the BIC caribou population went through the latter part of a population increase, a population crash (Miller & Gunn 2003) and an initial population recovery (M.A.D. Ferguson & RHTA, unpubl. data). For our study areas, SCA estimates based on Landsat imagery did not provide sufficient temporal coverage to help understand the impacts of snow cover on population trends of Peary caribou and muskoxen in the BIC. Nevertheless, we believe that SCA may prove useful in other arctic regions farther south where cloud cover and atmospheric water content may not be as problematic in late winter, and where higher sun angles may permit improved imagery over longer periods during late winter (e.g. March-May).

Another issue with our estimates of SCA was that in three of the four years when we did obtain useful imagery, we estimated SCA just below 100% (i.e. 94-100%). During our fieldwork in 2003 when our SCAs were 98-100%, we saw no signs of mortality or severe body condition among caribou or muskoxen on the BIC. Although our NDSI threshold could detect relatively mild winters (e.g. 1993; SCA = 83-88%), it could not detect winters that could be more severe for ungulates than that in 2003. Given this, we believe in retrospect that our use of Hall et al.'s (1995) 50% snow-cover criterion to determine the NDSI threshold for SCA may have overestimated the extent of snow cover within our study areas, and thus was not a useful criterion for a surrogate variable for monitoring long-term variations in the accessibility of forage through snow for arctic ungulates. In Norway, Nellemann (1996) found that places where wild reindeer might access forage (i.e. snow < 40 cm) accounted for 10-40% of the land in less rugged alpine areas and 50-80% in rugged areas. We have found no similar estimates at the landscape scale in the literature for the high arctic or elsewhere, pointing to the need for such information. We recommend that future development of NDSI thresholds should use a criterion based on field measurements of 75% or greater snow cover (i.e. plots must be at least 75% covered by snow to be considered snow covered). This should reduce the estimated SCA in most years, thereby potentially allowing detection of winters when ungulates may find it unusually difficult to access forage.

The Landsat imagery used in our study had a resolution of 30 × 30 m, but caribou on arctic tundra can utilize winter foraging sites that may not be detectable at this resolution (e.g. Ferguson et al. 2001). This limitation of Landsat and similar remotely-sensed data may be partially relieved by raising the snow-covered criterion to 75% and potentially to 90%. However, NDSI-derived estimates of SCA using high-resolution multi-spectral imagery could further improve its use as an index of winter severity for arctic ungulates. As climate change occurs in the future, further advances in the development and application of remotely-sensed indices of snow cover for occupied wildlife ranges will enhance our understanding and modelling of how Peary caribou and muskoxen may or may not adapt to such changes.

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