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Current management

Evaluation of caribou *Rangifer tarandus groenlandicus* survey methodology in West Greenland

Kim G. Poole, Christine Cuyler & Josephine Nymand

Abundance estimates are important to management of most harvested species of wildlife. In West Greenland, recent estimates of barren-ground caribou *Rangifer tarandus groenlandicus* population size have been derived from aerial surveys conducted in early March of numerous short (7.5 km) transects that focused on obtaining high detection probabilities. The resultant study area coverage was low ($\leq$ 1.6%), in part due to the survey design. In this article, we conducted a critical review of the current West Greenland caribou survey methodology using data from past surveys and recent GPS collar data, and present recommendations to improve the methodology. On an annual basis, movement rates of collared females were lowest in March, supporting survey timing. March distribution of collared caribou, however, differed markedly between 2009 and 2010, indicating that stratification flights prior to each survey are required to produce the most accurate and precise estimates. A viewshed analysis in GIS supported the use of a 300-m strip width, but demonstrated that the current 15-m survey flight altitude resulted in 4-5% availability bias due to the portion of the strip width hidden by topography and out of sight of observers, and a corresponding nil detection probability for caribou in these areas. A 30-m or 45-m flight height may be more appropriate to reduce the availability bias in this rugged terrain. Examination of the population composition data collected during and after abundance estimates suggested that robust calf:cow and bull:cow ratio data could be obtained with less sampling effort distributed proportionate to the population density. We suggest that systematic strip transects should be considered to increase survey coverage; this design would increase survey efficiency (ratio of helicopter time to coverage) and inherently increase precision. Distance sampling collected by group would be an improvement over the current negatively biased, transect-total method to calculate detection probabilities. Managers should ensure that sufficient resources are available to obtain robust estimates of abundance and composition of West Greenland caribou. These recommendations may be applicable to other areas in which ungulate populations exist in heterogeneous habitats with low sightability.

Key words: barren-ground caribou, census, Greenland, population estimation, sightability, survey, Rangifer tarandus

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Abundance of wildlife is one of the most common indicators monitored as input to management decisions (Caughley & Sinclair 1994, Krebs 1999). The type of management decision may be set in the context of sustainable harvesting (Skalski et al. 2005), or as input to environmental assessments for development projects (e.g. Cumberland Resources Ltd. 2005). However, the precision of abundance estimates is a function of a variety of sources of uncertainty, such as correcting for undetected animals (Elphick 2008), and can lead to a lack of statistical power to detect trends (Steidl et al. 1997). The uncertainties can be reduced through survey design; e.g. the requirements for accuracy (whether there is agreement between a measured value and its true value) may need to be balanced by ensuring a level of repeatability between concurrent surveys so that population trends can be estimated, or an accurate measure of density may take precedence over high precision (sampling error or repeatability; Caughley & Sinclair 1994, Mbugua 1996, Krebs 1999). The relationship between abundance estimates and uncertainty and resultant management decisions can be complex (e.g. Hauge 2011). For many wildlife populations, a formal management plan with goals and objectives identifies information requirements for management decisions, which in turn determine survey design (*cf*. Bathurst Caribou Management Planning Committee 2004). Although additional indicators of ecological change should be considered (Morellet et al. 2007), estimates of abundance are widely used to evaluate many conservation and wildlife programmes (Williams et al. 2002). Abundance of large ungulates can be estimated using a variety of techniques (e.g. Rönnegård et al. 2008, Russell & Gunn 2008); the optimal method depends largely on the management objective and financial constraints. Abundance estimates for caribou/reindeer *Rangifer tarandus* are conducted within its circumpolar range. Many populations of migratory barren-ground caribou *R. t. groenlandicus* and wild reindeer *R. t. tarandus* mass annually on calving grounds, which enables use of visual and photographic strip transect census techniques or photography of post-calving concentrations (e.g. Klokov 2004, Patterson et al. 2004, Hinke et al. 2005, Nishi et al. 2010). On the often rugged and mountainous Canadian High Arctic islands, Peary caribou *R. t. pearyi* estimates have been derived from systematic transect surveys (Jenkins et al. 2011, Species at Risk Committee 2012). Most of these estimates employ corrections for sightability (visibility) and other biases typically found in aerial surveys (Caughley 1974, 1977, Caughley & Sinclair 1994, Elphick 2008, Laake et al. 2008).

In West Greenland, caribou occupy a narrow coastal band of open and alpine tundra within the largely rugged and mountainous terrain between the Davis Strait and the Greenland ice cap. Four main populations occur in this area, i.e. the Kangerlussuaq-Sisimiut (KS) population in the north region, the Akia-Maniitsoq (AM) population in the central region, and the Ameralik and Qeqertarsuatsiaat populations in the south region (Fig. 1). The KS and AM populations are West Greenland's two largest indigenous caribou *R. t. groenlandicus* populations, and the Ameralik and Qeqertarsuatsiaat populations are a mix of indigenous caribou and semi-domestic

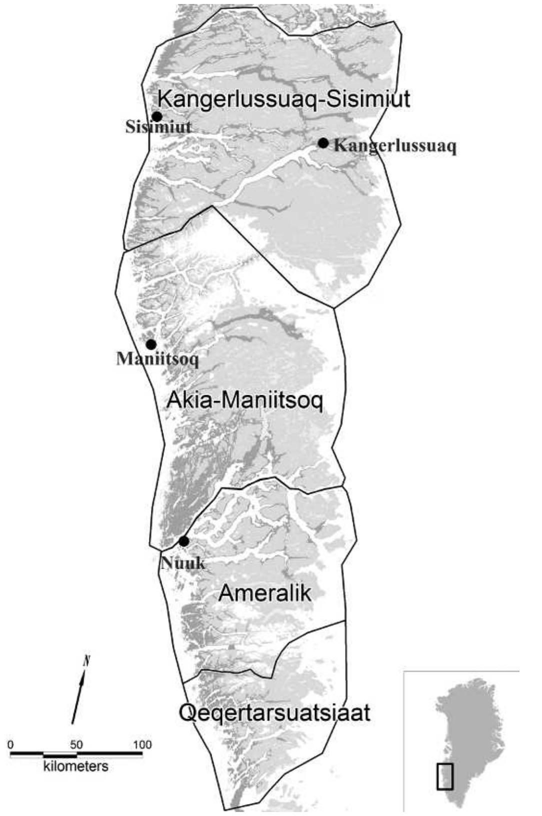

Figure 1. Occurrence of the four main West Greenland caribou populations.

reindeer *R. t. tarandus*. Barren-ground caribou in West Greenland are unique in that they do not have gregarious calving like most of their North American counterparts, and thus cannot be surveyed using conventional calving ground survey methods (Gunn & Russell 2008). Greenland caribou do not appear to aggregate in any particular season, requiring range-wide surveys to enumerate. Peary caribou generally demonstrate a similar dispersion pattern, which have been addressed through systematic transect surveys (Jenkins et al. 2011, Species at Risk Committee 2012). However, survey conditions for West Greenland caribou are especially challenging, mainly as a result of small groups of animals inhabiting rugged terrain with mottled and incomplete snow cover that allows boulders and vegetation to break up any uniform survey background.

Caribou hunting is important to commercial hunters, residents and outfitters in many of the coastal communities in West Greenland. The areas north of Nuuk are of particular concern because of two large industrial proposals (an aluminum smelter and associated hydro-development projects and an iron mine) and the effects they may have on caribou populations (Greenland Development 2012, Nanoq 2012).

The Greenland Institute of Natural Resources (GINR), which does applied research for the Greenland Government, surveys caribou abundance along the west coast of Greenland at roughly 5-year intervals (Cuyler 2007, Cuyler et al. 2011; revised in 2012 and references cited therein). The objectives of these surveys, which normally occur in early March, are to determine late-winter abundance, population structure and distribution (Cuyler 2007). The objectives of our review were to examine the existing Greenland caribou survey methodology using survey and satellite telemetry data collected from 2000 to 2010, and to offer recommendations to improve it. Our analyses focussed on the KS and AM populations north of Nuuk. Our recommendations could be applied to ungulate populations in other areas that exist in heterogeneous habitats with low sightability.

Current Greenland caribou survey methodology

The current survey methodology has remained largely unchanged since 2001 (Cuyler et al. 2002, 2005, 2007, 2011 (revised in 2012), Cuyler & Linnell 2004). West Greenland caribou study areas were based on geographically isolated populations, which have been assigned corresponding hunting regions. Within each study area a number of randomly located and oriented transects were surveyed by helicopter. Numbers of transects required for each study area were determined using 1996 survey data to plot variance of transect counts against number of transects, coupled with economic restrictions and sightability considerations (Cuyler et al. 2002). The transect length was 7.5 km, determined as the optimum size to produce a sufficiently large sample of transects for reasonable variance while retaining high sightability, and the short length reduced observer fatigue and maximized observer concentration (Cuyler 2007). The strip width was 300 m on each side of the helicopter, for a total strip width of 600 m. A total of 60 and 54 transects were deployed in the KS and AM areas, respectively, equating 1.0 and 1.6% of the study areas, respectively. Transects were generated with a rule of no transects < 2 km apart, and once established in 2000-2001, the same transect lines were retained for subsequent surveys. Areas of low and high caribou density were stratified prior to assigning random transects (Cuyler et al. 2002, 2005:Appendices 2 and 1, respectively). This stratification was based on the local knowledge and observed densities during aerial surveys conducted in the mid-1990s (Ydemann & Pedersen 1999, Cuyler et al. 2002) and was not altered in subsequent surveys.

Negatively biased population estimates arise if, among other things, the survey design leads to low detection rates (sightability) that are uncorrected. The current design attempted to maximize detection rates by flying low and slow and concentrating on a narrow strip width for a short length of time (Cuyler 2007). The surveys used an AS350 helicopter flying at 15-m altitude above ground level (agl) and at 45-65 km/hour (kph). Each 7.5 km transect took roughly 7-9 minutes to survey. A radar altimeter was used to maintain survey height. Strip width was verified at the airport over a known distance using laser range finders, and each observer marked their window with masking tape at the appropriate point.

March was selected as the optimal survey timing because collar data and observations from the 1990s suggested that the dispersion of caribou was high (reducing variance among transects), the caribou group size was small (generally < 6 animals, which reduces counting error and aids precision; Cuyler et al. 2002, 2005, 2007), and caribou movement was relatively low, which minimized movement among transects (Cuyler & Linnell 2004). During March, snow cover is generally at its maximum and flight direction was chosen to minimize solar glare.

Three observers and a pilot were in the helicopter. Two observers counted on the left side and one on the right side (rear seat). The pilot and front left seat observer made sure all area in front of the helicopter on the transect line was surveyed. Observers counted caribou independently of each other, with no verbal or other contact between observers while on transect. Manual click-counters were used to log the number of caribou seen on a specific transect by each observer. The number counted by each observer was recorded immediately following each transect, after which the click-counters were zeroed.

Estimation of study area abundance used standard Jolly (1969) methods (Cuyler et al. 2003:Appendix 3) based on the density of animals per sample unit (transect) calculated as the ratio between animals counted and area searched. For the raw totals used in the calculation, the highest count between the left side observers was used. The left front observer (CC) was the same for all surveys. Rear-seat observers occasionally switched between left and right sides during surveys, and personnel infrequently changed during the course of a survey. Sightability correction was applied using a design to account for the total number of animals observed on each strip comparing left front and left rear observers and not data collected by group or by individual; this resulted in a negative bias to the sightability correction (Cuyler et al. 2003:Appendix 4). The left rear seat detection probability was applied to the right rear seat observer. Thus, detection probabilities were calculated for left side front and rear seats; observer-specific detection probabilities were not calculated.

Sex and age composition data were collected to determine population structure and calf recruitment to aid in population monitoring and management (Cuyler et al. 2003, 2005). Data were recorded as male or female based on the presence or absence of a vulva and/or urine patch on the rump, and adult (age > 1 year) or calf (age < 1 year) based on body size. Caribou neither sexed nor aged were tallied as unknown. These data were collected from some transects when caribou densities were low, on some ferry flights between transects and during 'zigzag' flights specifically targeting high density areas for population composition work. The distribution of helicopter time between abundance counts on transects and population composition sampling was not quantified, but ignoring ferry time to and from refuelling and between transects it was roughly a 60:40 ratio.

Material and methods

Data sets

We obtained transect and population composition data collected during 2005 and 2010 surveys of the KS and AM populations (Cuyler et al. 2005, 2011; revised in 2012). Data collected comprised total numbers observed per transect and also bull, cow and calf counts for the population composition analysis. Composition data were spatially assigned to a 5×5 km grid developed for each study area.

In May 2008, 40 females from the AM population were collared with GPS collars with Argos and Iridium satellite uplink (Cuyler 2008). Capture effort was distributed throughout the study area. Collar fix rate was one, two or three hours, with the collars providing data from 58 to 814 days/animal ($\bar{x} = 476$ days, SD = 260.1). Using a combination of movement rates calculated in Excel and spatial movements in ArcView (Environmental Systems Research Institute, Redlands, California, U.S.A.), we cleaned the data set to remove locations from collars that were not moving (or obviously harvested), clear errors in location and the tail end of battery life when collar locations or transmission were intermittent. Data quality was high with the Iridium data set (96-98% fix success, > 95% 3D fixes), but more variable with the Argos data set (50-70% fix success; unknown 3D fix rate). To assist in survey design evaluation, we then used this database to examine seasonal movement rates and distribution of caribou during survey periods (3-15 March; corresponding to when surveys were usually conducted).

Movement rates and distribution

We calculated seasonal movement rates by collar fix rate (one, two or three hours) and only included locations with successful sequential locations. We calculated average movement rate (m/hour) for each individual for each date, and averaged rates by date among individuals. We applied a 7-day moving average to smooth the data.

We calculated year-specific centroids for each collared caribou for 3-15 March 2009 and 2010 using the mean location calculated in Program Animal Movement (Hooge & Eichenlaub 1997). Centroids for caribou with two years of data were linked to demonstrate fidelity in seasonal area selection between years.

We examined differences in the distribution of numbers of caribou observed on individual transects between years by plotting the number of caribou counted on transects for AM and KS 2005 surveys and ordered the frequency from lowest to highest counts among transects. We then overlaid the 2010 data by transect for each population.

Survey bias

Three main types of bias may affect aerial surveys. When densities are low, single or small groups of caribou are more likely to be missed resulting in sightability bias (also termed perception bias; Marsh & Sinclair 1989). Given heterogeneous terrain and difficult viewing conditions, sightability bias is likely a significant factor. Sightability bias was partially addressed in the current survey design (see above; Cuyler et al. 2003:Appendix 4). When densities are higher, it is often more challenging to accurately count larger groups (counting bias) and record data efficiently. Given low overall group size (mean of 3-5 animals; Cuyler 2007), counting bias is unlikely to be a significant problem with these surveys (Skalski et al. 2005). In addition, terrain features may hide some of the strip width when flown at low altitude, resulting in 'dead ground' (Cuyler 2007). When portions of a strip width are hidden by topography and out of sight of observers, the detection probability for animals in those areas is nil (termed availability bias; Marsh & Sinclair 1989). In rugged terrain, this could have a significant impact on the actual strip width and hence the population estimate. However, it is more difficult to cope with availability bias than with sightability bias (Marsh & Sinclair 1989, Laake et al. 2008).

To examine the extent of availability bias and aid in determining optimal survey flight height we conducted a viewshed assessment using GIS. We obtained recent 30 m ASTER II coverage for West Greenland (ASTER GDEM Validation Team 2011; available at: http://asterweb.jpl.nasa.gov/gdem.asp), which covered most of the KS and AM study areas. No smoothing or filtering was conducted on the original digital elevation model (DEM) data. Of the original 114 caribou transects, 110 were within the DEM coverage and were available for analysis. We removed six additional transects from further analysis after visual scrutiny suggested possible presence of DEM errors along portions of the transects, resulting in 104 transects in the final data set. We conducted analyses using raster-based GIS routines in Idrisi Kilimanjaro (Eastman 2003) and Mapinfo Professional Version 6.0 (MapInfo 2000). For each transect and using 100-m increments out to 400 m on each side of the helicopter, we determined the proportion of strip width area not available to observers at flight heights of 15, 30 and 45 m. Comparisons of percent area available among strip widths at various heights were conducted with a Generalized Linear Model (PROC GLM; SAS Institute, Cary, North Carolina, U.S.A.), with comparison among means with a Duncan multiple range test. We also examined the percent area available over the entire 300-m strip width at the three flight heights. Data are presented for each side of the transect line summed, thus proportion of 300-m strip width described pertains to the entire 600-m strip for the transect.

Stratification

Winter caribou distribution likely changes with changes in density, forage availability and snow condition (Skoog 1968, Russell et al. 1993, Bergerud et al. 2008, Collins et al. 2011), thus stratification from the mid-1990s may not be reasonable over time. For example, during the AM survey in 2010, the average caribou densities within high and low strata were virtually identical (Cuyler et al. 2011; revised in 2012). Pre-stratification (based on the most recent survey and other knowledge such as hunter records, collar data or distribution of vegetation) and/or stratification flights immediately prior to the surveys could result in more accurate stratification of the survey area, and hence better allocation of effort and greater precision of the estimates (Caughley 1977, Caughley & Sinclair 1994). To examine the influence of stratification, we applied previous survey results to the 2010 survey data. Based only on the 2005 survey data and distribution of transect totals, we re-stratified the AM and KS study areas into high stratum and assumed that the rest of the area and transects were in the low stratum. This re-stratification was conducted in a naive manner with no consideration of the recent distribution from the 2010 survey. We then applied the 2010 data to the revised stratification based on the 2005 caribou distribution and recalculated the 2010 estimate and coefficient of variation (CV; the ratio of the standard error to the mean).

Population composition

During the aerial surveys, as well as estimating abundance, caribou were classified into sex and age categories. Two issues facing collection of population composition data are the distribution of groups sampled relative to overall distribution of the population, and a sufficient sample size to obtain a reasonable estimate of age and sex ratios (Gunn & Russell 2008). Here we note that the sample unit is not the individual animal but the sample site or group. Caribou sex and age classes typically are segregated for parts of the year (e.g. Russell et al. 1993). Therefore, we examined the spatial distribution of composition data collected during the March 2010 survey of the KS population between original high and low density strata, and of the AM population among broad areas of low and high density within our study area. To examine minimum sample size required for composition data, we plotted calf and bull ratios (proportion of calf or bull per cow) for both populations by adding groups in the order collected against increasing sample size of groups examined. Because group size was small (generally 1-6 animals) and the calculation of a ratio with zero as a denominator (i.e. no cows observed in a group) results in a calculation error, we clustered groups by sequential clusters of 10 groups (in the order collect-

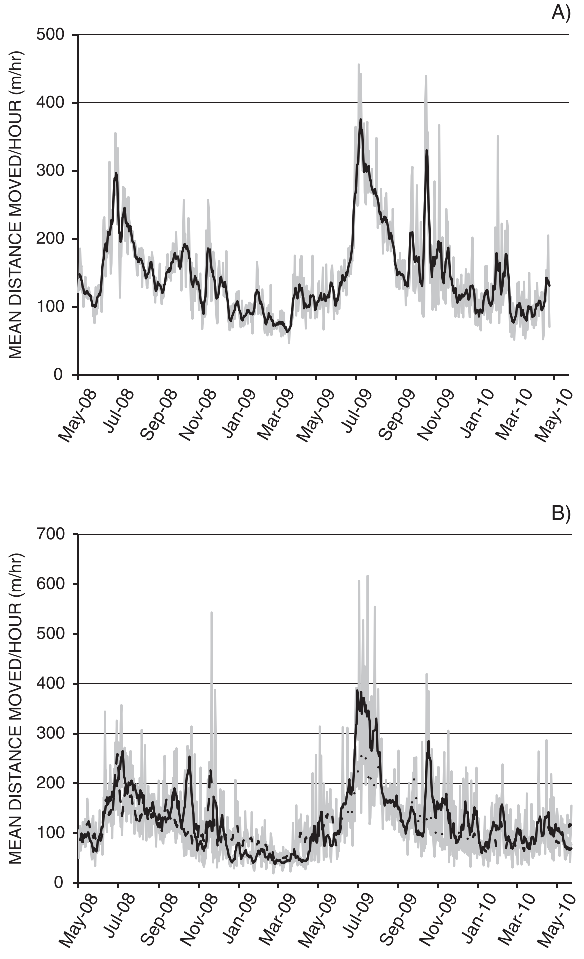

Figure 2. Average daily movement rates (m/hour) of 40 female caribou from the Akia-Maniitsoq population, during May 2008-May 2010. Data were summarized by collar type for Iridium (A; one hour fix rate) and Argos (B; two hours fix rate - solid line; three hours fix rate - dashed line). Thick solid or dashed lines represent 7-day moving averages.

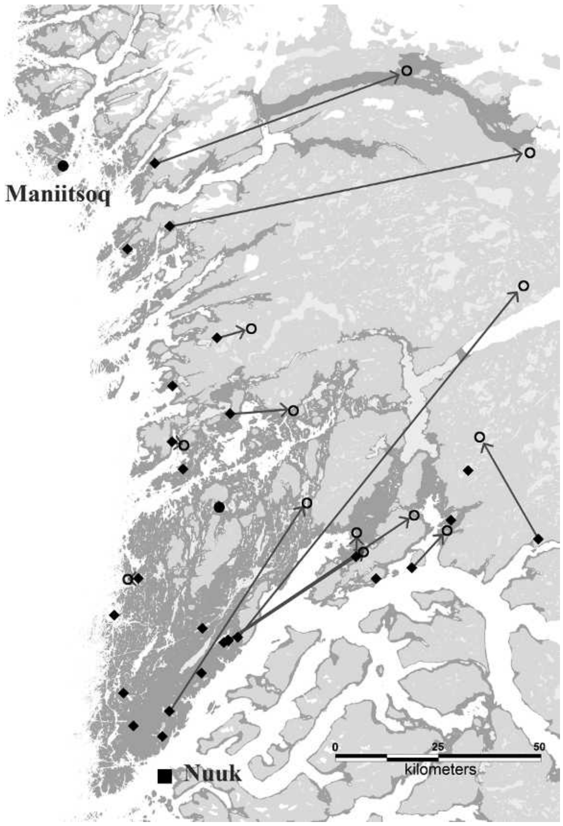

Figure 3. Centroids of areas used during the general survey period (during 3-15 March) by collared female caribou in the Akia-Maniitsoq population, during 2009 (⧫) and 2010 (○). Lines link March locations from the same individual in consecutive years; N = 27 cows, of which 14 were monitored in both years.

ed) and calculated variance and 90% CI adding one cluster at a time to examine changes in ratio and variance with increasing sample size. We used Tukey's Jackknife Method (Krebs 1999) to calculate the overall sex and age ratio CVs.

Results and assessment

Movement rates and distribution

On an annual basis, collared AM females moved the least between approximately 1-27 March 2009 and 2 March-6 April 2010 (Fig. 2). This lends support to using early March for survey timing, as potential movement among transects during the survey is minimized.

Early March distribution of collared AM cows appeared to differ markedly between 2009 and 2010, with a greater proportion of collared cows out towards the coast and southern areas in 2009, compared with proportionately greater use of more central and eastern areas during 2010 (Fig. 3). Distance between early March locations of individual cows varied from 0.1 to 110 km between years, although half were > 28 km ($\bar{x} = 35$ km, SE = 9.4, N = 14). All but one of these longer distance changes in early March locations were in a north-northeastern direction between 2009 and 2010 (see Fig. 3).

Counts from identical transects differed markedly between 2005 and 2010 surveys of the AM and KS populations (Fig. 4). Many of the transects with low counts in 2005 had significantly higher counts in 2010 in both areas and *vice versa*. These simple figures demonstrate the large variability in sightings by

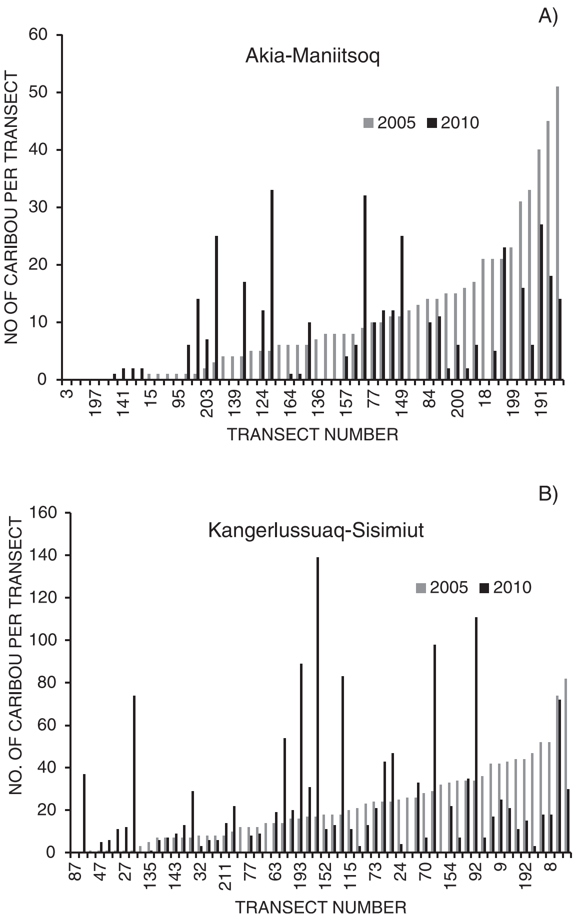

Figure 4. Distribution of caribou counted by transect for the 2005 and 2010 Akia-Maniitsoq (A) and Kangerlussuaq-Sisimiut (B) caribou surveys, ordered by transect totals observed in 2005.

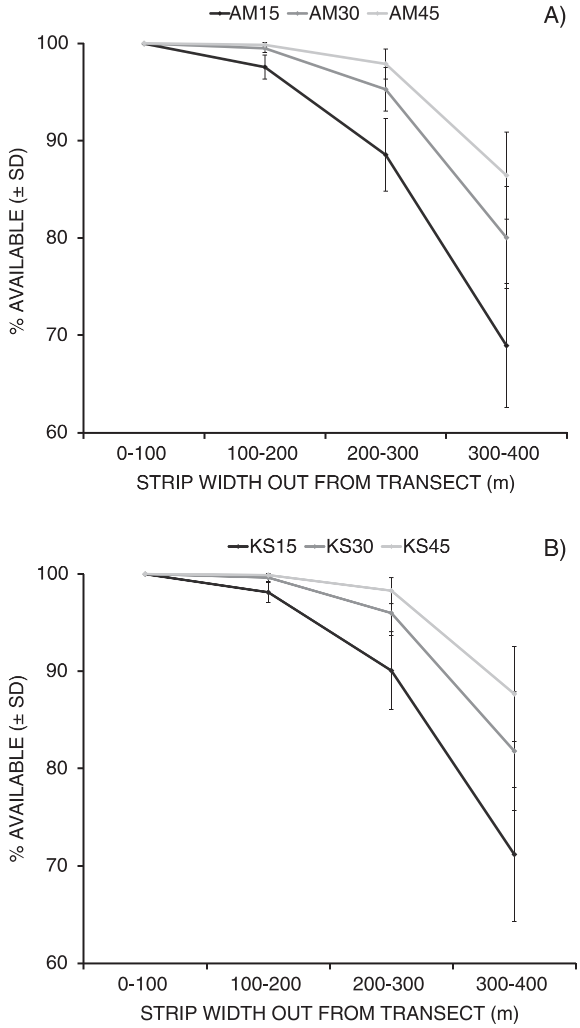

Figure 5. Percent of 100-m strip widths available at 15, 30 and 45 m flight heights during viewshed analysis for the Akia-Maniitsoq (A) and Kangerlussuaq-Sisimiut (B) study areas in West Greenland.

transect between years. This may represent broad changes in spatial distribution over time, or a scale issue of the size of the transects (4.5 km^2) relative to the fine-scale distribution of animals; i.e. animals may simply move off transects among years.

Availability bias

As expected, the viewshed analysis demonstrated that the percent of the 100-m strip width area available to observers declined with distance from the transect line and declined more rapidly at lower flight heights (Fig. 5). Availability differed among strip widths for each height in each study area ($F > 319.0$, $df = 3$ $P < 0.0001$) and did not overlap except for strip widths of 0-100 m and 100-200 m at 30-m and 45-m height in both areas (Duncan's multiple range test: $P < 0.05$). The drop in availability was most pronounced in the 300-400-m strip width at all heights, as well as the 200-300-m strip width at 15-m flight height. At 15 m height on average 10-11% of the 200-300-m strip area was not visible to the observers. Overall, 4-5% of the entire 300-m strip width area was not available for view at 15-m flight height, 1-2% at 30-m height and < 1% at 45 m height (Table 1). The percentage available of the entire 300-m strip width area differed among flight heights for both AM ($F = 167.2$, $df = 2$, $P < 0.0001$) and KS areas ($F = 149.9$, $df = 2$, $P < 0.0001$), with no overlap among heights (Duncan's multiple range test: $P < 0.05$).

Stratification

Based on the naive stratification from 2005 survey data, the revised total AM high density stratum

Table 1. Percent of 300-m strip width available at various flight heights in the Akia-Maniitsoq and Kangerlussuaq-Sisimiut study areas, West Greenland.

Area	Flight height (m)	Percent available	
		0	SD
Akia-Maniitsoq	15	95.2	156
Akia-Maniitsoq	30	98.2	85
Akia-Maniitsoq	45	99.2	57
Kangerlussuaq-Sisimiut	15	95.9	168
Kangerlussuaq-Sisimiut	30	98.5	85
Kangerlussuaq-Sisimiut	45	99.4	48

covered 5,648 km^2, compared to 10,037 km^2 within the high density stratum originally considered (Cuyler et al. 2011; revised in 2012). The 30 transects located in the high density stratum made up three disjoint areas, with 24 in the remaining low density stratum of 9,714 km^2. The original estimate (uncorrected for sightability) from 2010 was 24,000 caribou (CV = 0.18; Cuyler et al. 2011; revised in 2012). The revised estimate for 2010 after re-stratification based on the 2005 survey data was 17,400 caribou (CV = 0.14). This is approximately 28% lower and has higher precision than the original estimate. The densities on transect were 2.6 and 0.3 caribou/km^2 for the revised high and low density strata, respectively, compared with 1.6 and 1.5 caribou/km^2 considering the original stratification (Cuyler et al. 2011; revised in 2012).

For the KS population, the original estimate (uncorrected for sightability) from 2010 was 98,700 caribou (CV = 0.19; Cuyler et al. 2011; revised in 2012). The revised 2010 estimate after re-stratification based on the 2005 survey data was 94,700 caribou (CV = 0.14), 4% lower than the original estimate but again with tighter precision. Density changed marginally, dropping mainly in the low stratum from 2.5 to 2.1 caribou/km^2.

Population composition

The overall KS calf:cow ratio in 2010 was 0.28 calf/cow (CV = 0.09; Cuyler et al. 2011; revised in 2012). Distribution of calves was not even, as the low density stratum had higher calf ratios (0.40 calf/cow, CV = 0.26; N = 176) than the high density stratum (0.26 calf/cow, CV = 0.08; N = 1,559). The overall bull:cow ratio was 0.54 bull/cow (CV = 0.09), with higher bull ratios in the high density stratum (0.56 bull/cow, CV = 0.08) than in the low density stratum (0.45 bull/cow, CV = 0.29).

The overall AM calf:cow ratio in 2010 was 0.23 calf/cow (CV = 0.09; Cuyler et al. 2011; revised in 2012). The highest density core area (i.e. the south-central) had a lower calf:cow ratio (0.22 calf/cow, CV = 0.13; N = 889) than areas along the western coast (0.28 calf/cow, CV = 0.16; N = 175) and eastern inland (0.29 calf/cow, CV = 0.14; N = 216). Calf ratios were very low among a smaller sample in the northern portion of the study area (0. 11 calf/cow, CV = 0.42; N = 72). The overall bull:cow ratio was 0.38 bull/cow (CV = 0.09), with the high density core area with lower bull ratios (0.36 bull/cow, CV = 0.13) compared with the western coastal (0.46 bull/cow, CV = 0.22) and eastern areas (0.43 bull/cow, CV = 0.18). The northern area had very low bull ratios (0.25 bull/cow, CV = 0.47).

Calf:cow ratios generally stabilized after 150 (KS) and 180 (AM) groups, equating to roughly 450 and 800 animals, respectively (Fig. 6). However, differences in calf:cow ratios as sample size increased for

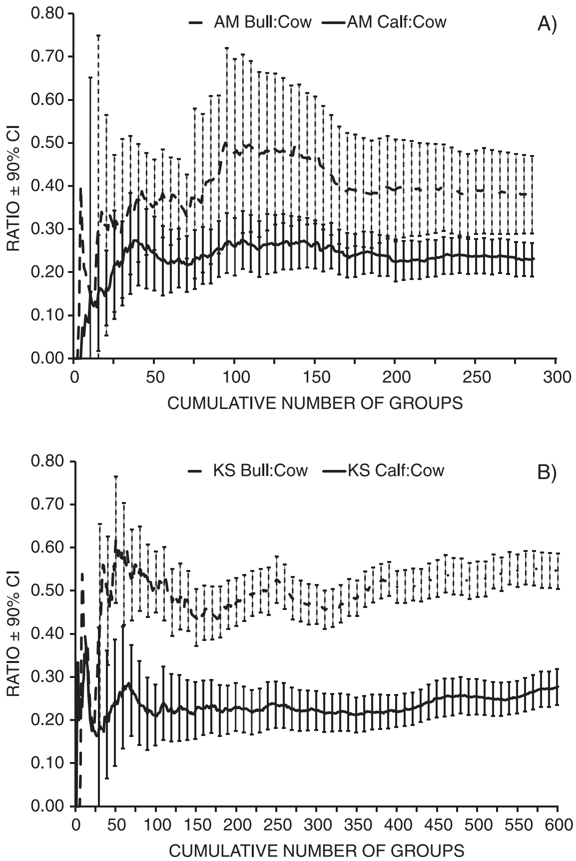

Figure 6. Calf:cow and bull:cow ratios for the Akia-Maniitsoq (A) and Kangerlussuaq-Sisimiut (B) composition data collected during 2010 plotted against cumulative number of groups sampled. Error bars (90% CI) from KS calf:cow ratios are shown and are based on data summed by groups of 10 (see text).

the KS were related to distribution of sampling. The increase in calf:cow ratio after about 400 groups was caused by sampling in areas to the northeast and southwest where ratios were higher than in the core area. Bull:cow ratios took more groups to stabilize, but again for the KS area, changes in bull ratios with increased sampling were related to the distribution of sampling effort.

Discussion

Survey conditions for West Greenland caribou are difficult. The current survey design developed in 2000 was in response to results from surveys conducted in the mid-1990s which produced low estimates of caribou abundance (Ydemann & Pedersen 1999) that were challenged by hunters and biologists (Cuyler 2007). The estimates from the mid-1990s may have been biased low because of survey design which resulted in very low sightability, with no sightability correction, which was thought to have been caused by fixed-wing aircrafts flying at high altitudes (> 150 m) and high speed (167 kph) over wide strip width (of 1.4 km; Cuyler 2007). These estimates resulted in restrictive hunting quotas during the 1990s (Cuyler 2007). Changes to survey methodology occurred in 2000-2001 to increase sightability, likely contributing to higher detection probabilities and subsequent higher population estimates (Cuyler 2007). These subsequent survey design changes placed almost all survey emphasis on increasing sightability, resulting in randomly placed, short transects flown at low altitude and at slow speed.

The current design, however, may have placed excessive emphasis on sightability and somewhat compromised accuracy (Caughley 1977, Krebs 1999). The short, randomly placed transects resulted in a very small sample zone (the actual area sampled during the survey) covering < 1.6% of the study areas, leading to additional randomness across individual estimates, less precision and questionable accuracy of the estimates (Caughley 1977, Krebs 1999). At very low coverage, small changes in estimated density can have huge implications at the population estimate scale. Although the design setup differs markedly, in most estimates of caribou abundance low density strata are systematically surveyed at a minimum of 10-20% coverage, with greater coverage of high density strata (Nishi et al. 2010, Jenkins et al. 2011, Species at Risk Committee 2012). Calving ground distribution surveys in northern Canada typically use 8% survey coverage, albeit of calving grounds where calving is gregarious, and while not intended to estimate population size, trends in estimated density on calving grounds can be determined using corrections for sightability (Nishi et al. 2010).

Systematic sampling of transects has several practical advantages over strict random sampling (Caughley 1977, Norton-Griffith 1978, Caughley & Sinclair 1994, Krebs 1999, Buckland et al. 2001). Systematic sampling reduces the disturbance of animals on a sampling unit caused by surveying an adjacent unit. However, the current transects were designed to be > 2 km apart, which likely minimized disturbance. Sampling effort being equal, systematic sampling also tends to increase the precision of the estimate over random sampling because the sampled units together provide a more comprehensive coverage of total variability (Caughley & Sinclair 1994). Finally, many short transects randomly scattered over the landscape tend to produce a low ratio of on and off transect flying (a measure of survey efficiency) and low coverage of sampled area per hour of flying (more time spent off transect). Longer, systematically spaced transects tend to generate higher survey efficiency and resultant coverage.

The current survey methodology is designed for a population estimate on a 5-year basis (thus low temporal resolution of trend information) with a high priority on minimizing sightability bias and maximizing number of transects (precision). The frequency of surveys is a compromise between the ability to detect trends (e.g. Nishi et al. 2010), the temporal scale of environmental perturbations (such as winter icing), management needs and financial constraints. Accuracy (ensuring that surveys reflect reality and are unbiased) should be balanced against precision of the estimates. The high number of transects increases the precision at the expense of accuracy as the coverage is so low that random chance can affect individual estimates. While trade-offs in precision and accuracy are inevitable (Caughley & Sinclair 1994), the low coverage of the current design should be moderated, because higher coverage would increase estimate accuracy and ultimately benefit management.

Seasonal movement and migration patterns within West Greenland caribou populations lack coordination in timing or direction of movement, although individuals have been reported to undergo either fairly consistent seasonal patterns or relatively localized year-round movements, which are often, but not always, concentrated closer to the inland ice cap (summarized in Cuyler et al. 2002, Cuyler & Linnell 2004). Our assessment of the recent AM collar data indicate that movement rates during March are indeed the lowest of the year, suggesting early March to be an optimal time for surveys. However, based on only two winters of data, AM caribou appear to select different areas between years, being located much closer to the coast in March 2009 and more inland in March 2010. From a survey perspective, this suggests that past distribution patterns may not be indicative of distribution in a given survey year. The large differences observed in transect totals for both AM and KS populations between 2005 and 2010 surveys also suggest changes in distribution patterns among years. These points argue for stratification prior to each survey.

The current correction for sightability by transect total is negatively biased, as the technique calculates maximum values of detection probabilities (Cuyler et al. 2003:Appendix 4). In addition, rear seat detection probabilities (P_r) are calculated for the left side of the aircraft (comparison required with the front seat observer) and therefore were applied to the right rear seat and observers who may have completely different ability to see caribou during surveys. Two options to address sightability bias have been used during recent caribou surveys in northern Canada (Jenkins et al. 2011, J. Boulanger, pers. comm.), the dependent observer method (Cook & Jacobsen 1979, Koneff et al. 2008) and distance sampling (also known as line-transect sampling; Buckland et al. 2001, Buckland 2006, Thomas et al. 2010). We discuss each of these options in turn below. Logistic regression sightability models can also be developed, but development costs are high and parameters likely complex and variable within this terrain and among surveys (Skalski et al. 2005).

The dependent observer method to correct observations for sightability depends on the primary observer and secondary observer on the left side of the aircraft to communicate about caribou observed by group, allowing data recording by the supplemental data recorder (Cook & Jacobsen 1979, Koneff et al. 2008). The front seat observer calls out all caribou he/she sees. The rear seat observer calls out groups not seen by the front observer and notes groups which the front observer saw, but were not seen by the rear observer. Front and rear seat observers switch roles to obtain observer-specific detection probabilities.

Distance sampling is an efficient method to estimate density in many open habitat situations and for a wide variety of vertebrates (e.g. Anderson et al. 2001, Bårdsen & Fox 2006, Buckland 2006). In distance sampling (Buckland et al. 2001, Thomas et al. 2010), once a group is sighted, the perpendicular distance from the transect line to the group is determined. For efficiency and to reduce disturbance, caribou group observations can be 'binned' into 100-m bins and left and right side detection probabilities calculated. The three key assumptions of distance sampling needed to produce an unbiased estimate of density are (Anderson et al. 2001, Buckland et al. 2001):

1) All animals of interest that were directly on the transect line were detected ($g(0) = 1$; within the first strip when binning).
2) Animals of interest were detected at their initial location before they moved in response to the observer (i.e. away from the aircraft).
3) Perpendicular distance (x) from the transect line to each detected cluster was measured accurately.

These assumptions could be reasonably met, although testing the assumptions is highly recommended (Elphick 2008). Failure to detect all individuals on or near the transect centre line was the main cause of bias in empirical tests conducted by Anderson et al. (2001). We suspect that detection probabilities for caribou along the flight line are probably very close to 1 given that the pilot and front-seat observer focus forward and along the flight line during survey, although we cannot otherwise verify this assumption. Even if animal movements were suspected prior to detection, the group would in most cases be assigned to the correct bin based on location or tracks. Binning into 100-m segments out from the aircraft could be conducted with reasonable accuracy (*cf.* Bårdsen & Fox 2006); estimation of 100-m distances out from the helicopter could be practised at an airport prior to the survey, and on occasion the helicopter could leave the flight line to verify perpendicular distance to observed groups (a task made very easy with knowledgeable use of a hand-held GPS; Marques et al. 2006). Laser range finders could also be incorporated to help calibrate distance measurement (Bårdsen & Fox 2006), taking into consideration that observer angle to the ground will affect actual distance out from the centre line of the transect. Iterative feedback early in the survey would ensure consistency.

During distance sampling, observers should be instructed to continue to focus within the 300-m strip width. Animals opportunistically observed beyond the 300-m strip width (in the 4th and 5th bins) would provide additional information for distance sampling analysis. Utilizing a well-designed data sheet, a recorder in the back seat could collect both group data, locations (GPS waypoint) and distance information. Note that the priority during surveys is to obtain group counts; on the occasions when caribou densities are too high and groups are encountered too rapidly, loss of some distance data will have little impact on detection probability calculations. Observer training is an important component of a reliable survey (Anderson et al. 2001).

The viewshed analysis indicated that availability bias increased with lower flight height and at greater strip width. If survey height were increased to 30 or 45 m while still retaining the 300-m strip width focus, then there would be a decrease in the mean amount of obstruction between animal and observer over the entire strip width. At 30 m flight height $< 2\%$ of the total strip width area was unavailable to observers and at 45 m height $< 1\%$. Higher flight height will allow observers to look more down into hollows or behind rises, which would reduce the number of caribou not available for viewing. Higher survey height would also result in a decrease in required eye movement (Skalski et al. 2005) and may increase flight safety and reaction time. We are aware that the high degree of camouflage provided the caribou by mottled backgrounds and flat light conditions of West Greenland surveys will reduce detectability of the small groups and often stationary individuals typical in Greenland in proportion to the increase in flight height, but this can be addressed using distance sampling (assuming $g(0) = 1$).

Our naive re-analysis of the 2010 AM and KS survey data based on stratification from the 2005 survey results demonstrated the importance of stratification to increase both the accuracy and precision of estimates. While results from the previous surveys may be useful to base stratification, inter-annual variation in distribution, possibly caused by winter weather and snow depth (Russell et al. 1993, Bergerud et al. 2008), may override previous patterns. Examination of the 2008-2010 AM collar data suggests that during early March, spatial fidelity at the annual scale may be low and the distribution of caribou differs between years, suggesting that the distribution observed in the most recent survey may not be indicative of distribution in any one winter. The shift in distribution of collared female caribou during the early March survey period between years suggests that a stratification flight prior to survey will provide the best data upon which to base the stratification.

The results of the population composition assessment suggest that composition effort should be allocated within each study area proportionate to density of the population (i.e. greater effort in high density stratum recognizing that ratios will differ among areas; Gunn & Russell 2008), and that sampling effort can be greatly reduced with little to no loss of accuracy or increase in variance. For efficiency it may be wise to conduct the transect survey for population estimate prior to initiating composition counts. These data could be rapidly summarized on a daily basis, with effort terminated when a specific CV is attained.

Estimating density or abundance of large ungulates is difficult and costly; the requirement for use of expensive helicopters coupled with difficult logistics in West Greenland are a prime example. However, even accurate and precise estimates of abundance provide limited information on the relationship between the population and its habitat (Morellet et al. 2007). While the focus of this article was to produce more precise and accurate estimates of West Greenland caribou herds, other indicators of ecological change should be considered to provide insights on population dynamics and habitat relationships that can feed into management. Population composition data are collected during 5-year abundance surveys (Cuyler et al. 2011; revised in 2012) and reproductive data have been examined (Cuyler & Østergaard 2005). Access and logistic difficulties may limit the types of indicators that can be practically and repeatedly monitored in West Greenland, but we suggest that greater consideration should be given to annual indicators of habitat quality (grazing pressure) and quality of individuals in the population (i.e. sampling or measurements from the hunter harvest). Annually, hunter harvest data are monitored and harvesters provide rump fat and body condition measurements, and caribou faeces (pellet) monitoring will begin in 2013 to examine trends in caribou habitat use and relative abundance (C. Cuyler, pers. comm.); however, we acknowledge that greater emphasis should be placed on annual monitoring to support population trends (Morellet et al. 2007).

Recommendations

Based on our assessment of the West Greenland caribou survey methodology, we propose the following recommendations:

1. A formal management plan or strategy should be developed as a requirement to set goals and objectives that will determine the information needs for management decisions, which in turn will aid in development of survey design. The objectives of the surveys should be determined (Krebs 1999), e.g. accurate population estimates, trend estimates and/or population composition data, keeping in consideration other possible indicators of change and tools that are available for management (quotas, season length and mechanized restrictions). Too many objectives for a single method such as aerial surveys can introduce inherent compromises in the sampling design and reduce survey efficiency.
2. As the basis for acceptable management decisions, sufficient effort and financial resources should be allocated to each survey to obtain a survey estimate with a CV of $\leq$ 15% (Nishi et al. 2010). Greater precision may be required for harvest management at critical times in cyclic changes in abundance (Gunn & Russell 2008).
3. Study areas should be stratified based on the most recent survey or other relevant information at minimum (Caughley 1977), and, ideally, on a stratification flight (fixed-wing or helicopter) conducted immediately prior to each survey. Stratification flights could be designed as a series of long transects bisecting the area, a spaghetti flight or reconnaissance lines examining uncertain boundary areas between expected high and low density strata.
4. Since the objective is to obtain the most precise estimate of the population as opposed to a precise estimate of each stratum, sampling effort/intensity should be allocated among strata according to the expected standard deviation of sampled unit counts in each stratum (Caughley 1977). Thus, the number of sampling units placed in a stratum should be directly proportional to the expected stratum estimate.
5. Methods to increase survey coverage should be adopted. Systematic coverage of strata using longer, evenly spaced transects to systematically sample caribou distribution within each stratum would increase survey efficiency (the ratio of time spent on and off transect) and increase precision (Caughley & Sinclair 1994, Krebs 1999). In this design, transects would normally be oriented perpendicular to the long axis of the stratum and would require sufficient funding to support adequate numbers of transects in each stratum (minimum of 10; Nishi et al. 2010). This is a robust and well-tested approach, which should improve flying efficiency and accuracy of the estimates.
6. Survey flight height should be increased to at minimum 30 m and preferably 45 m to reduce availability bias. Although higher survey altitude (which increases the mean distance between animal and observer) and slightly faster survey speed (to perhaps averaging 65 kph) may contribute to slightly lower proportion of animals observed on transect (which can be addressed through distance sampling), the additional height decreases availability bias and required eye movement (Caughley 1974, Skalski et al. 2005), and the faster speed may also increase flight safety and helicopter flight stability (P. Wiis, Air Greenland pilot, pers. comm.). In addition, faster flight speed would likely allow two assumptions of distance sampling to be better met: animals were detected at their initial locations in response to the helicopter and perpendicular distance to each caribou group was measured accurately (before major movement; Anderson et al. 2001, Buckland et al. 2001).
7. Distance sampling with binning should be adopted to calculate detection probabilities for each side of the helicopter. Distance sampling allows counting beyond a fixed strip width (thus increasing sample size compared to strip transects) and there is a large body of literature on the analysis of the data from the method. Distance sampling data from both sides of the aircraft could be recorded by a single designated recorder. The two observers on the left side would function as a single 'observer' for analysis. Analysis of distance sample data is relatively straight forward using Program Distance (Thomas et al. 2010), and has been successfully used for Peary caribou in mountainous terrain (Jenkins et al. 2011).
8. During each survey, more helicopter time should be allocated to the abundance estimate and less to collection of population composition data. Composition data should be collected after the abundance surveys are completed. Sampling effort should be roughly allocated by distribution of density. Less than 200 groups probably need to be surveyed to obtain an adequate estimate of at least the calf:cow ratio. Sampling effort should be focussed on calf ratios to track calf survival over time. Bull:cow ratios may vary more widely, possibly because of greater spatial segregation of the sexes.

We acknowledge that financial limitations will play a large part in changes to West Greenland caribou survey design. The Greenland government should provide sufficient resources to ensure that robust estimates of abundance and population composition can be obtained. Testing of any revised survey design through field studies or simulations (Elphick 2008) should be considered before being applied to subsequent surveys. Greater exploration of annual cost-effective population, individual and habitat indicator monitoring should be considered. The recommendations presented here may be applied to other areas where ungulate populations exist in heterogeneous habitats with low sightability, e.g. for boreal caribou *R. t. caribou* residing in small groups in patchy forested habitats (Courtois et al. 2003).

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