CANADIAN WILDLIFE BIOLOGY & MANAGEMENT

CWBM 2017: Volume 6, Number 1

ISSN: 1929–3100

Original Research

A Comparison of Calving and Post-calving Photo-surveys of the Bluenose-East Herd of Barren-ground Caribou in Northern Canada in 2010

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Abstract

Two photographic survey methods have long been used in Canada's Northwest Territories and Nunavut to estimate herd size in migratory barren-ground caribou herds (*Rangifer tarandus groenlandicus*). The calving photo-survey provides an estimate of the abundance of breeding females on the calving grounds in June and can be extrapolated to an estimate of herd size to account for caribou not on the calving grounds. The post-calving photo-survey is carried out in July when large dense groups of caribou formed in response to insects can be photographed and counted. We carried out both surveys for the Bluenose-East caribou herd in 2010 in Nunavut to provide a side-by-side comparison.

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The calving photo survey in early June produced an estimate of 51,757 ± 11,092 (95% Confidence Interval) breeding females on the calving grounds. We estimated 114,472 ± 15,845 ≥1-year-old caribou from the photographed and visually counted June survey strata. The estimate of breeding females was extrapolated to a herd size of 105,326 ± 40,984 ≥2-year-old caribou using estimates of sex ratio and pregnancy rate; an alternate extrapolation of 120,880 ± 13,398 ≥2-year-old caribou was derived from strata-based estimates of cows and an estimate of sex ratio. Counts of photographed caribou aggregations in July resulted in a total of 92,481 ≥1-year-old caribou in 39 groups. An estimate of herd size using a Lincoln-Petersen formula was 98,646 ± 13,965 ≥1-year-old caribou and an estimate using the Rivest estimator was 122,697 ± 31,756 ≥1-year-old caribou. The Rivest-derived estimate was likely closest to true herd size (all ≥1-year-old caribou). We compared strengths and limitations of the 2 survey methods, and their applicability for management.

Key Words: Barren-ground Caribou, Calving, Photo-survey, Population Estimate, Post-calving.

INTRODUCTION

Estimating population size in migratory caribou (*Rangifer tarandus*) herds that may number more than half a million (Bergerud *et al.* 2008) remains challenging in the 21st century. Two photographic surveys have been used since the 1980s in the Northwest Territories (NT) and Nunavut (NU) in northern Canada to estimate population size in migratory barren-ground caribou (*R. t. groenlandicus*) herds. Calving photo-surveys in June (Heard 1985) and post-calving photo-surveys in July (Valkenburg *et al.* 1985) take advantage of caribou aggregating spatially at a time when there is good separation between herds. Calving photo-surveys have been used more for eastern herds in NT and NU (Williams 1995; Nishi *et al.* 2007; Campbell *et al.* 2010). Post-calving photo-surveys have been used more for western herds in NT and NU (Patterson *et al.* 2004; Nagy and Johnson 2006), Alaska (Harper 2013), and Québec (V. Brodeur, 2016, Government of Québec, personal communication). A side-by-side comparison of the 2 methods had not been previously carried out in NT and NU, and was recommended by an independent review of the Government of Northwest Territories (GNWT) barren-ground caribou program (Fisher *et al.* 2009).

Calving photo-surveys, the first of the 2 methods, are carried out near the peak of calving in June and provide estimates of the abundance of breeding females on the calving grounds (Heard 1985; Nishi *et al.* 2007; Campbell *et al.* 2010). Movement rates of cows with newborn calves are limited, reducing the likelihood of movements inside or outside the survey area (Gunn *et al.* 2005). The survey area is defined by previous knowledge of a herd's calving grounds, recent locations of radio-collared cows, and extensive systematic reconnaissance flights that define the full distribution of breeding females. In the early years of calving photo surveys, surveys were completed without radio-collared caribou (e.g., Heard and Jackson 1990). However, calving may sometimes occur south of normally used calving grounds in years of late snowmelt (e.g., Porcupine herd in 2000 and 2001, Griffith *et al.* 2002), thus a sample of radio-collared cows in June is key confirmation that the bulk of the herd's cows are within the survey area.

Survey strata are defined on the calving grounds based on patterns of spatial aggregation and relative densities and composition of caribou observed during systematic reconnaissance flights. A photo plane flies transects of continuous photos over the higher-density strata with breeding cows at ground coverage of at least 30-40% (Heard 1985; Gunn *et al.* 2005; Nishi *et al.* 2007; Boulanger *et al.* 2014) and caribou are counted on the photos. Lower-density strata are re-flown by visual strip-transect methods. A ground and helicopter-based composition survey in all strata provides a precise estimate of the proportion of breeding females and of other sex and age classes in the survey area. The counts and composition percentages from each stratum are combined to derive an estimate of the number of breeding females on the calving ground (Gunn *et al.* 2005; Nishi *et al.* 2007; Boulanger *et al.* 2014).

Because most of the bulls and some of the yearlings and non-pregnant cows are not on the calving grounds in June, an extrapolation has been used to account for the missing caribou to derive an estimate of overall herd size (Heard 1985; Heard and Williams 1990). An estimate of sex ratio from fall composition surveys is used to account for the bulls, and an estimate of pregnancy rate is used to account for non-pregnant breeding-age cows (Heard 1985; Heard and Williams 1990; Nishi *et al.* 2007; Campbell *et al.* 2010). Since the 2010 Bluenose-East (BE) herd June survey described in this paper, a revised approach to accounting for breeding and non-breeding females on the calving ground survey area was first used by Campbell *et al.* (2016) for a 2014 calving photo survey of the Qamanirjuaq herd and more recently for a 2015 survey for the BE herd (Boulanger *et al.* 2016). This approach uses the estimated totals of breeding and non-breeding females on the June survey area directly, and a correction based on sex ratio is applied to account for bulls. We refer to the earlier extrapolation method as A, and the more recent one as B.

The large variance on early surveys of this type and the extrapolation calculations have led some biologists (Thomas 1998; Rivest *et al.* 1998) to question the value of the calving photo-survey as a method of counting caribou. Over the years, however, careful attention to allocation of survey effort has reduced the variance on estimates of breeding females (Nishi *et al.* 2007; Campbell *et al.* 2010; Boulanger *et al.* 2014). Biologists using this survey have emphasized that the method is repeatable and provides a reliable and relatively precise way of monitoring size and trend in the abundance of breeding cows, which are key demographic variables for the herd (Boulanger *et al.* 2011).

Post-calving photo-surveys are the second of the 2 survey methods and are usually carried out in early to mid-July when warm weather may lead caribou to aggregate in large groups of hundreds or thousands in response to biting flies. These groups can be photographed from small fixed-wing aircraft or helicopters and the caribou counted on the photos (Valkenburg *et al.* 1985; Patterson *et al.* 2004; Nagy and Johnson 2006; Alaska Fish and Game 2011). Groups of caribou without radio-collars are also photographed and counted. This survey includes male and female caribou in the herd that are at least 1 year old. In some surveys it is possible to count calves of the year (V. Brodeur, 2016, Government of Québec, personal communication). In the NT, the experience has been that some calves of the year are not always visible in tightly bunched groups of caribou, thus only ≥1-year-old caribou are counted (e.g., Nagy and Johnson 2006).

The post-calving survey depends on having adequate numbers of radio-collared caribou to find the groups (Valkenburg *et al.* 1985; Rivest *et al.* 1998; Rettie 2008), particularly because movement rates in July can be high due to biting flies and caribou may use large ranges during this season. The survey area is essentially defined by flying to the radio-collared caribou, with additional groups of caribou (without radio-collars) generally found incidentally near groups with radio-collars or en route flying to radio-collared caribou. Post-calving surveys appear capable of enumerating nearly the entire herd under the right field conditions with herd-wide aggregation and with adequate radio-collar numbers (e.g., post-calving surveys of the Western Arctic Herd in Alaska with 90-100 radio-collars; Alaska Fish and Game 2011; Harper 2013).

Post-calving surveys, like calving photo-surveys, have their limitations. Caribou may not aggregate tightly if the July weather has cool, wet or windy conditions when biting flies are less active. If the caribou are well dispersed, photography is not feasible and the survey fails. Post-calving surveys were attempted for the Porcupine herd annually from 2004 to 2010 and failed due to weather and insufficient caribou aggregation (Porcupine Caribou Management Board, www.taiga.net/pcmb/population.html). A further limitation of this survey is that estimation of caribou groups missed during the survey is difficult. If there are many small groups of caribou during post-calving (e.g., BE herd in 2000, Patterson *et al.* 2004), then a large number of radio-collars may be needed to find a high proportion of the groups (Rettie 2008). Under these conditions, there may also be multiple groups with no radio-collars, which may be less likely to be found than groups with radio-collars (Rivest *et al.* 1998).

Two methods have been used to estimate the proportion of the herd missed by the post-calving survey. One method has relied on the simple proportion of available radio-collared caribou in the herd found in photographed groups (e.g., Russell *et al.* 1996; Nagy and Johnson 2006). Some authors have suggested that only counts of groups with radio-collars should be used with the Lincoln-Petersen estimator (Russell *et al.* 1996, Patterson *et al.* 2004) whereas other studies have included caribou from groups without radio-collars (Nagy and Johnson 2006). In the current paper, we have included the groups without radio-collars in the Lincoln-Petersen calculations. The Lincoln-Petersen mark-recapture estimator was questioned by Rivest *et al.* (1998), as both population estimates and variance estimates are likely to be negatively biased. Rivest *et al.* (1998) proposed an alternate way of estimating missed caribou groups and an alternate way of estimating population size and variance from post-calving surveys. These methods are statistically more complex but have been increasingly adopted in Alaska (Harper 2013) and Québec (V. Brodeur, 2016, Government of Québec, personal communication), where the Rivest methods were developed.

After an attempted post-calving survey of the Bluenose-East (BE) herd in July 2009 failed due to poor weather and insufficient aggregation in portions of the herd, both calving and post-calving surveys of this herd were planned for 2010. Declines had been documented in this herd and neighbouring herds between 2000 and 2006 (Adamczewski *et al.* 2009). Attempting both surveys increased the likelihood of securing an up-to-date population estimate, and allowed for a side-by-side comparison of the 2 survey methods.

In the past, calving ground surveys were used for the Bluenose herd in the 1980s (e.g., 1983, Latour *et al.* 1986), followed by post-calving surveys for this herd in 1986, 198and 1992 (e.g., McLean and Russell 1992). Satellite radio-collaring studies initiated in the late 1990s then showed that the Bluenose herd was composed of 3 herds with individual calving grounds, one of them being the BE herd, and the other 2, the Bluenose-West and Cape Bathurst herds (Nagy *et al.* 2005). Dedicated post-calving surveys for the BE herd began in 2000 (Patterson *et al.* 2004).

A modified June calving photo-survey and a post-calving survey were carried out in 1993 on the George River herd in Québec/Labrador (Couturier *et al.* 1996) and produced similar population estimates. Our objectives in this paper are to compare results of the 2 BE 2010 surveys, to assess their strengths and limitations, and to assess their suitability for management. An earlier version of these results was documented in a government report (Adamczewski *et al.* 2014). In this paper we consider all ≥1-year-old caribou in June or July to be adults; however we note that our re-examination of the extrapolation calculations of Heard (1985) and Heard and Williams (1990) indicates that those calculations omit the yearlings and these estimates are effectively for ≥2-year-old caribou. We used both the earlier (A) and the more recent (B) extrapolation calculations for the BE June 2010 survey data.

Management context of calving and post-calving surveys in the NT

Although this paper is primarily focused on caribou survey methods, we provide some context on the management significance of the population estimates these surveys generate. Migratory barren-ground caribou herds have long been known to vary widely in abundance over time scales of decades (Zalatan *et al.* 2006; Bergerud *et al.* 2008; Beaulieu 2012) and have been of enormous significance to Aboriginal cultures in the Canadian north for thousands of years (Gordon 2008; Beaulieu 2012). Management plans for herds like the BE recognize these long-term fluctuations and tie management strategies for harvest, predators and land use to herd size, trend and other indicators. A plan called "Taking Care of Caribou" finalized in 2014 (ACCWM 2014) includes the BE herd and defines 4 colour phases for this herd as red (low herd size, ≤20,000), green (high herd size, ≥60,000), yellow (intermediate herd size, 20,000–60,000, and increasing) and orange (intermediate herd size, 20,000-60,000, and declining).

After the 2010 BE surveys described here, further calving photo surveys in 2013 and 2015 documented a rapid decline (Boulanger *et al.* 2014, 2016) with the extrapolated estimate of ≥2-year-old caribou in 2015 at 38,592 ± 4,733 (95% CI) and a near 50% loss of breeding females in just 2 years (Boulanger *et al.* 2016). These results, in combination with other indicators and Aboriginal Traditional Knowledge, have resulted in the herd being designated as in the orange declining phase, and led to a series of formal hearings in the NT and NU on management actions in 2016 for this herd, including severe reductions in harvest (e.g., WRRB 2016). Although many sources of knowledge are considered in management, the herd's size and trend, as defined by photo surveys every 2-3 years, are key sources of information.

Because of the importance of population estimates for barren-ground caribou management, the GNWT has since 2006 monitored 5 neighbouring herds (including the BE) every 3 years via photographic surveys to ensure that size and trend are adequately known. An assessment of preferable frequency of population surveys focused on trend and ability to detect change either by sequential *t*-tests or regression analysis, with an average Coefficient of Variation (CV) on breeding female estimates of 15%, and suggested that surveys every 3 years were appropriate for herds at low numbers (Boulanger 2011). Heard and Williams (1990) carried out an equivalent assessment and reached similar conclusions. Considerable effort has gone into increasing the precision of NT post-calving surveys through increased numbers of caribou radio-collars (e.g., Nagy and Johnson 2006; Rettie 2008) and optimal allocation of survey efforts has been used to increase precision of calving photo survey methods (e.g., Boulanger *et al.* 2014, 2016). The comparison described here for the BE herd was carried out to assess the comparability of the 2 survey methods with respect to estimates of adult caribou and adequacy of precision, using as a benchmark a CV of 20% or less (Pollock *et al.* 1990). True herd size in 2010 was not known and thus the accuracy of both surveys cannot be assessed directly. However, similar herd estimates from 2 very different survey methods in which a high proportion of the counted caribou is from high-resolution photos should provide some assurance that the methods are basically sound and can be used for management as described in the ACCWM (2014) plan for this herd.

MATERIAL AND METHODS

Calving photo-survey in June 2010

June reconnaissance survey and radio-collars

The study area was defined based on previous surveys of this herd's calving ground, local knowledge, and locations of 43 radio-collared cows and 4 radio-collared bulls in June 2010 (Figure 1). All radio-collars had either satellite (Argos)

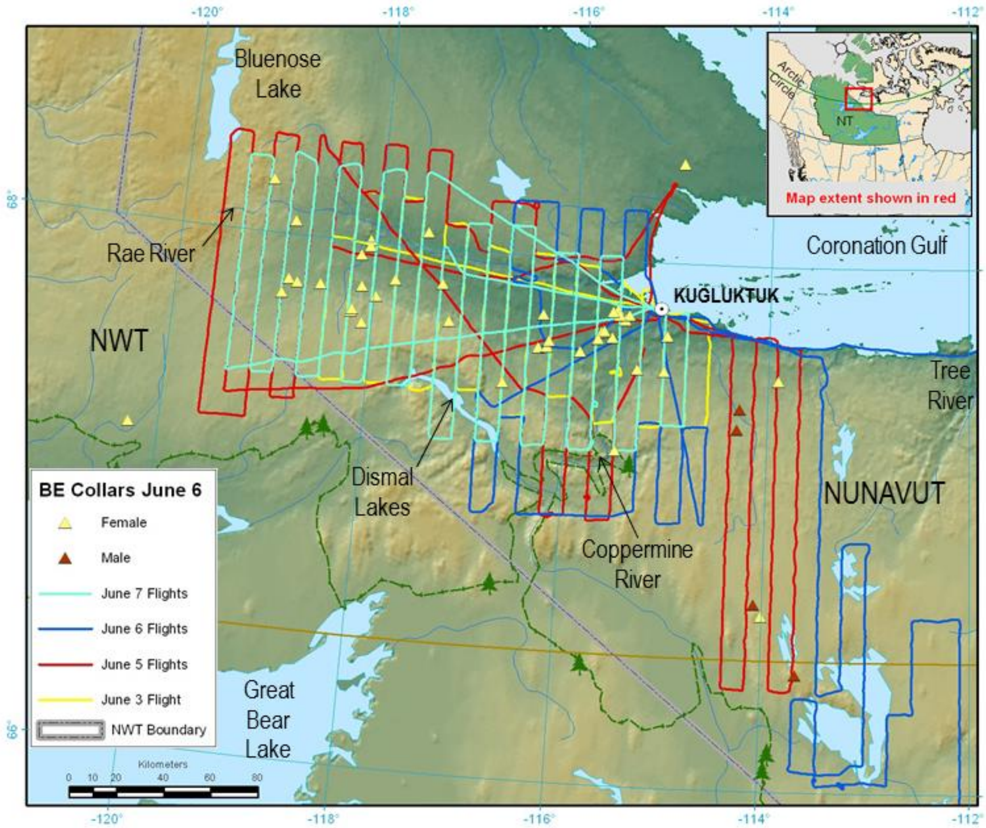

Figure 1. Reconnaissance flying over the Bluenose-East herd's calving ground and nearby areas at 10-km intervals on June 3, 5, 6, and 7, 2010. Radio-collar locations from 43 cows (yellow triangles) and 4 bulls (red triangles) for June 6 were also used to define the survey area.

transmitters and VHF (Very High Frequency) transmitters or GPS (Global Positioning System) satellite and VHF transmitters, with the satellite or GPS radio-collars programmed to provide at least 1 daily location at this time of year. Radio-collars were a number of models from Telonics, Inc. (Mesa, Arizona). These sources showed that the main cow-calf concentrations were consistently found in the Rae and Richardson valleys west of Kugluktuk, bounded in the west by Bluenose Lake (Figure 1).

Reconnaissance flying by 2 Cessna Caravan fixed-wing aircraft based in Kugluktuk was carried out on June 3, 5, 6, and 7 over the calving ground and nearby areas of the BE herd. The purpose of the initial flying was to map higher and lower densities of caribou, and to assess whether these areas had mostly breeding cows or non-breeding cows, yearlings and bulls. Flight lines were spaced at 10-km intervals in a north-south direction; survey elevation averaged 120 m above ground, and survey speeds averaged 150-160 km/hour, providing ground coverage of approximately 8%. Two observers and a recorder on each side of the aircraft recorded approximate abundance of caribou seen within a 400-m strip on either side of the plane. The presence of cows with calves, hard-antlered cows, bulls, yearlings, and non-breeding cows was recorded. Precise classification from fixed-wing aircraft was not practical, hence was estimated separately from a composition count later in the survey.

Observations from the reconnaissance flights were mapped in 10-km segments as densities of adult caribou: more than $10/km^2$ was high; 1.0-$9.9/km^2$ was medium; and 0.1-$0.9/km^2$ was low. In some segments no caribou were seen. Composition of caribou in 10-km segments was mapped using the following classes:

(1) *Cows with calves* — if at least 1 newborn calf was seen or if hard-antlered cows were seen. Hard-antlered cows were considered breeding cows that had either calved recently or were about to calve, and had not yet dropped their antlers;

(2) *Non-antlered cows* — if antlerless cows were seen, but no calves or hard-antlered cows;

(3) *Non-breeding caribou* — if cows without hard antlers and yearlings were seen; non-breeding cows may have small new antlers in velvet in June;
(4) *Bulls* — if bulls were seen;
(5) *Mixed non-breeders* — if non-breeding cows, yearlings and bulls were seen.
In the periphery of the study area, few caribou were seen and composition was sometimes recorded as unknown.

In addition to the 47 (43 cows and 4 bulls) known BE radio-collared caribou during the June and July 2010 surveys, within the range of the BE herd, 1 radio-collared cow from the Bathurst herd (eastern neighbour of the BE herd) died in mid-June 2010 north of the main BE calving area. Two radio-collared caribou from the Bluenose-West herd (western neighbour of the BE herd) were within the summer range of the BE herd in 2010. One of these was briefly east of Bluenose Lake in June and early July and then returned to spend the rest of the summer well west of Bluenose Lake in Bluenose-West summer range. A second radio-collared cow that calved on the Bluenose-West calving ground in 2009 was within the BE summer range in June and July 2010, and in June 2011. Low rates of exchange of radio-collared cows between neighbouring herds in NT/NU and elsewhere have been known for many years (Adamczewski *et al.* 2009; Boulanger *et al.* 2011; Davison *et al.* 2014). These 3 radio-collared caribou were considered as falling within this normal low rate of exchange and were not considered further in estimating population size.

The reconnaissance flights in early June 2010 confirmed previous information about the distribution of cows, calves and bulls in this herd , as we found very few cows with young calves or hard-antlered cows east of the Coppermine River. Bulls, yearlings and non-breeding cows were observed consistently in this area. A few lines were flown further east to ensure spatial separation from Bathurst caribou.

June 2010 survey strata, photos, and strip transect counts

Reconnaissance flying was used to define 6 survey strata including 1 high-density stratum (Figure 2) and 1 medium-density stratum with mostly cow-calf caribou, 2 visual low-density strata with mostly cow-calf caribou (north and northwest), and 2 strata flown visually with low-medium densities and mostly bulls, yearlings and non-breeding cows (east and south). The south stratum was extended south by 10 km further than the initial reconnaissance flight lines due to the densities of caribou seen at the southern ends of the lines during the reconnaissance flights.

An optimal-allocation algorithm was used to determine the number of transect lines and coverage for each of the 6 strata, depending on stratum size and densities of caribou seen during the reconnaissance flights. Following recommendations by Gunn *et al.* (2005), a minimum of 10 transect lines were used for each stratum to reduce variance. Consistent with previous surveys of this type, the high and medium strata were re-flown on June 8 and 9 with a Commander aircraft (Geographic Air Survey Ltd., Edmonton) at an elevation of approximately 610 m taking continuous photo-transects to provide ground coverage of 31.3% and 16.8% in the high and medium strata (Figure 2). A total of 7,000 photos were taken. These 2 strata are referred to as photo strata in the remainder of the paper, and the other 4 strata are referred to as visual strata.

The other 4 strata were re-flown on June 8 and 9 with strip-transect methods with ground coverage varying from 14.2% to 28.2%. Survey lines were flown at an elevation of 120 m and an average survey speed of 150 km/hour, with 2 observers and a recorder on each side of the aircraft. Wing struts were marked to define a strip of 400 m on the ground at 120 m above ground on either side of the aircraft, using methods originally described by Norton-Griffiths (1978), and followed by previous calving photo-surveys (e.g., Gunn *et al.* 2005; Nishi *et al.* 2007).

Caribou at least 1 year old were counted on the aerial photos by an experienced consultant (P. Roy) who had counted caribou on this type of aerial photo for several previous calving photo-surveys of the Bathurst herd (Gunn *et al.* 2005; Nishi *et al.* 2007) and the Qamanirjuaq herd (Campbell *et al.* 2010). The caribou counted on photos could not be classified as cows, yearlings or bulls, only as ≥1-year-old caribou. Newborn calves were not counted as they could not always be seen if hidden by larger caribou or if bedded. In this paper, we use the term “adult” caribou for any ≥1-year-old caribou in June or July. In the 4 visual strata, adult caribou seen by any of the 4 observers were recorded.

June 2010 composition survey

A composition survey was carried out June 8-12 to sample multiple caribou groups in each of the survey strata (Figure 3). The classification was carried out primarily from the ground with a telescope and tripod to minimize disturbance to caribou, with a helicopter used to fly from 1 group of caribou to the next. Caribou were classified as described by Gunn *et al.* (2005) and Nishi *et al.* (2007) as newborn calves, cows, yearlings, and bulls. Cows were further classified into the following categories: (1) antlered cows with a distended udder; (2) antlerless cows with a distended udder; (3) antlered cows without a distended udder; and (4) antlerless cows without a distended udder. The first 2 categories of cows corresponded to breeding cows based on the distended udder, and the third, to breeding cows that likely had lost their calves. The fourth category consisted of non-breeding females characterized by the absence of a distended udder

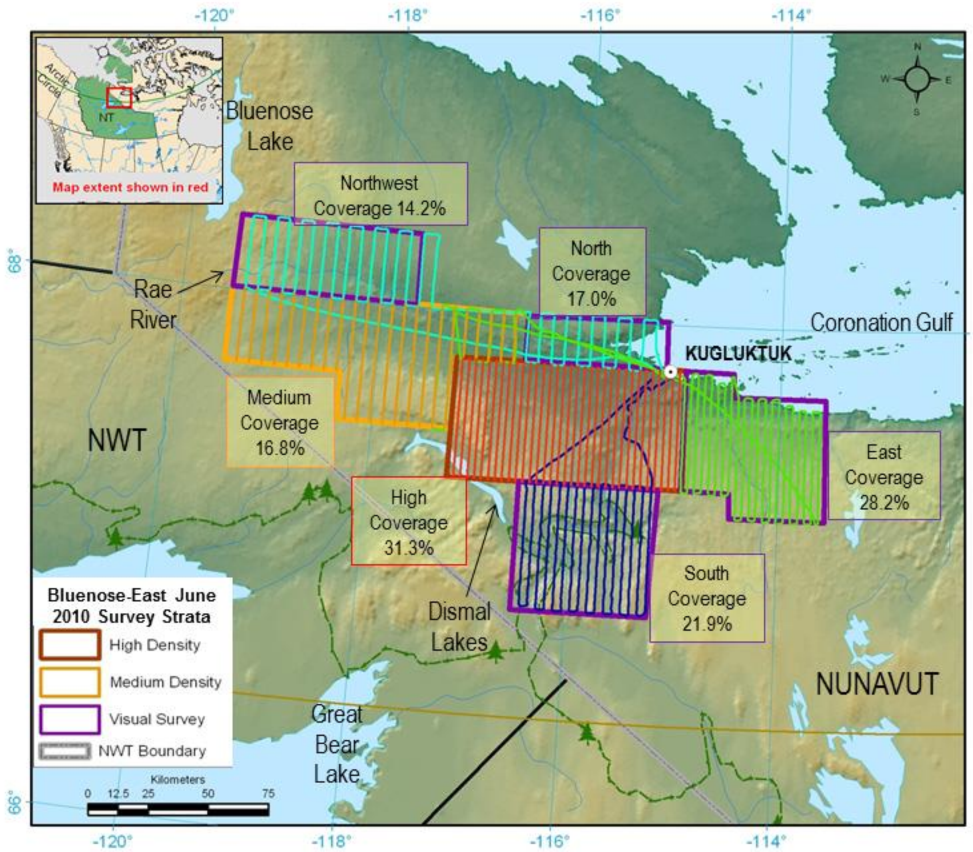

Figure 2. Survey strata, flight lines and coverage for the Bluenose-East June 2010 calving photo-survey. The high-density and medium-density strata were flown with the Commander photo-plane and the 4 strata outlined in purple were re-flown visually, with the area coverage as shown for each stratum.

and usually by the presence of new dark antler growth. Yearlings were distinguished based on their relatively small body size and short heads. Bulls were identified based on their reproductive organs, size and relatively large antlers in velvet.

Fall 2009 composition survey

To extrapolate from the estimated number of breeding females on the calving grounds to overall herd size, an estimate of herd sex ratio has been used from the fall rut in late October, as it is the one time of year when all sex and age classes are mixed (Heard 1985; Gunn *et al.* 2005; Nishi *et al.* 2007). A composition survey was carried out on October 19 and 20, 2009 on the BE range. The survey area was defined primarily by the locations of 31 radio-collared BE caribou. In addition, a fixed-wing reconnaissance survey was flown on October 16, 2009 to verify that substantial densities of caribou were associated with the concentrations of radio-collared caribou. Caribou were classified from the front seat of a helicopter as bulls, cows, and calves of the year. A total of 4,531 caribou in 79 groups were classified.

Post-calving photo-survey in July 2010

Field methods and photo counts

Reconnaissance flights over the BE summer range were carried out June 29 to July 4, to gain an overall sense of caribou distribution and composition of caribou groups (cows with calves, non-breeding cows, bulls and yearlings; Figure 4). The survey area was defined based on past July surveys of this herd and based on the locations of 47 radio-radio-collared caribou at the beginning of July. One survey crew was in a Helio-Courier equipped with Telonics RA-2AK dual antennae and an ATS receiver (Advanced Telemetry Systems Inc.) and the other survey crew was in a Cessna 185 equipped with Telonics RA-2AK dual antennae and a Telonics TR-5 Scanning-Receiver (Telonics, Inc.), with all flights based in Kugluktuk, Nunavut. After the initial reconnaissance flights, the 2 aircraft were used to check daily on radio-collared caribou and caribou associated with them, except during poor weather. Locations of all radio-collared caribou were received from a satellite link daily in the mornings and used to plan the day's flying. Exact locations of radio-collared caribou were found by homing in on their VHF signals.

Overall, caribou groups made up mostly of cows with young calves were found west of Kugluktuk in the Rae and Richardson valleys and these areas had the largest abundance of caribou. Mostly cow-calf groups were also found in lower densities north to the mainland coast (Figure 4). Bulls, yearlings, and non-breeding cows were primarily east of the Coppermine River and south-southeast of Kugluktuk, with a substantial area separating these groups from the cow-calf groups.

When caribou were seen to be forming groups of hundreds or thousands suitable for photography, every effort was made to account for all radio-collared caribou and caribou associated with them in the area, independently of group size. Caribou groups found without radio-collars were also photographed, and GPS locations of all groups were recorded. Multiple passes of either single photos of entire groups or multiple series of overlapping photos to cover larger aggregations were taken. Survey elevation was adjusted as needed. Photos were taken by 24 megapixel Nikon D3X cameras set for maximum resolution, through an open window of the Cessna 185 or through a "shooting window" on the left side of the Helio-Courier. VHF signals from the 47 radio-collars were monitored on all flights and the presence of individual radio-collared caribou was double-checked to properly identify them in the photographed groups.

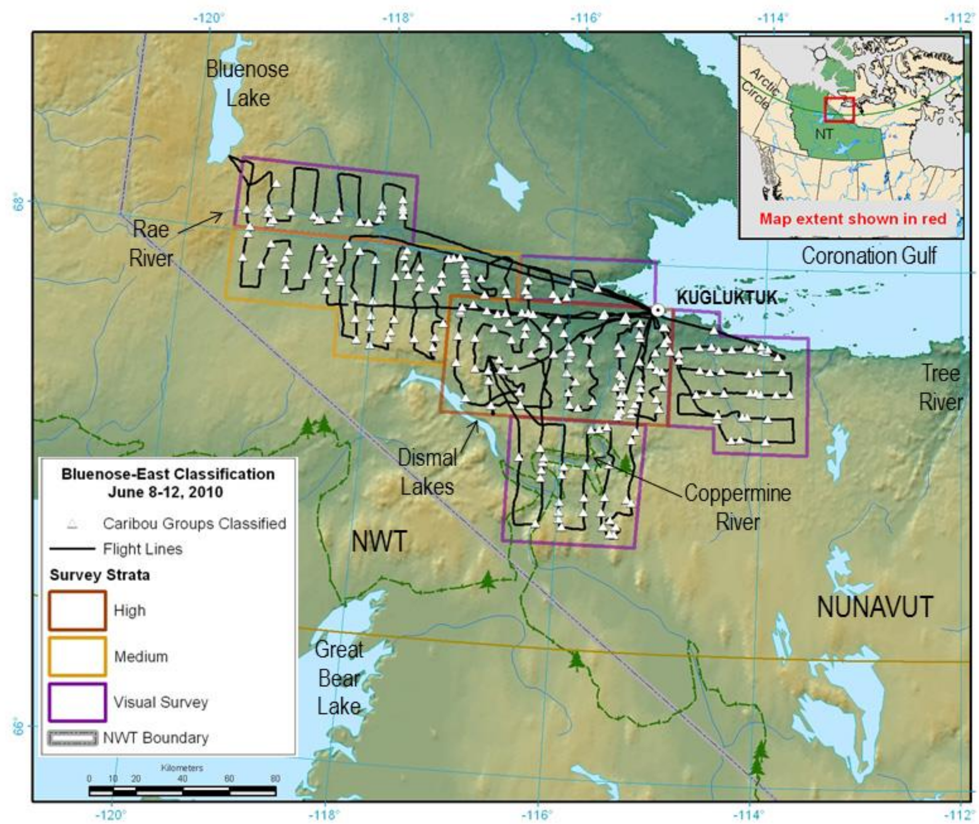

Figure 3: Locations (white triangles) and helicopter flight path (black lines) of caribou groups classified June 8 - 12, 2010 on or near the calving grounds of the Bluenose-East caribou herd.

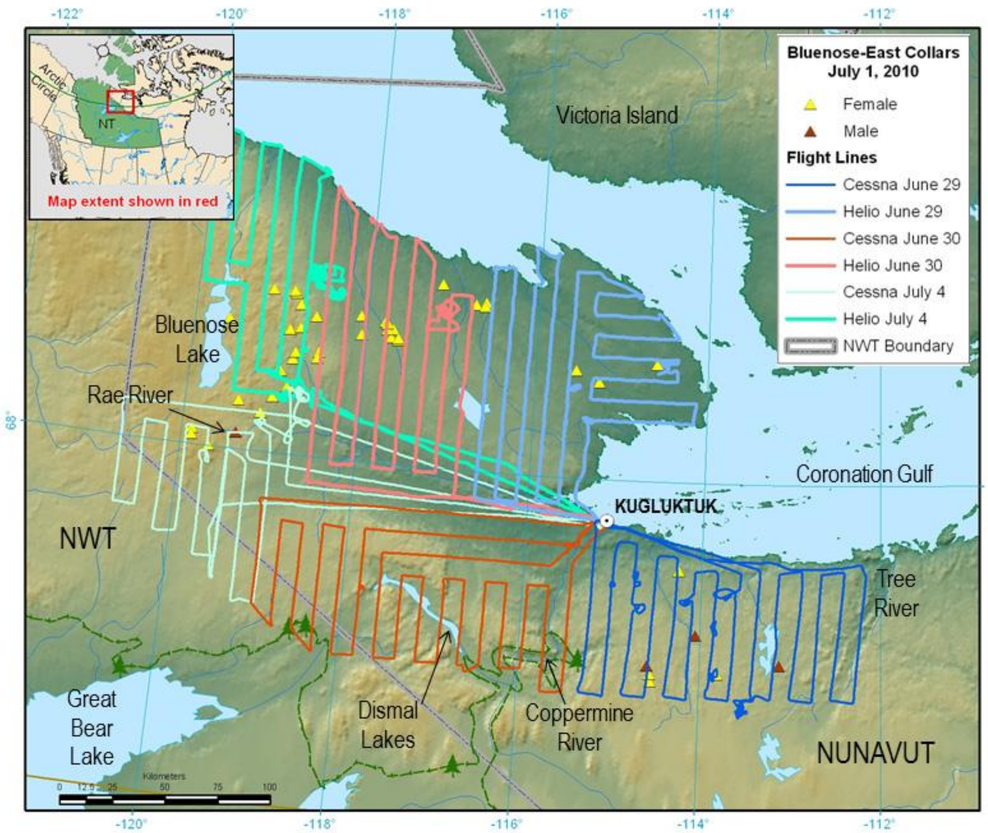

Figure 4: Initial reconnaissance flights at 10-km intervals at start of July 2010 Bluenose-East caribou post-calving survey June 29 – July 4, 2010. Radio-collar locations are from 43 cows and 4 bulls on July 1.

At the end of each day when photos were taken, the photos were downloaded and reviewed on laptop computers, and the best images were chosen for each group of caribou. Digital images were imported into the desktop mapping program Ozi Explorer (© D & L Software Ltd.) and converted to map files. Caribou on these images were then marked one after the other by placing a waypoint for each adult caribou. This method was developed by biologist J. Nagy and described in his survey reports (e.g., Nagy and Johnson 2006). All ≥1-year-old caribou were counted. Calves of the year were not counted as they could not be reliably identified under or behind larger caribou, particularly in more closely aggregated groups.

Caribou on each photo were counted at minimum by 2 of the authors independently (HS-C and JA). A third person independently counted a sub-set of the photos as a further check. On most photos, agreement among counters was close, with variation of totals well below 1 % (e.g., totals of 915 caribou vs. 918 caribou for a single photo). On a few photos of larger, tightly aggregated groups taken from higher elevations, the 2 authors who previously counted all the photos together counted the photos again to arrive at a final total.

Estimation of herd size and variance using Lincoln-Petersen estimator

White and Garrott (1990) augmented the Lincoln-Peterson Index to apply to radio-collared animals, a method that has been used in other post-calving surveys (Russell *et al.* 1996; Patterson *et al.* 2004; Nagy and Johnson 2006) to estimate population size. The formula is:

$$\mathbf{N = ((M+1)(C+1)/(R+1))-1}$$

Where:

N = estimate of population size during the census;

M = number of radio-collared caribou present in the herd (including all radio-collars known to be active during the survey);
C = number of caribou in all aggregations observed during the survey;
R = number of radio-collared caribou observed in these aggregations during the survey.
The 95% confidence interval for the estimate is calculated as:

$$\mathbf{N = 1.96\sqrt{(Var(N))}}$$

Where:
$$\mathbf{Var(N) = (M+1)(C+1)(M\text{-}R)(C\text{-}R)/((R+1)^2\,(R+2))}$$

These calculations were applied to the results of the July 2010 BE post-calving survey.

Estimation of herd size and variance using Rivest estimator

This section provides a basic summary of the Rivest approach; readers who want a more detailed statistical treatment are encouraged to read Rivest *et al.* (1998). All calculations were conducted using the R-package (R Development Core Team 2009) entitled "caribou" (Crépeau *et al.* 2012). The Rivest estimator considers the sampling of post-calving aggregations as a 2-phase sampling process. The first phase involves the initial radio-collaring of caribou and how the radio-collared caribou are distributed within the herd during the post-calving period. For this estimator, it is assumed that *n* radio-collared caribou are randomly distributed into *m* groups during the post-calving period. Given that radio-collared caribou are used to estimate detectability of groups, the Rivest estimator does not use data for groups of caribou that do not contain radio-collared caribou.

The second phase of sampling involves the actual aerial search for groups. For this phase, various models are proposed as to how the radio-collared caribou represent the groups, and how the radio-collared caribou and associated groups are detected. Each model is summarized below.

(1) *The homogeneity model* — this model assumes that caribou groups (with radio-collared caribou in the groups) are missed as a completely random event that is independent of the number of radio-collared caribou in the group or other factors. Each group will have the same probability of being detected by the aerial survey.

(2) *The independence model* — this model assumes that each radio-collared caribou in the group has the same independent probability of being detected and thus the overall probability of detecting a group increases as a function of the number of radio-collared caribou in the group. The assumption here is that the radio-collared caribou are independent so that a simple probability model can be applied to detection of the group.

(3) *The threshold model* — this model assumes that all groups with more than a threshold level of radio-collared caribou (symbolized by B) have a detection probability of 1. For example, it might be that, once more than 3 radio-collared caribou occur in a group, the group will always be detected whereas groups with 1 or 2 radio-collars are not always detected. For this model, all groups with 3 or more radio-collared caribou are assigned a detection probability of 1, and detection probability is estimated for groups with 1 or 2 radio-collars.

Each of these models can potentially describe detection probability variation in the data set. As part of the estimation procedure, a log-likelihood score is produced and the model with the highest log-likelihood is considered to best fit the data.

The estimate of herd size is then basically the summation of each group size divided by the probability of the observed group having at least 1 radio-collared animal included in it, and divided by the probability of the group being detected. The probability of having at least 1 radio-collared caribou is a function of the group size detection probabilities (which is associated with the underlying detection model described previously), the total group size of caribou counted relative to total herd size, and the overall number of radio-collars employed in sampling. It is through an iterative likelihood-based optimization procedure that each of these parameters is estimated to produce estimates of herd size.

An assumption of this method is that the radio-collared caribou are randomly distributed among the separate caribou groups that are photographed. This assumption can be tested by assessing the number of radio-collared caribou relative to group sizes that are counted. It is possible to test this assumption using a test for over-dispersion of the Poisson probability distribution. Over-dispersion applies to a case when non-independence of radio-collared caribou produces a distribution of radio-collared caribou relative to group sizes that is different from that if the caribou were randomly distributed. If over-dispersion occurs then both estimates of population size and variance from the Rivest estimator will be negatively biased (Rivest *et al.* 1998).

RESULTS

Calving photo-survey in June 2010

Reconnaissance survey June 3-7

Caribou observations recorded during the reconnaissance flights of June 3, 5, 6 and 7, 2010 were mapped as squares along the flight lines, with each square representing a 10-km segment, and darker red squares representing higher densities (Figure 5a). High (>10/km^2) and medium (1.0 - 9.9/km^2) adult caribou densities were generally west, southwest, south, and southeast of Kugluktuk, with lower densities in more peripheral areas. One high-density stratum, 1 medium-density stratum, and 4 low-density strata were defined based on the reconnaissance flights (Table 1).

The composition of caribou groups seen in 10-km segments was similarly mapped (Figure 5b). Cows with calves and hard-antlered cows were largely clustered in an elongated area in the Rae and Richardson valleys west of Kugluktuk. Further south and east in the survey area, non-breeding caribou predominated, with non-breeding cows and yearlings closer to the main cow-calf distribution and bulls in more peripheral areas south and southeast of Kugluktuk.

Caribou counted on photos and in visual strata

Overall, the high and medium density strata were photographed and contained 77.3% of the 28,478 adult caribou counted in the 6 survey strata, and a similar 76.1% of the adult caribou estimated for the entire survey area (Table 2). These 2 photographed strata also had the highest densities of adult caribou (10.5 and 8.2/km^2). The east and south visual strata had somewhat lower densities (3.7 and 3.9/km^2) and added proportionately to the overall total of caribou. The north and northwest visual strata had relatively low caribou densities (0.9 and 1.5/km^2).

Observations during the initial reconnaissance flights, along with composition recorded during June 8-12 indicated that the peak of calving likely occurred during June 6-9 with more than 50% of breeding cows observed after these dates having a calf at heel.

Caribou composition in June 2010 survey strata

The proportion of breeding females among adult caribou was below 50% in the high stratum, indicating a high number of non-breeding cows and yearlings (Table 3). The medium stratum, by contrast, had a much higher proportion of breeding females (77.0%) and relatively few yearlings. The calf:cow ratios for breeding females were high in the high and medium strata (86.0 and 81.2 calves:100 cows), but because of the large densities of non-breeding cows in the high stratum, the calf:cow ratio was much lower (49.6 calves:100 cows) when all cows were included, and somewhat lower (66.2:100) in the medium stratum. The proportions of breeding cows and estimates of adult caribou in each stratum were used to derive an estimate of 51,757 (± 11,092) breeding cows for the survey area.

Fall 2009 Bluenose-East composition survey and sex ratio

A total of 79 caribou groups and 4,531 caribou, including calves of the year, were classified in October 19 - 20, 2009 (Fig. 6, Table 4). This resulted in estimates of 46 calves:100 cows (± 3.5) and 42.9 bulls:100 cows (± 3.4). At the time of the survey, there were 31 active radio-collars in the BE herd, of which 30 were within or near the survey area. There were also 4 radio-collars from the neighbouring Bathurst herd to the north (Figure 6) but no caribou groups were classified among these radio-collared caribou.

Table 1. Transect sampling and size of strata for Bluenose-East June 2010 calving photo-survey.

	Stratum						
Variable	High	Medium	East	North	North west	South	Totals
Count method	Photo	Photo	Visual	Visual	Visual	Visual	n/a
Area of stratum (km^2)	4,840.0	4,453.9	2,996.4	1,118.3	2,259.6	3,006.9	18,675.1
Lines flown	33	23	21	10	16	16	n/a
Area sampled (km^2)	1,517.2	749.9	844.6	158.5	383.5	658.7	4,312.4
Coverage (%)	31.3	16.8	28.2	14.2	17.0	21.9	23.1

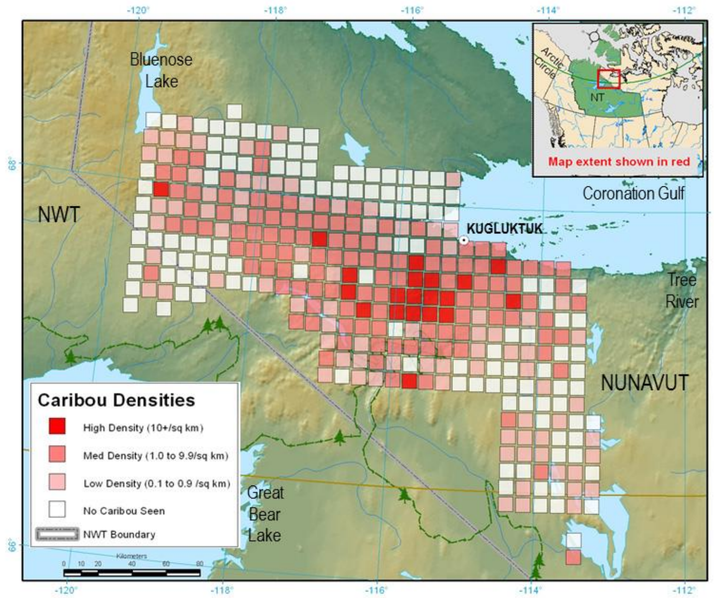

Figure 5a. Densities of adult caribou observed during June 2010 Bluenose-East caribou survey during reconnaissance flights, June 3, 5, 6 and 7. No caribou were seen in white squares and increasing densities are shown as lighter or darker pink squares, with the highest densities of >10 caribou /km^2 in red. Squares represent 10-km segments along flight lines.

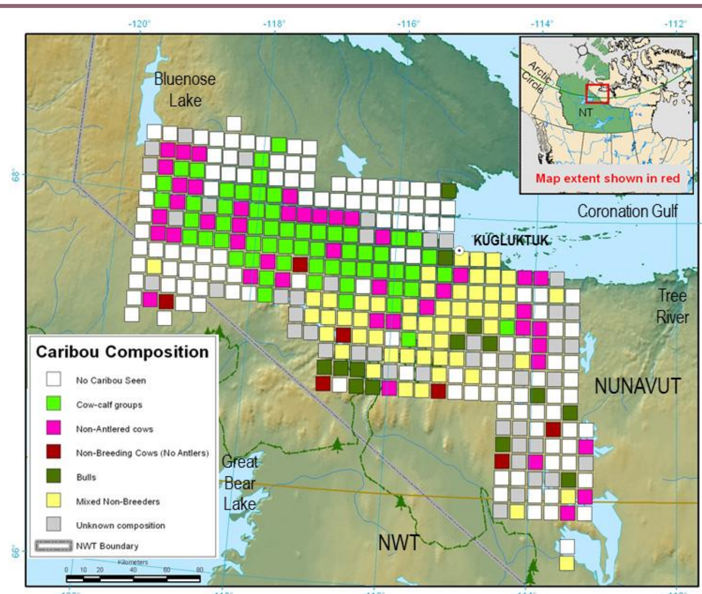

Figure 5b. Composition of Bluenose-East caribou groups during reconnaissance flights, June 3, 5, 6 and 7, 2010. The main cow-calf concentrations were light green squares, bull only areas were dark green and other types of caribou are as shown in the legend. Squares represent 10-km segments along flight lines.

Table 2. Adult caribou estimates by stratum from Bluenose-East June 2010 calving photo-survey. SE = Standard Error; CV = Coefficient of Variation.

	Stratum						
Variable	**High**	**Medium**	**East**	**North**	**North west**	**South**	**Totals**
Count method	Photo	Photo	Visual	Visual	Visual	Visual	n/a
Caribou counted	15,881	6,142	3,167	135	566	2,587	28,478
Density (caribou/km^2)	10.5	8.2	3.7	0.9	1.5	3.9	n/a
Estimated No. caribou 1+ year old in stratum	50,661.2	36,477.4	11,236.3	952.6	3,335.0	11,809.6	114,472
SE (N)	4,768.0	4,442.4	1,468.9	256.7	1,005.2	1,421.5	6,908.2
CV (N) as %	9.4	12.2	13.1	26.9	30.1	12.0	6.0

Table 3. June composition survey results and calculated stratum totals, ratios and variance from Bluenose-East June 2010 calving photo-survey. SE = Standard Error; CV = Coefficient of Variation.

	Stratum						
Variable	**High**	**Medium**	**East**	**North**	**North west**	**South**	**Totals**
Numbers classified							
No. groups classified	72	59	23	8	20	23	205
No. caribou classified	3,866	5,263	564	189	1,033	710	11,625
No. newborn calves	1,041	2,025	5	6	444	0	3,521
No. yearlings	497	157	99	40	12	132	937
No. bulls	230	23	219	10	3	353	838
No. cows	2,098	3,058	241	133	574	225	6,329
Calculated totals, ratios and variance							
No. caribou 1+ years old	2,825	3,238	559	183	589	710	8,104
No. breeding females	1,211	2,493	4	7	506	0	4,221
Proportion breeding females (%)	42.9	77.0	0.7	4.2	85.9	0	n/a
SE (% breeding females)	5.0	3.0	0.6	2.4	3.7	0	n/a
CV (% breeding females)	11.6	4.1	78.4	57.9	4.3	0	n/a
Estimated No. breeding females in stratum	21,784.3	26,993.3	80.4	39.5	2,859.7	0	51,757
SE (breeding females)	3,258.8	3,464.7	63.9	25.3	870.7	n/a	4,836
CV (% breeding females)	15.0	12.8	79.5	63.9	30.4	n/a	9.3
Calves: 100 cows, breeding cows	86.0	81.2	125	85.7	85.9	n/a	n/a
Calves: 100 cows, all cows	49.6	66.2	2.1	4.5	77.4	n/a	n/a

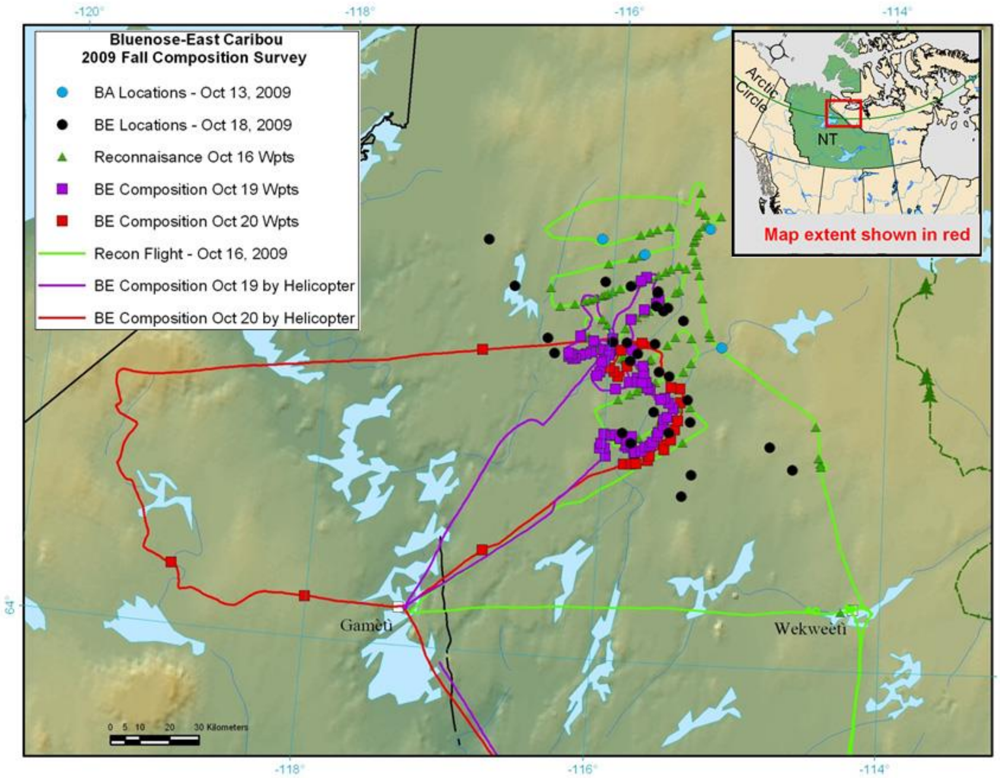

Figure 6. Composition survey flown October 19 and 20, 2009 in the range of the Bluenose-East caribou herd. Bluenose-East radio-collar locations are black dots and Bathurst radio-collar locations are blue dots. Composition of caribou groups near Bathurst radio-collars was not used for this survey.

Table 4. Composition survey results from October 19 and 20, 2009 for the Bluenose-East caribou herd. Ratios are shown ± 95% Confidence Interval.

No. groups classified	No. cows	No. calves	No. bulls	Total	Calves: 100 Cows	Bulls: 100 Cows
79	2,399	1,104	1,028	4,531	46.0 ± 3.5	42.9 ± 3.4

Estimated population size and proportions of cows, bulls and yearlings from June survey

The direct estimate of adult caribou from the June 2010 BE calving photo-survey included the total estimated number of ≥1-year-old caribou from the survey area of 114,472 ± 15,845 (95% Confidence Interval). The estimated number of breeding females, 51,757 ± 11,092, was divided by the proportion of cows in the herd (0.70, from bull:cow ratio of 42.9:100) from the fall 2009 composition survey and by 0.702 as the pregnancy rate for ≥1-year-old cows in the breeding season, resulting in an extrapolated estimate of 105,326 ± 40,984 ≥2-year-old caribou (Table 5, extrapolation A). The 0.702 pregnancy rate is based on an overall pregnancy rate of 285/406 from Dauphiné (1976, Table 14) for Qamanirjuaq ≥1-year-old cows in the breeding season in the 1960s. We note that Heard (1985) used a pregnancy rate of 0.72 based on the same source, which may have been a rounding error. We also used the more recent extrapolation method from Campbell *et al.* (2016), which included the estimated total of all ≥2-year-old cows in the survey area, divided by the same proportion of cows in the herd of 0.70 from the fall 2009 composition survey. This resulted in a second extrapolated estimate of 120,880 ± 13,398 ≥2-year-old caribou (Table 5, extrapolation B).

We used the totals of adult caribou from Table 2 for each stratum multiplied by the proportions of cows, bulls, and yearlings in Table 3 to estimate the total numbers of these 3 sex and age classes in the survey area in each stratum (Table 6). Cows made up 84,603 of the 114,472 adult caribou (73.9%) estimated for the survey area, and yearlings (13.2%) and bulls (12.9%) made up the remainder. If the yearlings are presumed to be divided equally among males and females (50:50 sex ratio), then the estimated totals overall of adult females and males were 92,174 (80.5%) and 22,298 (19.5%). This is equivalent to a ratio of 24.2 bulls:100 cows.

Post-calving survey in July 2010

Radio-collared caribou and photography of aggregated caribou

The movements of radio-collared caribou varied considerably in July. The main concentration of radio-collared cows in cow-calf groups was initially just east of Bluenose Lake (Figure 4) and later was concentrated further east and south (Figure 7). Caribou were concentrated in 3 sectors at the time photos were taken in July: bulls, yearlings and non-breeding cows were primarily in a southern sector east of the Coppermine River, most of the cow-calf groups and radio-collared cows were in a main sector west of Kugluktuk, and some smaller densities of cow-calf groups were in a northern sector. Aggregation of caribou suitable for photography generally did not last more than a day, and on some occasions changing weather meant that groups were tightly clustered for only a few hours. Caribou in the northern sector were the least likely to aggregate; caribou with and without radio-collars in this area tended to remain scattered except for the one day when photos were taken. Caribou in the southern sector were more likely to aggregate, which resulted in 2 separate sets of photos.

Caribou counted on photos from July survey

A total of 40 groups of caribou and 92,481 adult caribou were counted on photos from the July 2010 BE post-calving survey (Table 7). Two-thirds of these were in the main sector that had 30 radio-collars, with the remainder found about equally in the southern and northern sectors. The number of radio-collared caribou varied substantially among groups. There were 22 groups with radio-collars and 18 without radio-collars. Groups without radio-collared caribou were mainly between 1,000 and 2,000, with one group of 3,870 caribou. Groups with radio-collared caribou ranged from 1,000 to 11,652. Photos were taken on July 6, 9 and 12; over this time we monitored collared caribou locations daily and found no mixing between the main, northern and southern sectors.

In the northern sector, the largest group photographed had 3 radio-collars and 5,999 caribou, but there was also a group of nearly 3,870 with a single radio-collar. In the main sector, the larger groups generally had multiple radio-collars. In the southern sector on July 6, the largest group was 11,461 caribou with just 1 radio-collar, and another group of 4,080 also had only a single radio-collar. Figure 8 shows a small group of cows and calves from the July 2010 survey.

The 2 sets of photos of the southern sector resulted in 2 different counts. On July 6, 6 of 7 radio-collared caribou were found, 9 groups were photographed, and 16,917 adult caribou were counted on photos. On July 12, 7 of 7 radio-collared caribou were found, 4 groups were photographed, and 11,342 adult caribou were counted. We used the higher July 6 caribou count in the calculations of herd size. We assumed that the second set of photos was lower because the caribou had in the meantime formed different groups that resulted in a few thousand caribou without radio-collars that were not found on July 12.

Of the 47 radio-collared BE caribou in the survey area in July 2010, 44 were accounted for at the time of photos taken on July 6, 9 and 12. The other 3 were active GPS-satellite or satellite radio-collars. We assumed that these 3 radio-collared caribou and any caribou associated with them were in the survey area, given daily and changing GPS locations. However, although searched for when photos were taken in the area, they were not found at the time of taking photos due to erratic signals of VHF transmitters.

Table 5. Estimated number of breeding females and extrapolated population estimates (≥2-year-old caribou) for the Bluenose-East herd in June 2010. Extrapolation A used the estimate of breeding females divided by a sex ratio (42.9 bulls:100 cows, or proportion of females among adult population of 0.70) from an October 2009 Bluenose-East fall composition survey, and divided by 0.702 from an estimate of 70.2% pregnancy among ≥1-year-old cows in the breeding season in the herd (Dauphiné 1976). Extrapolation B used the total estimated number of cows on the June survey area divided by the proportion of females of 0.70. SE = Standard Error, CV = Coefficient of Variation, CI = 95% Confidence Interval.

Variable	Estimate	SE	CV as %	95% CI
No. breeding females	51,757	4,836	13.0	11,092
Proportion of females in entire herd	0.70	0.028	4.0	n/a
Proportion of females ≥ 2 year-old pregnant	0.702	0.072	10.0	n/a
Extrapolated estimate (A) of caribou at least 2-years-old	105,326	20,355	17.0	40,984
Extrapolated estimate (B) of caribou at least 2-years-old	120,880	5,841	4.8	13,398

Table 6. Estimated totals of cows, bulls and yearlings in each stratum, based on estimates of adult caribou in each stratum (from Table 2) and composition (from Table 3).

Variable	High	Medium	East	North	North west	South	Totals	% of Total
Estimated No. caribou 1+ year old in stratum	50,661.2	36,477.4	11,236.3	952.6	3,335.0	11,809.6	114,472	100
Estimated No. cows in stratum	37,623.7	34,449.6	4,844.3	692.3	3,250.1	3,742.5	84,603	73.9
Estimated No. yearlings in stratum	8,912.8	1,768.7	1,990.1	208.2	67.9	2,195.6	15,143	13.2
Estimated No. bulls in stratum	4,124.6	259.1	4402.1	52.1	17.0	5,871.5	14,726	12.9

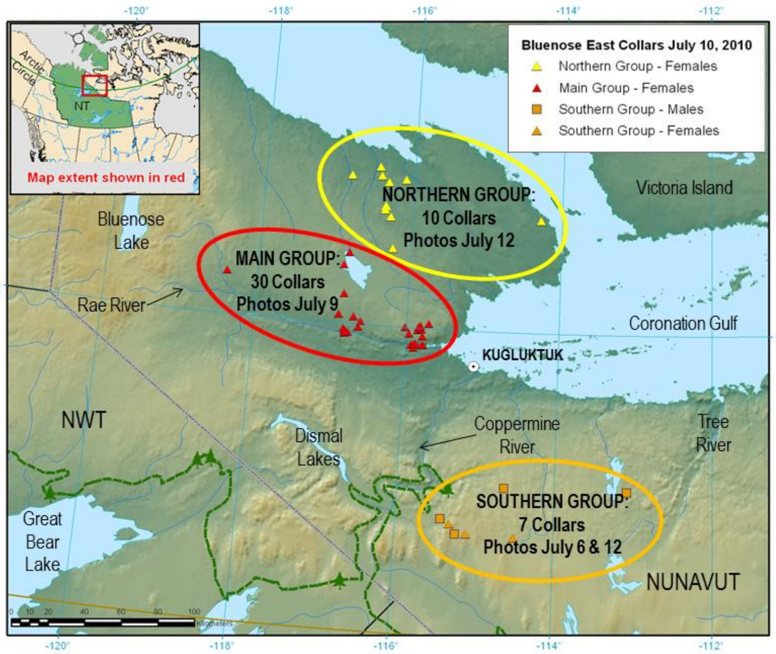

Figure 7. Locations of main, northern and southern sectors of caribou photographed during July 2010 post-calving survey of the Bluenose-East herd. Radio-collar locations are from July 10.

Figure 8. Small group of caribou cows and calves photographed during July 2010 post-calving survey of the Bluenose-East herd. Photo: B. Tracz, Environment and Natural Resources, Government of Northwest Territories.

Table 7. Groups of caribou, radio-collars, and caribou counted on photos from July 2010 Bluenose-East post-calving survey.

Southern Sector, photos July 6			**Main Sector, photos July 9**			**Northern Sector, photos July 12**		
Group No.	Radio-collars	Caribou	Group No.	Radio-collars	Caribou	Group No.	Radio-collars	Caribou
1	1	11,461	1	8	11,652	1	3	5,999
2	1	4,080	2	3	8,327	2	2	1,106
3	1	804	3	2	7,585	3	1	760
4	1	385	4	5	7,528	4	1	115
5	1	5	5	1	7,365	5	1	14
6	1	3	6	4	4,989	6	1	3
7	0	175	7	2	4,942	7	1	1
8	0	2	8	2	1,943	8	0	3,870
9	0	2	9	1	1,014	9	0	914
Totals	6 of 7	16,917	10	0	2,263	10	0	268
(used in estimate)			11	0	1,980	11	0	226
			12	0	1,523	12	0	175
Southern Sector, photos July 12			13	0	670	13	0	6
Group No.	Radio-collars	Caribou	14	0	242	14	0	2
1	2	5,711	15	0	79	Totals	10 of 10	13,459
2	2	4,629	16	0	2			
3	2	1,002	17	0	1			
4	1	1	Totals	28 of 30	62,105			
Totals	7 of 7	11,342						
(not used in estimate)								
			Overall Total	**44 of 47**	**92,481**			

Estimated herd size and variance with Lincoln-Petersen and Rivest estimators

An estimate of 98,646 ± 13,965 (95% CI) ≥1-year-old caribou in the BE herd in 2010 was derived using the Lincoln-Petersen estimator. For the Rivest estimator, only data for groups that had at least 1 radio-collared caribou were used. In general, numbers of radio-collared caribou increased with group size (Figure 9), although 3 groups greater than 4,000 had just one radio-collar.

A suite of detection models was applied to the post-calving data set. As an initial step, a test for randomness of the distribution of radio-collars in each caribou group was conducted using the independence, homogeneity, and threshold models (Table 8). In all cases, the null hypothesis of randomness was not rejected, suggesting that this assumption was reasonable for the BE 2010 data set.

The independence, homogeneity, and threshold models with thresholds of radio-collared caribou ranging from 2 to 5 were run and compared using log-likelihood scores. A threshold model that assumed that groups of caribou that had 5 or more radio-collars (B=5) had a detection probability of 1 had the highest likelihood score (2.415; Table 9). This model indicated that groups with a radio-collar sample size of < 5 had a detection probability of 0.91. A homogeneity model had a very similar likelihood (2.412) and in this case each group had a probability of 0.94 of being detected. A threshold model with B=2 radio-collars also had a very similar likelihood (2.409). The estimates and confidence intervals from these 3 models were very similar (122,697 ± 31,756; 120,495 ± 30,720; and 121,702 ± 31,231) with acceptable levels of precision (CV<14% for all estimates). The independence model had a lower likelihood but the estimate was only marginally higher at 127,101 ± 35,389. The probability of detection in this case corresponds to the individual radio-collared caribou and therefore the probability of detecting a group depended on the number of radio-collared caribou in the group. For this model the probability of detecting a group with one radio-collar was 0.83 and the probabilities of detecting a group having 3 or more radio-collars were very close to 1 (0.99).

DISCUSSION

Population estimates for the Bluenose-East herd from June 2010 calving photo-survey

The BE June 2010 calving photo-survey resulted in 3 estimates of herd size. An estimate of 114,472 ± 15,845 ≥1-year-old caribou resulted from counts of the 6 survey strata,

Table 8. Tests for randomness of radio-collared caribou relative to group sizes from Bluenose-East July 2010 post-calving survey.

Model	Z value	P value
Independence	1.11	0.133
Homogeneity	0.97	0.165
Threshold B=2	1.13	0.128
Threshold B=3	1.07	0.142

including the photographed strata that accounted for about 76% of all caribou counted. The first extrapolated estimate (A) of 105,326 ± 40,984 caribou was an estimate of ≥2-year-old caribou, based on further review detailed below, and was lower primarily because of the omission of yearlings in the extrapolation. The second extrapolated estimate (B) of 120,880 ± 13,398 was also an estimate of ≥2-year-old caribou. We suspect that all 3 of these estimates slightly under-estimated true herd size (all ≥1-year-old caribou).

The calving photo-survey was designed to provide a precise estimate of the abundance of breeding females on a herd's calving grounds (Heard 1985; Gunn *et al.* 2005; Boulanger *et al.* 2014). These surveys were initially carried out in the 1980s without radio-collared caribou (e.g., Beverly herd, Heard and Jackson 1990; Williams 1995), relying on the predictable return of pregnant cows to previous calving grounds. For the objective of assessing herd status, it could be argued that assessment of breeding female abundance is as valuable as an estimate of overall herd size. The use of a detailed composition survey in June allows for an in-depth assessment of herd demography (e.g., the proportion of breeding females on the calving ground and spatial or temporal variation in composition). The breeding female sector of the herd will generally be relatively stable over time and less influenced by annual variation in productivity; the annual increment of yearlings can vary widely from year to year (e.g., Boulanger *et al.* 2011). For the BE June 2010 survey, the first for this herd, the 43 radio-collared cows and 4 radio-collared bulls and extensive reconnaissance flying allowed us to map and survey the breeding cows on the calving grounds as planned, with good precision (CV of 9.3%).

The extrapolated estimate (A) of 105,326 ± 40,984 caribou should be considered a conservative herd estimate as it effectively is an estimate of ≥2-year-old adults. Yearlings are not included in the extrapolation because the pregnancy rate for yearlings (which would be 5-months-old during the previous fall breeding season) is effectively zero, as caribou calves almost never breed in their first year and rarely as yearlings (Dauphiné 1976; Thomas and Kiliaan 1998). Mean pregnancy rate for extrapolated estimates of herd size has been estimated by the ratio of caribou that are pregnant divided by caribou that are capable of being pregnant (0.702, Dauphiné 1976), and yearlings are almost never pregnant. If the proportion of yearlings present in the population were known, then the extrapolated herd estimate could be adjusted to include yearlings.

Heard (1985) and Heard and Williams (1990) recognized that an estimate of herd size extrapolated from the estimate of breeding cows using sex ratio and pregnancy rate was a "rough estimate" of overall herd size. Our results confirm their assertion. Some biologists showed little confidence in this method as an overall estimator of herd size (Rivest *et al.* 1998; Thomas 1998) because of the assumptions associated with the extrapolation of the breeding female estimate to total herd size, and the sometimes large variance of these estimates. The use of a fall sex ratio and an estimate of pregnancy rate in the extrapolation can lead to imprecise herd estimates and inflates variances around the extrapolated estimates when compared to the estimate of breeding females. As a percentage of the estimate, the 95% CI on the extrapolated estimate (A) of ≥2-year-old caribou was 38.9%, compared to 21.4% on the estimate of breeding females, 17.8% on the estimate of 1-year-old or older caribou on the June survey area, and 25.9% on the best Rivest estimate from the post-calving survey.

The estimation of sex ratio from 1 or more recent fall composition counts is preferable in the extrapolation to using a fixed sex ratio of 66 bulls:100 cows as initially used by Heard and Williams (1990, 1991); the sex ratio clearly can vary and was much lower in the BE herd in 2009 (42.9:100) than in the increasing herds surveyed by Heard and Williams in the 1980s. A further BE herd fall composition survey in October 2013 resulted in a similar bull:cow ratio of 42.6 bulls:100 cows based on a sample of 117 groups and 5,369 caribou (Boulanger *et al.* 2014), suggesting the 2009-2013

Table 9. Estimates of Bluenose-East adult caribou herd size in July 2010, based on detection models from Rivest estimation, ranked by log-likelihood. The Lincoln-Petersen estimate is given for comparison.

Detection Model	Log-likelihood	Detection probability	SE (Detection probability)	Estimated herd size $\hat{T}$	Standard Error SE ($\hat{T}$)	95% Confidence Interval (±)	Coefficient of Variation
Threshold (B=5)	2.415	0.91	0.069	122,697	16,202	31,756	13.2
Homogeneity	2.412	0.94	0.066	120,495	15,673	30,720	13.0
Threshold (B=6)	2.409	0.92	0.067	121,702	15,934	31,231	13.1
Threshold (B=2)	2.364	0.81	0.098	127,841	18,361	35,988	14.4
Independence	2.363	0.83[A]	0.087	127,101	18,055	35,389	14.2
Threshold (B=4)	2.361	0.90	0.072	123,872	16,349	32,045	13.2
Threshold (B=3)	2.313	0.88	0.079	124,934	17,060	33,438	13.7
Lincoln-Petersen				98,646	7,125	13,965	3.7

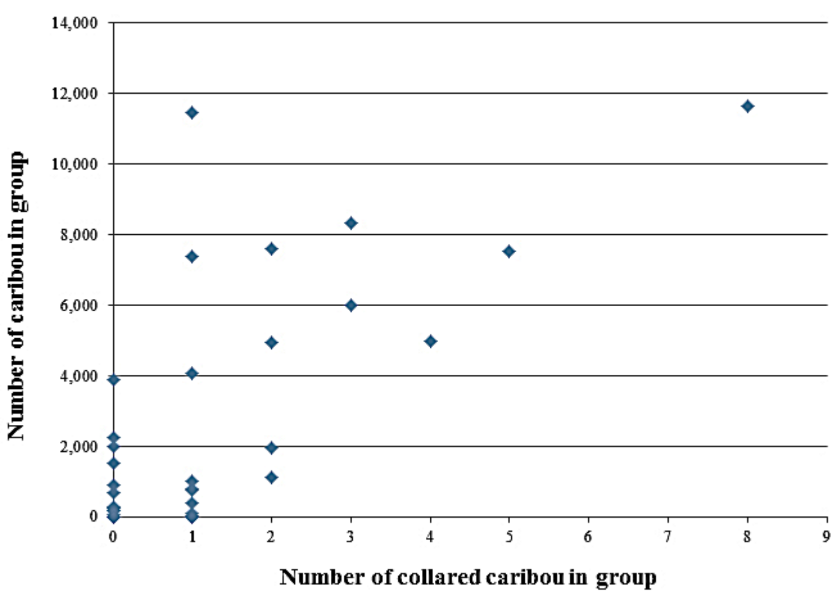

Figure 9. Number of caribou counted in individual groups as a function of the number of radio-collared caribou in each group, for Bluenose-East July 2010 post-calving survey.

herd's sex ratio was relatively constant over that period and that this ratio could be used reliably in the extrapolation.

The use of a fixed pregnancy rate in the extrapolation introduces potential error as pregnancy rates vary depending on cow condition (Gerhart *et al.* 1997; Russell *et al.* 1998). Pregnancy rates in hunter-killed Beverly caribou averaged 75.7% in ≥1-year-old females (605 of 800) from 1981 to 1987, a rate that can be compared directly to Dauphiné's (1976) 70% (285 of 406) for ≥1-year-old cows. Annual pregnancy rates in ≥4-year-old cows during this period in Beverly caribou ranged from 78 to 98% (Thomas and Kiliaan 1998). Pregnancy rate in ≥2-year-old cows in the George River herd varied over a similar range from 90-91% during the herd's increase to 78-80% near peak herd size and 69-77 % during its early decline (Bergerud *et al.* 2008). These estimates provide an index to the degree to which use of a constant pregnancy rate of 70% for ≥1-year-old cows based on Dauphiné (1976) might bias the extrapolation. A potential improvement in the extrapolation to account for non-breeding females would be the use of an estimate of pregnancy rate in the surveyed herd's females in the winter before the June survey, either from hunter-killed caribou (e.g., Thomas and Kiliaan 1998) or from fecal samples assayed for progesterone (e.g., Joly *et al.* 2015).

The revised (B) extrapolation approach to accounting for breeding and non-breeding females on the calving ground survey area was first used by Campbell *et al.* (2016); it may be a preferable approach to extrapolation than the earlier method (A) that uses ratios for both pregnancy rate and sex ratio. This approach uses the estimated totals of breeding and non-breeding females on the June survey area directly, and there is no calculation based on pregnancy rate. A correction based on sex ratio is still applied, and this extrapolation still omits the yearlings. This approach assumes that all ≥2-year-old cows (that are potential breeders) are within the June survey area; this assumption is more likely to be valid if there is an adequate number of radio-collared cows available and found within the survey area in June. Therefore, the reliability of this estimate will depend on whether survey strata included all breeding as well as non-breeding cows. In June 2010, 41 of 43 BE radio-collared cows were within the survey area, with the remaining 2 radio-collared cows found in peripheral areas with very low caribou densities.

The estimate of 114,472 ± 15,845 adults on the June survey area is based on sample counts of the full survey area, and 76% of the estimated numbers of adults were from the 2 photographed strata. We believe that we defined and surveyed a high proportion of the non-breeding cows, bulls and yearlings in the herd, most of them in the south and east strata that had very few cows with calves. The survey area included 45 of 47 radio-collared caribou in the herd, with the other 2 radio-collared caribou in areas with very low densities of caribou. However, the reconnaissance and composition survey results suggest that our survey area did not take in all the bulls, yearlings or non-breeding cows, particularly at the southern edge of the survey area. The bull:cow ratio calculated from June counts of strata and the composition survey was 24.2 bulls:100 cows, well below the 42.9 bull:100 cows estimated in October 2009 for this herd. The strata-based estimate of 114,472 ≥1-year-old caribou should be viewed with caution as an unknown proportion of the bulls, particularly, was missed.

Our June 2010 survey outcome suggests that a modified June photo-survey for barren-ground caribou that includes all herd sectors may be feasible, provided that there are adequate numbers of radio-collared cows and bulls, and if both the calving grounds and areas with non-breeding caribou can be comprehensively defined and surveyed. This could, however, be logistically challenging as the "trailing edge" of bulls, yearlings and non-breeding cows in early June may cover a large area with low caribou densities that extends south of the tree-line.

Population estimates for the Bluenose-East herd from July 2010 post-calving photo-survey

As with the June survey, the July 2010 BE caribou survey resulted in 2 population estimates: 122,697 ± 31,756 ≥1-year-old caribou from the best model of the Rivest estimator and 98,646 ± 13,965 ≥1-year-old caribou from the Lincoln-Petersen estimator. All the estimates from the Rivest models (Table 9) were similar (120,495-127,841) and had similar confidence intervals.

The estimate of 122,697 ± 31,756 from the Rivest estimator is the preferred population estimate of the 2 from the July 2010 BE post-calving survey, as the Lincoln-Petersen estimate most likely under-estimates herd size and produces an unrealistically low estimate of variance (Rivest *et al.* 1998). A fundamental assumption of the Lincoln-Petersen estimator is that all radio-collared caribou have equal probability of detection, and that each radio-collared caribou will be a random representation of all caribou, so that the recapture rate of the radio-collared caribou will reflect the true proportion of the population sampled. This assumption is problematic given that the number of radio-collared caribou is very small compared to herd size, and often larger groups have more radio-collars than smaller groups. The survey is built around flying to the radio-collared caribou, thus groups with no radio-collars are less likely to be found. On the BE 2010 survey, all radio-collars were searched for when photos were being taken, but the 3 radio-collars that were not found at the time of photography had erratic signals that did not allow us to home in on them. We had daily GPS or Argos locations for these 3 radio-collars, which indicated that they were active and moving, thus were part of the sample of radio-collars available. We found that VHF transmitters, particularly on older radio-collars, may sometimes be erratic. Thus some groups, particularly those with no radio-collars or a single radio-collar, may have lower detection rates than others. Analysis of detection probabilities for the current post-calving survey suggested that groups with several radio-collars were more likely to be detected than groups with a single radio-collar. Some ad-hoc methods have been proposed to account for bias issues with the Lincoln-Petersen estimator (Russell *et al.* 1996), however, these are subjective and often result in the loss of data from smaller group sizes (Rivest *et al.* 1998).

The homogeneity, independence and 5 threshold Rivest models produced similar estimates between 120,495 and 127,841, similar log-likelihood scores and similar 95% CIs; thus, there is little clear rationale to select one model over the others. In practice, it is very likely that a group with 2 or more radio-collars with functioning GPS/Argos and VHF transmitters would be found during a post-calving survey with good conditions and herd-wide aggregation. In attempted post-calving surveys of this herd in 2009 and 2012, conditions did arise where a portion of the herd, with associated radio-collars, did not aggregate sufficiently for photos and prevented a viable herd estimate. The results we obtained for caribou in the southern sector where the bulls, yearlings and non-breeding cows were also concentrated in July suggest that the number of radio-collars was somewhat low in this area, and that some caribou may have been missed. When photos were taken on July 6 in this area, 16,917 caribou in 9 groups were photographed and 6 of 7 radio-collars were found. Six days later, all 7 radio-collared caribou in this area were found but the total number of caribou counted (11,342) in 4 groups was more than 5,000 caribou lower. The groups found on the 2 days were quite different in size and radio-collar distribution, thus it is possible that several thousand caribou on July 12 had no radio-collars and were not found. As we noted for the June survey, there were just 4 radio-collared bulls (all in the southern sector, along with 3 radio-collared cows) during the July survey of this herd, compared to 43 radio-collared cows. A larger number of radio-collared bulls in closer proportion to the herd's bull:cow ratio would improve confidence in the population estimate from possible future post-calving surveys of this herd.

Post-calving survey methods with adequate cow and bull radio-collar numbers can result in estimates of overall herd size that include all the age classes (≥1-year-old) of the caribou population. The Rivest estimator can produce robust population estimates provided radio-collar sample sizes are adequate (Alaska Department of Fish and Game 2011; Harper 2013). Analysis of post-calving surveys of the Western Arctic Herd with 90-100 radio-collared caribou indicated that the Rivest estimates were generally very similar to the totals counted on photos, suggesting that the herd had effectively been censused or counted almost entirely (Alaska Department of Fish and Game 2011; Harper 2013). The biggest challenge of the post-calving survey method remains the possibility of caribou not aggregating sufficiently for photos due to poor weather conditions. As has happened with other herds, issues with portions of the herd not aggregating resulted in unsuccessful post-calving surveys of the BE herd in 2001, 2009, and 2012, and created challenges in BE surveys flown in 2000, 2005, and 2006.

MANAGEMENT CONSIDERATIONS

The preferred population estimate for the BE caribou herd in 2010 from July of 122,697 ± 31,756 adults had overlapping confidence intervals with the June strata-based survey estimate of 114,472 ± 15,845 adults, and differed by 6.7% of the post-calving estimate. The alternate extrapolated estimate (B) of 120,880 ± 13,398 ≥2-year-old caribou basedon strata-based estimates of all cows divided by the sex ratio was very similar to the Rivest July estimate. Because we suspect that the June strata-based estimate of 114,472 ≥1-year-old caribou slightly under-estimated the bulls, yearlings and non-breeding cows in the herd, we suggest that the July estimate of 122,697 adult caribou is likely closest to the true population size (≥1-year-old caribou) for the BE herd in 2010. This estimate had a CV of 13.2%, an acceptable variance below Pollock *et al.*'s (1990) 20% benchmark, and the other Rivest models all generated very similar herd estimates. The biggest problem in using the post-calving survey for this herd has been the lack of herd-wide aggregation that has occurred in several attempted surveys of this herd; attempted surveys in 2001 (Patterson *et al.* 2004), and in 2009 and 2012 in the present authors' experience resulted in failed surveys and no population estimate.

The estimate of breeding females from the June survey had a CV of 9.3% and the estimate of ≥1-year-old caribou in the June survey area had a CV of 6.0%, both of which should be acceptable for management purposes. Heard and Williams (1990) and Boulanger *et al.* (2011) emphasized the importance of size and trend in the breeding female sector of the herd to its dynamics. The extrapolated estimates of ≥2-year-old caribou remain rough estimates of herd size, as described by Heard (1985). The more recent approach to the extrapolation (B) developed by Campbell *et al.* (2016) uses only one ratio calculation and results in a lower variance than the earlier extrapolation (A) which uses 2 ratios. The BE 2010 estimate from this method of 120,880 was within 1.5% of the post-calving estimate of 122,697 and this approach may be preferable for June surveys where there are adequate radio-collar numbers to define the full distribution of all cows.

The June and July 1993 surveys of the George River herd by Couturier *et al.* (1996) differed somewhat from the methods and calculations we used, but the June and July 1993 George River population estimates showed good agreement. Statistically, this is a sample size of just 2 comparisons, and true herd size was not known in either case. However, the correspondence of the 2 pairs of estimates suggests that both survey methods are fundamentally sound, if carried out with adequate radio-collar numbers, field techniques that emphasize high precision, and appropriate analyses. Management recommendations about harvest or other factors (e.g., WRRB 2016) are generally based on a range in herd sizes and take other factors like trend and key demographic indicators into account (PCMB 2010; ACCWM 2014). In the case of the BE herd in 2010, the management plan (ACCWM 2014) would have identified the herd as in the green "high numbers" phase based on all the estimates generated from the June and July 2010 surveys.

ACKNOWLEDGEMENTS

Aerial surveys like the June and July 2010 BE calving and post-calving photo-surveys require months of planning, logistic support, careful field work, and analysis. We would like to thank Adam Bourque and Monika Koetzle for capably piloting the Cessna Caravans during the June survey, Perry Linton and Brett Van Hearden for capably piloting the Helio-Courier and Cessna 185 during the July survey, and Jesse Pierce for flying the helicopter during the June composition survey. Mathieu Dumond, Jorgen Bolt and Allan Niptanatiak provided excellent logistic support in Kugluktuk. A special thank you to Phil Spencer in Norman Wells for daily supplying the caribou radio-collar locations during the surveys and for the maps he created for this report.

Our thanks also to Jennifer Bailey for capable support with data entry and mapping during the June survey. Paul Roy once again meticulously counted photos from the June survey, as he has for these surveys for many years. Noel Doctor, George Mandeville, Kelvin Kotchilea, Joe Blondin, Nicole McCutchen, Kerri Garner, and Karin Clark were able observers during the June survey. Andrea Hrynkiw kindly assisted with the July field work and counting of caribou on July photos. Judy Williams provided her usual expert support with logistics and survey planning.

Funding was primarily provided by the GNWT, with assistance from the Nunavut government. These surveys represent a collaboration among Inuvik, North Slave and Sahtú ENR regional staff and ENR headquarters staff. Alasdair Veitch in Norman Wells provided cheerful support during the surveys and organized a community observer tour at the end of the survey in July. We would also like to thank senior management staff in ENR, including Susan Fleck, Nicole McCutchen, Ernie Campbell, and Gary Bohnet for ensuring that we were able to carry out these surveys with the resources and support that these expensive, time-consuming surveys depend on.

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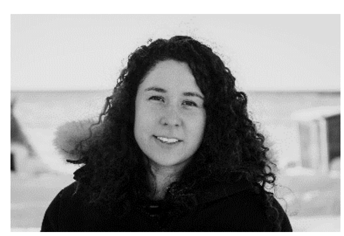
Bruno Croft began a BSc at the Université du Québec à Rimouski, then finished it at Acadia University. Bruno completed an MSc at the University of Saskatchewan in Wildlife Management. Bruno began working for the Government of the Northwest Territories, Environment and Natural Resources (ENR) as a wildlife technician in 1986, and has been a biologist and wildlife manager since 2006 with main responsibilities for barren-ground caribou monitoring and management in the North Slave region. Bruno figures he has probably spent more time in the air and in the field than anyone else for ENR since 1986.

Tracy Davison is a regional biologist for the Inuvik region of the Northwest Territories. The region stretches from the arctic islands to the Boreal forest and includes 2 land claim regions; the Inuvialuit Settlement Region and the Gwich'in Settlement Area. Tracy implements monitoring and studies in the region to ensure that the co-management boards have the best information possible to make management decisions. The primary species Tracy monitors are barren-ground caribou, Peary caribou, muskox, moose and Dall's Sheep.

Heather Sayine-Crawford holds a BSc in Biology from the University of Alberta and is working towards an MSc in fish and wildlife management from Montana State University. She was a wildlife biologist/manager with the Government of Northwest Territories in Norman Wells, NT for 7 years and worked on a variety of wildlife research and management projects in the Sahtú region of the Northwest Territories with most of her time focused on barren-ground caribou and Dall's sheep. In April 2017, she



moved to Yellowknife to begin a position as Manager of Wildlife Research and Management in the Wildlife Division.

Boyan Tracz holds a BSc(H) in Ecology from the University of Manitoba, and both a MSc in Ecology and a Master of Business Administration from the University of Alberta. Over the past few years, Boyan has focused his activities in the Northwest Territories, having been the Cumulative Effects Biologist in the Sahtú Region, and a Program Manager for the Cumulative Impact Monitoring Program. Boyan is currently working for the Wek'èezhìı Renewable Resources Board as their Wildlife Management Biologist.

Received 6 June 2016 – Accepted 7 December 2016