Estimates of caribou herd size using post-calving surveys in the Northwest Territories and Nunavut, Canada: A meta-analysis

Research *in* Rangifer · December 2018

DOI: 10.7557/2.38.1.4239

Estimates of caribou herd size using post-calving surveys in the Northwest Territories and Nunavut, Canada: A meta-analysis

John Boulanger[1], Jan Adamczewski[2] & Tracy Davison[3]

[1] Integrated Ecological Research, 924 Innes, Nelson, BC, Canada V1L 5T2 (Corresponding author: boulange@ecological.bc.ca).
[2] Wildlife Division, Environment and Natural Resources, Government of Northwest Territories, Box 1320, Yellowknife, NT, Canada X1A 2L9.
[3] Department of Environment and Natural Resources, Government of the Northwest Territories Inuvik, NT, Canada X0E 0T0.

Abstract: Post-calving surveys to estimate herd size of barren-ground caribou (*Rangifer tarandus groenlandicus, R. t. granti, and R. t. caribou*) have been used for caribou herds in Alaska, Yukon, Northwest Territories, Nunavut, and Québec/Labrador. The main field procedure uses relocation of collared caribou to locate aggregated groups of hundreds or thousands of caribou during times of high insect harassment that usually occur in July. These groups are then photographed to obtain a count of the caribou in the aggregated groups. Often some caribou are missed, and the count of caribou may be a negatively biased estimate of total herd size, unless a high proportion of the herd is found and photographed. To address this, some previous studies have used the Lincoln-Petersen estimator, which estimates the proportion of the herd counted based on the percentage of available collared caribou found during the survey. However, this estimator assumes equal probabilities of all groups of caribou being found, regardless of group size and the numbers of collared caribou in the group. These assumptions may not be valid, as larger groups are more likely to be found than smaller groups, particularly if there are several collared caribou present. This may lead to estimates that are biased low, along with an estimate of variance that may also be biased low. A two phase estimator developed by Rivest *et al.*, in 1998 became available in R statistical software in 2012. We analyzed 20 data sets from post-calving surveys in the NWT and NU carried out between 2000 and 2015 using the Rivest estimator to explore working characteristics of this estimator. We compared the Rivest estimates with Lincoln-Petersen estimates and total counts on each survey. We considered factors that influence precision of the Rivest estimator with a focus on sampling factors such as the proportion of collars found, the number of collars available, and natural factors such as the degree of aggregation of caribou in each survey (as indexed by the negative binomial dispersion parameter). In general, the Rivest estimator displayed acceptable precision when high proportions of caribou groups with collars were detected and counted, collar numbers were sufficient, and aggregation was adequate. Notable exceptions occurred in years of lower aggregation which resulted in many small groups with 0 or few collared caribou, and in these cases herd estimates had large variances and low precision. Estimates from the Rivest estimator, Lincoln-Petersen estimator, and total counts converged when sampling effort was high, collar numbers relative to herd size were high, and caribou were well aggregated in a limited number of groups. In other cases, estimates of the Rivest estimator were generally higher than Lincoln-Petersen estimates, presumably due to negative bias with the Lincoln-Petersen estimator. We provide a set of working recommendations to optimize field sampling to ensure reliable estimates of herd size using post-calving methods.

Key words: barren-ground caribou; estimation; post-calving survey; negative binomial; Lincoln-Petersen; Rivest estimator.

Rangifer, 38, (1), 2018: 39-78
DOI 10.7557/2.38.1.4239

Introduction

Post-calving surveys have been used to estimate population size of migratory caribou *(Rangifer tarandus groenlandicus, R. t. granti, and R. t. caribou)* herds in Alaska, Yukon, Northwest Territories, Nunavut and Québec/Labrador with the first survey in Alaska in 1961 (Davis *et al.,* 1979; Valkenburg *et al.,* 1985; Russell *et al.,* 1996; Patterson *et al.,* 2004; Harper, 2013; Adamczewski *et al.,* 2017). The main field procedure for this method is the use of collared caribou to locate aggregated groups of hundreds or thousands of caribou during times of high insect harassment that usually occur in July. The main objective of field procedures is to photograph the aggregations of caribou found and thereby obtain a near-count of total herd size.

The main challenge with this technique is that it is often difficult to locate all the aggregated groups and it is likely that some groups are missed; the total count of all photographed groups is thus an underestimate of total herd size by an unknown amount. From a statistical perspective this total count is problematic in that it is negatively biased as an estimate of herd size and has no associated estimate of variance. For trend monitoring, the total count becomes an index and trend estimates will only be valid if it can be assumed that the total amount missed is the same each year (Anderson, 2001), or if the estimation of herd size reliably accounts for the proportion of the herd that was likely missed in each survey.

An estimator for post-calving surveys of herd size that has been applied in the NWT and elsewhere is an adaption of the Lincoln-Petersen mark-recapture estimator (Lincoln, 1930) to collar data where the proportion of available radio collared caribou that are detected during the survey estimates the proportion of the herd that is found by survey flying (White & Garrott, 1990; Russell *et al.,* 1996). Fundamental assumptions of the Lincoln-Petersen estimator are that all collared caribou will have equal probability of detection, and that each collared caribou will be a random representation of all caribou so that the recapture rate of the collared caribou will reflect the true proportion of the population sampled. In the context of post-calving surveys, this assumption can be problematic given that the number of collared caribou is a very small proportion of total herd size and often the number of radio collared caribou in large groups is larger than in small groups. In addition, the survey is generally built around flying to the collared caribou, thus groups with multiple collars have a high likelihood of being found while smaller groups with one or no collars are more likely to be missed. Therefore, detection probabilities of caribou groups and collared caribou may not be equal and the varying size of groups and varying numbers of collars will mean that some groups have higher detection rates than others (Patterson *et al.,* 2004). As a result, estimates from the Lincoln-Petersen estimator may be negatively biased, and associated estimates of variance (confidence intervals) may also be negatively biased. This leads to a biased but apparently precise estimate, which can be misleading if used for management purposes. 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).

As an alternative to the Lincoln-Petersen estimator, Rivest *et al.* (1998) proposed a two-phase estimator of population size from post-calving surveys that circumvents many of the issues with the Lincoln-Petersen estimator. The main distinction of the Rivest estimator is that it more appropriately defines caribou groups rather than collared caribou as the sample unit for estimates and treats photographed groups of caribou with collars as a sample of all the groups in the herd. Using this approach allows for various models of how collared caribou represent aggregated groups to be proposed and allows for a more robust estimation of population size that better accounts for the effect of varying group sizes and varying numbers of collared caribou on estimate precision. Until recently, the Rivest model was not applied to post calving data sets with the exception of Patterson *et al.* (2004), who conducted a limited analysis of the Bluenose-East 2010 post calving data set. In 2012, the estimator became available as the *caribou* package (Crepeau *et al.,* 2012) in R statistical software (R Development Core Team, 2009) allowing fitting of a full suite of Rivest models. This estimator has been adopted in Alaska (Harper, 2013) and in the Northwest Territories (Adamczewski *et al.*, 2017, this paper).

The main objective of this paper is to assess trends across 20 post-calving survey data sets from the Bluenose-East (BE), Bluenose-West (BW), Cape Bathurst (CB), and Tuktoyaktuk Peninsula (TP) Herds carried out in the NWT and NU between 2000 and 2015 (Figure 1). We compared the general performance of the Rivest estimator across the range of post-calving data sets and compared Rivest estimates with Lincoln-Petersen estimates and total counts. We note that the data sets analyzed ranged from relatively large herd sizes (BE herd that sometimes exceeded 100,000 caribou) with resulting limited collar coverage (i.e. relatively low number of collared caribou relative to overall herd size) to relatively small herds (CB and TP herds with 4,000 or fewer caribou), and higher collar coverage and sampling effort. Comparison of these data sets provided a useful way to determine sampling thresholds and guidelines that will help ensure reliable post-calving estimates of herd size.

Materials and Methods

Field methods

The general method of post-calving surveys is aerial survey of groups of caribou that are aggregated due to insect harassment. This may occur as early as late June or later in July, but occurs most often in the first half of July. Radio collared caribou are used to locate groups and often the majority of groups contain radio collared caribou. Survey flying usually begins near July 1, and continues until either the survey is completed or it is clear in late July that the post-calving period has ended.

Surveys occur within a narrow window of time to minimize mixing of groups and possible double counting of caribou. For smaller herds, a single aircraft has generally been sufficient to photograph all groups in one day or occasionally over 2-3 days. For the BE herd in 2010 that exceeded 100,000, two aircraft were used to find all the collars and cover the full summer range in a day (Adamczewski *et al.*, 2017). In some surveys, an initial systematic reconnaissance survey has been used across the known summer range of the herd and guided by collared caribou locations (e.g. Adamczewski *et al.*, 2017); however, the movement rates of caribou in the insect season can be high (30-40km/day) and the caribou can have a very clumped distribution that changes frequently, so the distribution defined by such a reconnaissance survey is only useful for a day or two. More commonly, the survey crew center their flying around the last known set of collar locations and focus on locating a high proportion of these collars. In earlier years (before 2007), some of the collars used were satellite collars and some were VHF collars that could only be found if the aircraft was within a few miles. Since 2007, collars used have been almost entirely satellite or GPS-satellite, with daily locations during the survey period. Under these conditions, the day's flying is focused on the last set of collar locations, although the exact locations when photos are taken still depend on homing in on the VHF signal. Additional groups with no collars are generally found incidentally in the vicinity of

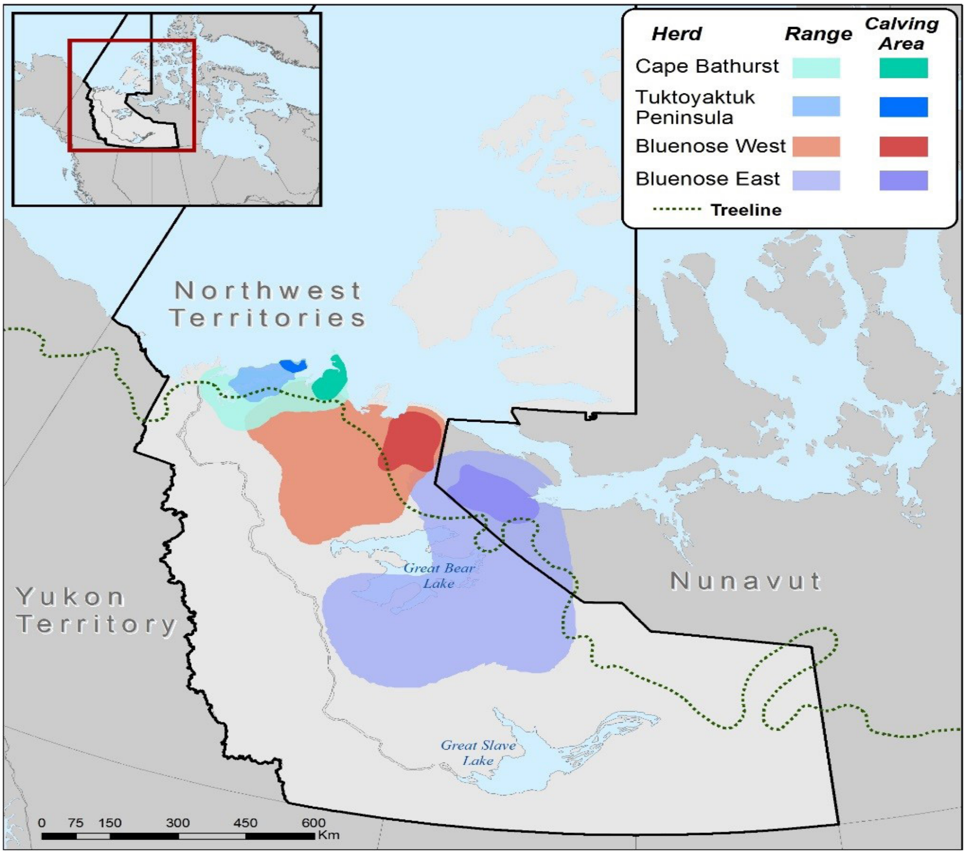

Figure 1. Annual ranges of the caribou herds whose post calving survey data were used in this study. The majority of the herds occurred in Northwest Territories with some overlap of the Bluenose East into Nunavut, Canada.

groups with collars or in flying to and from recent collar locations. Groups with and without collars are located and photographed to allow accurate counts of caribou within each group (Russell *et al.,* 1996; Rivest *et al.,* 1998).

The chief weakness of this method is that it is weather-dependent; the survey is most likely to succeed during warm dry weather with limited winds. If caribou do not aggregate sufficiently, or if part of the herd does not aggregate, then photography is not possible and the survey fails. This occurred, for example, with the BE herd in 2001, 2009 and 2012, and in the past has failed in multiple years for the Porcupine herd (http://www.pcmb.ca/herd). In the field it is usually readily apparent if a caribou group is sufficiently aggregated for photography, with well-defined edges; many groups will be contained within a single photo or they may be spread over a series of overlapping photos. Caribou groups that are more dispersed where the edges of the group are difficult to define are not suitable for photography. Multiple photo passes are made over each group. Photos are converted to GPS map files and caribou are counted on-screen by placing waypoints on each caribou 1 year old or older (Adamczewski *et al.*, 2017). Young calves born in June are not usually counted as they may be hidden behind adults, particularly in groups that are tightly aggregated. All photos are counted independently by at least two observers. In our experience, counts from two obervers are usually very similar (e.g. totals of 915 caribou vs. 918 caribou for a single photo) and the difference in counts by two obervers is usually well below 1% (Adamczewski *et al.*, 2017).

Post-calving surveys have been conducted on the BE, BW, CB, and TP herds (Patterson *et al.,* 2004; Nagy & Johnson, 2013; Davison *et al.,* 2014; Davison *et al.,* 2016; Adamczewski *et al.,* 2017; Davison *et al.,* unpublished) in the Northwest Territories (NWT) and Nunavut (NU) (Figure 1). We analysed results of 20 surveys on these herds between 2000 and 2015. Appendix 1 provides details on each survey.

Estimation methods

<u>Rivest estimator</u>

The Rivest estimator considers the sampling of post-calving aggregations as a two phase sampling process. The first phase involves the distribution of collared caribou within the post-calving groups encountered during the survey. For this estimator it is assumed that *n* caribou are collared and that these caribou randomly distribute themselves into *m* groups during the post-calving period when the survey occurs. In general, the probability of a group containing at least one collared caribou $\hat{P}_{\geq 1\text{collar}}$ increases with group size. The second phase of sampling involves the actual aerial search for groups. For this phase, various models are proposed as to how groups with collared caribou are detected $\hat{P}_{\text{group}}$. Three models are considered:

1. *The homogeneity model.* This model assumes that caribou groups (with collared caribou in the groups) are missed as a completely random event that is independent of the number of collared caribou in the group or other factors. Therefore, each group will have the same probability $\hat{P}_{\text{group}}$ of being detected by the aerial survey. The Lincoln-Petersen estimator essentially assumes a homogeneity model of detection of groups.
2. *The independence model.* This model assumes that each collared caribou in the group has the same independent probability of being detected and therefore the overall probability of detecting a group $\hat{P}_{\text{group}}$ increases as a function of the number of collared caribou in the group.
3. *Threshold model.* This model assumes that all groups with more than a threshold level of collared caribou (symbolized by *B*) have a detection probability of 1. For example, it might be that once more than 3 collared caribou occur in a group the group will always be detected whereas groups with 1 or 2 collars are not always detected. For this model, all groups with 3 or more collared caribou get a detection probability of 1 and detection probability $\hat{P}_{\text{group}}$ is estimated for groups with 1 or 2 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. Threshold models are run across the range of observed sizes of collars in groups.

The estimate of herd size (symbolized $\hat{T}$) is then basically the summation of each group size divided by the probabilities of the group being observed *and* having at least one collared animal included (which is estimated by the product of $\hat{P}_{\text{group}}$ and $\hat{P}_{\geq 1collar}$.

$$\hat{T} = \sum_{i=1}^{n\ groups} \frac{group\ size}{\hat{p}_{group} * \hat{p}_{\geq 1 collar}}$$

It is through an iterative likelihood-based optimization procedure that each of these parameters is estimated to produce estimates of herd size. Given that collared caribou are used to estimate detectability of groups, the Rivest estimator does not use data for groups of caribou photographed with no collars. Intuitively, if caribou are aggregated into larger groups and therefore likely contain at least 1 collar then $\hat{P}_{group}$ and $\hat{P}_{\geq 1 collar}$ will be close to 1 and the resulting estimate will be close to the total count of caribou observed.

An assumption of this method is that the collared caribou are randomly distributed within the separate caribou groups that are photographed. 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 collared caribou produces a distribution of collared caribou relative to group size that is different from the distribution if the caribou were randomly distributed. If over-dispersion occurs, then estimates of population size and variance from the Rivest estimator will both be negatively biased (Rivest *et al.*, 1998).

All Rivest estimator calculations were conducted using the R-package (R Development Core Team, 2009) entitled *"caribou"* (Crepeau *et al.,* 2012). Confidence limits were based upon multiplication of the standard error of the estimate times 1.96. The lower limit of the confidence limit was constrained to be equal or greater than the minimum number of caribou counted during the survey.

Lincoln-Petersen estimator

The Lincoln-Petersen method has been used in several post-calving surveys in the NWT and NU (e.g. Nagy & Johnson, 2006) and elsewhere (e.g. Russell *et al.*, 1996) to obtain estimates of herd size. The Lincoln-Petersen estimate of herd size was calculated using the total count of caribou observed during the survey (*C*), the number of collared caribou available (*M*), and the number of collared caribou that were observed in groups (*R*); (Russell *et al.,* 1996; Patterson *et al.,* 2004). Herd size is then estimated as:

$$\hat{N} = \left(\frac{(M+1)(C+1)}{R+1}\right) - 1$$

with variance estimated as:

$$Var(\hat{N}) = \frac{(M+1)(C+1)(M-R)(C-R)}{(R+1)^2(R+2)}$$

Some authors have suggested that only counts of groups with collars (*C* in the LP equation) should be used with the Lincoln-Petersen estimator (Russell *et al.,* 1996; Patterson *et al.,* 2004) whereas other studies have included counts of groups observed without collars (Nagy & Johnson, 2006) under the assumption that groups without collars were often in close proximity to collared groups and therefore constituted part of the population represented by collared caribou. We calculated the estimate using both methods to assess the sensitivity of estimates to this assumption.

If all the available collared caribou are found in photographed groups, then the *M* and *R* terms in the Lincoln-Petersen herd size equation cancel each other and the Lincoln-Petersen estimate equals the count of caribou observed in all groups. The *M-R* term in the variance estimate becomes 0 leading to an estimate of 0 variance. In this case it is assumed that a census of the herd has occurred with all individuals counted.

Analysis of factors affecting estimates

As with any statistical estimator, the performance of the Rivest estimator will depend on sample size, sampling effort, and how animals are distributed relative to sampling efforts. We initially explored factors that can be controlled by the survey crews such as the sample size of collars available, and on the proportion of the collars that are located (which is proportional to overall survey effort) and their effect on estimate precision.

The reliability of post-calving herd estimates is also based on how strongly the caribou aggregate during the survey. This factor cannot be controlled in terms of study design but often it can determine the relative success of a survey. To index aggregation, we estimated the mean group size and the negative binomial dispersion parameter (θ) (Anscombe, 1948; White & Bennetts, 1996; Krebs, 1998) from the distribution of observed group sizes for each survey. If the groups are well aggregated, then θ should be small (<0.5). Larger values of θ indicate a more random (Poisson) distribution of groups which is not desirable for estimates, since it becomes less likely that a substantive portion of groups will be found and photographed. We used values of θ as a covariate to help explain differences in levels of precision from the Rivest estimator. The *MASS* package (Venables & Ripley, 2013) in program R was used to estimate θ using a maximum likelihood estimator (*theta.ml* (*counts*, *mean*) command where *counts* is a vector (list) of group counts and *mean* is the mean group count). We used all groups observed to estimate θ, including groups that had no collared caribou.

We used graphical methods and multiple regression analyses (Zar, 1996) to determine optimal working properties of the Rivest estimator as defined by estimated precision of estimates. We defined adequate precision as an estimate with a coefficient of variation of less than 20%, which is generally deemed suitable for management studies (Pollock *et al.,* 1990), however, we suggest managers assess precision needed for estimates dependent on management objectives. A regression analysis was used to determine ranges of sample sizes and sampling effort, as indicated by the proportion of collared caribou that would be needed to achieve adequate estimate precision at different levels of aggregation (as estimated by the negative binomial θ). The fit of the regression model was assessed using r^2 (coefficient of determination) as well as parameter significance (Zar, 1996).

Results

Summary of data sets

The herds sampled using post-calving methods varied in size from the relatively large BE herd of over 100,000 caribou to the TP herd that was less than 4,000 caribou at the time the surveys occurred (Table 1). The number of collars used in surveys ranged from 24 to 63 per herd. Levels of aggregation varied from well aggregated (θ=0.2) to much less aggregated (θ=0.9). There were 20 surveys in total between 2000 and 2015. Specifics of each survey are given in Appendix 1.

General comments on performance of the Rivest estimator

Estimates were derived from the Rivest model estimates with the highest likelihood score (Table 2). Precision of the Rivest estimator was adequate (CV<20%) in 14 of the 20 data sets used in the comparison. Threshold models with various cut-points in terms of collar group size had the highest likelihoods in 15 of the 20 data sets. This indicates that the general pattern for group detection was for groups with lower numbers of collars to have detection rates that were less than 1 but detection rates became 1 once a critical sample size of collars was achieved per group. The actual number of collars per group needed for detection to be 1 was dependent on the total group size as well as the number of collars per group. A homogeneity model was selected in one study, and the independence model was not selected in any of the data sets. For the TP herd (2006 and 2015) and CB Herd (2012), all estimators had similar likelihood scores and estimates, presumably due to a large proportion of the herd being counted during the survey.

The assumption of randomness of collars across caribou groups was violated in 5 of 20 surveys. One example of this was the BW 2009 survey where the distribution of collars and groups was irregular with one group of approximately 2,500 caribou having 12 collared caribou and a group of similar size only containing 1 collared caribou. In this case, it was likely that there may have been an aggregation of collared caribou that was not easily related to group sizes observed. As a result, the hypothesis that collared groups were distributed randomly was rejected and it is possible that estimates from this survey were negatively biased.

Effect of proportion of collars located during the survey

One of the most immediate factors that might influence performance of the Rivest estimator is the relative proportion of available collars located and photographed during the survey. This proportion is a rough indicator of the ability of the aerial survey to find the majority of the caribou herd and should have some bearing on the ultimate precision of the estimate. Results from the comparison of data sets indicated that acceptable levels of precision occurred when 80% or more of the collars were located with 3 studies showing lower levels of precision (CV>20%) when less than 80% were located (Figure 2).

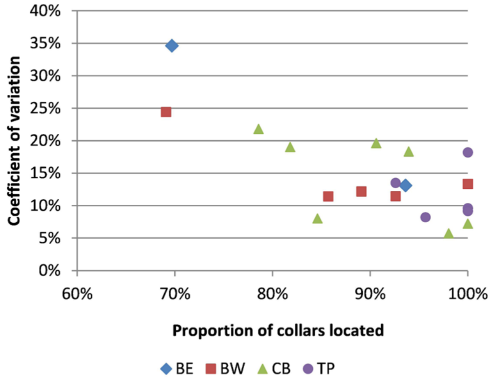

Figure 2. The relationship between proportion of available collars located and estimate precision with herd surveyed, for caribou herds in Northwest Territories and Nunavut, Canada, 2000-2015. Estimates are displayed from the Bluenose-East (BE), Bluenose-West (BW), Cape Bathurst (CB) and Tuktoyaktuk Peninsula (TP) herds.

Effect of sample size of collars relative to herd size on the Rivest estimator

A related question in terms of sample size is the effect of the number of collared caribou available during the survey relative to the size of the caribou herd. Intuitively, larger caribou herds should require a larger number of collared caribou to adequately sample the herd, which can be indexed by the number of collared caribou relative to estimated herd size. Smaller herds such as the CB and TP herds had higher numbers of collared caribou per caribou in the herd, which is one potential reason why precision of estimates for these herds was more uniformly acceptable. In contrast, surveys of the BW and BE herds had higher numbers of caribou per collar and more variance in precision of estimates. For these herds, the degree of aggregation of animals played a larger role in determining estimate precision (Figure 3).

The effect of aggregation of groups on the Rivest estimator

In general, stronger aggregation of caribou increased the precision of Rivest estimates (Figure 4). When strong aggregation occurred, larger numbers of collared caribou were likely to be found in a limited number of larger caribou

Table 1. Summary of post-calving data sets for caribou herds in the Northwest Territories and Nunavut, Canada, between 2000 and 2015 assessed in this study. Further details on each data set are given in Appendix 1.

Herd Year	July dates	Collars available	Collars detected	Caribou counted		Group size	Aggregation Index	
				All groups	Groups with collars	Mean	θ	SE
Bluenose-East								
2000	2-6	33	23	85,438	73,814	2183.2	0.90	0.24
2010	6-12	47	44	92,481	80,081	1156.6	0.27	0.05
Bluenose-West								
2005	6	63	54	17,875	16,824	446.9	0.33	0.06
2006	4	66	31	10,902	10,809	546.7	0.30	0.11
2006	7-8	66	66	17,781	16,378	137.3	0.35	0.05
2009	12-13	54	50	16,595	15,108	103.7	0.33	0.10
2012	6	55	38	14,252	12,863	230.5	0.30	0.06
2015	18	55	49	13,637	13,628	545.8	0.33	0.08
Cape Bathurst								
2005	9	32	29	2,213	2,213	74.7	0.40	0.12
2006	9	33	27	1,508	1,490	64.0	0.38	0.13
2006	9	33	31	1,714	1,389	33.6	0.48	0.12
2006	13	39	33	1,514	1,703	79.3	0.21	0.07
2009	18	28	22	1,534	1,423	360.9	0.47	0.12
2012	6	24	24	2,427	2,247	42.3	0.19	0.04
2015	18	51	50	2,216	2,203	184.7	0.24	0.08
Tuktoyaktuk Peninsula								
2006	9	27	27	2,866	2,677	65.8	0.40	0.10
2006	13	27	27	3,078	2,894	110.9	0.29	0.09
2009	13	27	25	2,556	2,138	108.2	0.60	0.23
2012	7	23	22	2,101	1,987	151.6	0.27	0.11
2015	6	26	26	1701	1,698	170.1	0.36	0.13

groups. As a result, these larger groups often had high detection rates and the probability that these groups contained at least one collared caribou approached 1. Subsequently, the estimate of herd size was usually precise and often similar to the total number of caribou counted. This relationship is shown if the negative binomial dispersion parameter (θ) is plotted against Rivest estimator precision. In most studies, θ had to be below 0.5 for adequate precision. Two exceptions to this were the BW surveys which had aggregation indices of less than 0.4 but higher coefficients of variation. For these two surveys a lower (<70%) of collars were located which also reduced estimate precision. The BE 2000 survey had the lowest level of aggregation and the highest coefficient of variation of the surveys compared.

Table 2. Summary of herd estimates using the Rivest estimator for post-calving surveys used in meta-analysis for caribou herds in the Northwest Territories and Nunavut, Canada, 2000-2015. The model used for estimates had the highest likelihood score of models considered. Further details on each analysis are given in Appendix 1. Estimates with the lowest CVs and highest likelihoods were the preferred ones.

Herd Year	Rivest Estimator						
	Model	$\hat{T}$	SE ($\hat{T}$)	Confidence Interval		CV	p[a]
Bluenose East							
2000	TB2[b]	279,358	96597.3	90,027	468,689	34.6%	0.550
2010	TB8	121,702	15934.3	92,481	152,933	13.1%	0.142
Bluenose West							
2005	TB6	26,228	2999.02	20,350	32,106	11.4%	0.642
2006	TB9	25,331	5837.25	13,890	36,772	23.0%	0.810
2006	TB6	28,461	3791.2	21,030	35,892	13.3%	0.120
2009	TB12	21,773	2491.6	16,889	26,657	11.4%	0.024
2012	TB9	32,326	7899.1	16,844	47,808	24.4%	0.000
2015	TB3	21,535	2620.4	16,399	26,671	12.2%	0.536
Cape Bathurst							
2005	H	3,566	700.4	2,213	4,939	19.6%	0.000
2006	TB7	2,462	468.1	1,545	3,379	19.0%	0.237
2006	TB3	2,288	419.3	1,714	3,110	18.3%	0.031
2006	TB7	2,039	162.6	1,720	2,358	8.0%	0.600
2009	TB4	2,925	638.7	1,673	4,177	21.8%	0.759
2012	H	2,447	175.3	2,427	2,791	7.2%	0.646
2015	T B2	2,524	144.9	2,241	2,808	5.7%	0.042
Tuktoyaktuk Peninsula							
2006	-[c]	4,188	760.86	2,866	5,679	18.2%	0.450
2006	-[c]	3,320	318.09	3,078	3,943	9.6%	0.450
2009	TB2	2,889	390.5	2,556	3,654	13.5%	0.092
2012	TB2	2,237	182.7	2,101	2,595	8.2%	0.769
2015	-[c]	1,930	176.9	1,701	2,277	9.2%	0.481

[a] P-value for test of randomness of collared caribou relative to group size.
[b] TB refers to a Rivest threshold model with the number referring to the number of collars where detection probability = 1. H refers to the Homogeneity model and I refers to the Independence model.
[c] All models returned the same likelihood score and estimates.

Regression analysis of factors affecting estimate precision

We conducted a regression analysis to determine the factors strongly influencing Rivest estimator precision. These included the proportion of available collars located and photographed (Figure 2), the number of caribou collared relative to herd size (Figure 3) and the degree of aggregation of the herd (Figure 4). Of the covariates considered, the degree of aggregation and the proportion of collars located and photographed were significant predictors of estimate precision (Table 3). The r^2 value for the model was 0.81, indicating that the regression model explained 81% of the variation in the data set.

The regression results are illustrated by a plot of predicted precision as a function of the proportion of collars located across the range of observed levels of aggregation (Figure 5). In this case, a θ value of 0.19 was the highest level of aggregation observed (CB herd, July 9, 2006) and 0.9 was the lowest level of aggregation (BE herd, 2000) with the mean level of aggregation at 0.37 and a lower level of aggregation represented by the 90^{th} percentile of theta of 0.53. The main conclusion is that if caribou are very aggregated (θ=0.2), acceptable levels of precision (CV<20%) can be achieved with less dependence on the proportion of collared caribou located. At mean levels of aggregation (θ=0.37), at least 70% of the collars need to be located, and up to 90% of the collars need to be located if aggregation is relatively low. If caribou are not substantially aggregated (θ=0.9), then it is not possible to get a precise estimate even if all the collared caribou are located.

Correspondence of Lincoln-Petersen and Rivest estimates

In 4 of the 20 data sets the Lincoln-Petersen estimate was equal to the number of caribou counted due to all of the collared caribou being observed in photographed groups (Table 4). In this case, the estimated variance was 0. Estimated precision was high for all LP estimates with coefficients of variation of less than 20%. Estimates from groups that contained collars were 5.9% lower (std. dev.=7.0%, min=0%, max=16.4%, n=20) than estimates that used total counts of all caribou. The variance was minimally affected by whether groups with collars were included or excluded, with similar coefficients of variation. We used the estimates that used all caribou groups observed, with or without collars, for comparison with the Rivest estimates, given that it was likely that collared groups and non-collared groups were in close proximity and it was likely that collared groups helped in detecting non-collared groups during the aerial search process. In other words, it was likely that all groups (with or without collars) had a probability of containing collars and

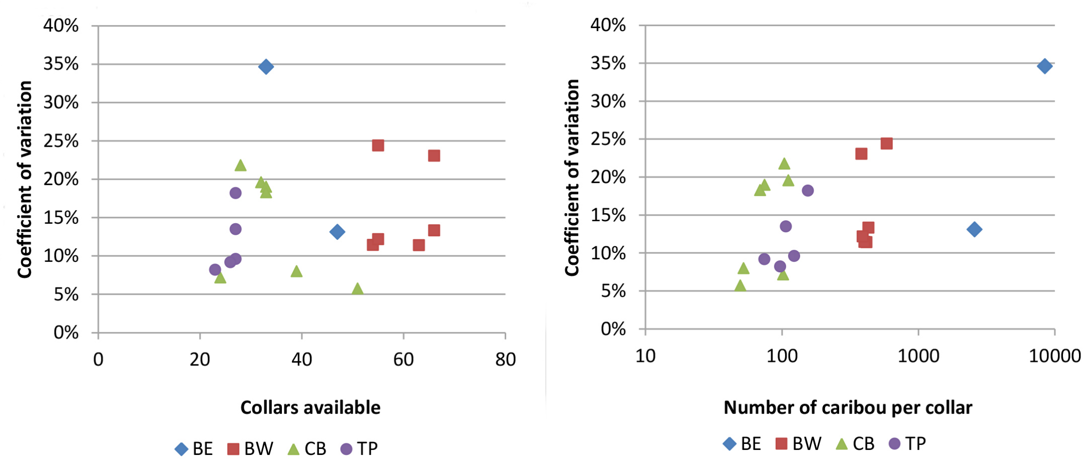

Figure 3. The relationship between the number of caribou collared (left graph) and the number of estimated caribou per collared caribou ($\hat{T}$)/No. of collared caribou; right graph) with Rivest estimator precision (CV) for caribou herds in the Northwest Territories and Nunavut, Canada, 2000-2015. Estimates are displayed from the Bluenose-East (BE), Bluenose-West (BW), Cape Bathurst (CB) and Tuktoyaktuk Peninsula (TP) herds.

therefore inclusion of non-collared groups was justifiable.

Lincoln-Petersen estimates were 21.0% lower (std.=14.3% min=2.0%, max=56.7%, n=20) on average than the Rivest estimates (Table 2). The difference was most pronounced for the BW and BE herds where the relative sample size of collars to overall herd size was lower. Confidence limits from the Rivest estimator included the Lincoln-Petersen estimate in 17 of 20 surveys. However, confidence limits of the Lincoln-Petersen estimator did not overlap the Rivest estimator in 12 of 15 surveys. For the remaining 5 surveys there was no variance or confidence interval estimate for the Lincoln-Petersen estimate (Table 4), because all the collared caribou were found.

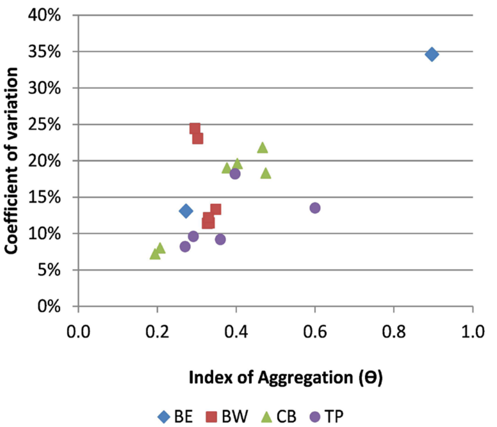

Figure 4. Relationship between Rivest estimator precision and aggregation as estimated by the dispersion parameter of the negative binomial distribution (θ) for caribou herds in the Northwest Territories and Nunavut, Canada, 2000-2015. Estimates are displayed from the Bluenose-East (BE), Bluenose-West (BW), Cape Bathurst (CB) and Tuktoyaktuk Peninsula (TP) herds.

Rivest and Lincoln-Petersen estimates were most similar when the majority of caribou groups were counted by the Rivest estimator as indexed by the total caribou counted divided by the Rivest herd estimate (Figure 6). This occurred when herds were well aggregated,

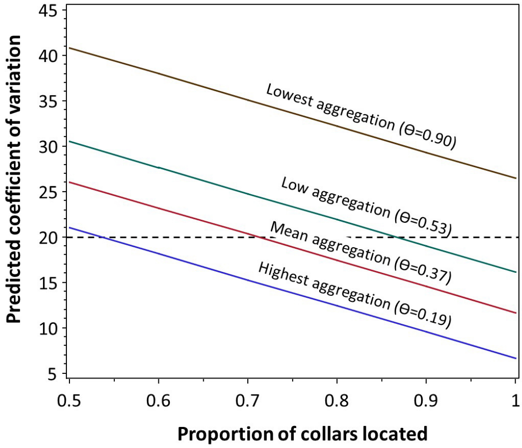

Figure 5. Predicted levels of precision as a function of roportion of available collars located across highest observed level of aggregation (θ=0.19), mean levels of aggregation (θ=0.37), lower levels of aggregation (90th percentile of θ=0.53) and the lowest level of aggregation (θ=0.9) from regression analyses (Table 3) for caribou herds in Northwest Territories and Nunavut, Canada, 2000-2015.

the majority of collared caribou were located, and most of the caribou were in a few groups. In these cases, the detection probabilities of groups ($\hat{P}_{group}$) for the Rivest estimator were 1 for all groups or for the majority of groups which had larger numbers of caribou. In these situations, the probability of at least one collared caribou in a group was close to 1 indicating that the herds had effectively been censused (all caribou in the herd were counted) in the survey, as also indicated by similar likelihood scores and estimates for the Rivest models. This mainly occurred in the TP and CB herds which were small and contained in relatively small areas where it was possible to conduct intensive surveys when compared to the larger BW and BE herds.

Discussion

Performance of the Rivest estimator

From a statistical perspective, the Rivest estimator provides an improvement in post-

Table 3. Regression analysis results for factors affecting the precision of post-calving survey estimates as indicated by the coefficient of variation for caribou herds in the Northwest Territories and Nunavut, Canada, 2000-2015.

Parameter	Estimate	SE	Confidence interval		t-value	p
Intercept	0.301	0.059	0.176	0.426	5.06	<.0001
Aggregation (θ)	0.279	0.051	0.172	0.386	5.50	<.0001
Proportion of collars located	-0.288	0.058	-0.411	-0.164	-4.92	0.0001

Table 4. Lincoln-Petersen estimates of herd size from post-calving surveys using all caribou counted and caribou only in groups that contained collared caribou for caribou herds in Northwest Territories and Nunavut, Canada, 2000-2015.

Herd Year	Caribou counted		Lincoln-Petersen All groups			Lincoln-Petersen Collared groups only		
	All groups	With collars	$\hat{N}$	SE($\hat{N}$)	CV	$\hat{N}$	SE ($\hat{N}$)	CV
Bluenose East								
2000	85,438	73,814	121,038	13126.6	10.8%	104,570	11340.5	10.8%
2010	92,481	80,081	98,646	3635.3	3.7%	85,420	3147.8	3.7%
Bluenose West								
2005	17,875	16,824	20,800	1040.8	5.0%	19,577	979.5	5.0%
2006	10,902	10,809	22,827	2868.0	12.6%	22,632	2843.5	12.6%
2006	17,781	16,378	17,781			16,378		
2009	16,595	15,108	17,897	668.3	3.7%	16,293	608.3	3.7%
2012	14,252	12,863	20,465	1780.5	8.7%	18,470	1606.7	8.7%
2015	13,637	13,628	15,274	698.8	4.6%	15,263	698.4	4.6%
Cape Bathurst								
2005	2,213	2,213	2,434	131.0	5.4%	2,434	131.0	5.4%
2006	1,508	1,490	1,831	141.6	7.7%	1,810	139.9	7.7%
2006	1,714	1,389	1,821	76.2	4.2%	1,476	61.6	4.2%
2006	1,514	1,703	1,781	115.4	6.5%	2,004	129.9	6.5%
2009	1,534	1,423	1,934	178.4	9.2%	1,794	165.4	9.2%
2012	2,427	2,247	2,427			2,247		
2015	2,216	2,203	2,259	43.0	1.9%	2,246	42.7	1.9%
Tuktoyaktuk Peninsula								
2006	2,866	2,677	2,866			2,677		
2006	3,078	2,894	3,078			2,894		
2009	2,556	2,138	2,753	140.9	5.1%	2,303	117.8	5.1%
2012	2,101	1,987	2,192	90.9	4.1%	2,073	85.9	4.1%
2015	1,701	1,698	1,701			1,698		

calving survey estimation methodology over the Lincoln-Petersen estimator. It provides a model-based method to estimate the number of caribou missed in the surveys that properly uses caribou groups and associated collared caribou in the group as the sampling unit. By doing this, more robust estimates of herd size and associated estimate variance are produced if the general assumptions of the post-calving method are met. The level of precision of the Rivest estimator is lower than that of the Lincoln-Petersen estimator. However, this variance estimate most likely reflects the true degree of statistical uncertainty in estimates, and the low variance or 0 variance from Lincoln-Petersen calculations is likely unrealistically low. Despite lower precision, the coefficients of variation for Rivest estimates were still within levels considered acceptable by managers (CV<20%; Pollock *et al.,* 1990) for most of the data sets we analyzed.

The main constraint of applying the Rivest estimator is having a suitable number of collared caribou to allow the modeling of detection probabilities of groups as indicated by groups with radio collars. The Rivest estimator cannot use data for groups without collars and therefore an imprecise estimate becomes more likely if collar sample size is reduced relative to the size of the herd (Figure 3) or a lower proportion of available collars is located (Figure 2). In addition, if caribou are less aggregated due to lower insect harassment then it will be more likely that multiple smaller groups with no collared caribou will occur unless collar sample size is very high. Therefore, it is essential that suitable numbers of collars are employed, and that sampling is conducted during times of peak aggregation. If aggregation does not occur sufficiently, then it is likely that no estimator or count will provide a reliable estimate of herd size from post-calving surveys (Figure 5). An earlier simulation study based upon the CB, BW and BE herds in 2006 recommended

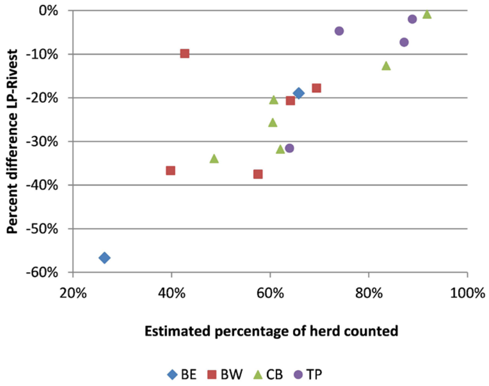

Figure 6. Comparison of difference between Lincoln Peterson and Rivest estimates ((LP estimate-Rivest estimate)/Rivest estimate) as a function of estimated proportion counted (total caribou counted/Rivest herd size estimate) for post-calving surveys of caribou herds in the Northwest Territories and Nunavut, Canada, 2000-2015. Estimates are displayed from the Bluenose-East (BE), Bluenose-West (BW), Cape Bathurst (CB) and Tuktoyaktuk Peninsula (TP) herds.

a sample of 30 collars for the relatively small CB herd, 40-60 collars for the BE herd, and 60 collars for the BW herd to allow an 80% probability of detecting at least 90% of the herd (Rettie, 2017). This analysis also identified the importance of group size distribution (many small groups vs. few large groups) as a key factor in the likely success of post-calving surveys

The assumption of randomness of collared caribou relative to groups was violated in 5 of 20 studies. Rivest *et al* (1998) discussed possible methods to confront this issue such as modelling the distribution of collars in groups as a negative binomial as opposed to a Poisson distribution. However, these enhancements have not been incorporated into the caribou program in R. The net result of violation of this assumption is a potential negative bias in estimates.

Performance of the Lincoln-Petersen estimator

The results of this study suggest that estimates from the Lincoln-Petersen model will generally be negatively biased due to heterogeneity of capture probability of collared caribou within groups: larger groups with multiple collars are more likely to be found than smaller groups with one collar or particularly groups with no collars. The true number of caribou in each herd is not known and therefore bias cannot be inferred by comparison of the Rivest and Lincoln-Petersen estimates. However, model selection results from the Rivest estimator demonstrated different levels of detection for groups as a function of the number of collars within each group (Table 2) as indicated by selection of the threshold models in 15 of the 20 data sets. If the assumption of equal probabilities of detection of groups ($\hat{P}_{group}$) was met, then the homogeneity model would most likely be chosen. The modelling of unequal probability of detection of groups ($\hat{P}_{group}$) as well as the probability of a group having at least one collar ($\hat{P}_{\geq 1 collar}$) with the Rivest estimator addresses two sources of heterogeneity bias that are not accounted for with the Lincoln-Petersen estimator. Subsequently, estimates from the Rivest estimator are generally higher than from the Lincoln-Petersen estimator. The Lincoln-Petersen estimator is likely to be negatively biased both in terms of the point estimate but also in terms of the estimate of precision, resulting in a "biased but apparently precise" estimate unless herds are well aggregated and the vast majority of caribou in the herd are enumerated. In this case estimates from the Lincoln-Petersen estimator, Rivest estimator and total count of caribou converge (Figure 6).

In post-calving surveys of the Western Arctic Herd (WAH), which has at times numbered more than 400,000, collar numbers have generally been 90-100, survey coverage has been intensive with multiple survey aircraft and Rivest estimates have shown a high degree of convergence with totals counted on photos (Alaska Department of Fish and Game, 2011; Harper, 2013). These results suggest that the WAH has effectively been censused during multiple post-calving surveys, as apparently occurred in the much smaller CB herd in the NWT in 2006, 2012 and 2015. Results for the small TP herd in the NWT likewise have shown a fairly close correspondence between Rivest estimates and total counts. Under these conditions which include reasonable levels of aggregation and relatively high collar numbers, the Lincoln-Petersen estimates would likely be very similar to the Rivest estimates and total counts. Post-calving surveys of the Teshekpuk herd in Alaska (Harper, 2013) generally used lower collar numbers (35-60) than in the WAH, and in these surveys the Rivest estimates were higher than the total counts by an average of 16.3%, similar to the differences we found. As collar numbers increased over the years for the Teshekpuk herd, the difference between total counts and Rivest estimates grew smaller (Harper, 2013), suggesting that higher collar numbers led to increased group detection probabilities.

A recent report from Québec (Brodeur *et al.*, 2017) suggested that the Lincoln Petersen estimator is suitable for post-calving surveys of the George River and Leaf River herds, given recent advances in collaring technology, high collar numbers and a large survey effort used to locate all caribou groups. While the Lincoln Petersen estimate may be close to herd size in some circumstances, we suggest that the use of the Rivest estimator and associated aggregation index introduced in this manuscript allow a statistical test of whether a near-census of a herd has occurred, in which case the minimum count, the Lincoln Petersen estimate, and Rivest estimate will be similar. This type of information would not be available with exclusive use of the Lincoln-Petersen estimator. We therefore suggest that Rivest estimates be used for all post-calving surveys especially given the relative ease of obtaining estimates using the *caribou R* package.

Use of the negative binomial aggregation index to assess performance of Rivest estimator
We suggest that the negative binomial index can be used to retrospectively analyze data and potentially determine scenarios when reliable post-calving estimates are not possible. A notable example of a year with a poor Rivest estimate was the BE herd in 2000. In this year, the herd did not aggregate well as exemplified by the aggregation index (θ=0.90) suggesting the poorest aggregation of any data set considered. In addition, a lower proportion of the collars were located which may also have been caused by poor aggregation (Patterson *et al.,* 2004). The majority of the groups for this year only contained 1 to 3 collars with many groups having 0 collars, and the numbers of collars available and found were low (Appendix 1). As a result, the estimate was imprecise (CV=35%) and not reliable. Basically, there was not enough information in the data set to adequately model the relationship between collared caribou and group sizes. Some claims have been made that the Rivest estimator was "biased" when aggregation is poor based upon the Bluenose 2000 results (Patterson *et al*., 2004). In terms of statistics, bias cannot be inferred from this result given that bias is not really meaningful when precision of an estimate is low (wide confidence limits). Basically, a coefficient of variation much over 20% should raise a "red flag" from the Rivest estimator or any other estimator. It could be argued that the general requirements for the Rivest estimator are not necessarily unique to this estimator alone. The general challenge of the post-calving method is assuring that survey conditions are sufficient for reasonable enumeration of aggregations. In addition, collar sample sizes should be adequate so that most groups can have a reasonable probability of being detected. If they are not, then it is likely that no estimator can provide a reliable population estimate from these surveys. The advantage of the Rivest estimator in this context is that it provides a statistical assessment of how survey conditions were met through statistical interpretation of the precision of herd size estimates.

Recommendations
We make the following recommendations for the use of the Rivest estimator and successful post-calving surveys. First, the precision of the Rivest estimator depends partially upon finding a substantial proportion of the collared caribou in the herd. In general, at least 80% of collared caribou should be located and photographed in groups to ensure adequate precision (Figure 5). Under ideal conditions, nearly 100% of the collars will be found and photographed; however, we have occasionally had surveys (e.g. BW herd in 2012) where a limited portion of the herd, with associated collars, did not aggregate sufficiently for photos. If less than 80% of collars are located after substantial effort, then it may be that the herd is not well aggregated, and a lower precision estimate will result (Figure 5). Second, the sample size of collars required depends on the estimated herd size. Estimates with adequate precision were obtained for the Tuktoyaktuk Peninsula and CB herds with sample sizes of 20-30 collars whereas sample sizes of greater than 50 collars were required for the BE and West herds. Aggregation of caribou is a critical factor with results demonstrating the difficulty of obtaining reliable estimates when aggregation is low even with substantial sampling effort. The negative binomial θ term provides a way to compare the degree of aggregation across surveys. We suggest that this coefficient can provide a diagnostic of the influence of aggregation on estimate precision.

Management context: herd status and management for four herds
Management of the CB, BW and BE herds in the NWT and NU is primarily defined in a management plan finalized in 2014 (ACCWM

2014) while a management plan for the TP herd, whose range is solely in one land claim region, remains to be developed. The ACCWM plan uses a color chart with four phases (red, low numbers; green, high numbers; yellow, intermediate and increasing; and orange, intermediate and declining) and numerical thresholds between phases. As an example, the red phase for the BE herd is 20,000 or less, the green phase is above 120,000, and the threshold between green and either yellow or orange is at 60,000. The co-management boards making up the ACCWM hold an annual status meeting where each of the three herds is assessed, using available demographic data and other monitoring, including reports from the communities within each herd's range. Management of harvest and other actions is tied to the color phase that each herd is considered to be in, with the strongest actions for herds in the red phase. Population estimates for each herd are key to defining herd size and trend, although they are not the sole information used in assigning herd status. In 2016-2017, through a number of meetings that included the GNWT and co-management boards in the ACCWM, a transition from LP estimates to Rivest estimates was agreed to as a more robust way of estimating herd size and variance from post-calving surveys in the TP, CB and BW herds.

In 2016 the Wekèezhìı Renewable Resources Board (WRRB) held a hearing to consider management actions for the BE herd, which had by 2015 declined to about 38,600 caribou from more than 100,000 in 2010 and was assessed as being in the orange phase (WRRB 2016). The WRRB determined that harvest in that land claim area should be limited to 750 bulls/year (WRRB 2016). Similar hearings resulted in limitation of BE harvest in NU of 340 caribou/year and 150 caribou in the Sahtú region of the NWT. Population surveys for the BE herd switched in 2010 from a post-calving survey to a calving photo survey (Adamczewski *et al.*, 2017) after multiple failed post-calving surveys.

The BW herd has been roughly stable between 21,000 and 28,000 between 2005 and 2015 (this paper, Rivest), after a large decline 2000-2005 (ACCWM 2014). The Wildlife Management Advisory Council (Northwest Territories) (WMAC(NWT)), Gwich'in Renewable Resources Board (GRRB) and SRRB made recommendation to limit harvest for this herd to a 4% annual rate and 80% bulls (ACCWM 2014). Harvest limitations for the herd are unlikely to change unless the herd shows clear evidence of recovery.

The CB herd has been roughly stable at about 2500 caribou 2006-2015 (this paper, Rivest) after a large decline 2000-2005 (ACCWM, 2014). This herd is considered to be in the red phase, thus the WMAC(NWT) and GRRB made recommendations to close harvest of the CB herd by creating no-hunting zones (ACCWM, 2014). The TP herd has declined steadily from 4,188 caribou in 2006, when it was first surveyed, to 1,930 in 2015 (this paper, Rivest), leading to increased discussions about harvest limitation.

The overall trends in the four herds where post-calving surveys have been used, and associated management, have not been altered by the transition from LP estimates to Rivest estimates, although individual survey estimates have increased by varying percentages and an average increase of 21.0%. A new round of population surveys for all four herds in 2018 is planned, and thereafter herd status will be assessed and management may be re-evaluated. We suggest that greater attention be paid in future in management discussions to the quality of Rivest-generated estimates, including the degree of aggregation, the adequacy of collar numbers, the proportion of collars found in photographed groups, and the overall precision of the estimates. The 2012 BW survey had poor aggregation in groups associated with 17 of 55 collared caribou, for which photos were not feasible, and the coefficient of variation was a relatively high 24.4%. These results mean that this population estimate should be used with caution when compared to other surveys of this herd with better aggregation and higher precision, such as the 2009 and 2015 surveys.

References

ACCWM. 2014. Advisory Committee for Cooperation on Wildlife Management: Taking Care of Caribou: the Cape Bathurst, Bluenose-West, and Bluenose-East barren-ground caribou herds management plan. Yellowknife, NWT, c/o Wekèezhìı Renewable Resources Board, 102A, 4504-49 Avenue, Yellowknife, Northwest Territories, Canada.

Adamczewski, J., Boulanger, J., Croft, B., Davison, T., Sayine-Crawford, H. & Tracz, B. 2017. A comparison of calving and post-calving photo-surveys for the Bluenose-East herd of barren-ground caribou in northern Canada in 2010. — *Canadian Wildlife Biology and Management* 6: 4-30.

Alaska Department of Fish and Game. 2011. Caribou management report of survey-inventory activities 1 July 2008-30 June 2010. P. Harper, editor. Juneau, Alaska, USA.

Anderson, D.R. 2001. The need to get the basics right in wildlife field studies. — *Wildl. Soc. Bull.*29: 1294-1297.

Anscombe, F.J. 1948. The transformation of Poisson, binomial and negative binomial data. —*Biometrika* 35**:** 246-254. https://doi.org/10.2307/2332343

Brodeur, V., Rivard, S., Dussault, C., Harvey, L. & Tallon, J. 2017. The Use of Satellite Telemetry to Estimate the Abundance of a Migratory Caribou Population. Ministère des Forêts, de la Faune et des Parcs, Quebec.

Crepeau, H., Rivest, L.P., Courtrier, S. & Baillargeon, S. 2012. Package "caribou" (R): Estimation of caribou abundance based on large scale aggregations monitored by radio telemetry, Version 1.1, Universite Laval, Quebec City.

Davis, J.L., Valkenburg, P. & Harbo, S. 1979. Refinement of the aerial photo-direct count extrapolation caribou census technique,Final Report Federal Aid in Wildlife Restoration Project W-17-11, Job 3.25R. pp. 23. Alaska Department of Fish and Game, Juneau, AK.

Davison, T., Callaghan, K., Popko, R. & Milakovic, B. 2014. Population estimates of Tuktoyaktuk Peninsula, Cape Bathurst and Bluenose-West barren-ground caribou herds, using post-calving photography, July 2009. Department of Environment and Natural Resources, Government of the Northwest Territories, Yellowknife, NWT, Manuscript Report No. 239.

Davison, T., Sayine-Crawford, H., Callaghan, K. & Pongracz, J. 2016. Population estimates of Tuktoyaktuk Peninsula, Cape Bathurst and Bluenose-West barren-ground caribou herds, using post-calving photography, July 2012. Department of Environment and Natural Resources, Government of the Northwest Territories, Yellowknife, NWT, Manuscript Report No. 258.

Harper, P. (Ed.). 2013. Caribou management report of survey-inventory activities 1 July 2010–30 June 2012. Alaska Department of Fish and Game, Species Management Report ADF&G/DWC/SMR-2013-3, Juneau, Alaska.

Krebs, C.J. 1998. *Ecological Methodology (Second edition)*. Benjamin Cummins, Menlo Park, California.

Lincoln, F.C. 1930. Calculating waterfowl abundance on the basis of banding returns. — *U.S. Department of Agriculture Circular* 118**:** 1-4.

Nagy, J. & Johnson, D. 2013. Estimates of the number of barren-ground caribou in the Cape Bathurst and Bluenose-West herds derived using post calving photography, July 2005. Department of Environment and Natural Resources, Government of the Northwest Territories, Yellowknife, Northwest Territories, Manuscript report No. 212.

Nagy, J.A. & Johnson, D. 2006. Estimates of the number of barren-ground caribou in the Cape Bathurst and Bluenose-West herds and reindeer/caribou on the upper Tuktoyaktuk Peninsula derived Using Post Calving Photography, July 2006. Department of Environment and Natural Resources, Government of the Northwest Territories, Yellowknife, Northwest Territories, Manuscript report No. 171.

Patterson, B.R., Olsen, B.T. & Joly, D.O. 2004. Population estimate for the Bluenose-East caribou herd using post-calving photography. — *Arctic* 57**:** 47-58. https://doi.org/10.14430/arctic482

Pollock, K.H., Nichols, J.D., Brownie, C. & Hines, J.E. 1990. Statistical inference for capture-recapture experiments. — *Wildl. Monographs* 107: 1-97.

R Development Core Team. 2009. R: A language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria.

Rettie, W.J. 2017. Determining optimal sample sizes for monitoring barren ground caribou populations. Department of Environment and Natural Resources, Government of the Northwest Territories, Yellowknife, NWT, Manuscript report No. 264.

Rivest, L.P., Couturier, S. & Crepeau, H. 1998. Statistical methods for estimating caribou abundance using postcalving aggregations detected by radio telemetry. — *Biometrics* 54: 865-876. https://doi.org/10.2307/2533841

Russell, J., Courtrier, S., Sopuck, L.G. & Ovaska, K. 1996. Post-calving photocensus of the Riviere George caribou herd in July 1993. — *Rangifer* 9**:** 319-330. https://doi.org/10.7557/2.16.4.1273

Valkenburg, P., Anderson, D.A., Davis, J.L. & Reed, D.J. 1985. Evaluation of an aerial photo census technique for caribou based on radio-telemetry. *Second North American Caribou Workshop* (eds T.C. Meredith & A.M. Martell), pp. 287-299. Montreal: Centre for Northern Study and Research, McGill University.

Venables, W.N. & Ripley, B.N. 2013. Program MASS: Support Functions and Datasets for Venables and Ripley's 'Modern Applied Statistics with S', fourth edition, by W. N. Venables and B. D. Ripley. Springer, 2002, ISBN 0-387-95457-0.

White, G.C. & Bennetts, R.E. 1996. Analysis of frequency count data using the negative binomial distribution. — *Ecology* 77: 2549-2557. https://doi.org/10.2307/2265753

White, G.C. & Garrott, R.A. 1990. *Analysis of Wildlife Radio-tracking Data*. Academic Press, New York.

Wekèezhìı Renewable Resources Board (WRRB). 2016. WRRB Reasons for Decission Final Report, Part A - Bluenose-East Herd. Wekèezhìı Renewable Resources Board, 102A, 4504-49 Avenue, Yellowknife, Northwest Territories, Canada.

Zar, J.H. 1996. *Biostatistical analysis,* Third edn. Prentice-Hall, London.

Manuscript recieved 19 October 2017
revision accepted 21 August 2018
manuscript published 9 December 2018

Appendix 1-Details on analyses of individual data sets

This section provides listings of field data and summaries of each of the post-calving survey data sets used in the paper. Lower confidence limits were constrained to be equal to the total count of caribou during the survey.

Bluenose-East (BE) herd

Table 1. Field data for the Bluenose-East 2000 post calving survey.

Date	Group	No. of collars	Caribou counted	Date	Group	No. of collars	Caribou counted
02-Jul	8	3	4,975	02-Jul	15	1	2,844
02-Jul	9	3	7,109	06-Jul	19	1	2,493
02-Jul	5	2	16,727	06-Jul	20	1	1,953
02-Jul	10	2	5,468	06-Jul	21	1	11,334
04-Jul	17	2	3,424	06-Jul	22	1	5,461
30-Jun	1	1	2,023	01-Jul	2	0	1,386
02-Jul	3	1	1,787	02-Jul	4	0	452
02-Jul	6	1	11,389	02-Jul	7	0	682
02-Jul	11	1	1,745	02-Jul	12	0	3,249
02-Jul	13	1	3,558	04-Jul	16	0	2,904
02-Jul	14	1	3,148	06-Jul	18	0	1,925
				Total		**23**	**96,036**

2000

The BE herd was surveyed in 2000 (Patterson *et al.*, 2004) from July 2 to July 6. Of 33 collars that were available, 23 were detected, with 1 to 3 collars per group of caribou observed. Patterson *et al.* (2004) in their Table 1 derived a total count of 84,412 adult caribou for the BE herd in 2012; the reduction from 96,036 was based on estimated overlap with BW collared caribou. The adjusted 84,412 total was used in Fig. 15. The Rivest estimate in Fig. 15 was adjusted downward by the same factor to 245,545; however, all Rivest estimates for this survey had low precision.

Table 2. Rivest model estimates and Lincoln-Petersen (LP) estimates for Bluenose-East herd 2000 survey.

Detection Model	Log-likelihood	Detection probabilities		Estimate of herd size			
		Estimate	SE	$\hat{T}$	SE ($\hat{T}$)	CI(±)	CV
Threshold (B=2)	-6.48	0.52	0.11	279,358	96597.3	189,331	34.6%
Homogeneity	-6.47	0.70	0.11	204,944	62474.5	122,450	30.5%
Independence	-6.37	0.43	0.10	250,961	83547.8	163,754	33.3%
Threshold (B=3)	-6.28	0.63	0.11	239,048	74442.9	145,908	31.1%
LP (all groups)				121,038	13126.6	25,728	10.8%
LP (collared groups only)				104,570	11340.5	22,227	10.8%

A threshold Rivest model with groups of 2 or more collars having detection probabilities of 1 had the highest likelihood. Groups with less than 2 collars had detection probabilities of 0.5.

All Rivest herd estimates were imprecise (CV>31%) and ranged between 204,944 and 279,358. Lincoln-Petersen estimates were substantially lower. Patterson *et al.* (2004) used only groups with collars for Lincoln-Petersen estimates so this estimate is included in addition to an estimate using counts from all groups.Tests for random distribution of collars suggest this assumption was not violated in the BE 2000 survey.

Table 3. Tests for randomness of collar distribution for the Bluenose-East 2000 survey.

Model	Z	p-value
Threshold (B=3)	-0.124	0.550
Independence	-0.056	0.523
Homogeneity	-0.119	0.547
Threshold (B=2)	0.056	0.478

2010

The Bluenose-East herd was primarily surveyed from July 6-12, 2010, at which time caribou groups congregated into 3 geographic areas (Main, Southern and Northern). During this time 47 collared caribou were monitored of which 44 were located within photographed groups. Thirty nine groups were counted on photos which amounted to a total count of 92,481 caribou (Adamczewski *et al.*, 2017).

Table 4. Field data for the Bluenose East 2010 post-calving survey.

Date	Group	No. of collars	Caribou counted
Groups with collars			
06-Jul	Southern	1	11,461
06-Jul	Southern	1	4,080
06-Jul	Southern	1	804
06-Jul	Southern	1	385
06-Jul	Southern	1	5
06-Jul	Southern	1	3
09-Jul	Main	8	11,652
09-Jul	Main	3	8,327
09-Jul	Main	2	7,585
09-Jul	Main	5	7,528
09-Jul	Main	1	7,365
09-Jul	Main	4	4,989
09-Jul	Main	2	4,942
09-Jul	Main	2	1,943
09-Jul	Main	1	1,014
12-Jul	Northern	3	5,999
12-Jul	Northern	2	1,106
12-Jul	Northern	1	760
12-Jul	Northern	1	115
12-Jul	Northern	1	14
12-Jul	Northern	1	3
12-Jul	Northern	1	1
Groups without collars			
12-Jul	Northern	0	3,870
12-Jul	Northern	0	914
12-Jul	Northern	0	268
12-Jul	Northern	0	226
12-Jul	Northern	0	175
12-Jul	Northern	0	6
12-Jul	Northern	0	2
06-Jul	Southern	0	175
06-Jul	Southern	0	2
06-Jul	Southern	0	2
09-Jul	Main	0	2,263
09-Jul	Main	0	1,980
09-Jul	Main	0	1,523
09-Jul	Main	0	670
09-Jul	Main	0	242
09-Jul	Main	0	79
09-Jul	Main	0	2
09-Jul	Main	0	1

A threshold model with group sizes of 8 or more caribou having a probability of detection of 1 had the highest log-likelihood score. Estimates were precise and relatively similar between the Rivest models.

Table 5. Rivest model estimates and LP estimate for the Bluenose-East 2010 survey[1].

Detection Model	Log-likeliood	Detection probabilities		Estimate of herd size				
		Estimate	SE	$\hat{T}$	SE ($\hat{T}$)	Confidence limit		CV
Threshold (B=8)	2.474	0.92	0.067	121,702	15,934.3	92,481	152,933	13.1%
Threshold (B=5)	2.415	0.91	0.069	122,697	16,202.2	92,481	154,453	13.2%
Homogeneity	2.412	0.94	0.066	120,495	15,673.3	92,481	151,215	13.0%
Threshold (B=2)	2.364	0.81	0.098	127,841	18,361.2	92,481	152,933	13.1%
Independence	2.363	0.83	0.087	127,101	18,055.5	92,481	163,829	14.4%
Threshold (B=4)	2.361	0.90	0.072	123,872	16,349.6	92,481	162,490	14.2%
Threshold (B=3)	2.313	0.88	0.079	124,934	17,060.2	92,481	155,917	13.2%
Lincoln-Petersen				98,646	3635.3	92,481	105,772	3.7%

[1] In earlier analyses of this data set, a threshold model with B=5 was found to have the best log-likelihood. Those results were used by Adamczewski *et al.* (2017). The difference is 1005 caribou for the herd estimate.

Table 6. Tests for randomness of collared caribou across groups for the Bluenose-East 2010 survey.

Model	Z	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

Bluenose-West (BW) herd

2005

The Bluenose-West 2005 survey was conducted on July 6 (Nagy & Johnson, 2013). Sixty three caribou with collars were available during the survey, of which 54 were detected in photographed groups. Overall, 17,875 caribou were counted of which 16,824 were in groups that contained one or more collared caribou.

Table 7. Field data for the Bluenose-West 2005 post calving survey.

Group	No. of collars	Caribou counted
8	6	1,750
19	2	1,678
9	7	1,321
10	3	1,256
6	1	619
13	3	591
11	2	571
18	1	556
17	4	470
2	1	360

Group	No. of collars	Caribou counted
4	1	338
3	0	282
1	1	203
5	0	185
7	0	33
12	1	12
14	1	7
15	0	1
16	0	1
20	1	1

Table 7. Continued.

Group	No. of collars	Caribou counted
28	0	1
39	1	2
29	0	44
30	0	3
26	0	1
33	0	116
31	0	1
38	0	135
37	0	71
22	2	857
24	0	1
23	1	826
21	10	4,913
25	1	91
27	0	3
32	1	83
34	2	308
35	1	11
36	0	170
40	0	3

A Rivest threshold model with group sizes of 6 or greater having a detection probability of 1 and groups of less than 6 having a detection rate of 0.78 had the highest likelihood. The resulting herd estimate was reasonably precise with a CV of 11.4%. The model estimates ranged between 25,370 and 27,863.

Table 8. Rivest estimator results and LP estimate for the Bluenose-West 2005 survey.

Detection Model	Log-likelihood	Detection probabilities		Estimate of herd size			
		Estimate	SE	$\hat{T}$	SE ($\hat{T}$)	CI(±)	CV
Threshold(B=6)	15.60	0.78	0.09	26,228	2999.02	5,878	11.4%
Threshold(B=10)	15.33	0.83	0.09	25,370	2813.98	5,515	11.1%
Threshold(B=4)	15.31	0.75	0.10	26,826	2967.00	5,815	11.1%
Homogeneity	15.30	0.86	0.09	25,632	2783.88	5,456	10.9%
Threshold(B=3)	15.18	0.70	0.10	27,464	3104.98	6,086	11.3%
Independence	15.12	0.36	0.09	27,542	3166.07	6,206	11.5%
Threshold(B=2)	14.86	0.59	0.10	27,863	3252.04	6,374	11.7%
Lincoln-Petersen				20,800	1040.8	2,040	5.0%

Tests for randomness of collared caribou across groups suggested that this assumption was met for all the models that were considered in the BW 2005 survey.

Table 9. Tests for randomness of collared caribou across groups for the Bluenose-West 2005 survey.

Model	Z	p-value
Homogeneity	-0.007	0.503
Threshold(B=3)	-0.055	0.522
Independence	-0.014	0.505
Threshold(B=2)	0.039	0.485

2006

The 2006 BW survey was conducted on two sampling occasions; a smaller number of groups were counted on July 4, and then sampling was repeated on July 7 and 8, with a larger number of groups being counted (Nagy & Johnson, 2006).

Table 10. Field data for the Bluenose-West 2006 post calving survey.

Group	No. of Collars	Caribou counted
July 4, 2006		
1	12	5,388
2	9	3,358
3	4	644
4	2	1,196
5	1	135
6	1	74
7	1	7
8	1	7
9	0	80
10	0	13
Total	**31**	**10,902**

Group	No. of Collars	Caribou counted
July 7 and 8, 2006		
1	10	3,028
2	7	1,511
3	6	1,271
4	3	486
5	2	173
6	2	384
7	2	283
8	2	757
9	1	844
10	1	86
11	1	8
12	1	689
13	1	1,223
14	1	136
15	1	97
16	1	3
17	1	377
18	1	229
19	1	2
20	1	511
21	1	3
22	1	310
23	1	418
24	1	284
25	1	75
26	1	105
27	1	1365
28	1	616
29	1	114
30	1	6
31	1	35
32	1	2
33	1	22
34	1	337
35	1	7
36	1	24
37	1	354
38	1	127
39	1	76
40	0	3
41	0	199
42	0	12
43	0	189
44	0	4
45	0	3
46	0	27
47	0	137
48	0	208
49	0	111
50	0	81
51	0	32
52	0	4
53	0	1
54	0	153
55	0	2
56	0	9
57	0	23
58	0	23
59	0	8
59	0	8
60	0	9
61	0	1
62	0	2
63	0	3
64	0	5
65	0	154
Total	**65**	**17,781**

For the July 4 data set, a Rivest model with detection rates of groups with greater or equal to 9 collared caribou showing detection probabilities of 1 displayed the highest likelihood score. Detection rates were relatively low (.22) for groups with less than 9 collared caribou. Rivest model estimates for the July 4 sampling session varied between 25,000 and 30,000 caribou with good to marginal precision. In comparison, the Lincoln Petersen estimate was 22,827.

For the July 7 and 8th data set, a threshold model with groups with 6 or more collared caribou showing detection probabilities of 1 and groups with less than 6 collars still showing high detection rates (0.97) was most supported. All models estimated high detection probabilities and in general estimates were very close and in the range of 28,000 caribou.

The two estimates basically suggest that the majority of groups were counted on July 7 and 8 compared to July 4th. Reassuringly, the estimates from the 2 sessions are relatively close despite the differences in the number of groups counted. This result suggests that the Rivest estimator was effectively estimating the fact that groups were missed on July 4th, but bias cannot be inferred from these results given that the true number was not known. The July 7-8 estimate is preferred due to higher precision and a higher proportion of collars found.

Table 11. Rivest Estimator results for the Bluenose-West July 4 and July 7-8, 2006 data sets (Nagy & Johnson. 2006). The Lincoln-Petersen estimate is based on Nagy & Johnson (2006).

Detection Model	Log-likelihood	Detection probabilities		Estimate of herd size			
		Estimate	SE	$\hat{T}$	SE ($\hat{T}$)	CI(±)	CV
July 4, 2006							
Threshold(B=9)	28.45	0.22	0.10	25,331	5837.25	11,441	23.04%
Threshold(B=4)	28.28	0.15	0.06	33,067	4964.98	9,731	15.01%
Independence	28.17	0.84	0.05	28,291	4671.63	9,156	16.51%
Homogeneity	27.98	0.47	0.17	26,700	2567.38	5,032	9.62%
Threshold(B=12)	27.86	0.35	0.15	25,429	3084.58	6,046	12.13%
Threshold(B=2)	27.09	0.10	0.05	29,273	5394.27	10,573	18.43%
Lincoln-Petersen				22,827	2868.0	5,621	13%
July 7-8, 2006							
Threshold (B=6)	6.97	0.977	0.027	28,461	3791.2	7,431	13.32%
Threshold (B=7)	6.96	0.980	0.028	28,381	3791.7	7,432	13.36%
Threshold (B=10)	6.94	0.982	0.028	28,310	3783.4	7,415	13.36%
Homogeneity	6.93	0.985	0.029	28,262	3758.9	7,367	13.30%
Threshold (B=4)	6.93	0.977	0.027	28,461	3791.2	7,431	13.32%
Threshold (B=3)	6.88	0.975	0.027	28,508	3796.1	7,440	13.32%
Independence	6.80	0.031	0.030	28,621	3818.1	7,483	13.34%
Threshold (B=2)	6.80	0.969	0.031	28,626	3819.0	7,485	13.34%
Lincoln-Petersen				17,781			

Tests for randomness of collared caribou distribution suggested that collared caribou were randomly distributed within groups for both the July 4 and July 7-8 data sets in the BW 2006 survey.

Table 12. Tests for randomness of collared caribou for the Bluenose-West July 4 and July 7-8, 2006 data sets.

Model	Z	p-value
July 4, 2006		
Independence	-0.861	0.805
Homogeneity	-0.808	0.790
Threshold (B=2)	-0.817	0.793
July 7-8, 2006		
Homogeneity	1.180	0.119
Threshold (B=3)	1.211	0.113
Independence	1.238	0.108
Threshold (B=2)	1.239	0.108

2009

For the BW 2009 survey, larger groups had more collared caribou with one notable exception where group 42 of 2,515 had only one collared caribou (Davison *et al.*, 2014). There were 54 collared caribou during the survey. Of these, 50 collars were found during the survey in 21 groups with 15,108 caribou counted in all groups that had collars. If groups without collars are considered then 16,595 caribou were counted.

Table 13. Bluenose-West 2009 post calving field data.

Date	Group	No. of Collars	Caribou counted
12-Jul-09	1	2	950
12-Jul-09	3	1	25
12-Jul-09	6	0	3
12-Jul-09	9	0	25
12-Jul-09	12	0	13
12-Jul-09	13	0	4
12-Jul-09	14	0	84
12-Jul-09	15	0	5
12-Jul-09	16	1	486
12-Jul-09	17	1	258
12-Jul-09	18	1	51
12-Jul-09	19	1	24
12-Jul-09	20	0	6
12-Jul-09	21	0	1
12-Jul-09	22	0	3
12-Jul-09	23	0	1
12-Jul-09	24	0	5
12-Jul-09	25	10	3,210
12-Jul-09	26	3	1,162
12-Jul-09	27	3	195

Date	Group	No. of Collars	Caribou counted
12-Jul-09	28	4	1,446
12-Jul-09	29	2	287
12-Jul-09	30	0	70
12-Jul-09	31	1	741
12-Jul-09	32	12	2,539
12-Jul-09	33	0	163
12-Jul-09	34	0	1
12-Jul-09	35	1	254
12-Jul-09	36	1	62
12-Jul-09	37	1	166
12-Jul-09	38	0	1
12-Jul-09	40	1	363
12-Jul-09	41	0	599
12-Jul-09	42	1	2,515
12-Jul-09	43	0	19
12-Jul-09	44	1	190
12-Jul-09	52	0	6
12-Jul-09	53	0	1
12-Jul-09	54	0	3
12-Jul-09	55	0	1

Table 13. Continued.

Date	Group	No. of Collars	Caribou counted
12-Jul-09	56	0	1
12-Jul-09	57	0	3
13-Jul-09	58	0	1
13-Jul-09	59	0	1
13-Jul-09	60	0	7
13-Jul-09	61	0	1
13-Jul-09	63	0	14
13-Jul-09	64	1	1
13-Jul-09	65	0	6
13-Jul-09	66	0	20
13-Jul-09	67	0	1
13-Jul-09	68	0	3
13-Jul-09	69	1	183
13-Jul-09	70	0	415
	Total	**50**	**16,595**

Model selection results from the Rivest estimator suggested that a threshold model with groups with 12 or more collars displaying detection rates of 1 and groups that had less than 12 collars displaying detection probability of 0.90. The homogeneity model assumes that collar mixing in groups is random and that all groups will have the same detection probability (of 0.93). The estimate of herd size from the best threshold model was 21,773 (± 4,884) caribou with a CV of 11.4% for the estimate, and similar to the other estimates.

Table 14. Rivest estimator results and LP estimate for the Bluenose-West 2009 data set.

Detection Model	Log-likelihood	Detection probabilities		Estimate of herd size			
		Estimate	SE	$\hat{T}$	SE ($\hat{T}$)	CI(±)	CV
Threshold(B=12)	19.42	0.90	0.09	21,773	2491.6	4,884	11.4%
Homogeneity	19.34	0.93	0.09	21,425	2459.7	4,821	11.5%
Threshold(B=10)	19.19	0.88	0.08	22,068	2621.7	5,139	11.9%
Threshold(B=3)	19.17	0.82	0.09	22,716	2871.4	5,628	12.6%
Threshold(B=4)	19.16	0.86	0.09	22,210	2733.4	5,357	12.3%
Independence	18.87	0.21	0.09	22,981	3002.5	5,885	13.1%
Threshold(B=2)	18.75	0.78	0.10	23,104	3047.3	5,973	13.2%
Lincoln-Petersen				17,897	1306.5	1,310	7.3%

Tests for randomness of collar distribution across groups suggested this assumption may have been violated. Therefore, estimates of herd size for the Rivest estimator may be negatively biased for this survey. Regardless, they are higher than the Lincoln-Petersen estimates for the BW 2009 data set.

Table 15. Tests for randomness of collared caribou for the Bluenose-West 2009 data set.

Model	Z	p-value
Homogeneity	1.979	0.024
Threshold (B=2)	2.207	0.014
Independence	2.192	0.014
Threshold (B=6)	2.160	0.015

2012
Fifty five collared caribou were available during the 2012 post calving survey (Davison *et al.*, 2016). Of these 38 were detected in photographed groups. Field observations suggested that the herd did not aggregate as well as in other years, which was the main reason that 17 collared caribou were not in photographed groups.

Table 16. Caribou groups counted for the 2012 Bluenose-West survey.

Group	No. of Collars	Caribou counted	Group	No. of Collars	Caribou counted	Group	No. of Collars	Caribou counted
1	9	1,949	12	1	448	23	1	211
2	0	2	13	0	559	24	0	1
3	0	24	14	1	1	25	3	547
4	1	183	15	0	1	26	2	350
5	3	596	16	0	3	27	2	3,652
6	1	117	17	0	1	28	0	696
7	0	101	18	1	1,423	29	2	747
8	1	174	19	3	822	30	1	3
9	1	1	20	1	408	31	1	1
10	1	129	21	1	316	17	0	1
11	0	1	22	1	785	18	1	1423
						Total	**39**	**15,676**

A threshold model with groups of 9 or more collars having detection probabilities of 1 and other groups with lower detection rates was most supported. Estimates were generally imprecise with coefficients of variation > 20%.

Table 17. Rivest Model estimates and LP estimate for Bluenose-West 2012 survey.

Detection Model	Log-likelihood	Detection probabilities		Estimate of herd size			
		Estimate	SE	$\hat{T}$	SE ($\hat{T}$)	CI(±)	CV
Threshold (B=9)	-1.21	0.63	0.10	32,326	7899.1	15,482	24.4%
Homogeneity	-1.47	0.69	0.12	28,969	7354.7	14,415	25.4%
Threshold (B=3)	-1.63	0.54	0.09	38,370	9440.6	18,504	24.6%
Independence	-1.82	0.50	0.08	36,144	8168.2	16,010	22.6%
Threshold (B=2)	-2.36	0.45	0.09	37,307	8018.3	15,716	21.5%
Lincoln-Petersen				20,465	1780.5	3,490	8.7%

Tests for randomness of collar distribution across groups suggested this assumption was violated and as a result, herd estimates may be negatively biased.

Table 18. Tests for randomness of collared caribou for the Bluenose-West 2012 data set.

Model	Z	p-value
Homogeneity	3.552	<0.001
Threshold (B=3)	3.711	<0.001
Independence	3.854	<0.001
Threshold (B=2	4.136	<0.001

2015

In 2015, 25 groups of caribou were counted of which 22 contained collared caribou (Davison *et al.*, unpublished). Forty nine of 55 available collars were located within photographed groups.

Table 19. Summary of collar and group data for the 2015 Bluenose-West post calving survey.

Group	No. of Collars	Caribou counted	Group	No. of Collars	Caribou counted
19	11	3,524	11	1	60
2	6	987	12	1	505
6	4	1,010	15	1	448
1	3	1,045	16	1	554
5	3	831	17	1	471
18	3	613	22	1	1
21	3	2300	23	1	1
8	2	157	24	1	1
3	1	472	25	1	1
4	1	1	13	0	1
7	1	371	14	0	2
9	1	146	20	0	4
10	1	131	**Total**	**49**	**13,637**

Model selection results indicated that a threshold model with groups of 3 or more having a sighting probability of 1 had the highest likelihood. The estimate from this model (21,535) was reasonably precise with a CV of 12.2%. Other Rivest model estimates were similar.

Table 20. Model selection and herd size estimates for the Bluenose-West 2015 post-calving survey.

Detection Model	Log-likelihood	Detection probabilities		Estimate of herd size			
		Estimate	SE	$\hat{T}$	SE ($\hat{T}$)	CI(±)	CV
Threshold (B=3)	14.54	0.73	0.10	21,535	2620.4	5,136	12.2%
Threshold (B=17)	14.22	0.86	0.09	20,676	2508.8	4,917	12.1%
Threshold (B=4)	14.17	0.84	0.09	21,059	2495.9	4,892	11.9%
Homogeneity	14.13	0.89	0.09	20,531	2356.3	4,618	11.5%
Independence	13.80	0.28	0.09	21,760	2622.2	5,140	12.1%
Threshold (B=2)	13.51	0.70	0.10	21,907	2638.3	5,171	12.0%
Lincoln-Petersen				15,274	698.8	1,369	4.5%

Tests for randomness of collar distribution across groups suggested that this assumption was not violated during the 2015 survey with non-significant tests for all models.

Table 21. Tests for randomness of collars across group sizes for the 2015 Bluenose-West survey.

Model	Z	p-value
Threshold (B=3)	-0.091	0.536
Homogeneity	-0.139	0.556
Independence	-0.031	0.512
Threshold (B=2)	0.0051	0.498

Cape Bathurst (CB) herd

2005

Thirty two collared caribou were monitored during sampling that occurred on June 9, 2005. Of these, 29 were located within photographed groups (Nagy & Johnson, 2013).

Table 22. Field data for the 2005 Cape Bathurst post calving survey.

Group	No. of Collars	Caribou counted	Group	No. of Collars	Caribou counted
6	10	492	5	1	1
15	3	174	7	1	173
1	2	7	10	1	6
8	2	228	11	1	421
9	2	138	12	1	453
2	1	22	13	1	15
3	1	9	14	1	1
4	1	73	**Total**	**29**	**2,213**

The most supported Rivest model was the homogeneity model, however, other model estimates were relatively similar. Tests for randomness of collared caribou distribution across groups suggested a non-random distribution, and therefore it is likely that these estimates are negatively biased.

Table 23. Rivest estimator results and LP estimate for Cape Bathurst 2005 survey.

Detection Model	Log-likelihood	Detection probabilities		Estimate of herd size			
		Estimate	SE	$\hat{T}$	SE ($\hat{T}$)	CI(±)	CV
Homogeneity	0.18	0.91	0.11	3,566	700.4	1373	19.6%
Independence	-0.06	0.21	0.10	3,967	793.7	1556	20.0%
Threshold (B=2)	-0.08	0.77	0.12	4,029	811.9	1591	20.1%
Threshold (B=3)	-0.09	0.84	0.10	3,812	732.3	1435	19.2%
Threshold (B=10)	0.31	0.86	0.09	3,739	706.8	1385	18.9%
Lincoln-Petersen				2,434	131.0	257	5.4%

Table 24. Tests for randomness of collar distribution for the Cape Bathurst 2005 survey.

Model	Z	p-value
Homogeneity	3.547	0.000195
Independence	3.892	0.000050
Threshold (B=2)	3.939	0.000041
Threshold (B=3)	3.793	0.000074

2006

Three sampling sessions for the CB herd were conducted in July 2006 (July 6, 9 and 13) and 33 collared caribou were monitored (Nagy & Johnson, 2006). The largest number of groups detected was on July 9.

Table 25. Summary of field data on three dates for the Cape Bathurst herd in 2006.

Group	No. of Collars	Caribou counted
July 6, 2006		
1	1	6
2	9	364
3	1	1
4	1	7
5	1	161
6	4	197
7	0	2
8	7	350
9	1	2
10	0	16
11	1	146
12	1	256
Total	**27**	**1,508**

Group	No. of Collars	Caribou counted
July 13, 2006		
1	1	1
2	2	106
3	7	225
4	19	1367
5	1	1
6	0	1
7	1	3
8	0	5
9	0	2
10	0	2
11	0	1
Total	**31**	**1,714**

Group	No. of Collars	Caribou counted
July 9, 2006		
1	6	166
2	3	58
3	1	192
4	2	106
5	0	14
6	4	70
7	3	128
8	3	224
9	1	6
10	1	34
11	0	1
12	0	15
13	0	48
14	1	1
15	1	67
16	1	264
17	0	2
18	1	53
19	0	35
20	0	9
21	1	18
22	1	2
23	0	1
Total	**30**	**1,514**

Estimates were run for each survey date. In general, estimates were reasonably similar for each sampling session with the highest level of precision obtained on July 13, which was presumably due to the higher level of aggregation at this time (19 collared caribou in one group of 1,367 caribou). This estimate is the preferred one for the herd in 2006.

Table 26. Rivest Estimator results and LP estimates for the Cape Bathurst herd July 6, 9, and 13, 2006 data sets. The Lincoln-Petersen estimate is based on Nagy & Johnson (2006).

Detection Model	Log-likelihood	Detection probabilities		Estimate of herd size			
		Estimate	SE	$\hat{T}$	SE ($\hat{T}$)	CI(±)	CV
July 6, 2016							
Threshold (B=7)	12.78	0.65	0.168	2462	468.1	917	19.0%
Threshold (B=9)	12.51	0.75	0.177	2297	376.6	738	16.4%
Homogeneity	12.30	0.82	0.160	2193	321.0	629	14.6%
Threshold (B=10)	12.27	0.82	0.160	2193	321.0	629	14.6%
Threshold (B=4)	12.15	0.54	0.138	2729	508.1	996	18.6%
Independence	11.10	0.45	0.133	2701	509.8	999	18.9%
Lincoln-Petersen				1831		278	8.0%
July 9, 2016							
Threshold (B=3)	-3.53	0.79	0.119	2288	419.3	822	18.3%
Threshold (B=6)	-3.73	0.89	0.092	2117	364.9	715	17.2%
Homogeneity	-3.78	0.91	0.088	2076	352.4	691	17.0%
Threshold (B=4)	-3.80	0.87	0.099	2163	371.8	729	17.2%
Independence	-3.95	0.23	0.114	2311	432.6	848	18.7%
Threshold (B=2)	-4.10	0.75	0.125	2338	438.8	860	18.8%
Lincoln-Petersen				1661	149.0	292	5.0%
July 13, 2016							
Threshold (B=7)	41.97	0.71	0.202	2039	162.6	319	8.0%
Threshold (B=2)	41.84	0.60	0.219	2038	172.0	337	8.4%
Independence	41.80	0.36	0.196	2038	168.5	330	8.3%
Threshold (B=19)	41.69	0.86	0.202	1998	152.3	298	7.6%
Homogeneity	41.67	0.94	0.152	2036	162.9	319	8.0%
Lincoln-Petersen				1821		149	4.0%

Tests for randomness of collar distribution across groups suggested this assumption was only violated on July 9. Inspection of the data suggested irregular groupings of caribou with one group of 6 collared caribou in a group of only 166 caribou suggesting aggregation of collared caribou that was different than the levels of aggregation of other caribou groups.

Table 27. Tests for randomness of collared caribou for the Cape Bathurst 2006 data sets.

Model	Z	p-value
July 6, 2013		
Homogeneity	0.716	0.237
Independence	1.194	0.116
July 9, 2013		
Threshold (B=3)	1.865	0.031

Model	Z	p-value
Independence	1.884	0.030
Threshold (B=2)	1.900	0.029
July 13, 2013		
Threshold (B=2)	-0.254	0.600
Independence	-0.268	0.606
Homogeneity	-0.203	0.580

2009

Twenty eight collared caribou were available during the Cape Bathurst 2009 survey of which 22 were observed in photographed groups (Davison *et al.*, 2014). Overall, 1,534 caribou were counted. Only 111 caribou in 3 groups were seen without collared caribou within the groups.

Table 28. Post calving field data for Cape Bathurst 2009 survey.

Date	Group	No. of Collars	Caribou counted
18-Jul-09	8	5	511
18-Jul-09	9	5	282
18-Jul-09	10	4	267
13-Jul-09	1	1	1
13-Jul-09	2	1	14
13-Jul-09	3	1	2
13-Jul-09	4	1	1
18-Jul-09	6	1	59
18-Jul-09	11	1	15
18-Jul-09	12	1	127
18-Jul-09	13	1	144
18-Jul-09	5	0	4
18-Jul-09	7	0	66
18-Jul-09	14	0	41
Total		**22**	**1,534**

Rivest model analysis suggested that a threshold model with detection probabilities of 1 for groups with 5 or more collars was most supported. Groups with less than 4 collars had a detection probability of 0.57. This model produced an estimate of 2,925 caribou compared to an estimate of 1,934 caribou from the Lincoln-Petersen estimator. Estimates had marginal precision (CV>20%).

Table 29. Rivest estimator results for the Cape Bathurst 2009 data set. The Lincoln-Petersen estimate is based on Davison *et al.* (2014).

Detection Model	Log-likelihood	Detection probabilities		Estimate of herd size			
		Estimate	SE	$\hat{T}$	SE ($\hat{T}$)	CI(±)	CV
Threshold (B=4)	5.53	0.57	0.13	2,925	638.7	1252	21.8%
Threshold (B=5)	5.21	0.67	0.16	2,706	554.4	1087	20.5%
Threshold (B=3)	4.97	0.57	0.13	2,925	638.7	1252	21.8%
Homogeneity	4.85	0.79	0.14	2,595	457.2	896	17.6%
Independence	4.49	0.42	0.13	2,897	630.1	1235	21.8%
Threshold (B=2)	4.04	0.57	0.13	2,925	638.7	1252	21.8%
Lincoln-Petersen				1934	350.1	350	18.1%

Tests for randomness of collared caribou across groups suggested that this assumption was met with the CB 2009 data set.

Table 30. Tests for randomness of collared caribou for the Cape Bathurst 2009 data set.

Model	Z	p-value
Threshold (B=3)	-0.705	0.759
Homogeneity	-0.743	0.771
Independence	-0.658	0.745
Threshold (B=2)	-0.592	0.723

2012

For the 2012 Cape Bathurst post calving survey, 24 collared caribou were available during the survey and all 24 were found in photographed groups, with 2,427 caribou counted in collared and non-collared groups (Davison *et al.*, 2016).

Table 31. Field data collected for Cape Bathurst 2012 post calving survey.

Group	No. of Collars	Caribou counted
23	11	1410
10	6	523
12	5	265
1	1	2
22	1	47
3	0	3
4	0	140
	0	19x1[A]
11	0	15
17	0	2
Total	**24**	**2,427**

[A]19 observations of single caribou

The Rivest model estimates were similar for the homogeneity and threshold models with detection probabilities of groups equal to 1 in all cases. In this case, the Rivest models basically estimated that a high proportion of the herd had been found and therefore all models converged on the same estimate of caribou. The Lincoln-Petersen estimate equaled the number of caribou counted with no estimate of standard error.

Table 32. Rivest model estimates and LP estimate for Cape Bathurst 2012 post calving survey.

Detection Model	Log-likelihood	Detection probabilities		Estimate of herd size			
		Estimate	SE	$\hat{T}$	SE ($\hat{T}$)	CI(±)	CV
Homogeneity	21.76	1.00	0.00	2,447	175.3	344	7.2%
Independence	21.76	0.00	0.00	2,447	175.3	344	7.2%
Lincoln Petersen				2,427	0.0		

Tests for randomness of collared caribou were similar (Z=-0.375, p=0.646) for all models which suggested the assumption of randomness was not violated.

2015

In 2015, 50 of 51 collared caribou were observed in 9 groups totaling 2203 caribou in the CB herd. In addition 3 groups composed of 13 caribou were observed without collared caribou (Davison *et al.*, unpublished).

Table 33. Summary of field data for the 2015 Cape Bathurst survey.

Group	No. of Collars	Caribou counted	Group	No. of Collars	Caribou counted
4	32	1200	8	1	1
3	8	759	10	1	1
2	3	168	12	1	2
11	2	69	6	0	8
1	1	1	7	0	4
5	1	2	9	0	1
			Total	**50**	**2216**

A threshold model with all groups of 2 or more collars having sighting probabilities of 1 had the highest log-likelihood score. Groups with less than 2 collars had a sighting probability of 0.83. Estimates from this model were precise and relatively similar to estimates from the other Rivest models.

Table 34. Rivest model estimates and LP estimate for the Cape Bathurst 2015 post calving survey.

Detection Model	Log-likelihood	Detection probabilities		Estimate of herd size			
		Estimate	SE	$\hat{T}$	SE ($\hat{T}$)	CI(±)	CV
Threshold (B=2)	84.16	0.83	0.15	2,524	144.86	283.9	5.7%
Independence	84.14	0.16	0.14	2,524	144.38	283.0	5.7%
Threshold (B=32)	84.12	0.95	0.11	2,548	149.77	293.6	5.9%
Threshold (B=3)	84.08	0.88	0.13	2,523	142.78	279.8	5.7%
Homogeneity	84.07	0.98	0.09	2,524	159.49	312.6	6.3%
Threshold (B=8)	84.07	0.91	0.12	2,526	140.59	275.6	5.6%
Lincoln Petersen				2,259	43.0	84.3	3.7%

Tests for randomness of collars across groups indicated that this assumption was potentially violated as indicated by p-values of less than 0.05. In this case the Rivest estimates may be slightly negatively biased.

Table 35. Tests for randomness of collar distribution for the Cape Bathurst 2015 post calving survey.

Model	Z	p-value
Homogeneity	1.73	0.042
Independence	1.75	0.040
Threshold (B=2)	1.75	0.040
Threshold (B=3)	1.75	0.040

Tuktoyaktuk Peninsula (TP) Herd

2006

On July 9 and 13, 2006, the Tuktoyaktuk Peninsula Herd was sampled with all 27 collared caribou detected in photographed groups (Nagy & Johnson, 2006). On both dates, collared caribou were detected as single individuals so that the collar size equaled the group size.

Table 36. Summary of sampling for the Tuktoyaktuk Peninsula Herd on two dates in July 2006.

Sessions		
Group	**No. of collars**	**Caribou counted**
July 9, 2006		
1	5	951
2	3	112
3	3	167
4	3	230
5	2	293
6	2	364
7	1	8
8	1	18
9	1	8
10	1	16
11	1	352
12	1	82
13	1	1
14	1	1
15	1	74
16	0	7
17	0	16
18	0	38
19	0	5

Sessions		
Group	**No. of collars**	**Caribou counted**
20	0	35
21	0	84
22	0	4
Total	**27**	**2866**
July 13, 2006		
1	10	1627
2	7	335
3	4	317
4	2	135
5	1	1
6	1	228
7	1	250
8	1	1
9	0	147
10	0	9
11	0	13
12	0	1
13	0	13
14	0	1
Total	**27**	**3078**

Identical log-likelihood scores and estimates were returned for all models for both survey dates suggesting the herd had been effectively censused during the survey. The estimate for July 13 is preferred as it had higher precision.

Table 37. Rivest Estimator results and LP estimate for the Tuktoyaktuk Peninsula herd on July 9, 2006.

Detection Model	Log-likelihood	Detection probabilities		Estimate of herd size			
		Estimate	SE	$\hat{T}$	SE ($\hat{T}$)	CI(±)	CV
Independence	-1.6045	0.00	0.00	4188	760.96	1491	18.2%
Homogeneity	-1.6046	1.00	0.00	4188	760.86	1491	18.2%
Threshold (B=2)	-1.6046	1.00	0.00	4188	760.86	1491	18.2%
Threshold (B=3)	-1.6046	1.00	0.00	4188	760.86	1491	18.2%
Threshold (B=4)	-1.6046	1.00	0.00	4188	760.86	1491	18.2%
Threshold (B=5)	-1.6046	1.00	0.00	4188	760.86	1491	18.2%
Threshold (B=6)	-1.6046	1.00	0.00	4188	760.86	1491	18.2%
Lincoln Petersen				2677	0.0		

Table 38. Rivest Estimator results and LP estimate for the Tuktoyaktuk Peninsula Herd on July 13, 2006.

Detection Model	Log-likelihood	Detection probabilities		Estimate of herd size			
		Estimate	SE	$\hat{T}$	SE ($\hat{T}$)	CI(±)	CV
Homogeneity	15.4796	1.00	0.00	3320	318.09	623	9.6%
Independence	15.4795	0.00	0.00	3321	318.11	623	9.6%
Threshold (B=2)	15.4796	1.00	0.00	3320	318.09	623	9.6%
Threshold (B=3)	15.4796	1.00	0.00	3320	318.09	623	9.6%
Threshold (B=4)	15.4796	1.00	0.00	3320	318.09	623	9.6%
Threshold (B=6)	15.4796	1.00	0.00	3320	318.09	623	9.6%
Threshold (B=7)	15.4796	1.00	0.00	3320	318.09	623	9.6%
Threshold (B=10)	15.4796	1.00	0.00	3320	318.09	623	9.6%
Threshold (B=9)	15.4796	1.00	0.00	3320	318.09	623	9.6%
Lincoln Petersen				2894	0.00	0	0.0%

Tests for randomness returned similar scores for all models for both July 9 (Z=-0.47, p=0.68) and July 13 (Z=0.52, p=0.3) suggesting that the assumption of randomness was not violated for surveys on either date.

2009

The Tuktoyaktuk Peninsula Herd was surveyed in 2009 with 27 collared caribou available during the survey. Of these 25 were detected with 2,556 caribou being counted during the survey (Davison *et al.*, 2014). Of these, 2,138 were in groups that contained at least one collared caribou.

Table 39: Post calving field data from Tuktoyaktuk Peninsula herd on July 13, 2009.

Group	No of Collars	Caribou counted	Group	No of Collars	Caribou counted
12	8	372	3	0	2
17	4	357	4	0	2
18	3	633	6	0	42
13	2	169	8	0	6
14	2	85	9	0	7
19	2	397	10	0	109
5	1	4	15	0	12
7	1	44	16	0	8
11	1	35	20	0	150
23	1	42	21	0	47
1	0	1	22	0	30
2	0	2	**Total**	**25**	**2,556**

A model that assumed detection probabilities were one for groups that had 2 or more collars was most supported with detection probabilities of 0.67 for groups that had less than 2 collars. The estimate of herd size from this model was 2,889 (±765) caribou with a CV of the estimate of 13.5%. Interestingly, this estimate was reasonably close to the Lincoln-Petersen estimate.

Table 40: Rivest Estimator results for the Tuktoyaktuk Peninsula Herd in 2009. The Lincoln-Petersen estimate is based on Davison *et al*. (2014).

Detection Model	**Log-likelihood**	**Detection probabilities**		**Estimate of herd size**			
		Estimate	**SE**	$\hat{T}$	**SE ($\hat{T}$)**	**CI(±)**	**CV**
Threshold (B=2)	4.96	0.67	0.19	2,889	390.5	765	13.5%
Independence	4.84	0.27	0.15	2,899	390.1	765	13.5%
Threshold (B=8)	4.78	0.89	0.11	2,917	391.5	767	13.4%
Homogeneity	4.71	0.93	0.10	2,841	410.8	805	14.5%
Threshold (B=4)	4.64	0.87	0.12	2,953	398.8	782	13.5%
Lincoln-Petersen				2,752	275.2	539	10.0%

Tests for randomness of collared caribou across groups suggested that this assumption may have been weakly violated which could cause a negative bias in estimates and associated variances.

Table 41. Tests for randomness of collared caribou for the Tuktoyaktuk Peninsula herd 2009 data set.

Model	**Z**	**p-value**
Threshold (B=2)	1.33	0.092
Independence	1.30	0.097
Homogeneity	1.23	0.110
Threshold (B=3)	1.26	0.104

2012

Twenty three collars were available during the 2012 Tuktoyaktuk Peninsula herd post calving survey. Of these, 22 were observed with the majority in a single group of caribou (Davison *et al*., 2016).

Table 42. Field data for the 2012 Tuktoyaktuk Peninsula Herd post calving survey.

Sessions			**Sessions**		
Group	**No. of collars**	**Caribou counted**	**Group**	**No. of collars**	**Caribou counted**
4	19	1,871	3	0	1
2	2	95	5	0	72
7	1	21	6	0	38
1	0	3	**Total**	**22**	**2,101**

A threshold Rivest model with groups sizes of 2 or more having detection rates of 1 and group sizes below having detection rates of 0.5 had the highest log-likelihood, but all model estimates were very similar and had high precision.

Table 43. Rivest model estimates and LP estimate for the 2012 Tuktoyaktuk Peninsula Herd post calving survey.

Detection Model	Log-likelihood	Detection probabilities		Estimate of herd size			
		Estimate	SE	$\hat{T}$	SE ($\hat{T}$)	CI(±)	CV
Threshold (B=2)	4.96	0.67	0.19	2,889	390.5	765	13.5%
Independence	4.84	0.27	0.15	2,899	390.1	765	13.5%
Threshold (B=8)	4.78	0.89	0.11	2,917	391.5	767	13.4%
Homogeneity	4.71	0.93	0.10	2,841	410.8	805	14.5%
Threshold (B=4)	4.64	0.87	0.12	2,953	398.8	782	13.5%
Lincoln-Petersen				2,752	275.2	539	10.0%

Table 44.Tests for randomness of collars for the 2012 Tuktoyaktuk Peninsula herd survey.

Model	Z	p-value
Threshold (B=2)	-0.736	0.769
Independence	-0.734	0.768
Homogeneity	-0.723	0.765
Threshold (B=3)	-0.730	0.767

2015

In 2015, all 26 collared caribou were counted in photographed groups in the TP post calving survey. Of the groups detected, 3 did not have collared caribou with 15 caribou total in the non-collar groups (Davison *et al.*, unpublished). Overall, 1701 caribou were counted in the survey.

Table 45. Field data for the 2015 Tuktoyaktuk Peninsula Herd post calving survey.

Sessions		
Group	No. of collars	Caribou counted
1	14	1,011
2	1	354
3	4	57
4	1	15
5	2	131

Sessions		
Group	No. of collars	Caribou counted
6	3	116
7	0	12
8	1	2
9	0	2
10	0	1
Total	**26**	**1701**

Log-likelihood scores and Rivest estimates were identical for all models which indicates that all the groups were very detectable (sighting probability=1). The Lincoln-Petersen estimate equaled the count of caribou observed given that all the collars were accounted for in observed groups.

Table 46. Rivest model estimates and LP estimate for the 2015 Tuktoyaktuk Peninsula herd post calving survey.

Detection Model	Log-likelihood	Detection probabilities		Estimate of herd size			
		Estimate	SE	$\hat{T}$	SE ($\hat{T}$)	CI(±)	CV
Independence	18.00	1.00	0.01	1,930	176.9	346.8	9.2%
Homogeneity	18.00	1.00	0.00	1,930	176.9	346.7	9.2%
Threshold (B=2)	18.00	1.00	0.00	1,930	176.9	346.7	9.2%
Threshold (B=3)	18.00	1.00	0.00	1,930	176.9	346.7	9.2%
Threshold (B=4)	18.00	1.00	0.00	1,930	176.9	346.7	9.2%
Threshold (B=17)	18.00	1.00	0.00	1,930	176.9	346.7	9.2%
Lincoln-Petersen				1,701	0.0		

Tests for randomness of collars indicated that this assumption was not violated during the TP 2015 survey.

Table 47. Tests for randomness of collars across groups for the 2015 Tuktoyaktuk Peninsula herd survey.

Model	Z	p-value
Independence	0.049	0.481
Homogeneity	0.049	0.481
Threshold (B=2)	0.049	0.481
Threshold (B=3)	0.049	0.481