The Use of Satellite Telemetry to Estimate the Abundance of a Migratory Caribou Population

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PRODUCTION TEAM

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Summary

The aerial surveys of the migratory caribou populations in the Rivière aux Feuilles herd (RAFH) and the Rivière George herd (RGH) have been conducted using the capture-mark-recapture (CMR) approach, since the effectiveness of this method has been demonstrated. This report presents the steps in the preparation and execution of an aerial survey of a migratory caribou population, based on the use of a sufficient number of satellite telemetry collars distributed randomly and between males and females. This approach makes it possible to valorize the simplicity of the Lincoln-Petersen Model, as proposed by Chapman (1951, in White and Garrott, 1990). The methodological prerequisites and basic premises of the model that must be observed to ensure the scientific rigour of this model are presented according to the specific nature of the behaviour of migratory caribou. The preparations and technical facets related to sampling groups of caribou and counting by means of photographs are described in detail. Lastly, the calculation of the abundance of a population and its confidence interval is presented along with the evaluation criteria of the outcome's validity. The use of the CMR approach to evaluate the abundance of a migratory caribou population is, however, conditional upon the major groupings of caribou that occur briefly during specific environmental conditions.

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Introduction

Two migratory caribou populations are found in Québec, i.e. the Rivière aux Feuilles herd, which lives there exclusively, and the Rivière George herd, whose distribution area extends to Labrador. The aerial surveys of the migratory caribou populations are conducted using the capture-mark-recapture approach since its effectiveness has been demonstrated (Russell *et al.*, 1996). Surveys conducted by means of the CMR approach are possible in large aggregations of caribou, whose locations are known because a sufficient number of animals in the population are wearing a telemetric collar. Such aggregations occur principally in the summer, following the post-calving period, when harassment by biting insects encourages the caribou to group together (Figure 1). Under exceptional circumstances, the aggregations can also occur during the spring or fall migration when the caribou follow converging migratory paths. The CMR method has replaced the surveys previously conducted during calving in Nunavik and Labrador, in particular because this method produces a more reliable estimate when the conditions for its execution are present. The gain is attributable to the simultaneous counting of all population segments of adult caribou (≥ 1 year), and occasionally calves, compared with the calving survey which hinges on an extrapolation based solely on the gestating female segment occupying the calving grounds. The CMR thus facilitates the estimation of the size of the population by sampling the vast majority of the population. The approach considerably reduces potential biases by reducing the number of parameters to be estimated and the attendant margin of error.

Figure 1. Typical landscape of the summer habitat of the Rivière aux Feuilles herd in the Monts Puvirnituq (61.5° N. and 74° W.). The caribou assemble there in their thousands, which allows for the realization of a capture-mark-recapture survey. The tundra is the most favourable habitat for surveys, since the absence of forest makes it easier to take photographs that will then be used to count the caribou in each group.

The following conditions are necessary to estimate the population size by means of the CMR approach:

1. the population is closed and therefore varies solely in light of births and deaths;
2. the individuals collared are randomly dispersed in the population (khi-two test);
3. the method makes it possible to recapture (photograph) a large proportion of the collared individuals;
4. the methods of analysis compensates for potential biases related to the number and composition of the sample of collared individuals (sample size, behavioural characteristics, and so on).

The quality of telemetric monitoring and, therefore, of the sampling of the population, benefits considerably from technological breakthroughs and the reduction in the cost of telemetric collars. It is now possible to collar sufficient males and females and ascertain their position on a daily or possibly more frequent basis. The regular transmission of the location of numerous animals allows the survey team to go directly to all significant groups of caribou. This detailed knowledge of the caribou's movements reduces uncertainty over the location of the collared animals and, therefore, the overall population, thereby eliminating the need to effect flight lines to delineate a study area and confirm beforehand the number of active collars (see Couturier *et al.*, 2004). Accordingly, the use of complex statistical models (Rivest *et al.*, 1998; Crépeau *et al.*, 2012) intended to compensate for fragmentary information on the location of the caribou or an occasionally insufficient number of collared animals is no longer necessary.

The following text presents in detail the migratory caribou survey approach used in the Nord-du-Québec region and its methodological requirements. The approach emphasizes the simplicity of the Lincoln-Petersen Model, as proposed by Chapman (1951, in White and Garrott, 1990), by minimizing potential bias through satellite technology and a sufficient sample size of collared animals.

Prerequisites and preparation of the survey

Telemetric monitoring that is representative of the population

Governments have used radio-collars in Québec and Labrador since the 1960s to monitor migratory caribou populations. Technological development has enhanced telemetric monitoring by placing collars equipped with an Argos satellite transmitter on certain caribou. The first satellite transmitters enabled the satellites to calculate and transmit the approximate position of the collared caribou (less than 100 m to more than 1 500 m) at a five-day interval through a telecommunications service. The Argos transmitters were used starting in 1986 in the RGH and in 1993 in the RAFH. More recently, the addition of a Global Positioning System (GPS) receiver to the radio-collar and the diversification of satellite telecommunications systems have facilitated the transmission of a very precise location using an Argos, Iridium or Globalstar satellite transmitter. Telemetric collars equipped with a GPS receiver and a satellite transmitter were used for the first time in 2007 in the RAFH and the RGH. The radio-collars equipped solely with a VHF radio transmitter, without a satellite transmitter, have not been used since 2001 on migratory caribou either in Québec or in Labrador. In 2017, all of the telemetric collars in the RAFH and the RGH were equipped with a VHF radio transmitter, GPS and a satellite transmitter that transmits a location daily.

The attainment of good telemetric coverage of the population implies that the collared animals are dispersed randomly in the overall distribution area. Animal-collaring expeditions are planned according to this objective. They are carried out by helicopter in the winter at the most opportune time to capture animals with a net gun. The large winter aggregations of caribou and the extensive networks of tracks in the snow contribute to maintaining a representative sample of the population, since they reveal groups of caribou on the fringes of concentrations that are already known. To produce periodic aerial surveys, regular collaring expeditions are necessary to replace the collars at the end of their useful life and ensure the maintenance of a sufficient sample and adequate coverage of the distribution area.

The number of collared animals of each sex that properly represents the population varies depending on the parameter to be measured. Since 2010, the Québec and Newfoundland and Labrador governments have sought to maintain roughly 80 to 100 active collars in each of the caribou populations. This target satisfies the needs associated with the estimate of the monitoring rate of males and females, the cartography of the calving grounds and other seasonal habitats. Furthermore, the number of collared animals is potentially sufficient to conduct a CMR survey or offers a solid base that facilitates the effective targeting of the requisite effort to attain complete coverage of the distribution area anticipated at the time of the survey.

The distribution of collars between males and females corresponds roughly to the sex ratio in the populations. Since both populations are subject to long-term demographic monitoring, the annual variability in the male/female ratio can be considered. For example, the sex ratio for the RAFH was, on average, 37 males/100 females from 2001 to 2015 and 41 males/100 females during the 2016 fall classification. While large groups of caribou are mixed at the time of survey, groups exclusively comprising males are typically observed on the fringes of groups made up of animals that mainly come from the calving grounds. This behaviour is more often observed when a population comprises several hundred thousand animals and the large number of males promotes their grouping together after the spring migration. It is estimated that the maintenance of 40-odd collars on males allows for monitoring of their demographic parameters and to properly locate groups of males, since the biggest groups usually contain more than one collared animal. The groups of males are often located south of females that make a hastier, longer spring migration than the majority of males, in order to reach the calving grounds in time to give birth to their calf.

The performance of the collars confirms that all of the collared animals have an equivalent probability of detection, a basic premise of the Lincoln-Petersen Model. The detection of groups of migratory caribou for counting purposes depends on the satellite collars that transmit one or more locations at regular intervals (12 to 48 hours) by Globalstar, Iridium or Argos link. The use of a portable Internet satellite router is a key element of the methodology, since regular access to the locations facilitates the adaptation of a flight plan several times a day. A summer (post-calving) survey does not require a structured flight along flight lines as is the case for moose and caribou, since the detection phase hinges entirely on the collars.

Estimation of the adequate number of telemetric collars

The sample size and the type of collars active at the time of the survey vary mainly according to the efforts invested in monitoring populations and the lifespan of the collars (three to five years), as well as the research projects under way. It is essential that the number and distribution of the collars make it possible, at least theoretically, to pinpoint all of the groups of caribou in the population when aggregation conditions are ideal. While the premise is fundamental, it can only be validated at the time of the survey since the adequate number of collars depends on the number of groups that the population forms during sampling. The relationship between the abundance of a population and the number of groups that form at the time of the survey is, however, difficult to predict, since the size of the groups varies according to population abundance and environmental conditions. The number of animals collared for surveys that have generated an outcome whose statistical accuracy is acceptable (confidence interval of < 20%, α = 0.10; Table 1) offers, however, indications concerning the relationship between the abundance of the population and adequate sample size.

Table 1: Characteristics of the sample of collared animals in relation to the number of groups and the abundance of the adult population (≥ 1 year) of migratory caribou for the seven surveys conducted using the CMR method in Québec and Labrador, whose confidence interval was < 20% (α = 0.10)

Survey	No. of adults[1]	No. of groups	No. of collared animals	No. of collars in the biggest group	Average No. of caribou/ group	Average No. of adults/ collar	Average No. of collars/ group
RGH 1993	451 000	28	92	8	16 107	4 902	3.3
RGH 2001	210 000	27	109	10	7 778	1 927	4.0
RGH 2010	57 003	13	71	10	4 385	803	5.5
RGH 2012	21 375	22	90	16	972	238	4.1
RGH 2014	10 900	29	99	29	376	110	3.4
RGH 2016	7 194	21	63	29	343	114	3.0
RAFH 2016	166 587	42	117	19	3 966	1 424	2.8

[1] Calculated according to the Lincoln-Petersen Model without using the threshold for the minimal size of a group that qualifies for analysis (see Russel *et al.*, 1994).

Generally speaking, the size of the groups increase according to the abundance of the population, since the number of groups is less variable. The succession of surveys describing the decline of the RGH offers an example of changes in the parameters according to population abundance (Table 1). However, the number of big groups, which contribute significantly to the estimate of abundance, is dwindling with the decline in the population. The size of the sample of collared animals in the population that would adequately facilitate the detection of all groups of significant size could be proportional to the size of the population. For example, the number of collars in the biggest group in the RGH in 2014 and in 2016 (Table 1) suggests that a smaller number of collared animals would not have compromised the detection of the groups. The average number of caribou/group, adults/ collar and collars/group vary considerably for a given survey and are largely affected by population abundance. The parameters thus constitute approximate indications of the size of an adequate sample according to the abundance of the population. The distinction of the number of groups observed during the survey of the RAFH, compared with the inventories of the RGH, suggest that aggregation behaviour could also vary depending on the population.

The following criteria are used to determine if the number of collared animals is adequate, according to the aggregation conditions observed at the time of the survey:

1. few or no caribou are observed during movements between the aggregations of caribou. An arbitrary threshold of < 2% of the total number of caribou counted in the groups is used. The higher the percentage, the higher the probability that the survey is underestimating the abundance of the population;
2. all of the big groups observed are minimally represented by a collared caribou.

The potential for attaining such conditions must be assessed before a survey is conducted by analyzing the cartography of the locations, seeking indications of observations of caribou from the communities and local users, and engaging in extensive location during collaring expeditions. When a considerable number of caribou are reported in sectors not represented by collared animals or huge aggregations are represented by an insufficient number of collared animals, the planning of an aerial survey may require the addition of collars to obtain an adequate sample size.

Environmental conditions that are conducive to aggregations

The occurrence of large groups of migratory caribou, occasionally of very high density, is not guaranteed every summer since the aggregations stem from a compromise between different constraints that the caribou are facing. Caribou depend on the short summer to feed through diversified, quality browsing and thereby satisfy their needs related to suckling, growth and the storage of fat. Insects usually take refuge in the vegetation, which encourages the caribou to group together in snow-covered, sandy or rocky areas (Figure 2) ideally exposed to the wind in order to limit intensive harassment. Since these areas are less suited to feeding and caribou are found in high density, the aggregation behavior would limit the quality of their diet.

Once preparations for collaring the animals have been completed, the possibility of conducting a survey must be evaluated after calving, in late June. A qualitative analysis of the caribou's movements and climatic data (airports, research stations and climate monitoring, national parks, and so on) must be conducted daily. The convergence of the trajectory of collared animals suggests that groups are forming or could quickly form if climatic conditions became favourable to the emergence of insects. It is, therefore, important to regularly assess if the ambient temperature is conducive the emergence of insects (ideally > 12°C). In the weeks preceding the survey, the ambient temperature must foster the emergence of insects, minimally during the day, and the prevailing winds must be below 15 to 20 km/h through the caribou's distribution area. In the tundra, such conditions rarely occur and a cold, windy weather system spread over several consecutive days can compromise a survey in the late stage of preparation.

Figure 2: A small group of caribou take advantage of one of the last small islands of snow to refresh themselves and limit their exposure to biting insects (July 30, 2016, RAFH survey).

The window of opportunity favourable to a survey usually lasts several days and occurs at different times, depending on the caribou's location during the summer. For example, the aggregation peak of the RGH (approximately July 13) usually occurs two weeks before that in the RAFH (approximately July 30). The emergence of sheep-nostril flies (*Hypoderma tarandi* and *Cephenemyia trompe*, parasites whose sexual forms resemble a fly) in early August is also a factor to be considered, since the flies agitate the groups of caribou, which can disperse, thereby compromising the survey. The deterioration of environmental conditions can force the cancellation of a survey under way. The feasibility and success of a survey can only be confirmed upon its completion.

Logistical preparations

This type of survey is conducted by helicopter. It requires the placement of fuel in isolated areas where it is anticipated the main groups will be located. The population's behaviour in previous years provides valid indications in this respect. The use of facilities offered in Inuit communities is sometimes possible, but the caribou are mainly located in the centre of the Ungava Peninsula.

The RAFH is usually in the Monts Puvirnituq, where it is possible to stay in a mineral exploration camp. In the case of the RGH, the outfitting operations located on the shore of Rivière George and the Government of Newfoundland and Labrador research station, located near the calving grounds in the Hebron Fjord area, are strategic. The scarcity of campsites means that fuel is also stored in caches reserved solely for refuelling, thus enhancing the survey team's effectiveness, which is mainly limited by the aircraft's range. Regular confirmations of the location of collared animals, access to fuel in the summer distribution area and the use of base camps near the caribou reduce the logistical constraints linked to the study of a migratory species in isolated a remote environment.

Realization of the sampling

VHF telemetry

The recapture phase of the CMR methodology is carried out by validating the presence in a group of a collared animal through the detection of the radio signal emitted by the collar. VHF telemetry is thus a very important component of a caribou census and demands special attention to ensure the smooth functioning of each component of the system.

The helicopter is equipped with three directional antennas (Figure 3), linked to the telemetric receivers by switches that allow for the simultaneous or exclusive activation of the forward, left or right antenna. VHF telemetry being a crucial component of the survey technique, it is recommended that two or three members of the crew have a receiver to engage in out-of-phase scanning of all frequencies. The listening time for each frequency is determined by a slight increase in the pulsation frequency of the slowest active collar, e.g. 2.25 seconds for a pulsation of 30 beats per minute.

While the approximate position of the collars is known through satellite communications, VHF telemetry makes it possible to detect the radio signal of nearby collars, obtain the fine-scale location of groups and, once the group has been delineated, pinpoint the collared animals it contains. In flight, the team engages in telemetric scanning of VHF frequencies on an ongoing basis in order to detect collared animals at any time.

The telemetric equipment must be properly installed in the helicopter and replacement components must be available. The telemetric equipment comprises:

- directional antenna fasteners approved by Transport Canada;
- directional antenna specific to the collars' VHF frequency range;
- RG-38 coaxial cables of varying lengths and robust connectors;
- port multipliers to divide the signal among the users;
- directional switch boxes to simultaneously or independently control the three antennas;
- VHF receivers;
- a communications sharing switch between the VHF receiver and the helicopter's communications system;
- compatible audio port adaptors for the helicopter's communications system headsets (bantam jack).

Figure 3: Example of one of the three type "H" directional antennas attached to the helicopter's skids using a fastener approved by Transport Canada and connected by means of a coaxial cable to the VHF telemetry system.

The smooth operation of the telemetry system must be verified beforehand on the ground by positioning a radio-collar in each of the directional axes of the antennas. A second test in flight is also necessary to verify the level of interference from the helicopter's electronic system or static electricity in each of the antennas.

Determination of the status of the collared animals

The number of animals collared in a population varies regularly because of the number of deaths, defective collars or, in rare cases, the end of the useful life of the battery or one or more collars. The number of collars active at the time of the survey must, however, be determined accurately, since it represents a variable used to calculate the estimate of population abundance. Radio and satellite transmitters are used to determine if a collar is active at the time of the survey.

It is assumed that the smooth operation of a collar's satellite transmitter guarantees that of its VHF transmitter. VHF telemetry is usually reliable when the equipment is in good condition and used properly. It is nevertheless possible that irregularities can occur and that the collar's VHF signal is not detected despite its proximity. This phenomenon can be explained by a minor equipment defect, interference from electromagnetic pollution, or human error. It is virtually impossible to confirm if a VHF signal has not been detected because of a permanent defect. In most cases, an animal that was not detected by radio signal during the survey was simply out of range. The animal's position can rarely be investigated for lack of time or fuel. A collar is deemed to be active during the survey if it minimally meets one of the following criteria:

1. the collared animal's collar regularly transmitted different locations during the survey, confirming that it was alive;
2. the VHF frequency of a collared animal is confirmed in a sampled group.

Sampling of caribou groups

When a group of caribou is pinpointed, the helicopter flies around the edge of it to circumscribe its expanse. The absence of caribou on the fringes of the group is validated visually by an expanded overflight to confirm the quality of the aggregation conditions. The spatial configuration of a group can vary considerably. A group can be contained on a small stretch of snow, cover the entire slope of a hill or extend more than 10 km along a trail. Fragmented groups but located nearby (< 1 km) are usually merged in the analyses to simplify the telemetric work. In the presence of a dense aggregation, the aircraft first flies over the clearly defined group at an altitude that does not disturb the caribou. When the caribou are slightly dispersed, the aircraft flies at a lower altitude that fosters the aggregation of the animals in order to facilitate photographing. The precise location of the group must be noted. When a group is dispersed over a vast area or along a trail, the GPS tracking of the initial overflight becomes useful to the pilot and the crew members to create a spatial reference used to plan photographing.

The number of collared animals integrated into a group is decisive in the calculation of the abundance of the population. The identity of the collars is noted in flight by two or three crew members who engage in independent telemetric listening. After scanning the entire VHF frequency table twice, the crew members share their findings for validation purposes. A frequency that is not confirmed by all of the crew members must be confirmed through specific listening.

The simultaneous use of several VHF receivers (Figure 4) increases the listening time on each frequency in order to reduce bias linked to human error and technical problems (wiring, port multipliers, switches, signal strength, calibration of frequencies, and so on). Teamwork thus enhances the accuracy and efficacy of the sampling period.

The group is photographed at the most opportune moment, often as soon as it is detected when it is small or of good density (Figure 5), or once telemetric scanning has been completed when it is advantageous to use the helicopter to gradually drive the animals on the periphery towards the centre of the group. Big groups make it often necessary to take several successive photographs, at intervals that variable depending on the aircraft's speed, the caribou's movements, and the size of the group. Photographs can be taken through the opening of the door window when the group is small. The use of an aircraft with a sliding door is advantageous to broaden the horizon of the photograph when the groups are dispersed over vast areas. Otherwise, the photographing of big groups requires the removal of the doors on one side of the aircraft. The execution of two or occasionally three photography sessions for a given group is recommended when lighting or aggregation conditions are difficult, since the quality of each of the photographs and the continuity of the superimpositions of the framing cannot be validated effectively in flight.

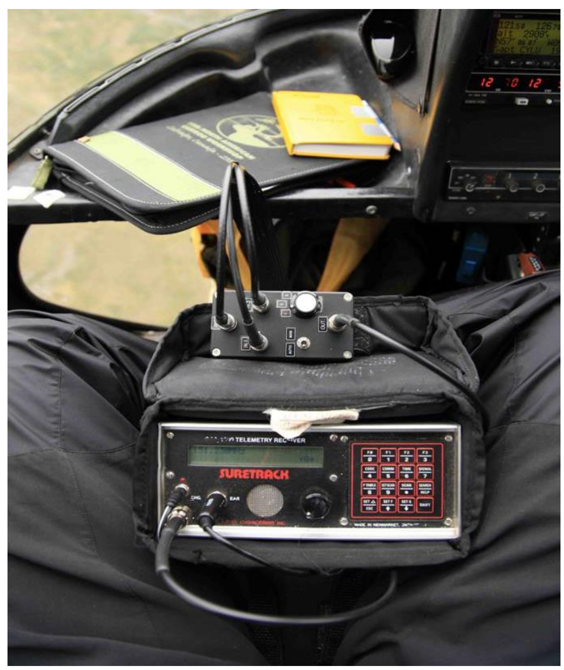

Figure 4: A VHF telemetry radio receiver and switch box to select directional antennas.

The use of a digital camera with a 50-million pixel sensor allows for photographing at high altitude, broader shots when the groups are of low density, and the identification of fawns in most cases. It is important to rely on the initial overflight of the group to plan the photographing strategy (routes, variations in altitude) and avoid taking photographs against the sunlight.

The sampling of the groups provides a great deal of information that must be systematically processed in flight. Accordingly, the list of VHF frequencies heard during the team's transits or validated in the groups and their location, the location of the groups and the number of photographs corresponding to each of the attempts for each of the groups must be input in a structured manner. A list of the technical data and all of the collared animals is consulted regularly (Table 2). It establishes, in particular, the correspondence between the cartography of the locations and the VHF frequencies heard in flight and allows for monitoring the collared animals that have been sampled in order to guide decision-making respecting navigation and sampling.

Certain telemetry-related technical facets must be considered when the collared animals in a group are validated. For example, collared animals that belong to two separate groups can sometimes appear to be in the same group, despite the use of directional antennas, when the helicopter and the two collars are in the same axis. The animals must be located strategically by using the directional antennas and the adjustment of the receiver gain. This task requires good vigilance since the position of a second group would be perceived alternately in the three antennas when the helicopter turns around the target group. It is also important to consider that a collar's VHF signal strength varies depending on the model and the manufacturer. The collars' signal strength, indicating their proximity, can thus vary for a given VHF receiver gain setting. It is, therefore, important for the staff responsible for telemetry during the survey to be experienced, familiar with the use of the VHF receivers, and aware of the distinctive features of the collars used.

Figure 5: All of the caribou in this sector assemble on this beach near the coast of Hudson Strait, probably to escape harassment by insects.

A collar’s frequency may not have been heard in a group because of a technical problem such as a deficient VHF signal, or human error. Since a collar transmits several GPS positions a day, it is possible to accurately investigate the position of the animals that were not heard in relation to the position of the groups sampled. The presence of a collared animal that has not been heard can be validated later by using precise information on the time of the GPS locations, its temporal and spatial relationship to other collared animals in a given group, and the spatial delimitation of the groups sampled. In certain cases, an animal can be added *a posteriori* to the number of collared animals in a group when its location can be clearly associated with that of a group sampled.

Table 2: Example of a table assembling technical data on collared animals that facilitates navigation planning and underpins decision-making in flight when the radio signal of a collared animal is detected. The fields are described below.

SatID	VHFreq	AnimalID	Sex	AnimalStat	Photo	BPMVif	Pulse
10673	151.860	2009080	F	Alive	Group 8	30	single
10688	148.310	2013117	M	Alive		30	double
10937	150.110	2006022	F	Alive	Group 3	40	single
123498	149.350	2008043	F	Unknown		40	single
…							

SatID: ID number of the Platform Terminal Transmitter of the collar's satellite telecommunications system.

VHFreq: frequencies of the VHF radio beacon.

AnimalID: a unique ID number assigned to an animal when it is first captured.

Sex: the sex of the animal (F = female; M = male).

AnimalStat: the animal's status (alive or dead). The animal's status may be unknown if its collar does not transmit a telemetric satellite location.

Photo: indicates if the animal has been photographed and in which group(s).

BPMVif: number of beats per minute of the VHF radio signal.

Pulse: the type of beat that the collar emits (single, double or triple), e.g. double; 30 bpm = bipbip... 2 seconds … bipbip.

Analysis of the findings

Counting of calves

The counting of calves during the survey provides important demographic information that facilitates an estimate of the abundance of the population overall and its annual trend. The high resolution of digital images and the smaller size of the groups stemming from current population decline now make it possible to considerably reduce bias inherent in the difficulty of counting calves during the survey. However, it is possible that conditions during photographing do not allow for the identification of calves on several photographs of a group or in a minority of groups because of inadequate resolution, improper camera settings, or the very high density of a group. The proportion of calves (number of calves/total number of caribou) in such photographs or groups can be estimated using good quality photographs of the same or another group. In the second case, since the breakdown of females accompanied by a calf is not homogeneous in the summer range, the estimate should be based on a group of similar abundance sampled in the same sector.

The characterization of the groups and the quality of the censuses are benefiting greatly from changes in digital imaging. Prior to 2012, photographic surveys were conducted during the summer when the resolution of cameras did not allow for the detection of calves on the vast majority of photographs. Under such conditions, calves that could be recognized on the photographs were not counted because this technical limitation resulted solely in an estimate of the adult population (≥ 1 year) in the summer. To obtain the total abundance of the population, the number of calves was derived from their proportion in the population, which was measured later during the fall classification. The use of the findings of the fall classification to round out the result of a survey meant adding the calves to the adult population that had survived from the time of the survey to the fall. The survival rates of adults from the summer to fall were estimated by the proportion of collared caribou of each sex that had survived since the survey, until November 1. The survival of adults and the proportion of calves in the fall were usually treated as constants to avoid modifying the initial confidence interval of the survey. This approach produced an estimate of the total population as of November 1, based on a summer survey and a fall classification. The counting of calves during the survey is thus highly advantageous from an analytical standpoint since it makes it possible to eliminate potential biases related to the distinction of a calf or an adult on the photographs and the imprecision stemming from the confidence interval of the survival of adults and the classification of calves in the fall.

Image processing and counting of groups

The number of photographs to be processed depends on the number of groups sampled, their density, and the camera's resolution. Certain groups on the move can require dozens or even several hundred photographs if several attempts have been made. When the size of a group surpasses that of a photograph, each photograph must be analyzed visually in relation to the neighbouring photograph using image processing software such as Photoshop or PhotoFiltre. A continuous mosaic is then defined by manually tracing the boundaries of each of the photographs using reference points in the landscape and the caribou. Each image file is, however, processed individually when the caribou that it contains are counted. The number of the adjacent photographs must thus be recorded on each photograph as a reference point, since a photograph can sometimes be adjacent to several photographs (Figure 6). The caribou that appear in each photograph selected in the mosaic are counted. The area to be processed must be clearly delineated to avoid excluding a caribou or counting it twice.

Once the mosaic has been completed, the caribou are counted by displaying the photographs one by one in the geomatics software (ArcMap by ESRI). Two layers of points, one for adults and one for calves, are edited in creation mode. A mouse click creates a point that is superimposed on the photograph, anchored to the coordinate of the pixel selected (Figure 7). The photograph can be enlarged (zoom in) and moved (pan) without compromising the relationship between a point and the caribou that it represents. Once all of the caribou have been counted, the number of caribou in the photograph can be determined using the number of lines in the attribute table of the layer of points. A photograph and its point files can be visualized later by different users to validate the count and the distinction between calves and adults.

The validation of the counts can be carried out differently, depending on the quality of the photographs and the size of the groups. The same observer, or a second observer, validates the photographs that do not pose a challenge in respect of the identification of adults and calves, to detect and correct inattention errors. Photographs in which the caribou are hard to distinguish from the background (Figure 8) and that require some degree of interpretation of contrasts must be validated by a second observer. The contrast between a caribou and the landscape is sometimes subtle. During moulting, the colour of caribou ranges from white to dark brown. Furthermore, calves are sometimes the same colour as adults (white, grey or dark auburn) and are usually distinguished by their smaller size. The detection and distinction of calves are a source of potential error. In rare instances, the validation of the count benefits from the collaboration of two observers and can necessitate the opinion of a third observer, when the first two cannot reach a consensus.

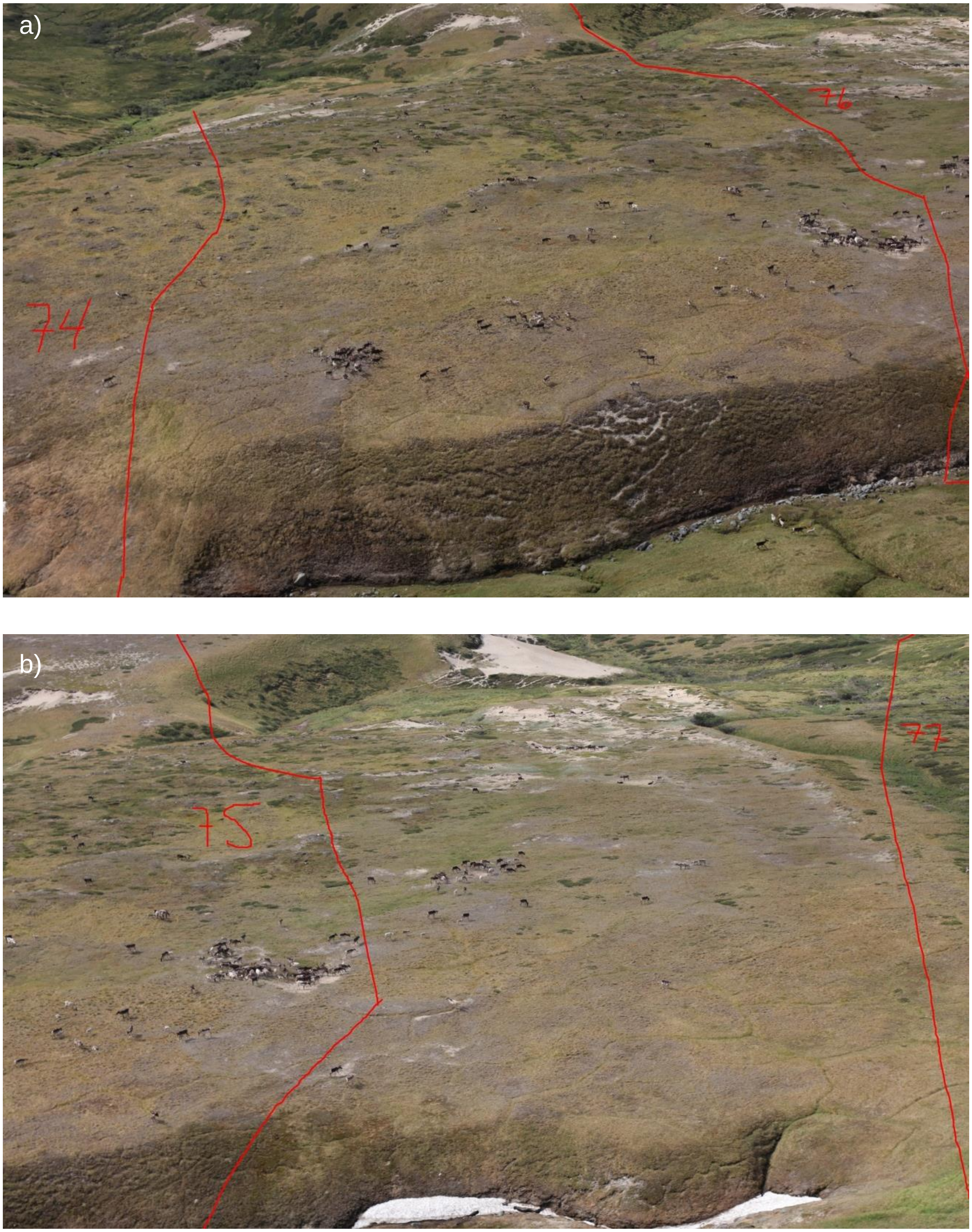

Figure 6: Photographs are analyzed using image processing software that allows to trace the boundaries of the mosaic that will prevail during counting and to identify the number of adjacent photographs. Photographs a) and b) present an example of the processing of two successive photographs (No. 75 and No. 76).

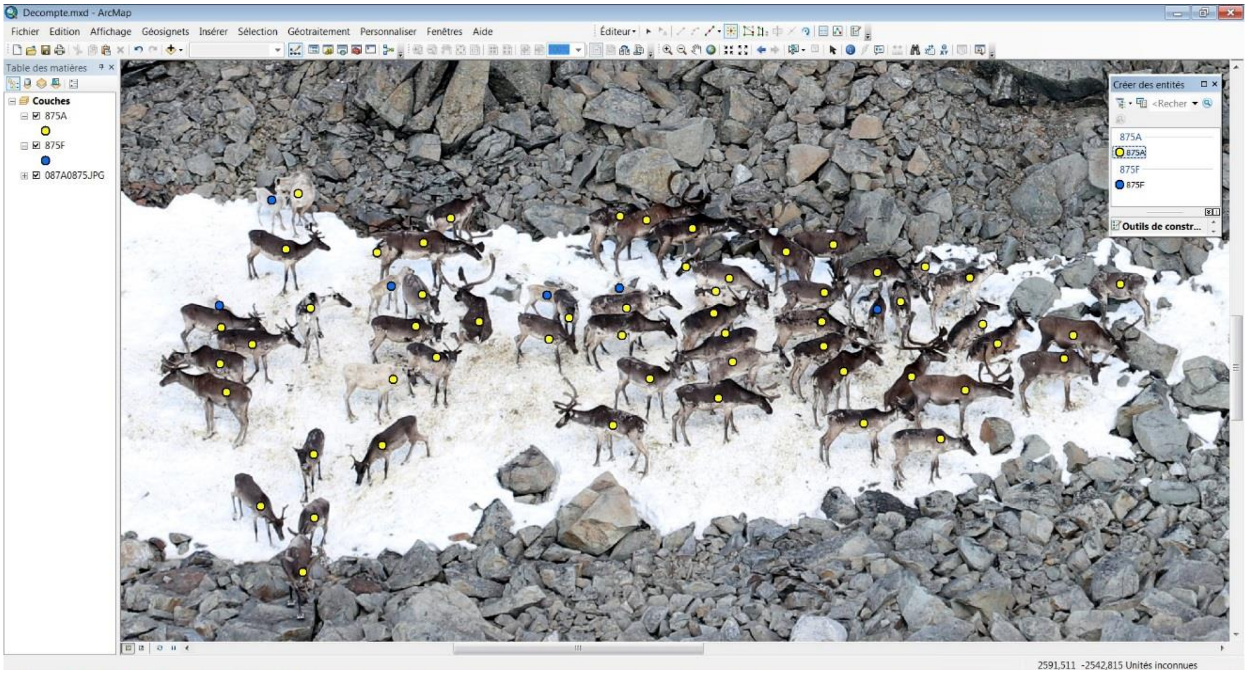

Figure 7: Example of the software interface used to count groups. The quality of the photographs greatly affects the ease with which this step can be carried out. This approach allows for considerable flexibility for the visualization of images and makes it easy to validate or modify the count.

The outcome of the validated count is then transferred into a summary file that describes each group of caribou observed during the survey. The file contains a sequential number to identify the group of caribou and the number of adults, the number of calves, the total number of caribou, the number of collared animals that it contains and their identity (VHF frequency, Satellite transmitter ID, animal ID, sex, status of the collar), as well as any relevant comment.

Analysis of atypical groups

The behavioural characteristics of migratory caribou and the variability of weather conditions in the summer distribution area lead to groups ranging in size from one caribou to several tens of thousands of caribou. For example, when population abundance is low, males are often found alone or in small groups of few animals on the fringes of large mixed concentrations. This behaviour has been clearly documented in the RGH since 2012, when the population was estimated at 27 600, and it became more pronounced in 2016 when the population was reduced to 8 900. The visit by a collared animal sometimes leads to the sampling of a single animal or few animals very remote from large concentrations of caribou. The decision whether or not to consider the animal or few animals as a group in the analyses must be based on the surrounding context. In such cases, overflight of the area makes it possible to determine whether the group is a valid sampling unit or an observation in a sector where aggregation conditions are unfavourable to a survey. If no other caribou is detected within a radius of roughly 2 km (approximately 12 km^2), this observation is deemed to be a group in the analysis since the method implies that the sampled groups overall are representative of the population's behaviour. If there is one or other caribou in the perimeter, this observation is not selected as a group because of the absence of aggregation of animals in the sector. The analysis must, therefore, consider the big aggregations and the scattered small groups that are travelling on the fringes of them so that the sample of groups accurately represents the population.

Migratory caribou travel daily over long distances that vary according to the time of year and environmental conditions. While telemetric locations provide a good indication of the position of a collared caribou, it must be borne in mind that the caribou can travel several dozen kilometres a day in the summer. Telemetry demands vigilance since the collared caribou are likely to travel at the time of sampling or engage in sustained movement following the sampling of the group to which they belong. For this reason, it is important to maintain good knowledge of the location of the animals sampled in relation to the unsampled animals. From day to day, it is possible for two or more small groups to converge at a given spot to form a bigger group. It is also likely that a collared animal will be sampled in a second group that contains one or more unsampled collared animals. Sampling in a sector where a high proportion of the population converges can thus pose a considerable logistical challenge. The following approach is used when processing groups that contain the same collared animal:

1. The groups are counted and the number of caribou represented by a collared animal is noted for each of the groups, e.g. group A of 1 000 caribou includes two collared caribou = 500 caribou/ collar.
2. The collared animal is selected solely in the group in which it represents the greatest number of caribou. The number of caribou that the collared animal represents is then subtracted from the group from which it is withdrawn, e.g. one collared animal from Group A is selected in Group B where it represents 800 caribou/ collar. Group A is then redefined as being 500 caribou represented by one collared animal.
3. If all of the collared animals from a group are found in another group where they represent a greater number of caribou, the group where the collared animals represent fewer caribou is withdrawn from the analysis.

Figure 8: It is sometimes hard to distinguish caribou in a barely contrasting background (a), which occasionally requires the adjustment of the contrast and brightness of the photographs. An enlargement of photograph a) is presented in b) to illustrate the importance of high-resolution digital photographs when photographs need to be taken at a relatively high altitude.

Calculation of population abundance

The calculation method (model) that allows for the estimate of the size of the population must make it possible to produce a realistic result, despite occasionally complex factors that influence the size and number of groups. Since caribou do not scatter randomly in the territory, it is important that the number of collars allows for the sampling of the majority of caribou in a population to avoid a bias caused by the heterogeneity of the density of caribou in the distribution area. The key factors that influence group size and explain that the formation of groups is not a random phenomenon are:

- behavioural heterogeneity due to sex and reproductive status;
- spatial proximity of breeding females from the calving grounds;
- the heterogeneity of climatic and topographical conditions in the summer distribution area (coastal and continental habitat);
- the catalytic effect of aggregation when there is a great abundance of caribou in a sector (critical mass).

Knowing that the factors that influence the variables of the model are not random, the methodology must seek a considerable sample of the population in order to incorporate such variability into the analysis and minimize the proportion of the outcome stemming from extrapolation. In such conditions, the accuracy of the model's result depends on the number of active telemetric collars and the number of sampled telemetric collars.

The premise of the random distribution of collared animals in the population is conditional upon the calculation of abundance. This premise is validated by a khi-two test (χ^2) that allows for a comparison of the number of collars observed in the groups with the number of collars expected in light of their size, according to the Poisson Probability Distribution. The degree of freedom for this analysis corresponds to the greatest number of collars observed in a group -1. The value of the statistic χ^2 is defined for a risk of error of 5% ($\alpha = 0.05$) and with the appropriate number of degrees of freedom.

Over the past decade, special attention has been paid to the maintenance of adequate telemetric monitoring of migratory caribou populations in Québec and Labrador. A sufficient number of telemetric collars has been used on site, thereby fostering the choice of the Lincoln-Petersen Method, a simple capture-mark-recapture model to estimate the abundance of populations. As explained earlier, the potential biases in this method, stemming from non-compliance with the model's methodological conditions, are reduced by the relatively high number of active telemetric collars and the ability to sample groups of variable abundance, since their detection is independent of their size (satellite collars). The estimate of the population size is obtained by means of the following formula:

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

where:

N = the estimated population size at the time of the survey;

M = the total number of collared caribou (equipped with an active collar) in the population at the time of the survey;

C = the total number of caribou inventoried in the groups sampled at the time of the survey;

R = the number of collared caribou, inventoried in the groups of caribou sampled at the time of the survey.

The confidence interval of the result of the model (N_i) is calculated as follows for a risk of error of 10% (α = 0.10; the value of the statistic *t* determined according to an infinite degree of freedom):

$$\boldsymbol{N_i} = 1{,}645\sqrt{\boldsymbol{Var}(\boldsymbol{N})}$$

where:

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

Since the model uses the sum of the caribou in the groups sampled (C) as a variable, the confidence interval of this model is not influenced by variability between groups, but solely by the total number of caribou in the groups sampled (C), the total number of collared animals in the population (M) and the number of collared animals sampled (R). This approach deems the grand variability in the size of groups of caribou to be normal and that it does not constitute a source of uncertainty for the estimate of the final result (N). The simple model thus implies that verifications be made to ensure that the validity of the result is not compromised by not considering the variance associated with the size and number of groups sampled.

The validity of the result (N) thus does not depend solely on the confidence interval of the result but also on the criteria that procure an assurance concerning the quality of the sample and the choice of a simple model:

1. no group of significant size not represented by a collared animal is observed at the time of the survey;
2. the most abundant groups are represented by more than one collared caribou;
3. the collared, unsampled animals at the time of the survey ($\boldsymbol{M} - \boldsymbol{R}$) are dispersed in the different sectors of density of caribou in the distribution area of the population at the time of the survey;
4. roughly 80% of the active collars were sampled during the survey ($\boldsymbol{M}/\boldsymbol{R}$).

Non-compliance with the criteria suggests that the number of telemetric collars is inadequate (criteria 1 and 2) or that the sampling effort is insufficient or poorly distributed in the summer habitat (criteria 3 and 4) to be representative of the population. This means that the abundance estimate is over- or underestimated, depending on the bias in question.

To conclude, there are CMR models other than the Lincoln-Petersen Model to estimate a migratory caribou population by means of telemetry (see Rivest *et al.*, 1998). A variant of the Lincoln-Petersen Model that uses a threshold for the minimum size of a group could also be used when the sample size of collared animals is sub-optimal or the population is relatively abundant (see Russell *et al.*, 1994 and Couturier *et al.*, 2014). However, this report does not seek to present a review or a comparison of the different statistical methodologies available. The technological breakthroughs described earlier support the use of the Lincoln-Petersen Model, which, despite the biases inherent in any statistical model, provides accurate results that adequately describe current variations in the abundance of migratory caribou populations in Québec and Labrador.

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