# Simulations of Harvest and Recovery for the Bathurst Caribou Herd, with Annual Variation

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# ABSTRACT

In the wake of the rapid decline of the Bathurst caribou herd from 2006-2009, management actions to try to stabilize the herd were debated by the Department of Environment and Natural Resources and co-management partners. Much of the herd's decline from peak numbers of about 470,000 in 1986 to an estimated 32,000 in 2009 was likely the result of a natural cycle that had occurred many times before. However, as the herd reached lower numbers, a hunter harvest estimated at 4,000-7,000 caribou/year (mostly cows) contributed significantly to the herd's decline. Restricting harvest was among the few management actions that were within direct human control. The modeling described here was carried out to help define a range of limited harvest options compatible with providing the Bathurst herd an opportunity to recover.

The approach that was taken was population modeling that incorporated variation in key demographic variables like calf survival. Deterministic modeling results in a single "determined" outcome for the herd under a certain set of conditions. Stochastic modeling is similar but instead of one model run for a certain set of conditions, hundreds of model runs are carried out and variables like calf survival are allowed to vary due to estimated amount of variation caused by biological, climatic, and other environmental factors. We ran this model under conditions of no harvest and different levels of harvest to estimate the impact of harvest on the Bathurst herd's future trend.

The outcomes in this case fell within a range of possible Bathurst herd sizes over a six-year period. Projected outcomes for the Bathurst herd included

(1) rapid decline: herd declining to 16,000 or less; (2) medium decline: herd declining to 16,000-23,000; (3) slow decline: herd declining to 23,000-32,000; (4) slow increase: herd increasing to 32,000-44,000; and (5) medium increase: herd increasing to 44,000 or more. The percentage of outcomes in each of the five classes could be seen as a probability of that outcome. This approach emphasized that the future trend of the Bathurst herd was not certain, but could vary in the real world, even with no harvest.

Overall, the modeling results pointed to a number of trends:

1. To recover, the Bathurst herd needed both higher cow survival and increased calf productivity.
2. If 2009 level of calf productivity continued, the most likely trend with no harvest was a slow or medium decline. The herd's chances of recovery were highest if harvest was zero in the next few years.
3. At harvest levels of 3,000-5,000 cows/year, the herd could not recover, regardless of calf productivity.
4. At lower harvest levels, particularly if the harvest was mostly bulls and 200-500 caribou in total, there was a risk of further decline, but there was little additional risk of decline compared to the risk associated with no harvest.
5. A limited harvest could be considered for an interim period (e.g. until the next population survey in 2012), acknowledging that there was a risk to the herd of further decline.

An adaptive management approach is essential for recovery of the Bathurst herd. Monitoring of productivity indicators (calf-cow ratios), numbers of cows on the calving ground and firm estimates of harvest would help further determine the relative recovery of the herd and allow better assessment of the applicability of model outcomes.

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## PLAIN LANGUAGE SUMMARY (J. Adamczewski)

In workshops and reports on the decline of the Bathurst caribou herd in late 2009 and early 2010, Environment and Natural Resources (ENR) used population projections from the Bathurst Caribou Calculator, a spreadsheet model first constructed for the Porcupine caribou herd, to look ahead and assess likely trend for the Bathurst herd under various sets of conditions. In particular, the modeling allowed us to consider how various levels of hunter harvest would likely affect the herd. This model is “deterministic”, which means that it projects the herd’s population trend as a single “determined” line with a single population estimate at any point.

In the real world, weather, calf survival, and other variables change from year to year, and there is uncertainty. ENR asked modeller/statistician John Boulanger to look at the Bathurst herd’s possible futures using a “stochastic” model. Instead of a single projection for the Bathurst herd, stochastic model is run hundreds of times for each set of conditions, with each model run having a different set of calf survival, cow survival, and other numbers changing from year to year. “Stochastic” essentially means that year to year variation is allowed for, and the outcome is a range of possibilities. For any set of conditions, the outcome is a projected population size, but there are, in effect, many lines and possible herd sizes over time. These can be grouped and the percentage of lines in each category can be added up. In this case the categories were:

- rapid decline (herd less than 16,000, half the 2009 estimate of 32,000);

- medium decline (herd between 16,000 and 23,000);
- slow decline (herd between 23,000 and 32,000);
- slow increase (herd between 32,000-44,000); and
- medium increase (herd over 44,000).

For each set of conditions, one or two of these categories were the most likely outcomes, with fewer outcomes in the other categories. These can be interpreted as the probabilities of the herd following each of these trends.

The work is summarized in the technical report from John Boulanger that follows. This introductory section provides a plain-language summary to illustrate some of the key outcomes. A larger range of harvest levels and demographic scenarios is presented in Boulanger's more detailed technical section. Most of this work was carried out in February and March 2010. ENR provided this draft report to the Wek'èezhìi Renewable Resources Board (WRRB) in 2010, to assist the board in considering a possible total allowable harvest for the Bathurst herd. As described by John Boulanger in his more detailed report, these analyses could also be used to help define a technically sound monitoring approach, and to contribute to an adaptive management program.

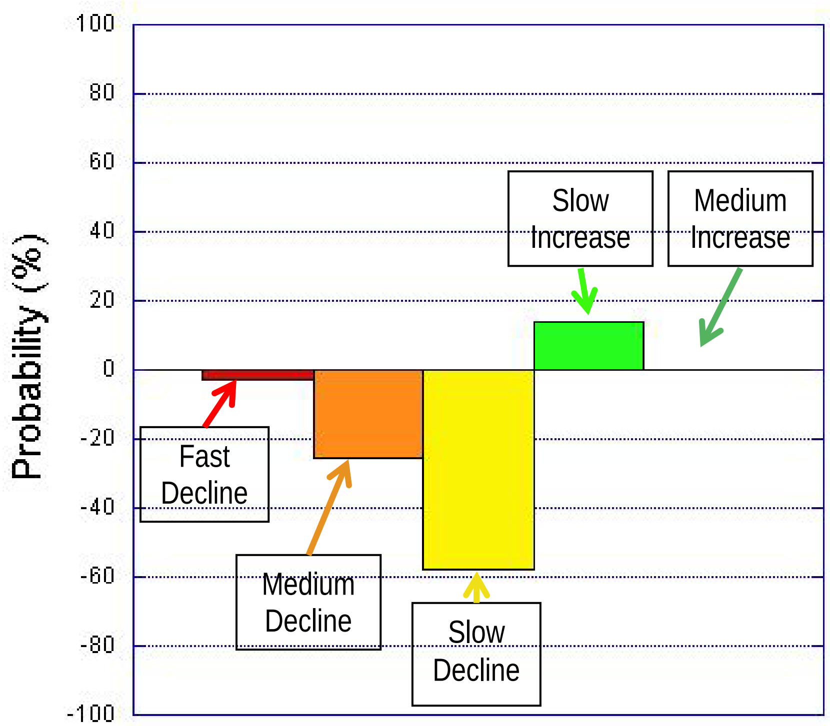


**Figure 1:** An example of the modeling output from the stochastic modeling. The size of the bar shows the likelihood of that outcome. Bars for decline are below 0, and bars for increase are above 0. In this case the most likely outcome is a slow decline and there is no chance of a medium increase.

The ordinary least squares (OLS) model, as described by Boulanger and Gunn (2007) and Boulanger et al. (2011), formed the basis for the harvest stochastic simulation model. The outputs from the stochastic modeling are shown as probabilities of each of the five outcomes listed above (Figure 1). Probabilities of decline are shown below the line, and probabilities of increase are shown above the line. In the example shown, the most likely outcome is a slow decline, with lower probabilities of faster decline and slow increase. A stable herd would have equal probabilities of slow decline (yellow) and slow increase (light green). Natural cow survival rates were assumed to be 88%, and all projections were for six years.

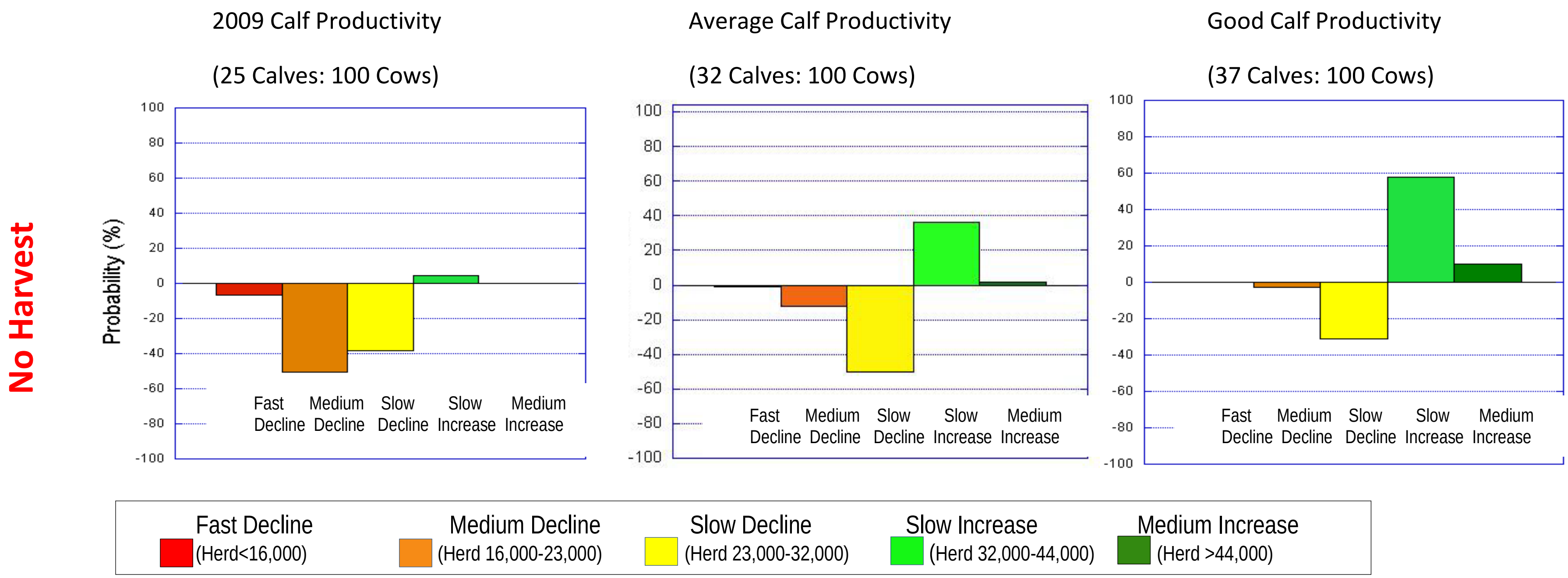


**Figure 2:** Likely six-year population trend for the Bathurst herd 2009-2015 with no harvest and calf productivity varying from 2009 levels (left) to average levels for the herd 1986-2009 (middle), and calf productivity for this herd before 1995 (right).

In Figure 2, likely population trend for the Bathurst herd 2009-2015 is shown assuming no harvest, and with the calf productivity the herd had in 2009. Calf productivity is shown as estimated spring calf:cow ratio. Note: the spring calf:cow ratios, as recorded in the field, showed higher values in 2008 and 2009, but were falsely high due to high cow mortality rates. This projection indicated that the herd’s most likely trend with no further harvest after the 2009 population estimate of 32,000 would be a slow or medium decline. Under these conditions, any amount of harvest could only increase the likelihood of further decline. In the middle graph in Figure 2 are likely outcomes if calf productivity improved slightly to average values for this herd between 1986 and 2009. On the right are likely outcomes if calf productivity improved to the level recorded for this herd before 1995. With no harvest and better productivity, the herd could stabilize or begin a modest increase.

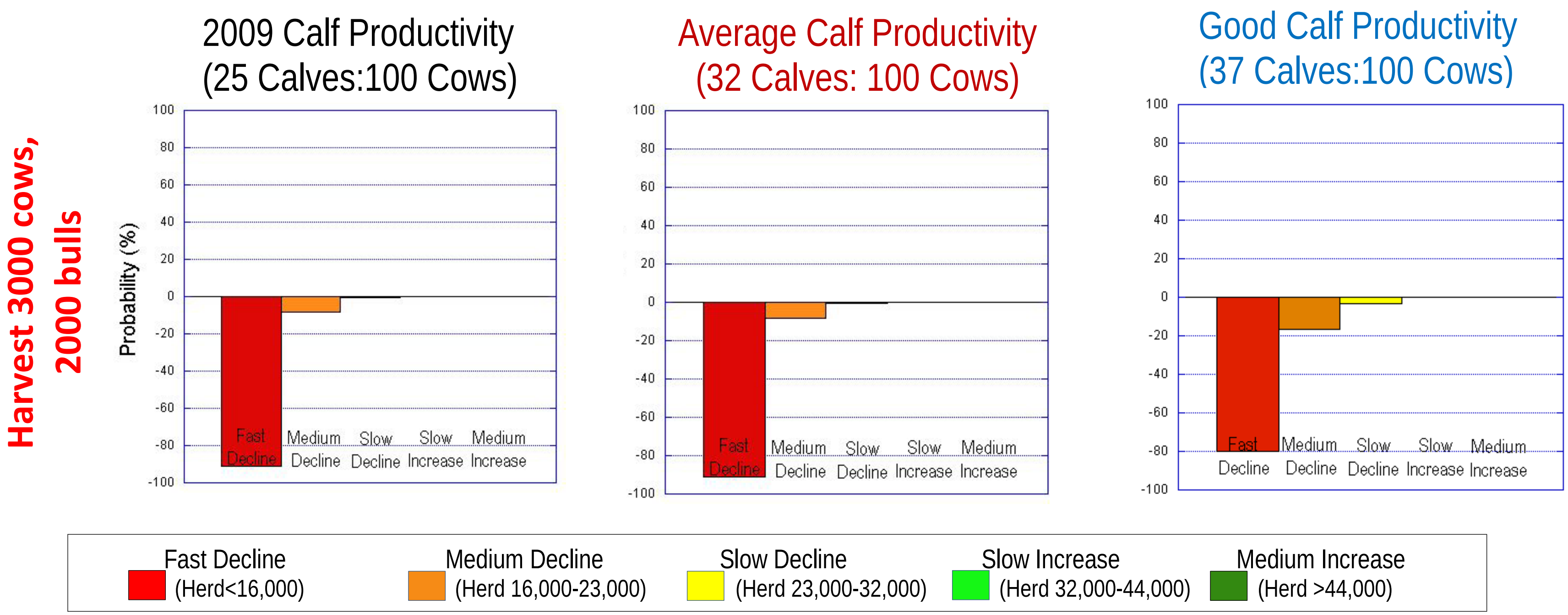


**Figure 3:** Likely six-year population trend for the Bathurst herd 2009-2015 with harvest of 3,000 cows and 2,000 bulls/year, and calf productivity varying from 2009 levels (left) to average levels for the herd 1986-2009 (middle), and calf productivity for this herd before 1995 (right).

In Figure 3 are likely outcomes for the same three levels of calf productivity and a harvest of 3,000 cows and 2,000 bulls. This is a conservative estimate of the likely Bathurst harvest in 2008-2009. With this harvest, the herd could only decline quickly, regardless of calf productivity. There was no level of calf production and survival that could compensate for these adult mortality rates and in particular the high cow mortality. Similar results were obtained for harvest of 6,000 (4,000 cows) and 7,000 (5,000 cows). At this scale of harvest, the risk of rapid decline was very high.

A smaller harvest of 1,000 caribou (750 bulls and 250 cows) was considered next, and the results are in Figure 4. At 2009 calf productivity, a medium decline would likely result, but if calf productivity improved to average levels, the decline would likely be slower, and at calf productivity at pre-1995 levels, the herd would likely be stable. Under these conditions, a harvest of 750 bulls and 250 cows would be sustainable. A further model run was carried out using a high calf productivity “best case scenario” of high pregnancy rate and high calf survival. Under these conditions, the Bathurst herd could sustain this level of harvest and still increase. Barren-ground caribou herds are capable of rapid growth when conditions are favourable. Unfortunately, most of the world’s caribou and reindeer populations were declining in 2009, so environmental conditions favouring rapid growth may not be likely in the near future.

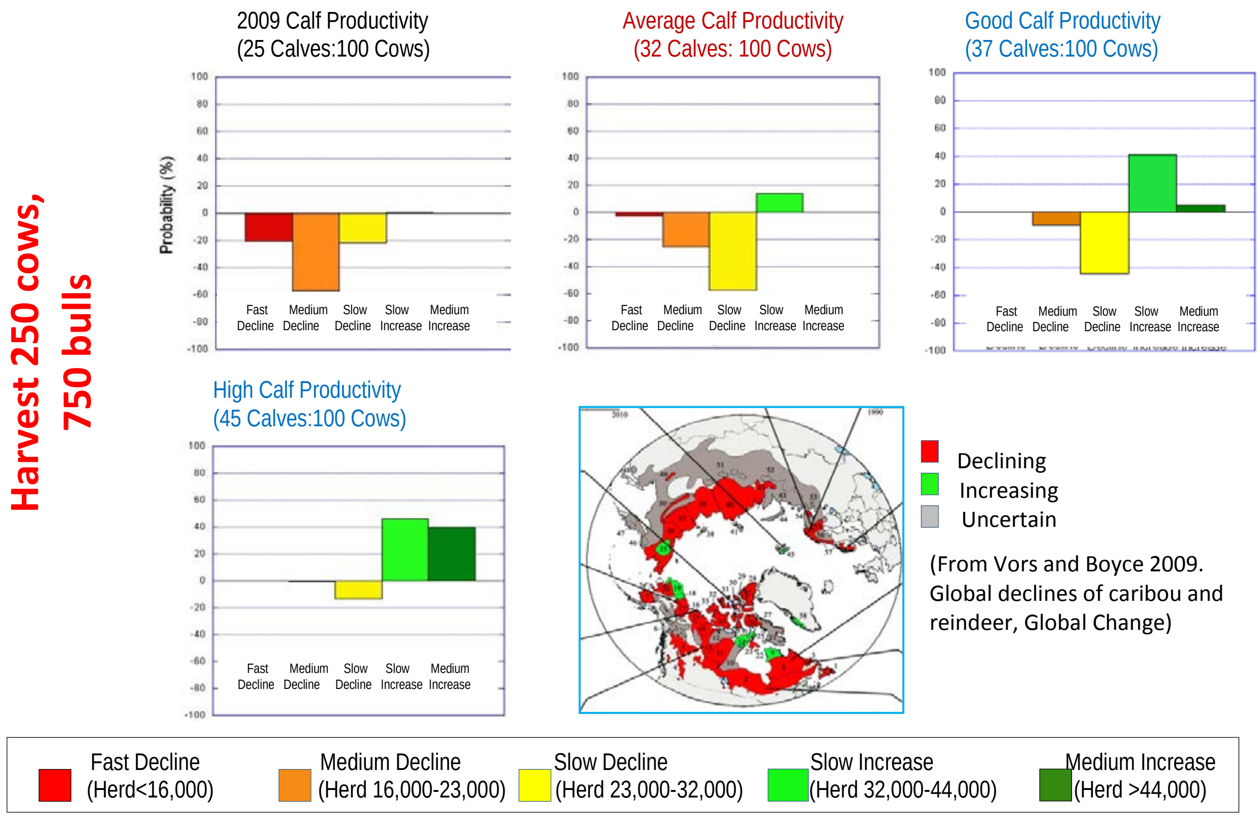


**Figure 4:** Likely six-year population trend for the Bathurst herd 2009-2015 with harvest of 1,000 caribou/year (250 cows and 750 bulls), and calf productivity varying from 2009 levels (top left) to average levels for the herd 1986-2009 (top middle), and calf productivity for this herd before 1995 (top right). On the bottom left is the likely outcome with high calf productivity; these numbers were a “best case scenario” of a high pregnancy rate and high calf survival. The bottom right figure shows population trend of global caribou and reindeer in 2009 (mostly declining), from Vors and Boyce (2009).

Two further harvest levels were considered: a harvest of 500 caribou (400 bulls, 100 cows) and harvest of 200 bulls (zero cows). These results are shown in Figure 5. At 2009 calf productivity, both these harvest levels would increase the likelihood of decline, but the decline would likely be relatively slow compared to the decline between 2006 and 2009. If calf productivity improved, the herd could be stable or might begin to increase slowly at these lower harvest levels. Further results with other harvest levels are described in Boulanger's more technical section that follows.

Overall, these modeling results point to a number of clear trends:

1. To recover, the Bathurst herd needs both higher adult survival, particularly in cows, and increased calf productivity.
2. If 2009 calf productivity continues, the most likely trend with no harvest is a slow or medium decline. From a caribou conservation perspective, the herd's chances of recovery are highest if there is no further harvest in the next few years.
3. At harvest levels of 3,000-5,000 cows and 2,000 bulls/year, the herd cannot recover, regardless of calf productivity.
4. At lower harvest levels, particularly if the harvest is mostly bulls and between 200 and 500 caribou in total, there is a risk of further decline, but the decline would likely be much slower than occurred between 2006 and 2009, with little increase in risk over a no-harvest scenario.

5. A limited harvest could be considered for an interim period (e.g. until the next population survey in 2012), acknowledging that there is a risk to the herd of further decline.
6. An adaptive management approach is essential for recovery of the Bathurst herd. Monitoring of productivity indicators (calf-cow ratios), cow numbers on the calving grounds and firm estimates of harvest would help further determine the relative recovery of the herd and allow better assessment of the applicability of simulation model outcomes.

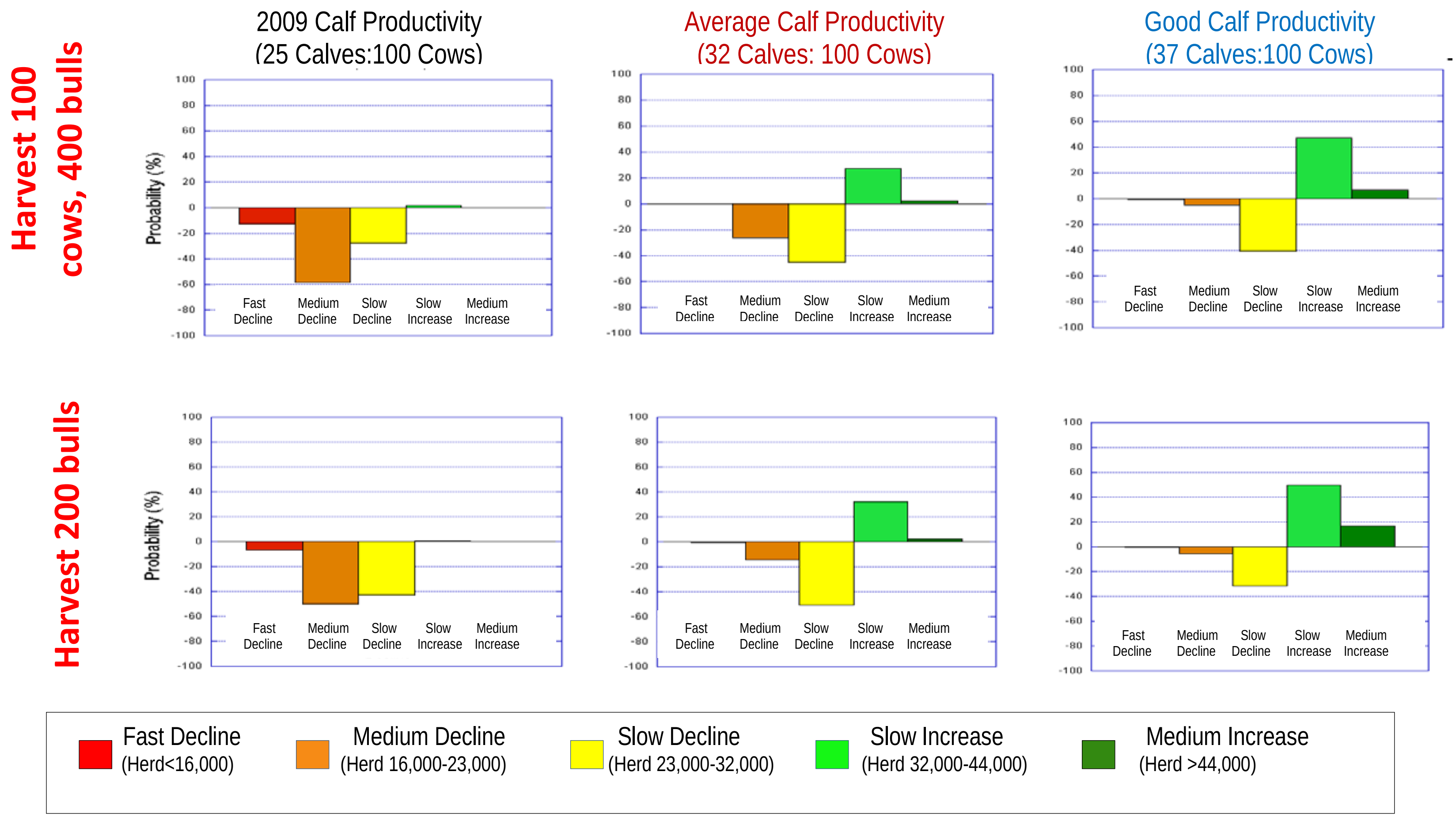


**Figure 5:** Likely six-year population trend for the Bathurst herd 2009-2015 with harvest of 100 cows and 400 bulls/year (top row), and a harvest of 200 bulls/year (bottom row).

# SIMULATIONS OF HARVEST AND RECOVERY FOR THE BATHURST CARIBOU HERD, MARCH 2010 (J. Boulanger)

## Introduction

In this report I explore scenarios for the recovery of the Bathurst herd under varying levels of harvest and management regimes. This work uses the stochastic population model as developed by Boulanger and Gunn (2007) and Boulanger et al. (2011) to simulate variation in demographic parameters in the Bathurst herd. There are many uncertainties that should be considered when forecasting recovery of the Bathurst herd. First, estimates from the deterministic OLS model of Boulanger et al. (2011) suggest that adult female survival and calf survival have varied greatly since 1985, and it is difficult to assess what future values of these parameters may be. This makes subsequent forecast of recovery difficult (Figure 6). Second, future trends in climate, harvest, and other covariates of demography are difficult to predict and therefore a wide range of potential scenarios for population trend is possible.

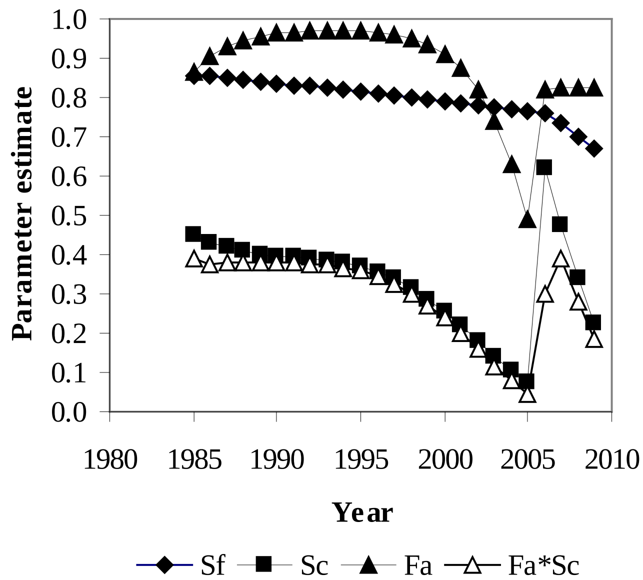


**Figure 6:** Trends in model-averaged estimates of parameter values from models in Table 1 for the Bathurst caribou herd (1985-2009) from Boulanger et al. (2011). Productivity as estimated by fecundity times calf survival is given for reference. Adult female survival (Sf), Calf survival (Sc), Fecundity (Fa) and productivity (Fa*Sc) are shown. Adult male survival (Sm) was 0.64 and yearling survival (Sy) was 0.86 for all years because temporal trends were not simulated in these parameters.

A stochastic model is basically a simulation model that is run hundreds of times with variation in demographic parameters simulated. The advantage of using a stochastic approach is that the outcomes include a range of possible "futures" for the herd. In the natural world, calf survival, pregnancy rate, and other variables change from year to year. The outcomes of stochastic modeling identify the most likely trends under a particular set of conditions, but they also make clear that there is uncertainty around those likely trends.

The main objective of this exercise was to use the stochastic model as an aid in setting management targets (i.e. herd sizes), and objectives while appropriately considering the uncertainty caused by natural variation in population parameters. Given uncertainty in Bathurst demography, any management of the Bathurst caribou herd should be adaptive with management goals that respond to future information on productivity, harvest, and other demographic indicators. Therefore, the model also generates predictions of all applicable demographic indicators as well as ranges of future herd sizes. The specific objectives of this exercise were as follows:

- Assess overall risk associated with various harvest management actions and population level targets as a function of natural variation in herd productivity and hypothetical harvest levels.
- Assess the probability of future herd sizes as based upon management objectives as well as the power to detect changes in population size. The monitoring interval between surveys is explicitly considered since this affects the power to detect population change.
- Predict field-based estimates of fall bull-cow ratios, calf-cow ratios, and breeding female numbers to be used in an adaptive management context to further refine management goals and simulations as more data become available.

## Methods

I considered a set of scenarios of varying herd productivity concurrently with variation in adult female survival as influenced by harvest levels, in consultation with ENR biologists. Productivity is difficult to control or manage compared to mortality/harvest and therefore it was important to consider all simulations across a range of likely productivity levels.

## Scenarios of adult productivity

Ranges of adult productivity were based upon the range of observed values from the OLS model (Table 2). Productivity can be conceptualized as the proportion of breeding age females that produce a calf that survives to become a yearling. The other parameter that can affect productivity is pregnant adult female survival. If female survival is low then cows are less likely to survive through pregnancy and less likely to produce a calf until weaning. This covariance is further explored in simulations that consider the effect of harvest on females.

**Table 1:** Productivity scenarios considered in simulations.

| Scenario | Sc | Fa | Productivity (Sc*Fa) |
|---|---|---|---|
| Low (2009) productivity | 0.22 | 0.83 | 0.18 |
| Average productivity | 0.33 | 0.88 | 0.29 |
| <1995 productivity | 0.4 | 0.95 | 0.38 |
| High productivity | 0.6 | 0.95 | 0.57 |

The values in Table 2 were mainly estimated from the Bathurst herd in the decline phase (1985-2009) and higher productivity values are possible. Several NWT/Nunavut herds increased rapidly in the early 1980s, and the George River herd in Quebec grew from about 5,000 in 1950 to about 600,000 in 1984 (Bergerud et al. 2008). To produce a higher productivity scenario I multiplied the highest level of fecundity observed (0.95 in 1994) times the highest calf survival observed (0.6 in 2006). This represents a “best case scenario” from estimated Bathurst herd demographic parameters. In comparison, values of productivity for the western Arctic herd in Alaska varied from 0.39-0.65 based upon field-based estimates and values estimated from a demographic model respectively (Haskell and Ballard 2007). The western Arctic herd was mainly in an increase phase during the time it was monitored by Haskell and Ballard (2007). Given this, the high productivity scenario would most directly correspond to a caribou herd in the increase phase.

The low productivity scenario is based upon the most recent 2009 estimates of productivity in the Bathurst herd. The lowest productivity actually observed for this herd was 0.04 in 2005. Low productivity in 2005 was a result of a variety of climatic/condition factors (Boulanger and Gunn 2007) and is not typical of the Bathurst herd. However, as discussed later, monitoring of productivity is an essential part of adaptive management. If low productivity levels are observed in subsequent years then this type of productivity scenario should be explored further. Recent spring calf:cow ratios for the Bathurst herd were deceptively high; ratios like this can be inflated by high cow mortality (Boulanger et al. 2011).

## Estimates of base survival without hunting mortality

One of the main objectives of the simulations was to consider the reduction of adult survival based on different levels of hunting mortality. Therefore, a base level of survival with no hunting mortality had to be estimated. This estimate assumed that only natural mortality (i.e. predation) affected caribou survival. This was done using estimated harvest from the Dogrib harvest study from 1988-1993 as compared to estimates of population size from the OLS model for that time period (Table 2). The proportion of the population harvested, or the proportion of mortality caused by hunting was estimated by the Dogrib estimate of harvest divided by the OLS population size estimate. This estimate was then added to the OLS survival rate estimate (which included hunting mortality) to estimate what survival would have been if there was no hunting (and predation mortality was constant). From this, estimates of survival without hunting of 0.87 and 0.72 for cows and bulls were estimated.

**Table 2:** Estimates of base cow and bull survival rates using OLS population and survival estimates and estimates of harvest from the Dogrib Harvest study.

| Year | OLS N Estimate | | Harvest | | Prop. N Harvested | | OLS Survival | | Survival No Harvest | |
|---|---|---|---|---|---|---|---|---|---|---|
| | Bulls | Cows | Bulls | Cows | Bulls | Cows | Cows | Bulls | Cows | Bulls |
| 1988 | 105,866 | 234,567 | 4,606 | 3,318 | 4.35% | 1.41% | 84.5% | 64.0% | 85.87% | 68.35% |
| 1989 | 101,303 | 230,563 | 3,855 | 4,730 | 3.81% | 2.05% | 84.0% | 64.0% | 86.10% | 67.81% |
| 1990 | 97,736 | 225,611 | 8,970 | 8,450 | 9.18% | 3.75% | 83.6% | 64.0% | 87.38% | 73.18% |
| 1991 | 94,728 | 219,798 | 10,073 | 11,626 | 10.63% | 5.29% | 83.2% | 64.0% | 88.49% | 74.63% |
| 1992 | 92,023 | 213,238 | 9,685 | 9,046 | 10.52% | 4.24% | 82.8% | 64.0% | 87.01% | 74.52% |
| 1993 | 89,301 | 205,878 | 7,712 | 13,107 | 8.64% | 6.37% | 82.3% | 64.0% | 88.70% | 72.64% |
| Average | | | 7,484 | 8,380 | 8.56% | 4.34% | | | 87.26% | 71.86% |

One issue with the Dogrib harvest study based estimate of adult female survival was that the OLS model indicated that survival was declining (Figure 6) suggesting female survival was higher in 1985 than the period of 1988 to 1993 used for the estimates in Table 2. I therefore also considered an adult female survival estimate based upon the 1985 OLS estimate. The OLS estimate of female survival for 1985 was 0.856 and the corresponding proportion of the population harvested, assuming 8,000 cows per year harvested from the Dogrib study (Table 2) was approximately 3.3% (Figure 7). This resulted in an estimate of adult female survival without harvest of 0.89. This estimate was less based on data since there was no corresponding estimate of harvest for 1985. However, it potentially better represented historic adult female survival before the decline in population size. I therefore averaged the estimate of female survival without harvest from Table 2 and this estimate to arrive at an estimate of adult female survival without hunting of 0.88.

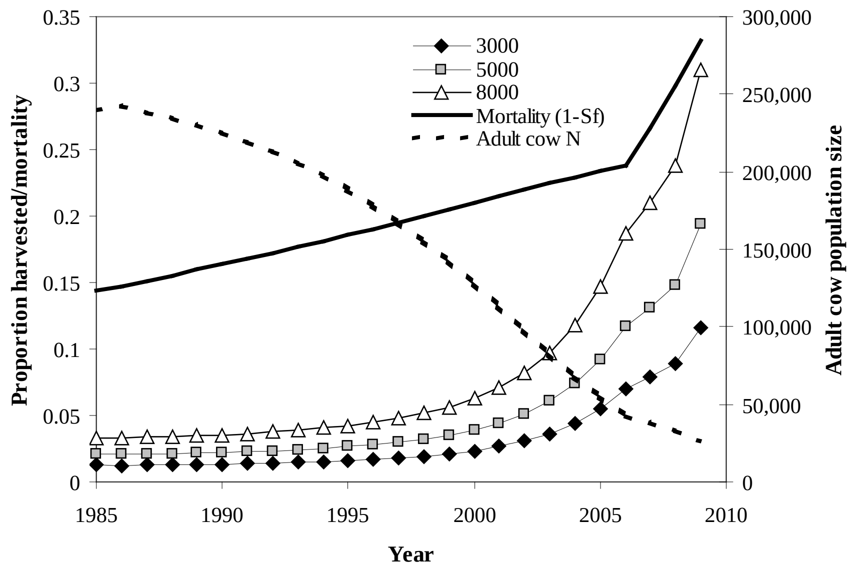


**Figure 7:** Trends in proportion of adult cows harvested annually as a function of model-averaged estimates of adult cow population size and hypothetical harvest levels for the Bathurst caribou herd (1985-2009) from (Boulanger et al. 2011). Model-averaged estimates of cow mortality rate (1- cow survival rate) for adult cows are also shown for reference.

As discussed later, the estimate of adult female survival of 0.88 assumes that mortality rates due to predation and other causes (i.e. 12%) have remained relatively constant since 1985. This assumption implies that predators have declined in unison with caribou so that they are preying upon the same relative proportion of the population. If predation rates relative to the population have increased then the estimate of natural mortality will be higher leading to a current "natural survival rate" with no hunting that is lower than 0.88. Unfortunately, data on predation rates or precise radio collared estimates of adult survival were not available to test this assumption. Implications of this assumption and future approaches to test this assumption are discussed later in the report.

## Process variation in demographic parameters

Boulanger et al. (2011) estimated biological or process variation in demographic parameters (Table 3). These estimates were also used for the harvest simulations. Directional change in parameters was not simulated beyond the effect of constant harvest on adult male and female survival rates.

**Table 3:** Process variation for demographic parameters as detailed in Boulanger et al. (2011). This is the natural variation that occurs in these parameters as estimated from field data.

| Parameter | CV (individual) | CV (time) |
|---|---|---|
| Adult female survival (Sf ) | 0.10% | 3.15% |
| Adult male survival (Sm) | 0.10% | 3.15% |
| Fecundity (Fa) | 8.50% | 1.39% |
| Calf survival (Sc) | 12.70% | 36.79% |
| Yearling survival (Sy) | 12.70% | 3.15% |

### Initial population sizes for simulations

The estimated population size for the Bathurst herd for 2009 and associated confidence interval was used as a starting point for simulations. For each simulation, an initial herd population size was generated based upon the point estimate ($\hat{N} =$31,897, SE=5,345.1, CI=20,965-42,829) and the associated SE to generate a random normal variable that was centered on the point estimate and was distributed similar to the confidence limit of the estimate. This random normal variable was then subdivided for adult cows and bulls based upon the 2008 estimated fall sex ratios. The proportion of the population that was yearlings and calves was then estimated using an assumed stable age distribution that was a function of initial demographic parameter values. POP-TOOLS (Hood 2009) in Excel was used to estimate stable age distributions for simulations.

### Harvest levels simulated

Two important questions were whether the herd could tolerate a continued limited hunt of females, and what the effect of a male dominated harvest on overall herd size would be. I therefore simulated harvest levels of 0-5,000 caribou with varying proportions of females harvested.

Another management question was the effect of the shutdown of harvest in 2010 on herd recovery. It had been estimated that the harvest of caribou during the winter of 2008-2009 was 7,000 caribou (5,000 cows and 2,000 bulls). I simulated the effect of immediate shutdown of this harvest in 2010 (basically a simulation with no hunting), shutdown of harvest in 2011, 2012, and no shutdown of harvest.

### Assessment of simulation outcomes

The goal of these simulations was not to forecast the exact time of recovery or the exact future population size of the Bathurst herd, but instead, to inform management on the probabilities of change in herd size based upon sets of management scenarios. To further this objective, simulations were evaluated in terms of the proportion of simulations that met specified management and monitoring-based herd population size ranges (Table 4). The proportions of simulations in this context could be interpreted as the relative probability of meeting a given management target.

Target levels were based upon the ability to detect changes in breeding female population size and management objectives. To estimate the power to detect change I assumed the level of precision of breeding female estimates from future surveys would be similar to the 2009 survey. I then estimated the difference in breeding female population sizes required to detect change in population size using a 2-tailed t-test with a $\alpha$ level of 0.1. In this case, the hypothesis would be a change in population size as opposed to a directional (negative or positive) change. Degrees of freedom for the t-tests were estimated using the formulas of Gasaway et al. (1986).

As discussed later, the t-test is not necessarily the most efficient method to compare estimates however this analysis was mainly intended to provide a general estimate of the power to detect trends which could be used to determine the appropriate intervals for calving ground based population estimates. An alternative is trend analysis from visual surveys of calving grounds. As discussed later, a power analysis on this approach is planned to compare with the t-test based method.

Breeding females are the best segment of the caribou population to use for trend estimates. However, management targets, especially when harvest sex ratio is favoured towards males, are usually based upon overall herd size. The t-test power analysis provided estimates of a lower breeding female population size needed to detect a decline and a higher breeding female population size needed to detect an increase based upon the 2009 estimate of 16,000 breeding cows. These lower and upper estimates of breeding females were then extrapolated to herd size using the 2008 bull:cow ratios and assumed proportion of females pregnant to set corresponding herd size targets.

Note that an inherent assumption with these targets is that sex ratio will not change appreciably in the short term so that breeding female population size can approximate future herd size. This may not be the case, however, and I suggest that these targets should be considered incrementally as new information about herd status is collected. For example, the relationship between breeding female population size and herd size can be incrementally adjusted as new data on bull:cow ratios (from fall composition surveys) are collected. In addition, once another calving ground photo survey is conducted, these targets could be changed.

**Table 4:** Levels of target populations for management used for simulations. Detectability is based upon the assumption that future spring calving photo surveys have the same level of precision as the 2009 survey. The correspondence of breeding female numbers and total herd size is based upon the estimated 2008 fall sex ratio.

| Management scenario and objectives | Target herd size range | Breeding female range | Comments |
|---|---|---|---|
| Detectable increasing herd size | >44,000 | >23,000 | Statistically detectable increase. |
| Potential increase (not detectable) | 32,000-44,000 | 16,000-23,000 | Potential increase but not statistically significant. |
| Potential decline (not detectable) | 23,000-32,000 | 12,000-16,000 | Potential decline that is not statistically detectable. |
| Decline first detected | 16,000-23,000 | 8,000-12,000 | Decline becomes detectable. |
| Herd in severe decline (detectable) | <16,000 | <8,300 | Approximately half the 2009 estimated size suggesting herd is still declining sharply. |

Another pertinent question for management was the timelines in which the herd might meet target herd sizes and the corresponding intervals in which management strategies should be evaluated. As time progresses, herd size changes, making apparent increases or declines more evident. Therefore, the interval for evaluation of population size (i.e. between spring calving ground surveys) was of interest in evaluating management targets as proposed in Table 4. The probabilities of the management targets were therefore evaluated at three, six, and nine years which correspond to possible intervals in which subsequent calving ground surveys might be conducted. These results help determine the optimal monitoring intervals needed to ensure detection of various herd size levels.

## Predicted demographic trends and field based estimates

A key use of this modeling was not just predictions in terms of population size but also predictions of field based measurements to further assess herd status. Therefore, I also generated predictions of most of the field-based measurements such as calf:cow ratios and bull:cow ratios. Breeding female population size was also predicted given that it was influenced by both overall herd size and the assumed productivity scenario, and level of fecundity.

The effect of harvest was explicitly considered for these estimates. For example, it is assumed that harvest occurs in mid-winter so that fall based measurements will not be affected as much as spring based measurements. Subtracting harvest from population sizes between the fall and spring estimates simulated this effect.

## Results

I used stacked bar charts that displayed the simulation outcomes in terms of productivity scenarios (Table 1), management targets (Table 4), and monitoring intervals (years until next calving ground survey) for the most applicable simulations. The idea of the bar-charts is to convey the probabilistic nature of the stochastic model outcomes in a graphical fashion. The colors of the stacked bars convey the relative risk of each outcome (much red=”very high risk” and much green=”less risk”).

There is a lot of information displayed when variation in productivity, monitoring interval, population target levels, and harvest levels are considered simultaneously. The stacked bar-charts efficiently summarize the range of simulation outcomes across a range of assumed productivities and monitoring intervals. A graph that has a lot of red means that the given harvest scenario has a high risk of rapid decline compared with a graph that is mainly yellow or green. Some combinations of higher calf productivity and low harvest can result in a stable or increasing herd; these could serve as estimators of a sustainable harvest under those conditions. This allows interpretation of risk of management strategies without detailed attention to individual simulation outcomes.

### Simulations with no harvest

Simulations with no harvest of either bulls or cows demonstrated that productivity must increase to levels that were seen before 1995 (0.38) for the herd to recover in over 50% of the simulations. If productivity stays low (2009 levels: 0.18) then the herd will continue to decline with the majority of simulations in the “red” zone by year nine. In contrast, with high productivity the herd could be in the “green zone” (i.e. increasing) for the majority of simulations in nine years (Figure 8).

Figure 8 also shows that if productivity is moderate then there is little apparent change in simulation results with survey interval. For example, there would be minimal chance of detecting change in the herd for productivity levels of 0.29 and 0.38 given that amber (slow declines) or yellow (slow increases) are not statistically detectable. However, if productivity is low or high, the proportion of simulations at different herd levels changes more dramatically as a function of monitoring interval. For example, a negative trend in population size (red) would be detectable in the majority of simulations by year six if productivity were low, and a positive (green) increase in population size would be detectable by year six if productivity was high.

In reality, productivity will probably vary over time so that the actual outcome would be a combination of each of the scenarios. This further demonstrates why apparent productivity (i.e. calf:cow ratios) have to be used with caution and are best considered in a model context (e.g. OLS model) when evaluating the status of the herd at different time intervals.

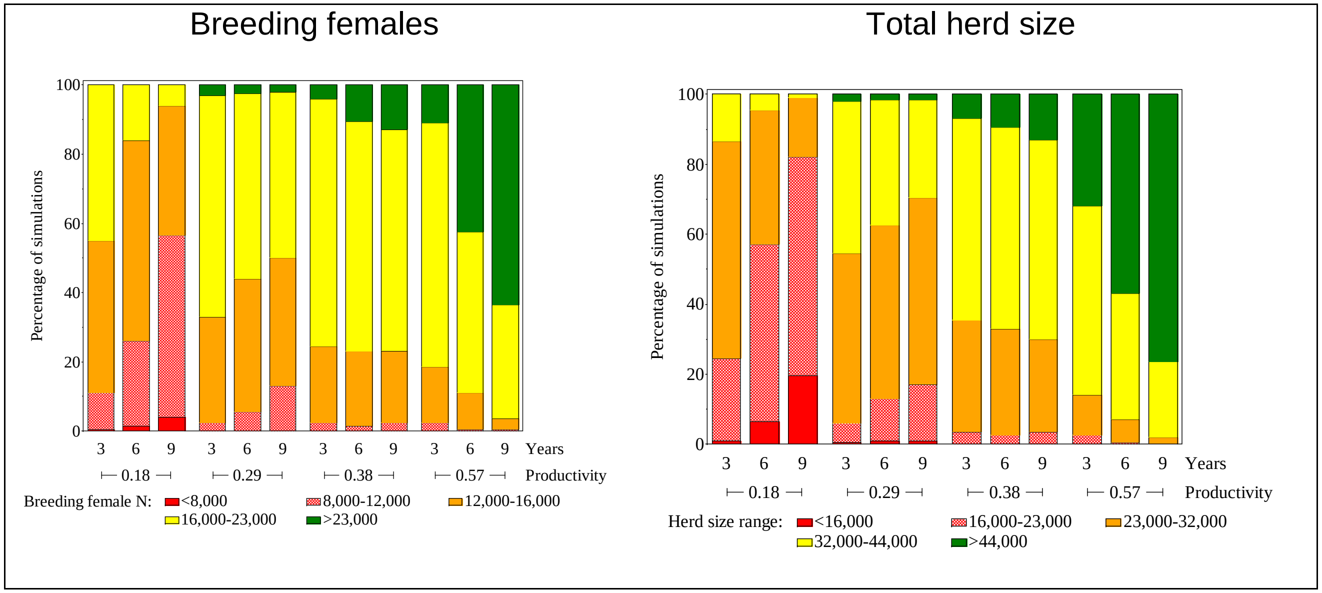


**Figure 8:** Results of simulations with no harvest (male or female) as a function of mean productivity and years since 2009. Each color on the bar denotes the relative proportion of simulations that resulted in a given range of herd sizes/management targets with the estimates of 16,000 cows and 32,000 caribou as a baseline. Declines that are coloured red and increases that are coloured green are statistically detectable. For these simulations adult female survival was 0.88 since no harvest was simulated. Productivity estimates correspond to productivity scenarios as listed in Table 1.

Figure 8 also illustrates that trends in breeding female numbers and herd size are almost identical. This is because the no harvest simulations have constant survival rates and therefore there is minimal change in the population sex ratio. Also, female mortality predominantly drives the herd size (in comparison to bull mortality) given that no effects of sex ratio on breeding success were simulated.

## Simulations with incremental change in current estimated harvest

The estimated harvest of caribou for the winter of 2008-2009 was 7,000 with 2,000 bulls and 5,000 cows harvested. I ran simulations where this harvest was continued for one year (until 2011) and two years (2012), then compared this to a scenario of no harvest and a scenario with continued harvest at this level (Figure 9).

The results suggest that with average productivity and no harvest shutdown, the herd would experience a critical decline in the majority of simulations evaluated at year three, and all simulations evaluated at year six and nine. With an immediate harvest shutdown, approximately 40% of the simulations suggested an increase at year three. As the year of harvest shutdown increased, the proportion of simulations in which the herd increased was reduced, suggesting higher risk of a severe decline with delays in changing harvest strategies.

Higher productivity partially offsets the effect of continued harvest. However, note that even with high productivity the majority of simulations suggest a declining population for the no change in harvest scenario (Figure 9).

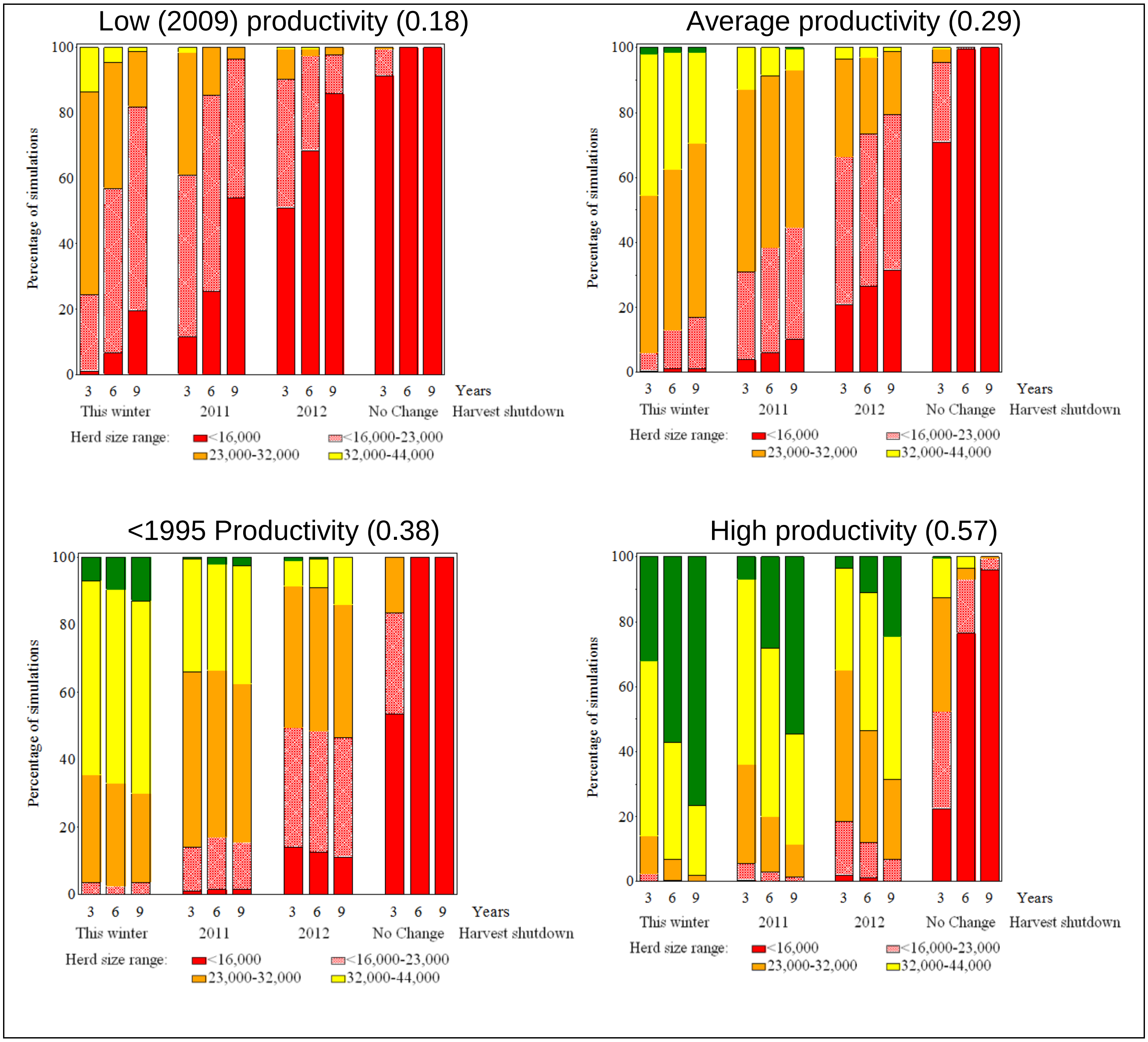


**Figure 9:** Results of simulations with differing scenarios for when the caribou harvest was shut down (reduced to 0 caribou annual harvest) across the "extremes" of productivity. Each color on the bar denotes the relative proportion of simulations that resulted in a given range of herd sizes/management targets. For these simulations productivity was set at the low (2009) or high productivity levels (Table 1).

## Simulations with constant harvest

### *Annual harvest of 2,500 caribou*

Simulations with higher harvest rates demonstrated the high sensitivity of herd size to any level of female harvest, and how high productivity buffers the effects of female harvest (Figure 10). For example, with an annual harvest of 2,500, there was noticeable change in simulation outcomes to a limit female hunt of 625 cows when productivity was low. But when productivity was higher there was minimal change in simulation outcomes.

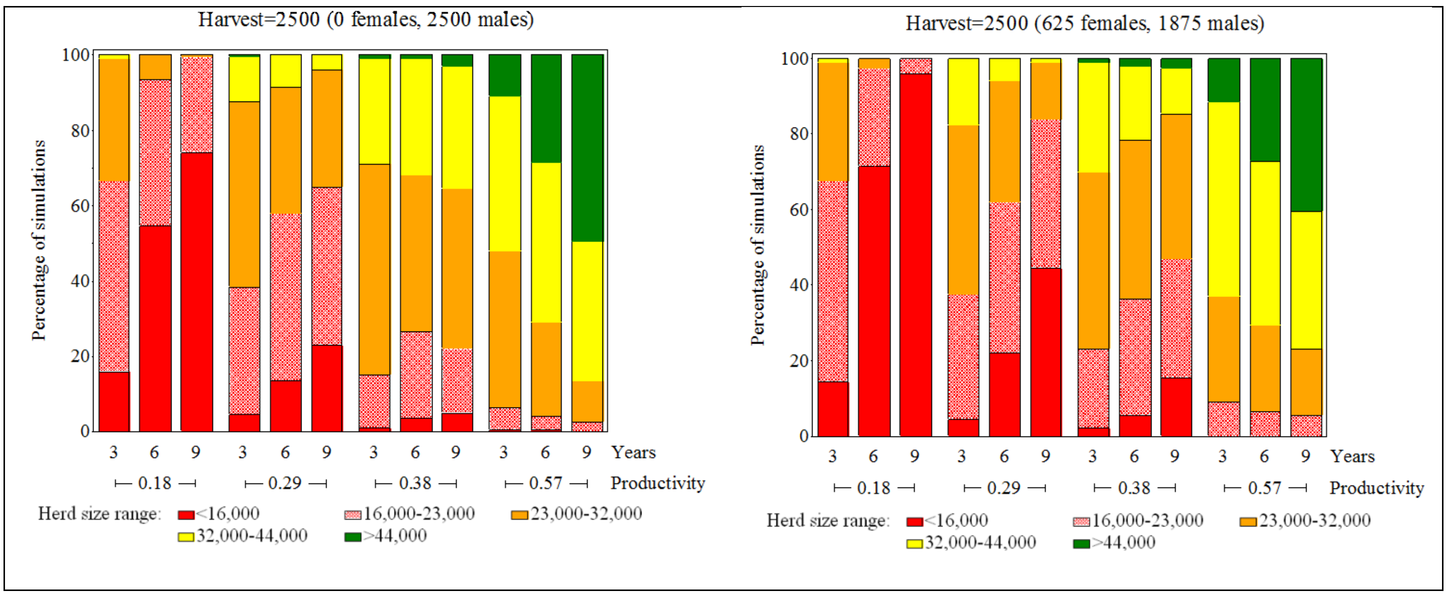


**Figure 10:** Results of simulations with an annual harvest of 2,500 caribou (with 0 or 625 females harvested) as a function of mean productivity and years since 2009. Each color on the bar denotes the relative proportion of simulations that resulted in a given range of herd sizes/management targets. Productivity estimates correspond to productivity scenarios as listed in Table 1.

### *Annual harvest of 5,000 caribou*

Simulations at high harvest levels demonstrated that regardless of productivity levels, the herd could not tolerate an expanded harvest of 5,000 caribou even if only males were harvested. Even with high productivity the majority of simulations suggest decline that increases as the monitoring interval increases. If 2,500 females are harvested the majority of simulations are in the "red zone" (Figure 11), i.e. there is a high risk of rapid decline.

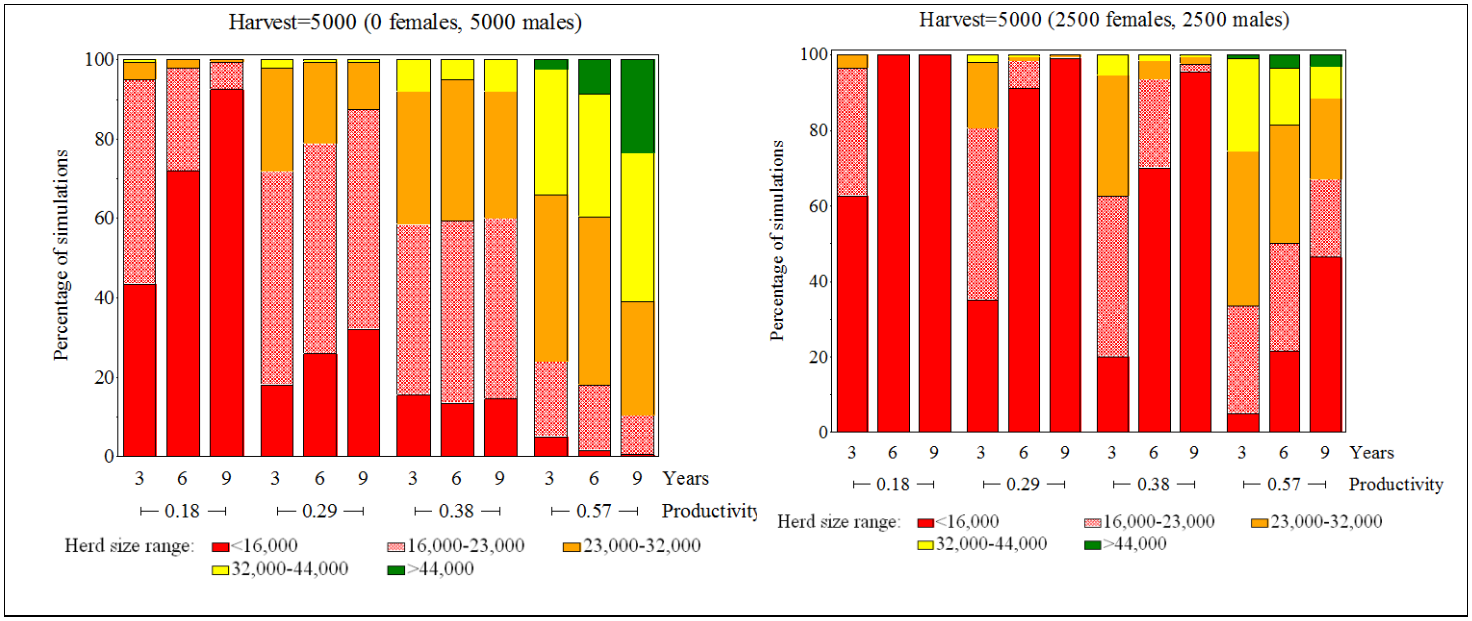


**Figure 11:** Results of simulations with an annual harvest of 5,000 caribou (with 0 or 2,500 females harvested) as a function of mean productivity and years since 2009. Each color on the bar denotes the relative proportion of simulations that resulted in a given range of herd sizes/management targets. Productivity estimates correspond to productivity scenarios as listed in Table 1.

### ***Annual harvest of 1,000 caribou***

Simulations with lower annual harvest suggested that if productivity is low the population will decline irrespective of the cow harvest level. In contrast, there was minimal effect of moderate cow harvest (≤250 cows) if productivity was high (Figure 12). This type of outcome could be used to consider a sustainable harvest for the herd under those conditions. The main effect of cow harvest can be seen in the middle levels of productivity. In this case, the probability of a "red decline" increases when productivity is 0.29 (evaluated at nine years) even with a cow harvest level of 125 caribou. A less pronounced probability of decline is evident when productivity is 0.38.

The overall effect of an annual harvest of 1,000 caribou is a reduced probability of overall recovery (the green zone) across all levels of productivity, if Figure 12 is compared to Figure 8 where 0 harvest is simulated.

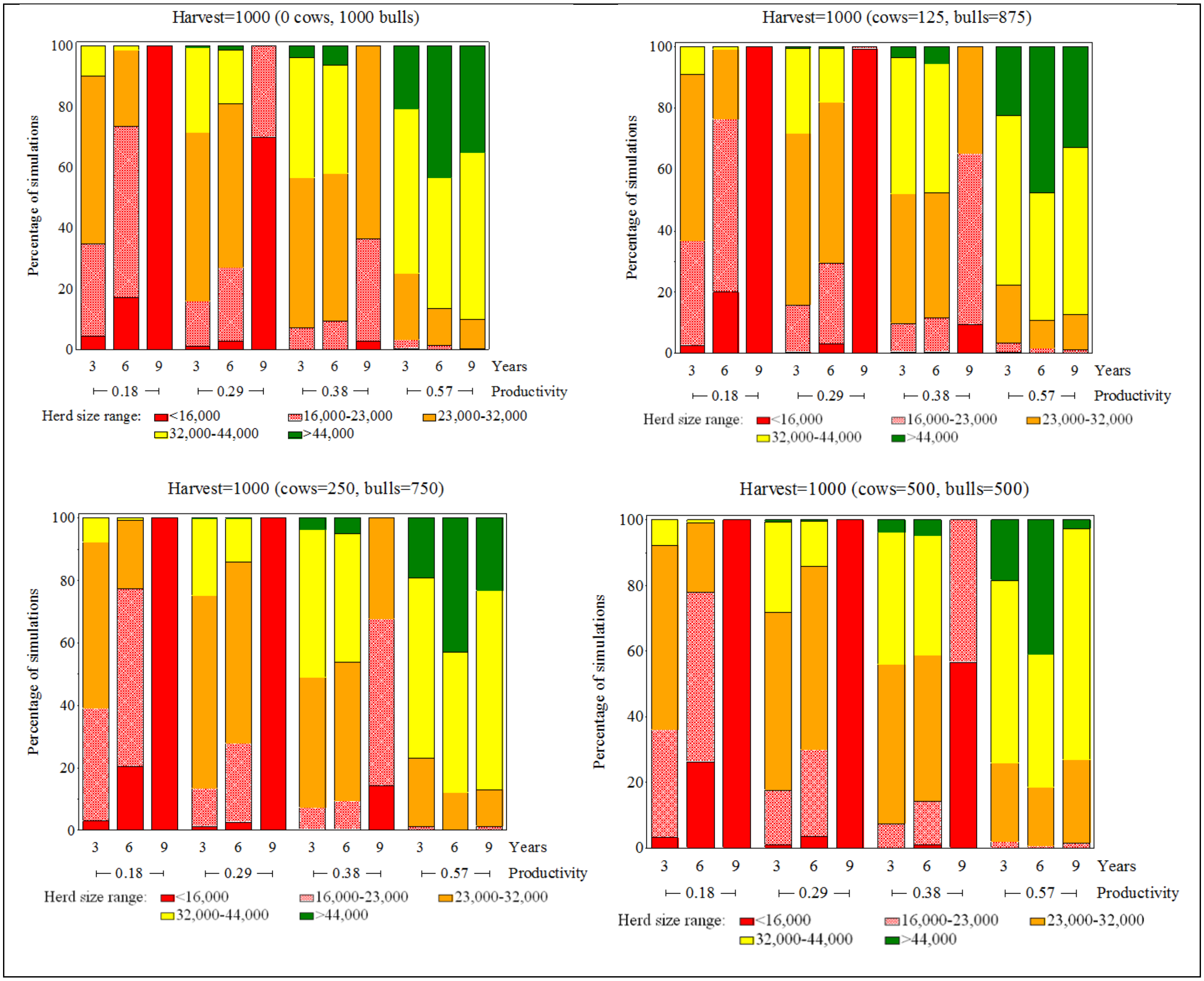


**Figure 12:** Results of simulations with an annual harvest of 1,000 caribou (with varying numbers of females harvested) as a function of mean productivity and years since 2009. Each color on the bar denotes the relative proportion of simulations that resulted in a given range of herd sizes/management targets. Productivity estimates correspond to productivity scenarios as listed in Table 1.

***Annual harvest of 200 caribou***

Simulations with an annual harvest of 200 suggested minimal influence of harvest on population trend compared to the effect of variation in productivity. In this case, the natural variation in demographic parameters is obscuring any detectable effect of harvest (Figure 13).

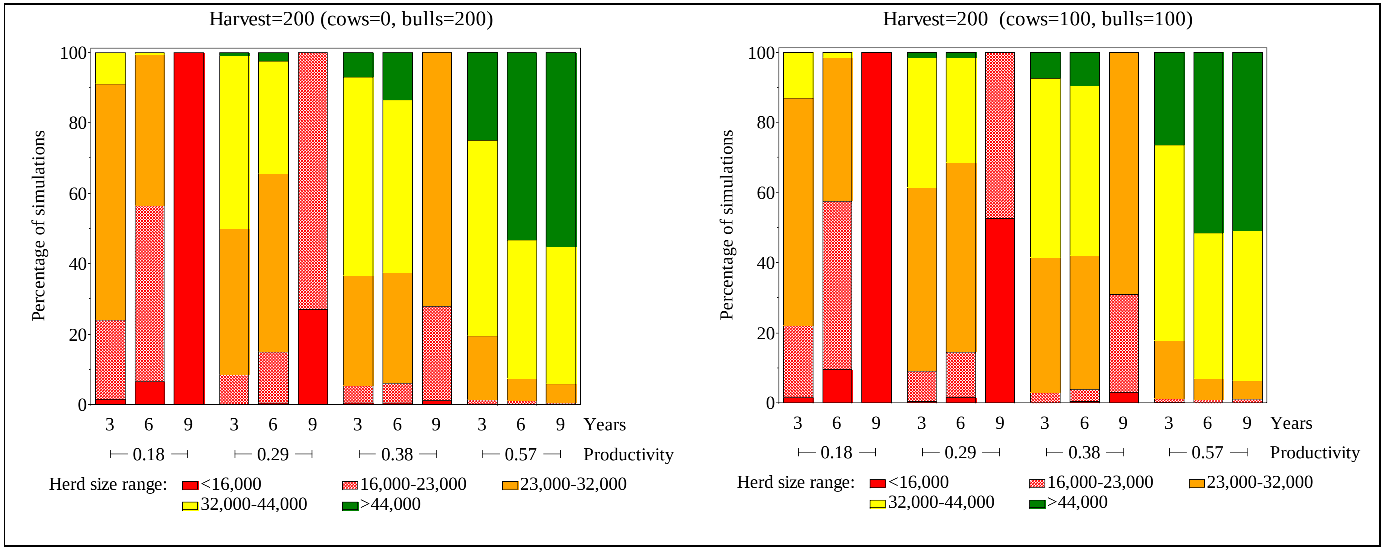


**Figure 13:** Results of simulations with an annual harvest of 200 caribou (with varying numbers of females harvested) as a function of mean productivity and years since 2009. Each color on the bar denotes the relative proportion of simulations that resulted in a given range of herd sizes/management targets. Productivity estimates correspond to productivity scenarios as listed in Table 1.

## Predicted trends in demographic parameters

### *Adult female survival*

One of the best illustrations of the effect of harvest on the population is trends in adult survival caused by varying levels of harvest and changing adult female population sizes. Figure 14 illustrates the effect of low productivity and a constant harvest on adult female survival. When productivity is low the population is more likely to decrease and therefore constant harvest effort reduces adult survival (Figure 14).

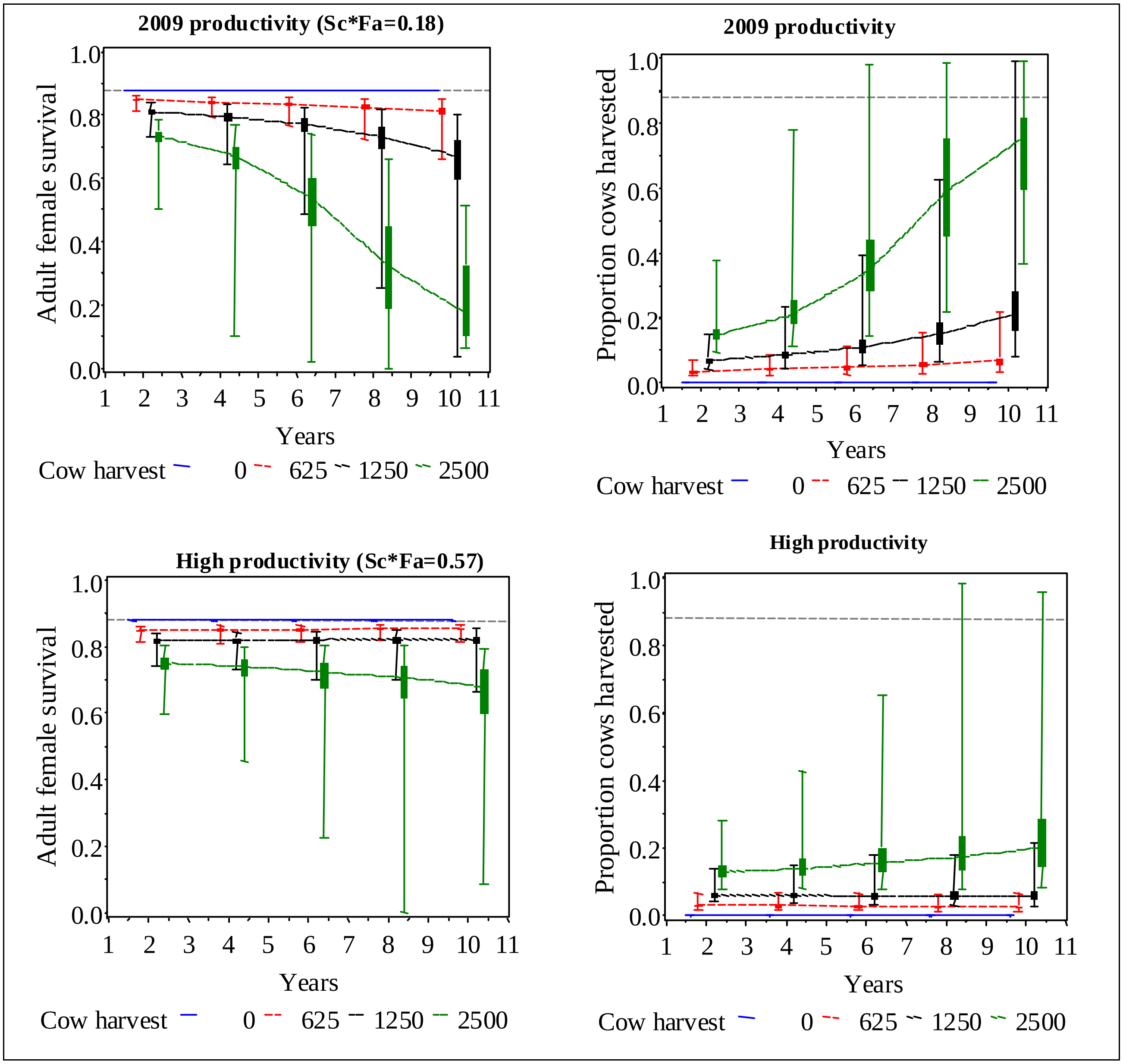


**Figure 14:** Trends in adult female survival for the low (2009) productivity and high productivity scenarios. Boxplots show the main grouping (boxes) and range of estimates (error bars) from multiple simulation runs. When productivity is low population size decreases sharply and the effect of proportional harvest on adult female survival is increased.

## Predicted trends in field based estimates

One of the most important uses of the model is the generation of predictions of indicators of herd status. For example, with the average productivity scenario, the bull:cow ratio decreases as larger numbers of bulls are harvested relative to cows (Figure 15). If even numbers are harvested then the bull:cow ratio is similar to estimates in 2009. I suggest that these predictions could be used to set lower acceptable limits for bull:cow ratios and estimate the appropriate time interval to estimate these limits.

In contrast, fall calf:cow ratios are not as affected by cow harvest since cow harvest occurs usually in the winter months after fall composition surveys. Spring calf:cow ratios are increased as a function of cow harvest since the number of cows each spring is potentially reduced compared to the number of calves (assuming harvest occurs after calf weaning).

A large number of harvest modeling scenarios is possible and I suggest that further model projections could be assessed based upon decisions made about harvest levels.

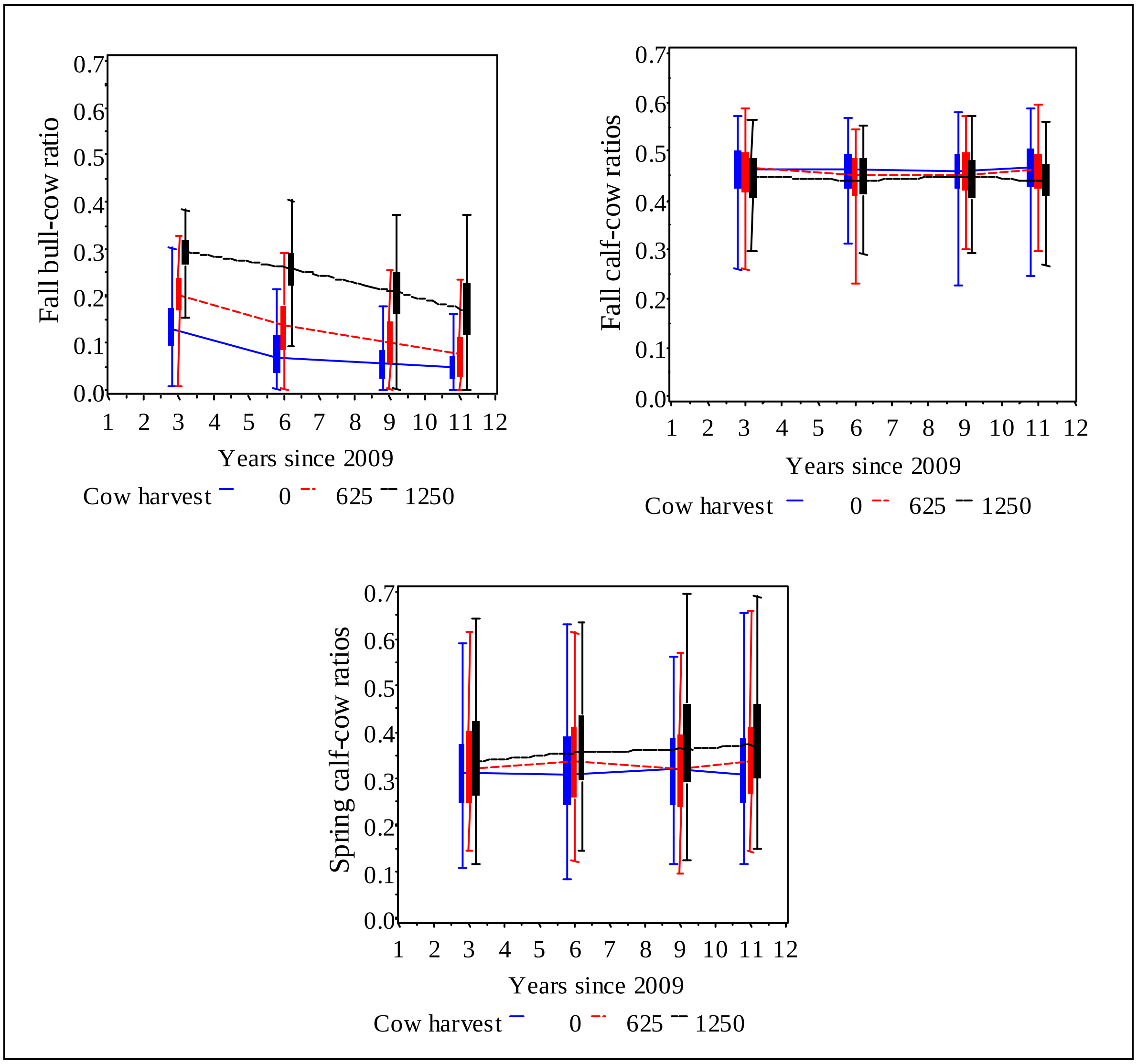


**Figure 15:** Predicted trends in field indicators for the average productivity scenario and a harvest of 2,500 caribou with varying numbers of cows harvested. Box plots show the main grouping (boxes) and range of estimates (error bars) from multiple simulation runs.

The model also can be used to assess predictions of calf:cow ratios based upon levels of productivity and determine the influence of harvest rate on estimates of productivity. These predictions could be used in unison with the OLS model to assess where the population may be in terms of overall status (see earlier bar chart figures and Figure 16).

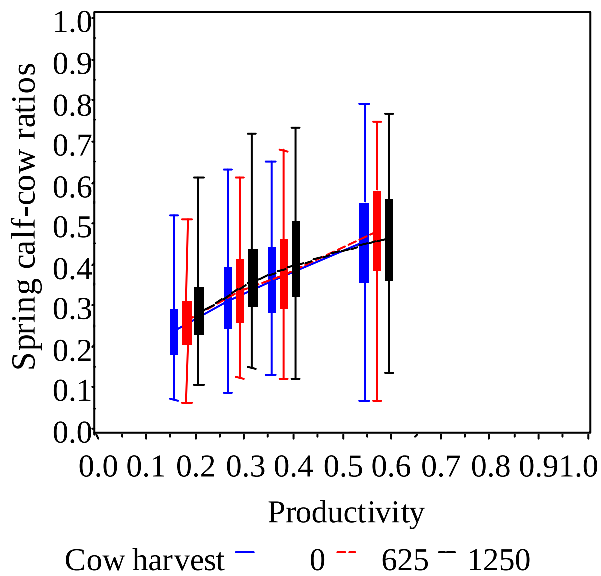


**Figure 16:** The correspondence of spring calf-cow ratios and productivity as a function of cow harvest levels given an annual harvest of 2,500 caribou. Box plots show the main grouping (boxes) and range of estimates (error bars) from multiple simulation runs.

## Discussion

This report presents an overview of the inputs and outputs of the stochastic simulation model. The following points should be considered when interpreting the simulations in this report.

- *Higher levels of harvest (2,500-5,000-7,000) from the Bathurst herd can only lead to further rapid decline.* Even with high calf productivity, the herd could not recover at this level of harvest. Therefore, immediate reduction of harvest is essential. At some of the lower harvest levels assessed, (200-500 caribou), there is a much lower likelihood of rapid decline, and the herd's likely trend is more variable depending on calf productivity.
- *Simulations illustrate that the ability of the herd to recover is very much influenced by productivity, not just by harvest levels.* Harvest can be

managed, while productivity is strongly influenced by weather and is less subject to human control. Given this it is difficult to forecast recovery just based on harvest management. Any harvest management strategy should be adaptive in which goals/targets/harvest are set based upon levels of productivity observed from field-based estimates.

- *Better estimates of true harvest level are essential to help refine herd recovery scenarios and determine the relative impact of harvest on adult female survival.* It would be possible to use harvest as a direct model input to allow better assessment of harvest levels on herd recovery. In this case, model runs could be focused on exact harvest levels rather than being run across a wide range of potential harvest levels. Reporting of harvest rates is one of the fundamental requirements of an adaptive management program.
- *The appropriate interval to evaluate herd status (i.e. spring calving ground surveys) should be considered in the context of observed productivity levels, relative risk, and power to detect change in population size.* The simulation model outcomes and the OLS deterministic model can be used to further refine management strategies as more information becomes available.
- *This model does not simulate any effects of reduced breeding success based on bull:cow ratios.* Given this, threshold levels of bull:cow ratios should be also established to ensure reasonable sex ratios as discussed in Mysterud et al. (2002). The model can generate predicted bull:cow

ratios that can then be used to evaluate the relative risk of male dominated harvest strategies to the overall population. As mentioned earlier, power analyses can be used to determine the relative power to detect a threshold bull:cow ratio for a given harvest sex ratio, productivity, and management regime.

- *The simulations assume that natural mortality rates have remained relatively constant.* If predation rates have also increased over time, or if predators took the same number of caribou each year as the population declined, then the adult female survival estimation without hunting will be less than 0.88. This will result in reduced population vigour and a higher likelihood of population decline for each of the scenarios. The only way to test this assumption would be to substantially increase the number of collared caribou to allow better estimates of natural survival. In addition, better estimates of harvest would allow a better assessment of the proportional impact of hunting on the herd. These results further argue for an adaptive management approach in which simulation runs and population targets are incrementally re-evaluated as more data become available.
- *Power analyses demonstrate limited power to detect moderate changes in herd size and therefore herd status should also be evaluated using productivity and survival rate estimates.* This also demonstrates that herd size along with productivity and adult survival should be simultaneously used to evaluate herd status through the framework of a population model.

Model based methods (Boulanger et al. 2011) can help interpret calf:cow ratios and bull:cow ratios that are influenced by many demographic factors. Note that the OLS model will generate a predicted population size as new data such as calf:cow ratios are produced. The model in this exercise generates predictions of all field based estimates. Power analyses can be used to further optimize appropriate intervals to sample for composition or sex ratio based upon assumed demographic and management scenarios.

- *Biological variation creates uncertainty in many outcomes and recovery scenarios are best interpreted as probabilities rather than estimated future population sizes.* It should be evident that estimation of exact future population sizes is not possible given uncertainty in various current aspects of herd demography.
- *Herd management targets are mainly in reference to the 2009 estimate and should be revised as new information on herd status becomes available.* For example, “increasing” herd status should not be interpreted to mean that the herd has recovered.
- *Regression analyses of relative counts from visual calving surveys present an alternative way to assess trends in herd status.* Future power analyses of this approach in comparison to the paired t-test and regression analysis of calving ground estimates may be conducted.
- *The modeling results could be used to assess the size of a sustainable harvest if calf productivity improves.* In the past, herds growing rapidly

were able to tolerate a significant harvest and still increase. Unfortunately, caribou and reindeer have been for the most part recently declining globally, which suggests that high productivity is not very likely in the near future.

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