Appendix S1

Section S1

Permits and Ethics Approval

Procedures for capturing caribou, care while in captivity, and monitoring radio-collared caribou complied with guidelines established by the Canadian Council on Animal Care (2003, 2017), with standards for live animal capture and handling and monitoring established by BCMOELP (1998). All activities were approved under BC Wildlife Act Permits FJ14-93094, FJ18-421458, and FJ19-568256.

Aerial wolf reductions were carried out by contractors to the Province of BC, as well as internal government staff, under the authority of the BC Wildlife Act (BCLaws 2021) between 2015-2020. The aerial wolf reduction considered here was permitted and received animal care approval through the Provincial Animal Care Review process for Scientific Permits (Wildlife Act Permit #’s: FJ15-169004, FJ15-165140, FJ-169006, FJ17-264123, FJ17-253645, FJ17-253804, FJ18-286980, FJ18-416476, FJ19-597709). The BC Animal Care Committee is chaired by the Provincial Wildlife Veterinarian and follows published animal care guidelines (CCAC 2003, 2017, BCMOELP 1998, Underwood and Anthony 2013). The aerial wolf reduction was exempt from the prohibitions in s.27 of the BC Wildlife Act against herding and hunting wildlife from an aircraft (exempt under s.3(1)(c)(ii) and 3(1)(c)(iii) of the Permit Regulation, B.C. Reg. 253/2000 from the prohibitions in s.27). Indigenous trapping and harvesting of predators, including wolves, was carried out between 2013-2021 under the authority enshrined in treaty rights on traditional territory. Maternity penning was permitted and underwent Provincial Animal
Care Review (Wildlife Act Permit #’s: FJ14-93094, FJ19-568256, FJ18-421458; and Special Use and Free Use Permit #’s: R14-G1420, 20767, S26316, S25789). Registered trapping by BC trappers was conducted under the authority of the Wildlife Act (Province of British Columbia 1996). No university personnel were involved in planning or conducting wolf reduction, maternity pens, or caribou collaring, thus obviating the need for university animal care review or approvals.

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Assessing potential biases of choosing females without calves for the pen-

We purposely target females without calves for the pen, as these females provide logistically easier and safer captures (no calf to also catch) and we judged that practice to be potentially less invasive than splitting adult females from their calves. We wanted to assess if this practice introduced bias in the outcome of penning, and the natal success of adult females with calves left free ranging, if adult females without calves were more able to produce a calf in the following natal period, and vice versa for those left free ranging with a calf. We assessed this potential bias using two approaches.

**APPROACH 1: Direct comparisons of body condition and calf production**

**Methods:**

*Data*-We compiled data between 2014-2020 on the location of caribou during the current and previous year (inside vs outside the maternity pen; Penned and Free, respectively), their success raising a calf during the current and previous year (to the time of capture, ~300 days post parturition), as well as their body condition when captured (a subjective rating: poor, fair, and good).
Analyses—All analyses were done in program R. We used bootstrapping to get errors around proportions generated from raw data, and generalized linear models, and generalized mixed models to assess multivariate relationships. Model selection was conducted via AICc. We first tested whether we did catch more females without calves (i.e., they did not have calves from last year with them), compared to the animals we left free. Secondly, we tested whether the body condition differed between animals that did or did not have a calf at time of capture. Finally, we used generalized linear and mixed models to test whether having a calf the year before influenced the probability of a female recruiting a calf in the following year. We test the influence of having a calf at time of capture, and the location of females during the current and previous year (Free or Penned), year, and animal ID, on the probability of recruiting a calf in the current year. If our capture practise had potential to bias our results, the influence of failing to have a calf the previous year could positively influence the probability of recruiting a calf in the pen.

Results

We compiled 78 records where female location during the current and previous year (inside vs outside the maternity pen; Penned and Free, respectively) was known, as was their success raising a calf during the current and previous year (to the time of capture, ~300 days post parturition). Of these 78 records, we had body condition measures for 38 of them. As expected, based on our capture protocol, we captured a lower proportion of females with calves for the pen (0.25 (0.14-0.37)) than those we left out of the pen (0.78 (0.68-0.90)) (Figure S1A). In essence, we captured most or all the adult females without calves the year previous (either lost sometime prior to capture, stillborn, aborted, or not pregnant). Females with calves
from the previous year appeared to have slightly poorer lower body condition than those without calves (Figure S1B).

Despite the bias in our selection of females without calves (Figure S1A), and potential differences in body condition (Figure S1B), we detected no measurable effect of whether the female was with a calf at time of capture on the probability of recruiting a calf the following year. This result was consistent whether we used a GLM or GLMM (which added in a random effect for year and animal ID), and thus we retained the simpler GLM. Model selection showed strong support for increased calf recruitment for females in the pen (LOCCY (location current year) model with 0.39 model weight). Ignoring whether females were penned, and just assessing whether the animals had successfully reared a calf the previous year (SRCLY) provided poor fit to the data and received little support (dAICc=10, weight=0). We predicted the probability of penned females having a calf based on whether they were or without a calf at capture using a model averaged prediction that accounted for any effects of SRCLY based on model weights. We show that there was no detectable difference in calf recruitment for penned females based on being with (0.66 (se=0.12)), or without (0.63 (se=0.08)) a calf at heel. These results suggest that the capture bias does not translate to a demographic bias between penned and free groups.

Table S1. Model selection results for the probability of successfully rearing a calf to 300 days. LOCCY= location current year, either in pen or free, LOCLY=location last year, either in pen or free, SRCLY=success rearing a calf to 300 days last year. We use 300 days as this is the age of calves when we do captures in March.

| Model           | df | AICc | dAICc | weight |
|-----------------|----|------|-------|--------|
| LOCCY           | 2  | 114.2| 0     | 0.39   |
| LOCCY + LOCLY   | 3  | 114.46| 0.27  | 0.34   |
| LOCCY + LOCLY + SRCLY | 4 | 115.72| 1.53  | 0.18   |
| LOCCY + LOCLY * SRCLY | 5 | 117.63| 3.43  | 0.07   |
| LOCLY + SRCLY   | 3  | 123.03| 8.83  | 0      |
| SRCLY           | 2  | 124.29| 10.1  | 0      |
Figure S1. A) the proportion of females with calves (i.e., calves from last year), and where those females were the current year. The difference manifests from our choice to catch females without calves for the pen for logistical and animal safety reasons. Distributions are the result of 1000 bootstrapped replicates of the proportions, B) Body condition for female caribou depending on whether they survived a calf to the time of capture or not. The mean proportion of the raw data is shown for each bar, with the 95% quantiles from 1000 bootstrapped replicates shown in brackets. C) The predicted influence from generalized linear model of being with a calf at time of capture on probability of recruiting a calf the following year after being in the pen, i.e., testing the nutritional hypothesis, with 95% confidence intervals.

**APPROACH 2: Test the expected vs observed frequencies of observations**

**Methods:**
We compiled calving histories of all females based on whether they had a calf (birthed and calf survived >14 days), or did not have a calf (either did not give birth, or calf survived <14 days). We calculated the proportion of observations that produced the following sequences:

- calf-no calf (calf the year before, no calf current year)
- no calf-calf (no calf year before, calf current year)
- no calf-no calf (no calf year before, no calf current before)
- calf-calf (calf the year before, calf current year)

We then randomized the data and also generated frequencies of the above sequences that we would expect by chance. If we detected significantly more observations of calf-no calf, and no calf-calf, we would view this as evidence of a bias resulting from our capture practise of targeting adult females without calves.

**Results**

We detected the following frequencies of sequences:

- calf-no calf 0.32
- no calf-calf 0.31
- no calf-no calf 0.13
- calf-calf 0.24

None of these frequencies deviated significantly (at alpha <0.05) from the expected (null) distributions (Figure S2).

We believe this is a second compelling line of evidence to suggest that our sampling of females without calves for the pen, and their resulting reproductive output, was unlikely to be strongly biased by our capture practise.
Figure S2. Expected distributions drawn randomly (grey histograms), their mean (black line) and the observed mean frequency (dashed line) for each sequence. P-value given in top right.
Demographic Process Model

Our IPM followed the two-stage approach developed by Moeller et al. (2021). We built an age-structured demographic process model with three age classes: 1) recruited calves (0.75 years old), 2) subadults (1.75 years old) and, 3) adults (2.75+ years old). We used a two-stage approach to implement the IPM, where vital rate parameters that were used within the demographic process model were estimated separately and outside of the IPM. First, mean and variance annual survival and recruitment rates were estimated using the program developed by Eacker et al. (2019). These estimates, in conjunction with other data sources, were then used as data inputs to the observation model portion of the IPM.

The full suite of data sources included: 1) population surveys that consisted of either the number of animals seen (a minimum abundance) or sightability-corrected estimates of abundance, the number of calves and adults (the latter being all animals >1.75 years old), and in some but not all cases, sex; 2) the sex, age, and number of animals that went into the Klinse-Za maternity pen, as well as recruitment and sex of calves born in the pen; 3) annual survival of adult females, and 4) recruitment rate of 10-month-old female calves (calves/non calf females), assuming a 50:50 sex ratio of these calves.

The number of female individuals in each stage at time $t$ was a function of the vital rate parameters of each stage. Total and age-class abundance was estimated each year by multiplying the estimated female-only estimates by an observed sex ratio. We defined the model year from March 1 to February 28 (or 29) because count data collection surveys took place in early March.

Female abundance for the subadult and adults age classes was modeled using a normal approximation of the binomial model. In the binomial model, abundance at time $t$ for age class $a$ is a binomially distributed random variable with parameters abundance ($N$) at time $t-1$ for age class $a$ and survival ($S$) at time $t$ (because survival was assumed to be the same for subadults and adults, it was unnecessary to index it by age class).

$$N_{t,a} \sim Bin(N_{t-1,a}, S_{(t)})$$

Eq. S1

The normal approximation for the binomial model took the form:

$$N_{t,a} \sim Norm(\mu_{(t,a)}, \tau_{(t,a)})$$

Eq. S2

For the Quintette IPM:

$$\mu_{t,s,a} = N_{(t-1,c)}S_{(t-1)}$$

Eq. S3
\[ \tau_{t,sa} = \left| \left( N_{(t-1,c)} + 1 \right) S_{(t-1)}(1 - S_{(t-1)}) \right|^{-1} \]  
Eq. S4

where \( c \) indicates calf and \( sa \) indicates subadult, and

\[ \mu_{t,ad} = \left( N_{(t-1,sa)} + N_{(t-1,ad)} \right) S_{(t-1)} \]  
Eq. S5

\[ \tau_{t,ad} = \left| \left( N_{(t-1,sa)} + N_{(t-1,ad)} \right) S_{(t-1)}(1 - S_{(t-1)}) \right|^{-1} \]  
Eq. S6

where \( ad \) indicates adult.

For the Klinse-Za IPM, a third index was included to indicate the inclusion of the free (\( f \)) and penned (\( p \)) population units. For the penned population unit, abundance values are known quantities:

\[ N_{t,sa,p} = \text{number of subadults put into maternity pen} \]

\[ \mu_{t,sa,f} = \left( N_{(t-1,c,f)} S_{(t-1,f)} \right) + \left( N_{(t-1,p)} S_{(t-1,p)} \right) - N_{t,sa,p} \]  
Eq. S7

\[ \tau_{t,sa,f} = \left| \left( N_{(t-1,c,f)} + 1 \right) S_{(t-1,f)}(1 - S_{(t-1,f)}) \right|^{-1} \]  
Eq. S8

and

\[ N_{t,ad,p} = \text{number of adults put into maternity pen} \]

\[ \mu_{t,ad,f} = \left( N_{(t-1,sa,f)} + N_{(t-1,ad,f)} \right) S_{(t-1,f)} + \left( N_{(t-1,sa,p)} + N_{(t-1,ad,p)} \right) S_{(t-1,p)} - N_{t,ad,p} \]  
Eq. S9

\[ \tau_{t,ad,f} = \left| \left( \left( N_{(t-1,sa,f)} + N_{t,ad,f} \right) S_{(t-1,f)}(1 - S_{(t-1,f)}) \right) \right|^{-1} \]  
Eq. S10

where \( f \) indicates the free population and \( p \) indicates the penned population.

Female abundance for the calf age class was estimated using a normal approximation of the Poisson model where \( R \) is recruitment at time \( t \). This recruitment rate incorporates pregnancy rate and neonatal survival of until age 9 months and represented only female calves.

\[ N_{t,c} \sim \text{Pois} \left( R(t) \left( N_{t,sa} + N_{t,ad} \right) \right) \]  
Eq. S11

The normal approximation for the Poisson model took the form:

\[ N_{t,c} \sim \text{Norm} \left( \mu_{(t,c)}, \tau_{(t,c)} \right) \]
For the Quintette IPM:

\[ \mu_{t,c} = R_{t}(N_{t,sa} + N_{t,ad}) \]  
\[ \tau_{t,c} = R_{t}(N_{t,sa} + N_{t,ad})^{-1} \]

For the Klinse-Za IPM:

\[ N_{t,c,p} = \text{number of calves born in maternity pen} \]
\[ \mu_{t,c,f} = R_{t}(N_{t,sa,f} + N_{t,ad,f}) \]
\[ \tau_{t,c,f} = R_{t}(N_{t,sa,f} + N_{t,ad,f})^{-1} \]

We applied a sex ratio to female abundance estimates for adults and calves to generate abundance estimates of males and females together. A yearly sex ratio for adults was calculated from survey data and the sex ratio for calves was assumed to be 0.5 across all years.

\[ N_{t,all \ adults} = \frac{(N_{t,sa} + N_{t,a})}{\text{Adult sex ratio}_t} \]
\[ N_{t,all \ calves} = \frac{N_{t,c}}{0.5} \]

**Observation Models**

**Adult and calf abundance model**

We drew the mean sightability-corrected abundance estimate obtained from the first stage of the IPM from a normal distribution to estimate total abundance of combined female and male subadult and adult caribou:
Abundance of combined male and female calves was similarly estimated using draws from normal distribution:

\[ n_{t, all \, adults} \sim \text{Norm}(N_{t, all \, adults}, \sigma_{t, all \, adults}) \quad \text{Eq. S19} \]

The variance for the normal distribution in each model (\( \sigma_{t, all \, adults} \) and \( \sigma_{t, all \, calves} \)) was the inverse of the squared standard deviation for the range of the abundance estimate corrected for sightability according to the sightability estimate bootstrap standard deviation.

Adult minimum count model

We incorporated counts of the minimum number of adult caribou known to be alive annually to further inform abundance estimates. These data were modelled as draws from a negative binomial distribution for the Quintette IPM and as random draws from a Poisson distribution for the Klinse-Za IPM.

For the Quintette IPM:

\[ m_{t, all \, adults} \sim \text{NB}(\theta, k) \quad \text{Eq. S21} \]

\[ k \sim \text{Unif}(1,50) \quad \text{Eq. S22} \]

\[ \theta \sim k/k + N_{t, all \, adults} \quad \text{Eq. S23} \]

For the negative binomial distribution, \( \theta \) is the probability of success and \( k \) accounts for overdispersion of count data.
For the Klinse-Za IPM:

\[ m_{t, all \ adults} \sim \text{Poisson}(N_{t, all \ adults}) \]

Eq. S24

The Poisson distribution was used in for the Klinse-Za IPM due to convergence issues when minimum count values approached abundance estimates; as \( r \) increases toward infinity, the negative binomial distribution approaches the Poisson distribution and thus was appropriate.

**Survival and recruitment**

We used the mean annual survival and recruitment estimates and standard deviations from the posterior distributions obtained from survival and recruitments models fit using the application described by Eacker et al. (2019). These were generated during the first stage of the two-stage IPM. These rates were drawn from a normal distribution:

\[ S_t \sim \text{Norm}(s_t, \varepsilon_t) \]

Eq. S25

\[ R_t \sim \text{Norm}(r_t, \omega_t) \]

Eq. S26

where the variance for each parameter (\( \varepsilon_t \) and \( \omega_t \)) was the inverse of the squared standard deviation of the posterior distribution for that parameter.

To allow variation between years, we used a linear predictor with a logit link function to add an annual random effect on both survival and recruitment parameter estimates. The linear predictor took the form:

\[ \text{logit}(S_t) = \alpha + \text{Annual Survival RE}_t \]

Eq. S27

\[ \text{logit}(R_t) = \alpha + \text{Annual Recruitment RE}_t \]

Eq. S28
where the random effect was a random variable from a normal distribution with mean = 0 and low precision (50). In the Klinse-Za IPM, survival rate and recruitment rate were known for the adult females that were in the penned population segment.

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Section S4

Demographic history

The first documented account of population surveys in the Moberly portion of the Klinse-Za subpopulation (i.e., roughly the eastern half of the subpopulation) was in 1991 with 182 caribou observed (Backmeyer 1991). Wood and Hengeveld (1998) observed 181 Moberly caribou in 1996. There was a 13-year lapse in surveys of this portion of the subpopulation until 2009 when Seip and Jones (2013) observed 48 caribou. The apparent steep decline in the number of caribou in the Moberly portion was confirmed in three following annual surveys (2011-2013) with only 35, 25, and 16 caribou observed over much broader survey areas (Seip and Jones 2013) compared to that surveyed by Wood and Hengeveld (1998) in 1996. The 16-year decline averaged ~15% annually, there had been no population recovery actions undertaken during that time, and in the absence of corrective management, the Moberly portion of the subpopulation was predicted to be extirpated by 2015 (McNay et al. 2013). Seip and Jones (2013) recorded frequent use of the adjacent Scott East portion of the subpopulation by caribou caught and marked in the Moberly portion of the subpopulation and our first year of maternity penning further contributed to overlap of caribou using the two areas, so we treated these caribou as belonging to the one subpopulation, Klinse-Za. There were only two reported population surveys in the Scott East portion of the subpopulation prior to our study, resulting in observations of 22 caribou in 2007 (Giguere and McNay 2007) and 20 caribou in 2013 (Seip and Jones 2013). One other caribou population adjacent to this study area was the Burnt Pine population which was declared functionally extirpated in 2013 with only 1 lone male observed that year (Seip and Jones 2013).

The first documented account of population surveys in the Quintette subpopulation occurred during an assessment of caribou response to early production of coal in the southern
portion of the area (Sopuck 1985). At that time 50 caribou were observed but within only a quarter of the population area. Following that, 154 caribou were observed in 2002 (Seip 2002) and the most recent largest number of caribou in the Quintette, 173, was observed in 2008 by Seip and Jones (2008). The Quintette population then apparently began a steep decline to a low of 62 caribou around 2016 (Seip and Jones 2016) prior to the initial use of wolf reduction as a population management action.

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**Section S5**

Here we compile additional results from the IPM that support model validation and additional insights of interest to some readers. We assessed the fit of modelled abundance for each subpopulation against minimum counts of caribou observed during aerial surveys that also included counting groups of animals found via VHF telemetry, and sightability corrected survey counts (i.e., abundance estimates) (Figure S3). Similarly, we contrasted observed annual survival and recruitment rates against modelled estimates from the IPM (Figure S4). In general, estimated vital rates fit observed rates well, and discrepancies generally occurred where small sample sizes in observed rates created erratic vital rates (i.e., perfect survival, or very low survival) in a given year. When these erratic vital rates were not reflected in the corresponding abundance changes, the IPM was able to inform and update more consistent and accurate vital rate estimates for those years.

Consistent with Bridger (2019) we estimate demographic responses during a period of refined wolf control when wolf reductions were estimated as exceeding 75% of the wolves present each winter (Figure S5). Results suggest Quintette demography increased more in this refined period than the entire wolf reduction period, but this increase was not reflected in the Klinse-Za potentially due to additional predators such as grizzly bears and wolverines.

Appropriately accounting for the effects of shifting age-structures was an important aspect of the IPM. Estimated annual age structures (Figure S6) highlight the influence recovery actions to small, declining populations on altering age structure. Post recovery actions the number of calves increases and the population begins to shift to a younger age structure, which is more accentuated in the Klinse-Za where wild-born and pen-born calves both end up as yearlings in the Klinse-Za “free” group.
Figure S3. Estimates of caribou population abundance within the Klinse-Za (left) and Quintette (right) population areas in northern British Columbia. The abundance includes male and female caribou, as well as recruited calves (>10 months old). Sightability-corrected abundance estimates as well as minimum counts overlaid. Error bands for modelled estimates represent 90% credible intervals.
Figure S4. Estimates of female caribou vital rates within the Klinse-Za free-ranging (left), Klinse-Za penned (center) and Quintette free-ranging (right). Modelled values from the IPM shown in red, and observed values as estimated from survival and recruitment in the Eacker et al. (2019) application shown in green. Error bands for modelled estimates represent 90% credible intervals.
Figure S5. The estimated effect of wolf reduction on caribou population growth for the refined portions of the recovery period (top) and various Klinse-Za effects shown together (bottom).

Figure S6. Age structures estimated from the IPM.
November 5, 2021

Nikanese Wah tzee Stewardship Society
10233-100th Avenue
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V1J 1Y8

Ecological Applications Editorial Office

Dear Editorial Staff:

RE: Authorship of manuscript ID EAP21-0390 “Demographic responses of nearly extirpated endangered mountain caribou to recovery actions in central British Columbia”

Reviewers of this paper have noted that initiation of recovery measures for caribou were undertaken by First Nations but this is not reflected in the author list on the manuscript. West Moberly First Nations and Saulteau First Nations are actively involved in the recovery of these caribou that are central to our culture, sense of place, and treaty rights. Through collaboration with scientists like Scott McNay and Clayton Lamb, we have been actively involved in the western science aspects of this program and are represented as co-authors on the Lamb et al. submission ‘Indigenous-led conservation: pathways to recovery for the nearly extirpated Klinse-Za mountain caribou’.

Although Indigenous Guardians from our respective Nations reside at the maternal pen around the clock and our community members reduce wolf density on the landscape, we look to our scientists McNay/Lamb to design sampling and collect the technical data required for more technical manuscripts such as McNay et al. We appreciate the concern expressed by reviewers of the McNay et al. manuscript however, we would like to assure the reviewers that we are aware of this work and consent to it proceeding in its current form. Although we appreciate being involved in the production of Western science, such as with Lamb et al., our focus is on-the-ground and legal conservation of our homelands. With limited time available, we are supportive of the technical manuscript presented by McNay et al to proceed as is.

Thank-you.
