An integrated population model for Rocky Mountain bighorn sheep in the Elk Valley

STEVEN F. WILSON, EcoLogic Research, 302-99 Chapel Street, Nanaimo, BC V9R 5H3, Canada, steven.wilson@ecologicresearch.ca
CHRISTINA SMALL, Teck Coal Limited, 421 Pine Avenue, Sparwood, BC V0B 2G0, Canada

ABSTRACT: The Elk Valley of southeast BC has a substantial population of Rocky Mountain bighorn sheep (*Ovis canadensis canadensis*) that are notable for their use of high-elevation winter ranges. The region is subject to extensive overlapping land uses. We integrated the results of on-going research and inventory efforts into a model that can be used to predict the effects on population trend of various stressors and mitigative management actions. The model is structured as a causal Bayesian Belief Network and includes 15 different factors and associated relationships. The structure and logic of the model was developed by a team of bighorn sheep experts and community members. Parameters were based on data, where available, and through expert elicitation. As currently structured and parameterized, the model is most sensitive to the abundance of suitable winter range, followed by annual range forage. The risk of pneumonia is considered low but of very high consequence if it occurs. Predation and winter severity are also significant drivers of population size. Causal Bayesian Belief Networks blend empirical evidence with expert and traditional knowledge and can be used to characterize cause-and-effect pathways in ecological systems to support management planning and decision-making.

Biennial Symposium of the Northern Wild Sheep and Goat Council 22:94-104; 2020

KEY WORDS Bighorn Sheep, *Ovis canadensis*, Bayesian Network modelling, population

INTRODUCTION

Bighorn sheep (*Ovis canadensis*) are a species of cultural and recreational interest in the Elk Valley of southeastern British Columbia (BC). The east side of the valley (known to contain the Elk Valley East Population Management Unit [PMU]) is home to a relatively large (>600 animals), stable subpopulation that is characterized by its use of high elevation winter range, in contrast with other subpopulations of the Kootenay region (Poole and Ayotte 2020). The Elk Valley is subject to a variety of overlapping land uses, including, but not limited to, mining, forestry, agriculture, human settlement, public recreation and hunting. Sustaining this subpopulation as land use evolves is a key conservation objective of the BC government, Indigenous communities, industry and public stakeholders. The objective of this project was to capture the knowledge generated by ongoing research and inventory, as well as expert and local knowledge, into a model that can be used to predict the population status of bighorn sheep, based on the current and future state of habitat and other biotic factors, and based on the various management actions that could be taken to mitigate stressors.

METHODS

The model is structured as a causal Bayesian Belief Network, illustrating the system as a directed acyclic graph (DAG; Elwert 2013) with relationships represented probabilistically (Marcot *et al.* 2006). We developed the model iteratively with experts and stakeholders through a series of workshops. The *nodes* of the model represent random variables and the directed *edges* represent the relationships among variables. The graph is "directed" because arrows indicate the hypothesized causal direction of relationships and is "acyclic" because feedbacks are not allowed. This is because a causal model implies a temporal ordering, such that an effect cannot influence the past by affecting its own cause.

Each node was assigned a number of discrete *states*, which represent the values that each node can assume. The relationships between nodes were then defined using probabilities, stored in tables associated with each node. Probability tables were populated using existing data, where available, as described in the following sections. Where data were not available, input was solicited from a small expert team through a workbook exercise, which presented questions about specific parameters and asked for probability assignments as well as confidence ratings. Responses from 10 separate workbooks were combined using prior linear pooling (Farr *et al.* 2018) and presented back to the experts for discussion and revision. Following this second round of elicitation, the model was populated with final parameters.

More general feedback was sought via polls conducted during a webinar with invited outdoor enthusiasts. Answers to 9 polling questions were received from up to 18 participants. Questions addressed many of the same nodes as the workbook questions completed by experts; specifically, nodes related to predation, health (including observations of contacts with domestics and observations of sick bighorn sheep), trends in winter severity and the relative role of different factors affecting over-winter survival.

The final model was analyzed to determine the sensitivity of the output to different input variables. This identified the most important factors hypothesized to be driving bighorn sheep population dynamics and therefore where interventions are likely to have the greatest impact. Model outputs were also graphed across the full range of various input values to characterize rates of response and to identify any non-linear relationships.

RESULTS

The model is composed of 15 inputs and associated relationships among nodes (Figure 1). There are five additional nodes that serve purely computational roles (beige nodes). Key bighorn sheep population variables are trend and their direct inputs (i.e., green nodes: *Annual adult female survival* and *Observed lamb:ewe ratios*), habitat abundance and condition (blue), predator-prey (green), weather (pink), human-cause mortality (yellow) and health and nutrition (red). The model predicted the probability of a positive population trend, given the conditions of the factors represented by the model nodes. The following sections describe each node and associated parameters.

Population Trend

Population trend is the output of the model and represents the probability of a positive or negative population response. The metric is lambda, based on the standard equation of Hatter and Bergerud (1991):

```
Population_trend
(Observed_lamb_ewe_ratios,
Annual_adult_female_survival) =
Annual_adult_female_survival/
(1-((Observed_lamb_ewe_ratios/5)/
(100+(Observed_lamb_ewe_ratios/5))))
```

Lamb:100 ewe ratios are adjusted to reflect estimated mortality between observation on surveys and time of recruitment.

Annual Adult Female Survival

Annual adult female survival (%) is estimated from all sources of mortality, based on the following equation:

```
Annual_adult_female_survival
(Human_related_mortality,
Predation_pressure,
Ewe_effect_condition,
Ewe_effect_pneumonia) = 1 -
Human_related_mortality -
Predation_pressure * (1 -
Ewe_effect_condition) -
Ewe_effect_pneumonia +
Ewe_effect_condition
```

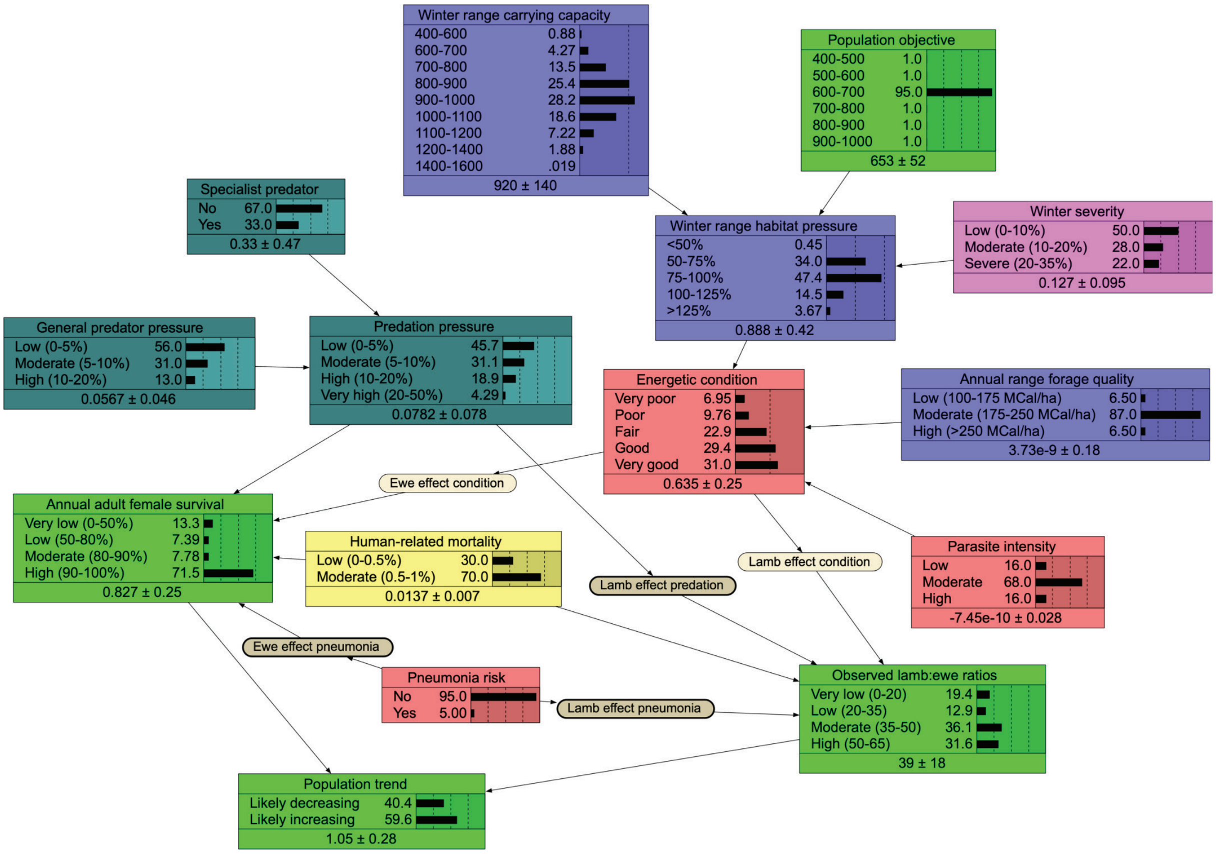

Figure 1. Structure of the bighorn sheep population model. Population variables are presented as light green nodes, habitat-related variables are blue, predator-prey are dark green, weather is pink, human-caused mortality is yellow and health and nutrition are red. Beige nodes are used for intermediate calculations. Each node is assigned discrete states and associated probabilities.

Observed Lamb-ewe Ratios

Observed lamb-ewe ratios is an estimate of the expected observed lamb:100 ewe ratios observed during mid-winter population surveys, using the equation:

```
Observed_lamb_ewe_ratios
(Human_related_mortality,
Lamb_effect_condition,
Lamb_effect_pneumonia,
Lamb_effect_predation) = 80 –
(Human_related_mortality * 0.75 +
Lamb_effect_predation * (1 –
Lamb_effect_condition) * 0.75 +
Lamb_effect_pneumonia + (0.3 – 0.3 *
Lamb_effect_condition)) * 100
```

Lamb survival rates to 10 months of age ranged between 0.41 and 0.54 in southwestern Alberta (Jokinen *et al.* 2008). The most recent Elk Valley survey recorded 48 lambs:100 ewes (Poole 2020). Note that there is some uncertainty in lamb:ewe ratios and their relationship with an increasing or decreasing population because of the difficulty of correctly classifying the sex of yearlings, and distinguishing 2-year-old ewes, which are less likely to give birth than older ewes (Festa-Bianchet 1988).

Population Objective

Population objective is the population size that represents the draft management objective. The February 2020 population estimate for the Elk Valley East PMU was 638 ± 85, based on an aerial total count survey and adjusted for a sightability of 0.77 (Poole 2020). The sheep population averaged about 400 individuals throughout the late 1980’s and 1990's and then peaked in 2010 at approximately 800 (Poole and Ayotte 2020). It is not known whether the peak in 2010 indicated a population that was close to the carrying capacity of the habitat at that time. Poole and Ayotte (2020) proposed a target population of 640 ± 20%. The model assumes an objective of approximately 650 sheep, with the state 600-700 assigned with a 95% probability and all other states being assigned 1%.

Winter Range Carrying Capacity

Winter range carrying capacity estimates the number of sheep that can be sustained on winter ranges within the Elk Valley East PMU.

Winter is a critical season for bighorn sheep because forage is naturally restricted and energetic requirements are high due to low ambient temperatures and increased mobility costs in snow. Therefore, the abundance of suitable winter ranges available to bighorn sheep is assumed to be a major determinant of the carrying capacity of this PMU. To be used, winter ranges need to be close to suitable escape terrain (e.g., Hamel and Côté 2007, Golder 2019b) and must be accessible by ensuring adequate connectivity among seasonal ranges.

The number of sheep that winter ranges can support is a function of area- and selection-based estimates of forage production and quality in relation to the average energetic requirements of bighorn sheep, as well as a "safe use factor," which is intended to protect the sustainability of forage supply from over-grazing (Golder Associates 2019d). The total area of winter ranges currently identified in the Elk Valley East PMU is 11,021 ha (Golder Associates 2019b, 2019c).

Detailed methods and results for the winter range forage estimates are presented in Golder (2020). Estimates were developed using different nutritional performance classes and safe use factors. For this model, we used the estimate for a safe use factor of 0.5 and the nutritional performance class *good.* The standard deviation applied was intended to roughly capture the upper and lower limits of population estimates based on safe use factors of 0.75 and 0.25, respectively. The node is assigned a range of 400-1600 sheep, using a normal distribution with mean of 920 and a standard deviation of 135.

Bighorn sheep compete for available forage with other species that use their ranges. This can be a significant problem on low-elevation winter ranges that are used by elk (*Cervus canadensis*) and often by domestic stock as well (Poole and Ayotte 2020). Off-take by other species in the growing season can reduce the standing crop available to sheep on winter ranges. Conflicts on high elevation winter ranges in the Elk Valley are expected to be less severe than in low-elevation ranges because there is no domestic grazing and elk use low-elevation winter ranges (Szkorupa *et al.* 2013).

Annual Range Forage Quality

Annual range forage quality estimated the total forage available to bighorn sheep within their annual range (MCal/ha).

Conditions on seasonal ranges can positively influence energetic condition by ensuring that sheep enter the winter season in good condition and can recover quickly in the spring, in particular before lambing and lactation. While forage outside the winter season is rarely limiting, sheep are limited by their rates of intake, which are in turn influenced by forage quality.

Annual range forage quality was assessed using the same data, models and assumptions of Golder (2020). Estimates for the Elk Valley East PMU ranged between 162–261 MCa/ha, depending on subunit. *Low, moderate*, and *high* classes were defined to capture the empirical ranges and were assumed to correspond to *high*, *moderate*, and *low* forage requirements, as specified in the winter range carrying capacity model. *Low* was assigned a coefficient of -0.5, *Moderate* = 0 and *High* = 0.5 and these values were passed to the *Energetic condition* equation (below).

Winter Range Habitat Pressure

Winter range habitat pressure estimates the adequacy of winter ranges to support the current sheep population objective, given the likelihood of severe winters that could reduce access to ranges:

```
Winter_range_habitat_pressure
(Population,
Winter_range_carrying_capacity,
Winter_severity) = Population /
(Winter_range_carrying_capacity * (1 -
Winter_severity))
```

This assumes that the main effect of severe winter is to make some portion of the winter range unsuitable for bighorn sheep due to deep snow. No other effects of severe weather (e.g., icing events, droughts) were included in the model.

Winter Severity

Winter severity represents the probability of severe conditions associated with deep snow that are sufficient to reduce the ability of winter ranges to support bighorn sheep.

The marginal probability table for this node was based on snow pillow data from nearby Mount Morrissey (Figure 2). Maximum snow-water equivalents from 1984 to 2020 were stratified into classes (0–400, 400–500, 500+), roughly calibrated to the adult female survival rates observed during 2010–11 (i.e., 2010 representing a *low* snow year and 2011 representing a *high* year). Public feedback suggested changing winter conditions, including (in decreasing order of reporting) an increase in freeze/thaw events, more extreme weather events in general, less snow and milder temperatures. This negative trend is evident in Figure 2.

General Predator Pressure

General predator pressure estimates the effect of the current density of predators on adult bighorn sheep survival. Experts assigned the following probabilities: *Low (0-5%)*: 56.1%; *Moderate (5-15%)*: 30.7%; and, *High (15-25%)*: 13.1%.

Poole (2013) recorded 20 mortalities among 41 radio-collared bighorn sheep over 27 months (2009-2011). Two were confirmed predation events, one by a grizzly bear (*Ursus arctos horribilis*) and one by a wolf (*Canis lupus*). There were also 6 mortalities of unknown causes recorded on private land, and the fates of 7 other sheep were unknown because radio-collars were lost prematurely. Predation is likely higher on adults than reflected in the collaring data, and predation on lambs is likely higher than on adults.

More generally, cougars (*Puma concolor*) are considered to be the most significant predator of bighorn sheep in the Kootenay region (Poole and Ayotte 2020). The public agreed that cougars were the most significant predator in the Elk Valley and many thought that predator populations in general were increasing.

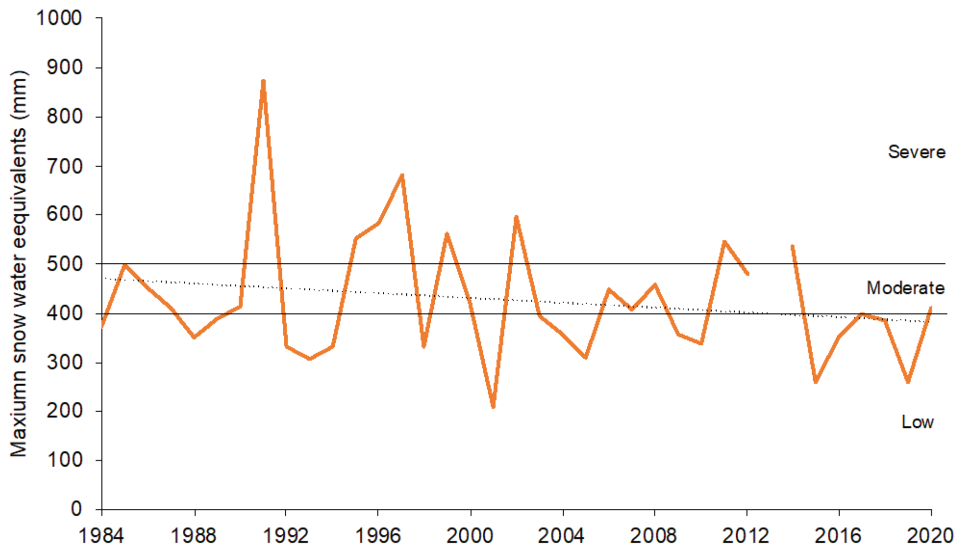

Figure 2. Mount Morrissey snow pillow data (1984-2020) used to calibrate the winter severity node (compiled by K. Poole). Class breaks were informed by survival rates observed among bighorn sheep in 2010-2011. The dotted line indicates the linear trend over time.

Specialist Predator

The specialist predator node estimates the probability that a cougar specializing on sheep could increase the overall predation rate on adult female sheep by 100%.

Experts assigned the probability of occurrence of a specialist predator to be 32.7%. There was feedback from the public indicating that some had seen evidence of cougars specializing on sheep.

Specialist predators can have substantial impacts on bighorn sheep populations (Festa-Bianchet *et al.* 2006, Bourbeau-Lemieux *et al.* 2011). Ross *et al.* (1997) concluded that a single, specialist cougar in southwestern Alberta killed 11 individuals, including 6 lambs, in a single winter. In the Kootenay region, cases of cougar specializing on sheep has been observed or suspected, but primarily in populations wintering at low elevations (K. Poole, *pers. comm.*). Because most bighorn sheep in the Elk Valley East PMU spend most of the year at moderate to high elevations, cougars are not considered as much a risk as they are elsewhere in the Kootenay region.

Predation Pressure

Predation pressure adjusts *general predator pressure* for probability of the occurrence of a *specialist predator*:

```
Predation_pressure
(General_predator_pressure,
Specialist_predator) =
General_predator_pressure +
Specialist_predator *
General_predator_pressure
```

Poole (2013) reported survival rates of 0.93 and 0.78 and attributed the lower survival in the second year to severe winter conditions. A survival rate of 0.93 is likely close to the theoretical maximum for a wild ungulate population (Loison *et al.* 1999), so it is unlikely that bighorn sheep during the study were suffering significant predation pressure. The study coincided with the highest recorded population size in the Elk Valley East PMU and likely reflected optimum conditions. Survival rates can vary with the age structure of populations because older ewes have higher mortality (Festa-Bianchet *et al.* 2003).

Experts estimated that predation on lambs is likely 2.6 times greater than that on adult females and this value was used in the *lamb effect predation* node to estimate the effect of predation on observed lamb:100 ewe ratios.

Parasite Intensity

Parasite intensity estimates the average, relative parasite load experienced by sheep in the population unit. The effect of parasite loading on fitness in livestock and related wild species is an area of active research (K. Ruckstuhl, *pers. comm.*). Recent work has clearly demonstrated that infections can negatively affect energetic condition and subsequent reproduction and survival (e.g., Roeber *et al.* 2013) and there is a link to range conditions if aggregations of sheep shed parasites that become sources of reinfection (K. Ruckstuhl, *pers. comm.*). No data were available to parameterize this node from the Elk Valley. Additional research and monitoring is required to characterize infection rates and impacts. Initial coefficients were –0.05 for *low*, 0 for *moderate* and 0.05 for *high*.

Energetic Condition

Energetic condition is an estimate of average, relative, overall energetic condition of sheep resulting from the interaction of range conditions and parasite intensity:

```
Energetic_condition
(Winter_range_habitat_pressure,
Annual_range_forage, Parasite_intensity)
= -Winter_range_habitat_pressure + 1.5 +
Annual_range_forage - Parasite_intensity
```

The subjective classes were mapped to a normalized range between 0 and 1 (e.g., *Very low* = 0 - 0.2, *Low* = 0.2 - 0.4, etc.). The equation generated weights among the inputs that approximates feedback provided by the technical team; specifically, experts assigned the following weightings: *Winter range habitat pressure*: 5.3; *Annual range forage condition*: 3.6; and, *Parasite* *intensity*: 1.1. Public feedback weighted annual range forage condition higher than winter range habitat pressure but weighted parasite intensity similarly.

Poor energetic condition can increase mortality directly through starvation but also indirectly through increasing susceptibility to predation and disease. There is weak evidence that indirect measures of energetic condition (e.g., chest girth and mass measured during capture) are correlated with survival for some bighorn sheep age-sex classes (Festa-Bianchet *et al.* 1997).

The relative effects of energetic condition on survival of lambs and ewes were estimated by experts and their parameters populated the *lamb effect condition* and *ewe effect condition* nodes, respectively. Specifically, the effect of being in *good* condition was estimated to improve survival by 36.9% for lambs and 25.3% for ewes, relative to *fair* condition, while being in *poor* condition was estimated to reduce survival by 64.7% for lambs and 44.1% for ewes, relative to *fair* condition.

Pneumonia Risk

Pneumonia risk is the probability in any given year that sheep in the Elk Valley East PMU are likely to come in contact with domestic sheep, leading to an all-age die off.

Experts assigned the probability of occurrence of a pneumonia outbreak in any given year to be 5%. Pneumonia is expected to affect lambs and ewes differently and experts estimated that annual mortality resulting from pneumonia would range between 53.0% and 94.3% for lambs and between 39.5% and 76.6% for ewes. These parameters were used in the *lamb effect pneumonia* and *ewe effect pneumonia* nodes.

Bighorn sheep wintering at low elevations in the East Kootenay have experienced pneumonia-related die-offs, but herds in the Elk Valley have not (Poole and Ayotte 2020). Of public respondents, 69% (n = 16) reported seeing evidence of risk of contact between bighorn sheep and domestics, as well as evidence of poor health. Four respondents reported observations of feral *Caprinae* within the past 4 years.

Human-related Mortality

Human-related mortality refers to the non-hunting mortality of sheep (only the female component of the population was modelled) recorded in the population unit. These were primarily road and rail mortalities.

The marginal probability table was derived from BHS Expert Team (2018) and Teck records, using the highest number of sheep recorded in either dataset for each year since 2010. The maximum number of mortalities recorded between 2000 and 2019 was 15 in 2014. Sex-age class was not reported for all mortalities, but assuming that mortality is independent of sex-age class and that approximately 70% of the total population is female (Poole 2020), then approximately 10 females were killed by these sources out of a total population of 600 animals or 420 females. This was used as the maximum rate of loss, which is approximately 2.5%.

Instantiation and Diagnostics

The model, when fully instantiated with available data and expert opinion, estimates the current condition of the Elk Valley East PMU in relation to the proposed draft population objective of approximately 650 bighorn sheep and predicts a 60% probability of a positive population trend (Figure 1).

A sensitivity analysis of the model indicated that the model output is most sensitive to the habitat input variables; specifically, winter range carrying capacity followed by annual range forage quality (Figure 3).

Increasing the winter range carrying capacity by 10% increases the probability of a positive population trend by about 6%. Holding the carrying capacity of winter range constant but increasing annual range forage quality by 16% could accommodate an increase in the population objective from 650 to 740 sheep, holding the probability of a positive population trend constant.

Pneumonia risk was the next most sensitive input. While the likelihood of an outbreak was estimated to be low (5% per annum), the consequence was considered to be very high and

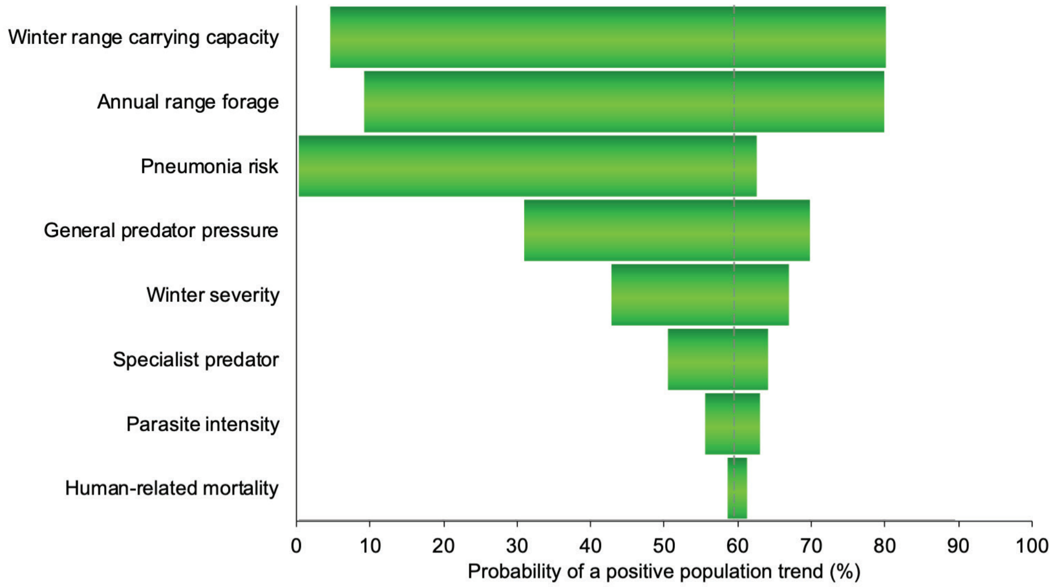

Figure 3. "Tornado" diagram of model sensitivity, with input variables ordered from the one that generates the largest variation in model output to the one that generates the smallest. The minimum and maximum of each bar indicates the effect on the probability of a positive population trend by changing the parameter to the lowest or highest values considered in the model.

could reduce the probability of a positive population trend to zero.

General predator pressure was estimated to have a greater effect than the risk of occurrence of a specialist predator causing an acute increase in adult female mortality. Reducing annual predation pressure to 0-5% of the adult female population is estimated to increase the likelihood of a positive population trend from about 60% to 72%.

The model predicts that a reduction in the frequency of severe winters will improve conditions for sheep by increasing, on average, the accessibility of winter ranges. For example, if the frequency of deep snow winters declines from approximately 1 year in 5 to 1 year in 20, the probability of a positive population trend increases by 3%, which is equal to increasing the carrying capacity of winter ranges by 50 sheep.

The instantiated model was relatively insensitive to changes in human-related mortality and parasite intensity because the range of parameters for both was relatively narrow.

Examining the shape of the response curves for each variable against a standardized axis (Figure 4), changes in the habitat variables are associated with a non-linear response in population trend under a fixed population objective of 650 sheep because additional habitat and forage provides diminishing returns to a fixed population size. All other inputs are stressors and are associated with negative and largely linear slopes, although this is partly due to the coarse precision of states and associated probabilities, particularly where parameters were estimated via expert opinion. Those inputs associated with steeper slopes cause relatively larger changes in the probability of positive population trends and the inputs ordered by slope in Figure 4 correspond to the order of bars from longest to shortest in Figure 3.

Focusing specifically on the expert input, the team was most certain about potential effects of pneumonia and least certain about condition-related mortality impacts and general predator pressure (Table 1).

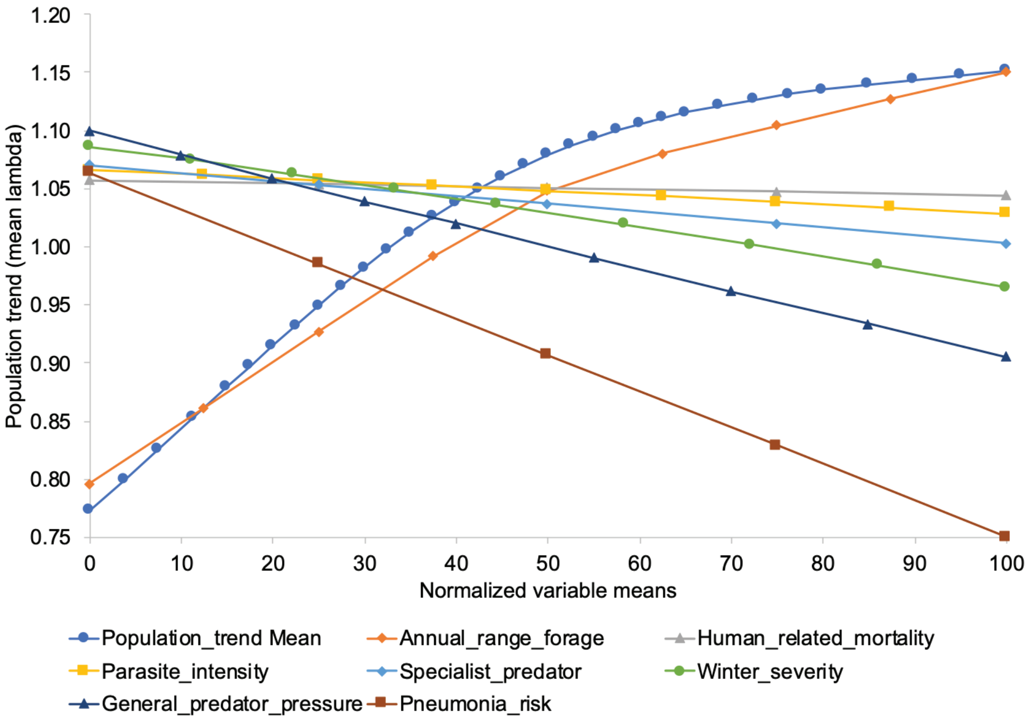

Figure 4. Response of population trend to changes in each input variable, measured against a standardized axis.

Table 1. Confidence (highest to lowest) and variability among experts (expressed as the coefficient of variation) in relation to the model parameters experts were asked to estimate.

Parameter	**Average confidence (1 = low, 5 = high)**	**Variability among experts (coefficient of variation)**
Pneumonia mortality lambs	3.5	0.16
Pneumonia risk	3.3	0.32
Pneumonia mortality ewes	3.2	0.21
Lamb predation	2.9	0.25
Energetic condition	2.9	0.30
Specialist predator	2.4	0.45
General predator pressure	2.2	0.56
Condition-related mortality	1.9	0.41

DISCUSSION

There are many interacting factors affecting the bighorn sheep population in the Elk Valley and the population model presented here represents the first attempt to characterize these factors in a causal framework and to estimate parameters. Like all models, it represents a simplification of the system and can address only circumstances that are reasonably foreseeable. Outputs are presented probabilistically, meaning that the most likely outcome is not necessarily the one that is always going to occur. In addition, there are many estimated parameters and relationships that could change substantially as knowledge of the system improves. As a result, model outputs should be considered adaptive management hypotheses based on best available information, rather than deterministic predictions about future system responses.

Development of the model identified a number of knowledge gaps that could be addressed through additional research. Perhaps most significantly, the interaction between energetic condition and winter and annual range condition is not well understood.

Although there is good evidence that improving annual range and sustaining winter range conditions can benefit bighorn sheep, it is unknown how changes in conditions affect subsequent survival and reproductive success. In the model these functions were estimated by experts but, ideally, they would be informed by data collected through future research. Detailed body condition data are difficult to collect but there might be opportunities to index the condition of sheep captured on cameras or by some other indirect means to provide information on energetic condition (e.g., Smiley *et al.* 2020). Indices could be correlated back to local and seasonal range conditions, although such indices might not be as reliable indicators of condition as reproductive performance.

In addition to snow depth, there are many other dimensions of weather that can affect sheep. These have been observed or hypothesized in other sheep populations and may be significant in the Elk Valley:

- Freeze-thaw and icing events that can restrict access to forage even when snow is shallow. If such events occur at critical times (e.g., during lambing) the effect on populations could be significant.
- Displacement of animals off of winter ranges by deep snow that might make them more susceptible to predation at lower elevations.
- Direct mortalities due to avalanches.
- Late or early snowfalls that affect sheep at times of greatest energy demand.
- Summer droughts that affect forage quality and hence weight gain by sheep.
- Spread of pathogens that may be facilitated by warmer weather.

Bighorn sheep are social animals and behaviours such as seasonal movements and range use can be habitual and persist for generations. As a result, sheep cannot necessarily be expected to respond immediately to management actions intended to improve conditions. For example, the model might predict a positive response to range improvements, but habitual behaviour might have to change significantly for any population response caused by the improvements to be realized. Investing in mitigation that is aligned with current behaviour might generate greater short-term benefits for the population.

Habitat improvements could include activities such as burning, seeding, weeding and/fertilizing and the most appropriate treatments are likely to vary with site characteristics (BHS Expert Team 2018). While there will always be unexpected events, knowledge will improve over time and the model can be refined to improve the reliability of predictions.

ACKNOWLEDGEMENTS

We would like the following for participating in workshops and contributing to model development: Ian Adams, Meghan Anderson, Chris Barker, Katrina Caley, Cathy Conroy, Bill Cuneliffe, Linda Cuneliffe, Elan Failing, Anna Fontana, Ted Gullison, Michael Harstone, Kevin Hurley, Kyle Knopff, Steven Hilts, Beth MacCallum, Kristen Murphy, Kevin Podrasky, Kim Poole, Kathreen Ruckstuhl, Kirby Smith, Irene Teske, and Marty Williams. Sean Beswick provided additional comments on an earlier draft and Marco Festa-Bianchet provided insightful comments on the manuscript. Funding was provided by Teck Coal Ltd.

LITERATURE CITED

BHS Expert Team. 2018. Bighorn sheep cumulative effects assessment report. Elk Valley, Kootenay-Boundary Region. Elk Valley Cumulative Effects Management Framework. Cranbrook, BC.

Bourbeau-Lemieux, A., M. Festa-Bianchet, J.M. Gaillard, and F. Pelletier. 2011. Predator-driven component Allee effects in a wild ungulate. Ecology Letters 14:358–363.

Brewer C.E., V.C. Bleich, J.A. Foster, T. Hosch-Hebdon, D.E. McWhirter, M. Rominger, M.W. Wagner, and B.P. Wiedmann. 2014. Bighorn sheep: conservation challenges and management strategies for the 21st century. Wild Sheep Working Group, Western Association of Fish and Wildlife Agencies, Cheyenne, WY.

Demarchi R.A., C.L. Hartwig, and D.A. Demarchi. 2000. Status of the Rocky Mountain Bighorn sheep in British

Columbia. BC Ministry of Environment, Lands and Parks Wildlife Bulletin No. B–99.

Elwert, F. 2013. Graphical causal models. Pages 245-273 In: S.L. Morgan (ed.), Handbook of Causal Analysis for Social Research. Handbooks of Sociology and Social Research. https://doi.org/10.1007/978-94-007-6094-3

Farr, C., F. Ruggeri, and K. Mengersen. 2018. Prior and posterior linear pooling for combining expert opinions: uses and impact on Bayesian networks – the case of the wayfinding model. Entropy 20:209. http://dx.doi.org/10.3390/e20030209

Festa-Bianchet M. 1989. Survival of male bighorn sheep in south- western Alberta. Journal of Wildlife Management 53:259–263.

Festa-Bianchet M., J.T. Jorgenson, C.H. Bérubé, C. Portier, and W.D. Wishart. 1997. Body mass and survival of bighorn sheep. Canadian Journal of Zoology 75:1372–1379.

Festa-Bianchet, M., T. Coulson, J.-M. Gaillard, J.T. Hogg, and F. Pelletier. 2006. Stochastic predation events and population persistence in bighorn sheep. Proceedings of the Royal Society B: Biological Sciences 273:1537–1543.

Festa-Bianchet, M., J.-M. Gaillard, and S.D. Côté. 2003. Variable age structure and apparent density-dependence in survival of adult ungulates. Journal of Animal Ecology 72:640-649.

Gaillard, J.-M., M. Festa-Bianchet, and N.G. Yoccoz. 1998. Trends in Ecology and Evolution 13:58–63.

Golder Associates. 2019a. Assessing the condition of high elevation grasslands in the Elk Valley, BC. Technical Memorandum to Teck Coal Ltd., Sparwood, BC.

Golder Associates. 2019b. Bighorn sheep habitat selection in the east Elk Valley. Prepared for Teck Coal Ltd., Sparwood, BC.

Golder Associates. 2019c. Estimating bighorn sheep carrying capacity in the Elk Valley: winter range mapping and winter forage list. Prepared for Teck Coal Ltd., Sparwood, BC.

Golder Associates. 2019d. Estimating bighorn sheep carrying capacity: forage biomass and percent cover. Prepared for Teck Coal Ltd., Sparwood, BC.

Hamel, S., and S.D. Côté. 2007. Habitat use patterns in relation to escape terrain: are alpine ungulate females trading off better foraging sites for safety? Canadian Journal of Zoology 85:933–943. https://doi.org/10.1139/Z07-080

Jokinen, M.E., P.F. Jones, and D. Dorge. 2008. Evaluating survival and demography of a bighorn sheep (*Ovis canadensis*) population. Biennial Symposium of the Northern Wild Sheep and Goat Council 27:138–159.

Keller, B.J., and L.C. Bender. 2010. Bighorn sheep response to road-related disturbances in Rocky Mountain National Park, Colorado. Journal of Wildlife Management 71:2329–2337. https://doi.org/10.2193/2006-486

Knopff, K. 2020. Estimating nutritional carrying capacity of bighorn sheep in the Elk Valley. Proceedings of the Northern Wild Sheep and Goat Council 22:36. https://youtu.be/WsmZ2GEn9Io

Loison A., M. Festa-Bianchet, J.M. Gaillard, J.T. Jorgenson, and J.M. Jullien JM. 1999. Age-specific survival in five populations of ungulates: evidence of senescence. Ecology 80:2539–2554.

Marcot, B.G., J.D. Steventon, G.D. Sutherland, and R.K. McCann. 2006. Guidelines for developing and updating Bayesian belief networks applied to ecological modelling and conservation. Canadian Journal of Forest Research 36:3063–3074.

MacArthur, R.A., V. Geist, and R.H., Johnston. 1982. Cardiac and behavioral responses of mountain sheep to human disturbance. Journal of Wildlife Management 46:351–358.

Poole, K.G. 2013. Habitat use, seasonal movements, and population dynamics of bighorn sheep in the Elk Valley. Prepared for BC Ministry of Forests, Lands, Natural Resource Operations, Cranbrook, and Teck Coal Ltd., Sparwood, BC.

Poole, K.G. 2020. Elk Valley East bighorn sheep inventory February 2020. Prepared for: Teck Coal Ltd., Sparwood, BC.

Poole, K.G., C.R. Smyth, I. Teske, K. Podrasky, R. Serrouya, G. Sword, and L. Amos. 2013. Bighorn sheep and Elk Valley coal mines; ecology and winter range assessment. Prepared for Teck Coal Ltd., Sparwood, BC.

Poole, K.G., and J. Ayotte. 2020. Kootenay region bighorn sheep management plan – draft for discussion. Prepared for BC Ministry of Forests, Lands, Natural Resource Operations and Rural Development, Cranbrook, BC.

Roeber, F., A.R. Jex, and R.B. Gasser. 2013. Impact of gastrointestinal parasitic nematodes of sheep, and the role of advanced molecular tools for exploring epidemiology and drug resistance - an Australian perspective. Parasites & Vectors 2013 6:153. https://doi.org/10.1186/1756-3305-6-153

Rominger E.M., H.A. Whitlaw, D.L. Weybright, W.C. Dunn, and W.B. Ballard WB. 2004. The influence of mountain lion predation on bighorn sheep translocations. Journal of Wildlife Management 68:993–999. https://doi.org/10.2193/0022-541X(2004)068[0993:TIOMLP]2.0.CO;2

Ross, P.I., M.G. Jalkotzy, and M. Festa-Bianchet. 1997. Cougar predation on bighorn sheep in southwestern Alberta during winter. Canadian Journal of Zoology 75:771–775. https://doi.org/10.1139/z97-098

Szkorupa, T., P. Stent, and B. Phillips. 2013. Elk valley elk inventory. BC Ministry of Forests, Lands and Natural Resource Operations, Cranbrook.

Smiley, R.A., C.D. Rittenhouse, T.W. Mong, and K.L. Monteith. 2020. Assessing nutritional condition of mule deer using a photographic index. Wildlife Society Bulletin 44:208–213. https://doi.org/10.1002/wsb.1070