CCSP Project Report on Land-use and Caribou Population Simulation for the Churchill, Berens, and Kinloch Caribou Ranges

Project Name: A decision support tool to assess the capacity of conservation actions to reduce threats to caribou populations

Rob Rempel (FERIT) and Matt Carlson (IEG)

July 20th, 2025

Executive Summary:

This project culminated in the creation of a comprehensive, web-based decision support tool for Boreal caribou management, built on the ALCES Flow simulation platform. The platform brings together up-to-date datasets on landscape composition, climate change trajectories, population vital rates and disturbance regimes. Science advice and support from the Ontario Ministry of Natural Resources (MNR), including reports and GIS files from the most recent forest resource inventories and caribou surveys in the study area, ensured that critical information on natural land-cover, anthropogenic footprint and observed recruitment and survivorship estimates, reflected integrated range assessments and forest inventory information. Within ALCES Flow, users can construct and explore a wide variety of land-use, disturbance, and wildlife-management scenarios, ranging from forest harvest, wolf control and altered moose harvest rates, and observe their cumulative effects on caribou populations. Analysis of such scenarios can contribute to caribou management from an adaptive management context, where the likelihood of conservation success can be simulated and evaluated before implementation on the ground. To demonstrate real-world applicability, we ran a series of simulation experiments focused on the area encompassed by the Trout Lake Forest, Lac Seul Forest, and Red Lake Forest Management Units (FMUs) in northwestern Ontario, examining how different forest and wildlife management options and interventions influence caribou long-term persistence. Operating at a one-square-kilometre resolution he landscape module reproduces future patterns of harvest, road development, wildfire and other disturbances by combining provincial Dynamic Caribou Habitat Schedule (DCHS) constraints with machine-learning predictions of where industry is most likely to operate; the same engine can be rescaled to represent business-as-usual, reduced or intensified harvest, salvage logging and a range of climate-driven burn rates.

Population dynamics are driven by habitat quality, fecundity, mortality and inter-specific interactions. Moose carrying capacity responds directly to changing forest age structure and to bioclimatic surfaces for temperature and precipitation; wolf numbers track moose density; caribou vital rates then follow empirically derived relationships, including relative carrying capacity models derived from GPS-based habitat models of resource selection, and predation mortality driven by wolf numbers. The moose-wolf-caribou (MWC) model was calibrated against recent Ontario survey data and validated against independent estimates of recruitment, survivorship and population growth (λ ~0.994under current conditions), demonstrating reasonably close agreement with Ministry of the Environment, Conservation and Parks (MECP) survey results conducted in 2023 and

2024 in the Kinloch, Berens, and Churchill Ranges, and supplementary surveys conducted recently for the Great Bear Gold Project EA in the Berens, Kinloch, and Churchill Ranges. However, these comparisons suggest that the MWC model may slightly overestimate recruitment rates, so future iterations of the model might consider lowering recruitment by slightly increasing wolf predation on young caribou.

Simulations showed that the combination of wildfire and harvesting at 80 percent of the approved Annual Allowable Cut (AAC) reduces mature conifer below the amount expected under natural disturbance, and increasing to 100 percent AAC exacerbates that loss, and contributes to a downward trend in the caribou population. The natural disturbance scenario, however, implicitly includes fire suppression, so further analysis should explore removing fire suppression to improve the comparison. Reduced harvest (50 percent AAC) slows but does not reverse habitat loss and downward population trend for caribou, because even modest logging accelerates moose expansion, which in turn drives higher wolf densities and lower caribou recruitment. Climate change strengthens these trophic cascades by raising wildfire rates and moose carrying capacity; holding climate constant diminishes, but does not eliminate, the negative trend in caribou numbers. Only scenarios that paired moderate harvest with direct wildlife management options (e.g., a two-percent wolf reduction and a 25-percent increase in moose harvest) achieved appreciable improvements, raising the projected 50-year caribou population by roughly five percent compared with unmanaged baselines.

The public interface for the assessment tool now lets users combine custom landscape projections with population simulations, download georeferenced outputs and repeat the analyses with their own spatial layers. A virtual workshop tutorial will explore these functions, and the recorded session remains available for wider viewing. Continued model refinement will focus on importing user-supplied cut-block sequences, delineating protected no-harvest zones and simulating additional industrial footprints such as mines and transmission corridors.

In summary, the project has produced a scientifically vetted platform that links land-use decisions to species outcomes, fills key data gaps for three interconnected caribou ranges and points to integrated management, moderate harvest, habitat retention and targeted predator-prey interventions, as the most promising path for sustaining Boreal caribou alongside economic forestry in north-western Ontario.

Acknowledgements

The science advisory team, Drs. Art Rodger, Jen Shuter (MNR), and Justina Ray (WCS Canada) played an invaluable role supporting development of the model, providing results from recent survey data, feedback on results, and discussing plausible scenarios for consideration in the study. Max Maxfield (retired, Resolute) provided valuable insights into the role and administrative limitations of the harvest option, salvage logging. Funding for this project was provided by the Province of Ontario under the Caribou Conservation Stewardship Program.

Contents

Executive Summary:.....1
Acknowledgements.....2
Background:.....3
Cumulative Effects.....4
Methods.....5
Simulation of Forestry Activities and Natural Disturbance.....5
Landscape, Disturbance, and Climate Data Layers.....9
Population Dynamics.....9
Caribou recruitment and interspecies relationships.....11
Moose Bioclimatic Model.....15
Moose-Tick-Climate Relationship.....17
Model testing and incorporating latest caribou survey results.....17
Model Validation.....20
Defining Scenarios:.....21
Scenario Analysis - Results and Discussion:.....23
References.....29

Background:

As part of the bilateral Caribou Conservation Agreement between Ontario and Environment Canada and Climate Change, FERIT collaborated with the Integral Ecology Group (with support from CNFER -- the Centre for Northern Forest Ecosystem Research) to develop a customized version of ALCES Flow to model the cumulative effects of wildlife management, climate change, and forest management, on caribou with the Churchill, Berens, and Kinloch ranges where caribou surveys have been recently conducted. The system integrates land-use models of forest harvest and natural disturbance with a population dynamics model of moose, wolves, and caribou. The caribou ranges encompass the Trout Lake Forest, Lac Seul Forest, and Red Lake Forest FMUs, and a key objective of the project is to develop accessible tools that would allow planners to examine through simulation how different forest and wildlife management options and interventions influence caribou long-term persistence in these areas of interest.

The predecessor to ALCES Flow, referred to as ALCES Online, was previously used by CNFER to model the cumulative effects of landscape disturbance and climate change on the moose-wolf-caribou (MWC) predator-prey system (Rempel et al. 2021). The ALCES Flow decision support tool was redeveloped to improve the underlying landscape and habitat models, increase simulation speed and resolution, reduce server costs, and provide a streamlined workflow to make the tool

easier to use. The tool consists of four interacting models: the landscape model and three population dynamics models (moose, wolf, caribou).

Cumulative Effects

The landscape model (accessible to assigned government staff using the Landscape Projection Tool) simulates potential future changes in land cover and forest age in response to the combined effects of fire, forestry, and other forms of development (e.g., mining). From a cumulative effects perspective, the forestry and mining sectors create stresses on caribou populations through creation of clear cuts and linear features (Figure 1). These anthropogenic stressors are bracketed by natural disturbance and climate change. This results in changes to landscape disturbance, including changes to habitat carrying capacity, as well as direct effects from linear features, such as noise avoidance, increased hunter access, and enhanced predator efficiency affecting caribou. The combination of linear features and changes to habitat result in changes to vital rates and dispersal of moose, wolves, and caribou (Figure 1). Moose can be positively affected by both forest disturbance and climate change, and increasing moose populations can lead to increased wolf densities, and subsequent predation on caribou. Thus, the model evaluates the causal relationship between forest disturbance and the dynamics of caribou populations and explores in a deeper manner the observed correlation between percent range disturbance and probability of caribou persistence (Environment and Climate Change Canada [ECCC] 2011, Johnson et al. 2020).

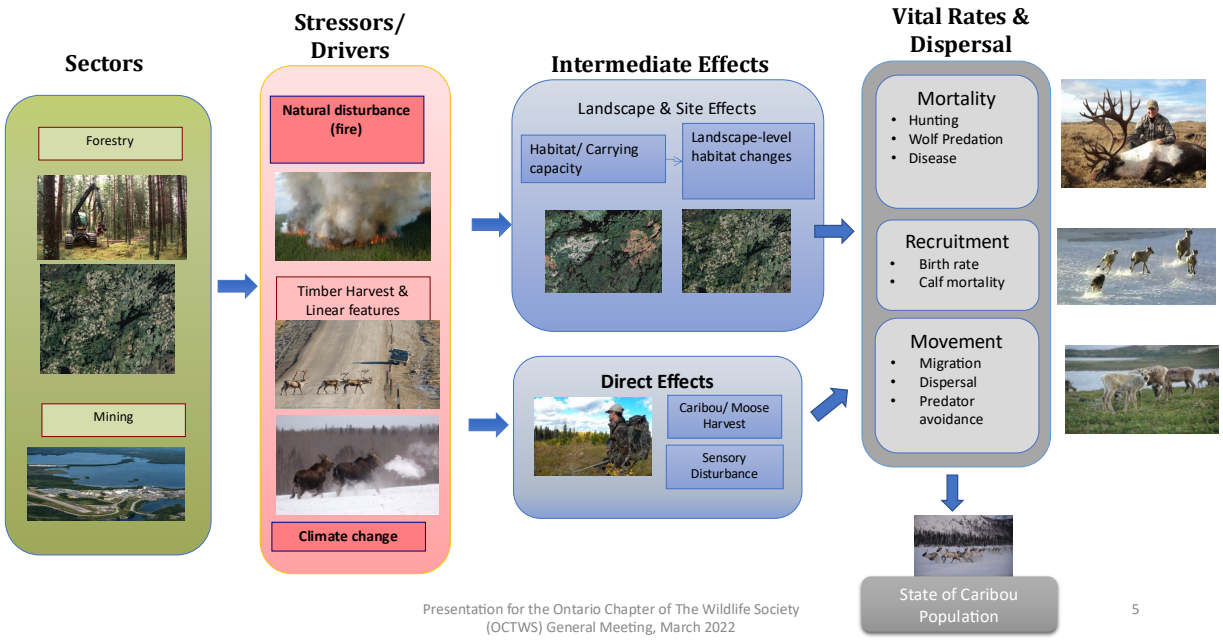

Figure 1. Relationship between sectors, drivers, intermediate effects and vital rates for the MWC model.

Methods

Simulation of Forestry Activities and Natural Disturbance

The Land-Use Simulator (ALCES Flow) creates patterns of fire, forestry, mining and infrastructure development, drawing on caribou-specific harvest block definitions ("dynamic caribou habitat schedule" [DCHS]), and allows users to modify harvest rates, road-building effort, wildfire scenarios (under no climate change, RCP 4.5 or RCP 8.5), and salvage logging. Outputs include georeferenced raster layers showing forest age-class distributions, land-cover summaries, and linear feature densities. The ALCES Flow harvest simulator is a machine learning (ML) program that was trained on Ontario data to simulate both harvest and road density patterns. The simulation of forestry is informed by forest management plans (FMPs) and DCHS, which attempt to distribute timber harvest temporally and spatially to support caribou habitat targets (Figure 2).

The default rate of forest harvest is identified in each forest management unit's (FMUs) forest management plan. The default rate of road development is based on the rate of road development that has occurred since 2007. It should be noted that harvest in the region is typically below the maximum permitted level. As such, the user may want to reduce harvest to 80% of the planned level during simulations (Rempel et al. 2021). The harvest scheduler is strategic in nature, as a single harvest type that combines deciduous and coniferous harvest was simulated because the forest types used in FMPs do not correspond with the forest types in the underlying land cover data, which makes it challenging to reliably assign separate coniferous and deciduous harvest areas. Furthermore, the relative magnitude of coniferous and deciduous harvest as identified in the harvest plans is approximately proportional to their availability on the landscape. Timber harvest is limited to dense forest older than 65 years. Salvage of burns is assumed to be compensatory by reducing planned harvest based on the spatial extent of merchantable forest burned within FMUs. To be salvaged, forest needs to be older than 65 years. It is assumed that regenerating stands will regrow as the same, pre-harvest forest type.

The portion of each FMU that is available for harvest each simulation interval is specified by the DCHS. Within eligible DCHS polygons, finer scale harvest and road development patterns are informed by historic patterns using the random forest machine learning models. The random forest models predict the spatial relative probability of harvest or forestry road development. The distributions of harvest and road development at the regional scale are heavily zero-weighted, so a two-stage hurdle model was used. The first stage of the hurdle model uses a binary classifier to predict the likelihood that the conversion area within a 500 m pixel is zero. The second stage of the hurdle model is a standard random forest regressor that is trained on the nonzero data. The result of the hurdle model is the nonzero regressor prediction multiplied by the probability of being nonzero. Note that the predictions from the harvest and road models are rescaled to equal the desired harvest and road development rate. Hence the hurdle model informs the spatial distribution of the land cover projections but not the rate.

Timber harvest and forestry road models were trained from historical harvest and road development occurring in 5-year intervals since 2007. The location of historical timber harvest was based on Forest Resource Inventory (FRI) digital maps, and the location of road development was

based on the MNR Road Segments[1] dataset. Model performance was optimized by constraining the model complexity (i.e., decision forest size and structure) once adequate performance was achieved. Models were initially supplied with a large list of candidate covariates. A recursive variable selection routine using 4-fold cross validation was used to identify a parsimonious covariate set for each conversion model.

Candidate covariates considered during development of the timber harvest model included:

- Eligible harvest area (per pixel)
- Average forest age (per pixel)
- Mean elevation (per pixel)
- Current forest area by type (per pixel)
- Current resource road area (per pixel)
- Density of eligible harvest area at 1, 3, 5, 10, 25, 50, and 100 km scales
- Density of eligible resource road area at 1, 3, 5, 10, 25, 50, and 100 km scales

Candidate covariates considered during development of the forestry road model included:

- Distance to new harvest areas
- Average forest age (per pixel)
- Mean, max, and min elevation (per pixel)
- Current forest area (per pixel)
- Density of new harvest area at 1, 3, 5, 10, 25, 50, and 100 km scales

Fire simulation is based on projected fire rates for homogenous fire regime zones (HFRZs) and relative burn rates being influenced by forest type and age (Figure 3). The fire rate varies by HFRZs as shown in the table below (Boulanger et al. 2014). Three fire rate scenarios are available in the tool: no climate change and under the two climate scenarios RCP 4.5 and RCP 8.5. Fire without climate change is based on the historical average from 1959 to 1999, by HRFZ. As rates are based on these recent historical observations, fire suppression is explicitly built into the HFRZ. Effectiveness of fire suppression improved in the early 1960s due to technological advances, such as lighter and portable fire pumps, purpose built aircraft, and improved fire detection systems. To avoid unrealistically sharp differences in fire rate between zones, the fire rates blend between HFRZs within a 30 km buffer on each side of a HFRZ boundary. Each HFRZ's annual fire area is the fire rate multiplied by the area of forested land cover (coniferous, mixed, deciduous, sparse treed, and shrub[2]. Within a HFRZ, the likelihood of burn is influenced by the cover type and forest age according to relative burn likelihoods from Bernier et al. (2016).

Table 1. Annual fire rate for the study area by homogenous fire regime zone for two time periods under three climate scenarios.

	Annual fire rate (%)

[1] The benefit of using the road segments dataset is that it provided the ability to identify roads built in 5-year intervals back to 2007.

[2] Shrub is included because the cover type commonly occurs within fire perimeters in historical fire data.

Homogenous Fire Regime Zone	Static climate (1959-1999)	RCP 4.5 climate scenario		RCP 8.5 climate scenario	
		current-2040	2041-2070	current-2040	2041-2070
Western Ontario	0.49	1.078	1.775	0.956	1.903
Lake Winnipeg	0.82	4.077	7.771	4.426	8.33
Western James Bay and Subarctic	0.11	0.351	0.47	0.277	0.514
Eastern Temperate	0.03	0.048	0.061	0.033	0.07

Table 2. Relative burn probabilities for forest type and age categories, based on Bernier et al. (2016).

	Young (<30 years)	Mature (30-89 years)	Old (>89 years)
Conifer	0.8	2	2.9
Mixed [3]	0.325	0.865	1.375
Deciduous, Shrubland, Sparse Treed [4]	0.15	0.4	0.63

The user can modify the amount of forest harvest, forestry roads, and wildfire by changing the scale factor in the landscape projection user interface. For example, a scale factor of 0.80 for harvest would allow the user to specify 80percent harvest of the AAC as the business-as-usual (BAU) schedule for the simulation. Landscape simulation outcomes are then available to inform habitat and population dynamic simulations for moose, wolf, and caribou. Guidance on how to use the landscape projection tool is available here. Through a future project we plan to add the ability to apply custom harvest schedules, assign no-harvest areas (i.e., protected areas), and import shapefiles to simulate other forms of development such as mines and infrastructure corridors (e.g., roads, transmission lines).

[3] Bernier, P. Y., S. Gauthier, P.-O. Jean, F. Manka, Y. Boulanger, A. Beaudoin, and L. Guindon. 2016. Mapping local effects of forest properties on fire risk across Canada. Forests 7:157.) provide fire selection ratios for two types of mixedwood forest: coniferous leading and deciduous leading. The average of these two selection ratios was used.

[4] Bernier et al. (2016) do not provide relative burn probabilities for shrubland or sparse treed forest types. The deciduous relative burn probabilities were assumed to apply because they were the lowest rates. It is reasonable to assume that sparse treed and shrubland types have low relative burn probabilities because of their low biomass, which is inversely related to burn likelihood (Bernier et al. 2016).

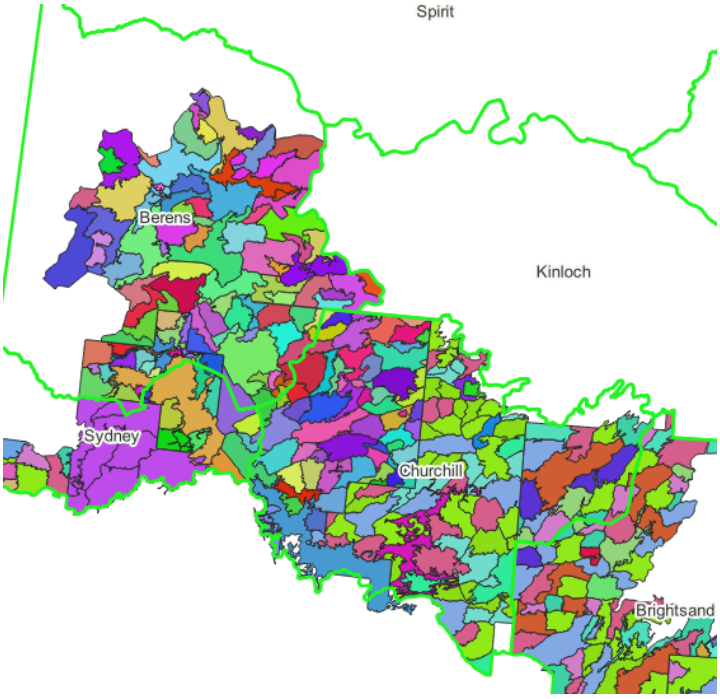

Figure 2. Provincial DCHS polygon layer, colored by block name.

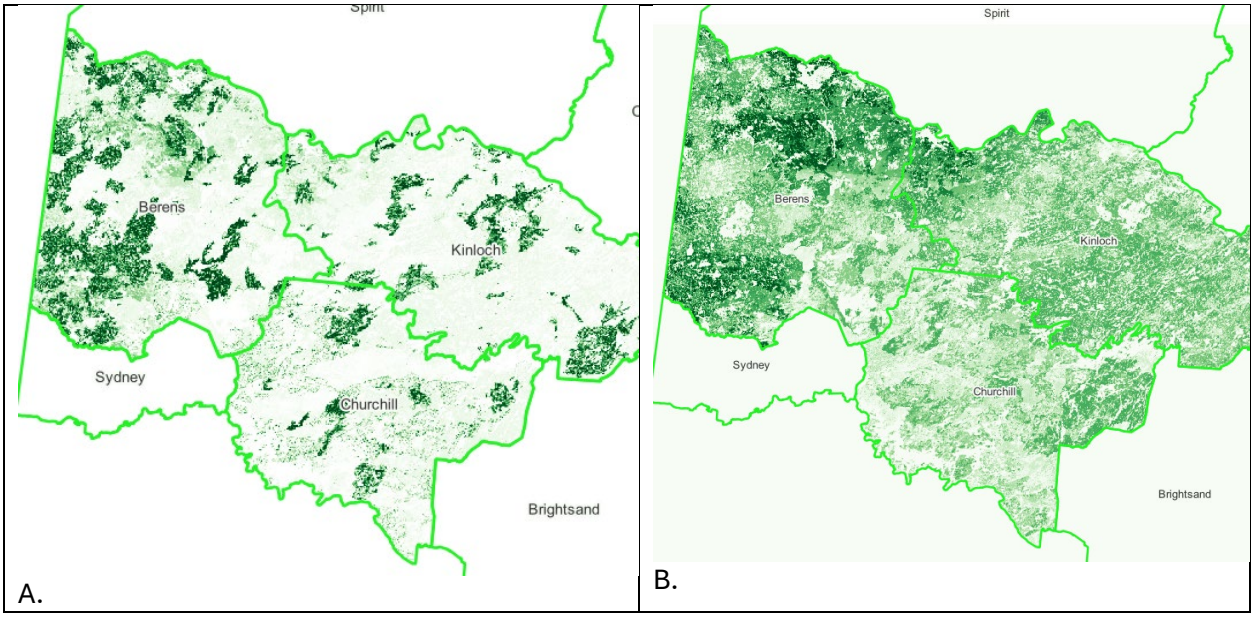

Figure 3. Simulated burn under RCP 8.5. Darker green represents a greater fraction (0-1) of hexagon pixels disturbed by fire. A) Fire pattern in 2028, with pattern dominated by existing burns; B) Fire pattern in 2068, with fire pattern dominated by spatially averaged new disturbance pattern.

Landscape, Disturbance, and Climate Data Layers

The landscape model imports existing layers to initialize model conditions, including a base layer of natural forest conditions in the absence of forest disturbance, with forest harvest, fire disturbance, roads and other linear features, and permanent disturbance layered on top of these. The underlying natural landscape layer was based on the Provincial Landcover 2000 (PLC2000) landcover map, as this was the map that the caribou RSF models and moose bioclimatic model were based on. The most recent (2024) FRI harvest and burn data from the PIAM database (from MNR) was then layered on the natural landscape map, together with most recent linear feature data. The MNR roads layer was used as the roads linear feature data source as this layer included temporary forestry roads and harvest trails associated with forestry activity.

From this starting point additional harvest and burns were simulated (as described above), with forest harvest spatially and temporally constrained by the most recent Provincial DCHS layer (as provided by MNR). Roads were simulated as linear feature density within the 1 km^2 simulation cells, as this is the parameter used in the caribou resource selection function (RSF) models. Fractional occurrence of forest types within cells was also used in the RSF models. The effect of fire and harvest was simulated by shifting age-class distribution at a spatial resolution of 500 m. For example, if a 500-m raster has a 10% likelihood of being burned, then 10% of the forest area within the raster was shifted to an age of 0. As described in the previous section, the likelihood of forest being disturbed by forestry and fire varied spatially in response to a variety of factors such as forest management plans, dynamic caribou habitat schedules, homogenous fire regime zones, forest type, and forest age. The approach presents data in a manner consistent with data requirements of the caribou and moose habitat models, but without over-extending the ability to predict exact location of future disturbance and creation of linear features. Through an upcoming project, we intend to expand the functionality to allow the user to apply harvest as discrete events if spatial harvest sequences (at the level of cutblocks) are available, such as can be generated by forest estate and harvest scheduling models such as Patchworks.

Climate change surfaces were developed and made available by Natural Resources Canada (Dan McKenny, person communication), and the layers used in the MWC model were average winter temperatures (AWT), average summer temperature (AST), and total cold period precipitation (ACP). These surfaces were used in the moose bioclimatic and winter tick models (Rempel 2011).

Population Dynamics

The population models (accessible using the Population Dynamics Tool) wildlife population dynamics in response to habitat, fecundity, mortality, and species interactions (e.g., predation) (Figure 4).

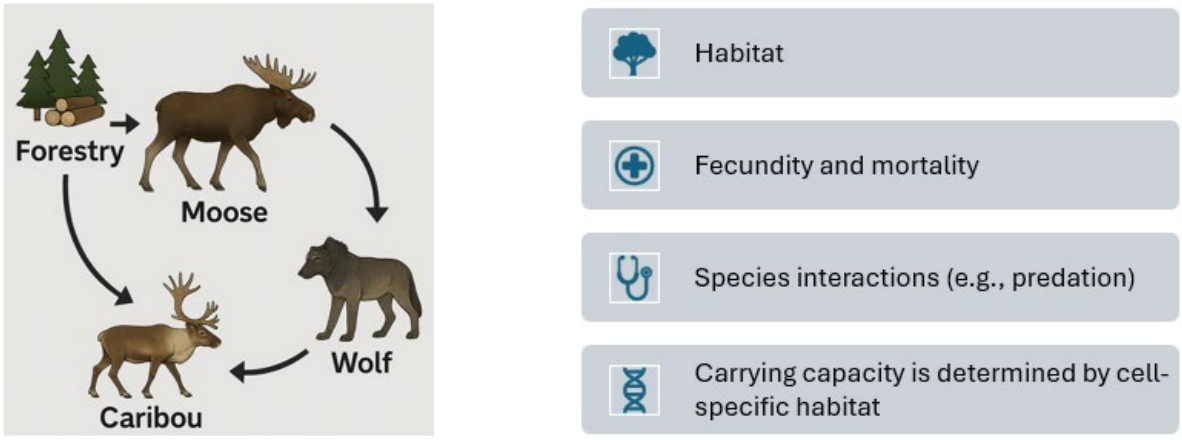

Figure 4. Major components in the MWC population dynamics model, including habitat, fecundity, species interactions, and carrying capacity.

The models are cell-based, where each cell can be viewed as essentially a Leslie-matrix population model with relative carrying capacity dictated by the cell's habitat (Figure 5). If a population within a cell approaches carrying capacity, then both density dependence and dispersal effects become active, and populations disperse based on a user-defined distance.

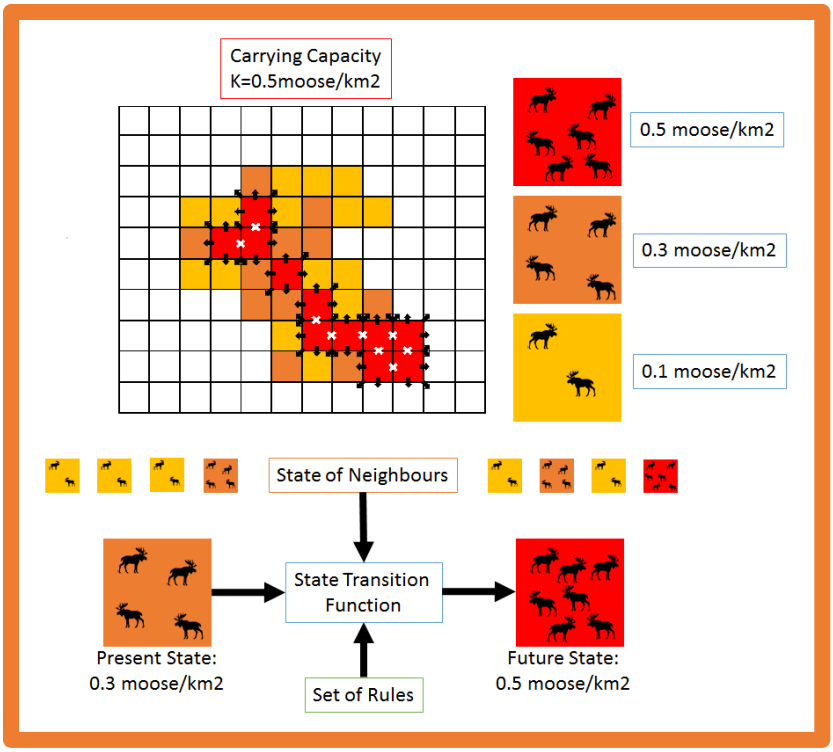

Figure 5. Cell-based model structure, with spatial effects of carrying capacity.

Caribou habitat is modeled using landscape simulations and updated versions of RSFs that are specific to each herd. The RSFs specify relative carrying capacity, with values ranging from 0 to 1, and absolute carrying capacity is defined as maximum caribou density, as suggested from literature review. Thus, each cell has a dynamic value for carrying capacity that varies as habitat and climate change across the landscape and through time.

Moose habitat is also modeled using landscape simulations and a bioclimatic model that relates climate, land cover composition, and forest disturbance to moose density (Rempel et al. 2021). Wolf habitat is a derivative of simulated moose density. Populations of each species are simulated using the dynamic habitat layers, survivorship (as affected by predation, density dependence, other forms of natural mortality, and harvest), fecundity (including density dependent effects), and dispersal. The interacting models allow for evaluation of multi-species responses, for example an increase in moose resulting from climate change and disturbance, a resulting numerical response of wolves, and subsequent changes to caribou predation rates. This then provides capability to simulate caribou conservation strategies. Guidance on how to use the population dynamics tool is available here. More information on the model logic Bergerud and Elliot (1986) is available in Rempel et. al (2021).

Caribou recruitment and interspecies relationships

A key factor in the caribou model is recruitment as recruitment is the process by which new individuals are added to the breeding population. In practical terms for ungulates such as moose and caribou, recruitment is usually quantified as the number of calves (or "young of the year") that survive to a specified age (often one year) per 100 adult females in the population. For caribou and moose recruitment is typically measured in late winter or early spring composition surveys. It's expressed as the number of calves per 100 adult cows that survived their first winter, or young-of-year (YOY) surviving, depending on timing of the survey. This metric integrates calf birth rates, overwinter survival and implicitly, factors such as predation, weather and habitat quality. Because recruitment directly affects the population's growth rate (λ), wildlife managers track it closely: high recruitment indicates good calf survival and potential for population increase, whereas low recruitment signals possible declines or increased mortality pressures

In our MWC population dynamics model, some of the factors that are integrated into observed calf: cow ratios are explicitly modelled. As such, recruitment is an outcome of the model, not an input, and we need to explicitly identify causal factors leading to "recruitment" (Figure 6). The model begins with fecundity, which is the maximum proportion of cows that give can birth to neonates. Here, fecundity is estimated as the actual observed pregnancy rate. Some pregnancies are naturally aborted, leading to unobserved birth rate of neonates. Some neonates are predated by wolves, leading to observed cow: calf ratios. Calves are not yet breading adults, and some calves are predated, leading to actual recruitment rate to adult breeding population (Figure 6).

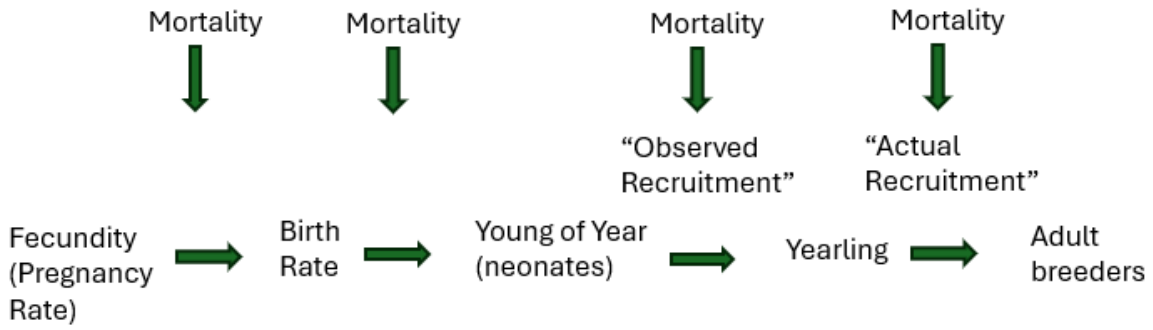

Figure 6. Recruitment process, and relationship between modelled mortality and observed recruitment from caribou surveys.

As density of wolves increases, adult caribou mortality increases while caribou recruitment decreases (Figure 7). Thus, any climate change or landscape disturbance effect that causes an increase in wolf populations will cause a decrease in caribou recruitment. In PopDyn, this interspecies relationship between wolf density and caribou mortality is specified by a lookup table (Figure 8), where the lookup table is based on the modelled relationships. Adult caribou mortality was modelled using the Bergerud and Elliot (1986) equations to increase linearly with wolf density (mortality = 4.766 + 0.699 × wolves per 1,000 km^2), while recruitment follows an exponential decay with predation pressure (recruitment =*exp(*3.340 − 0.127 × wolves per 1,000 km^2)) (Figure 7). Translating pregnancy rates into recruitment metrics allows the model to adjust young-of-year survivorship dynamically as wolf densities fluctuate.

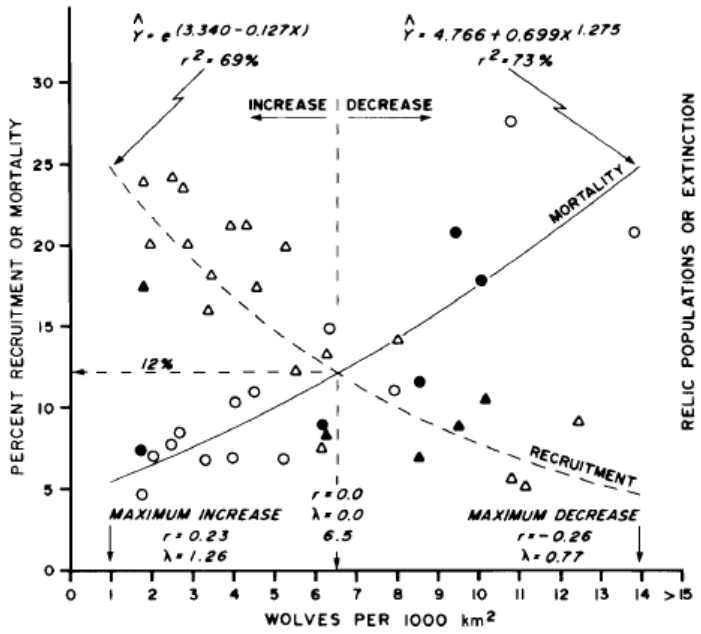

Figure 7. Model relationship from Bergerud and Elliot studies on wolf density and caribou recruitment and mortality.

Predation of Caribou By Wolves

The following tables defines the mortality rates for predation of caribou by wolves.

+ Insert Before | + Insert After | − Remove Row

Row	Wolf Density	YOY Mortality Rate	Mature Mortality Rate	Yearling Mortality Rate	Old Mortality Rate
0	0.001	0.705	0.05	0.05	0.05
1	0.0036	0.786	0.08	0.08	0.08
2	0.0053	0.83	0.11	0.11	0.11
3	0.0086	0.899	0.16	0.16	0.16
4	0.0126	0.934	0.22	0.22	0.22
5	0.0138	0.943	0.25	0.25	0.25

Figure 8. Image of PopDyn lookup table relating wolf density to caribou mortality rates.

Factors that affect wolf density are thus key to the model. A key modelled relationship is the density of moose relative to wolf density. Both climate change and forest disturbance through timber harvest are key stressors that effect, either positively or negatively, moose density. Again, the model utilizes past research by Bergerud et al. (2007) to model the relationship between moose density and predicted number of wolves, with wolf relative carrying capacity increasing as moose density increases (Figure 9). Their model (wolf = 27.217 × moose + 4.239) estimates wolf density, and based on this we defined a companion equation (relative K = 1.6505 × moose + 0.2571) defining relative carrying capacity used to create a lookup table (Figure 10)

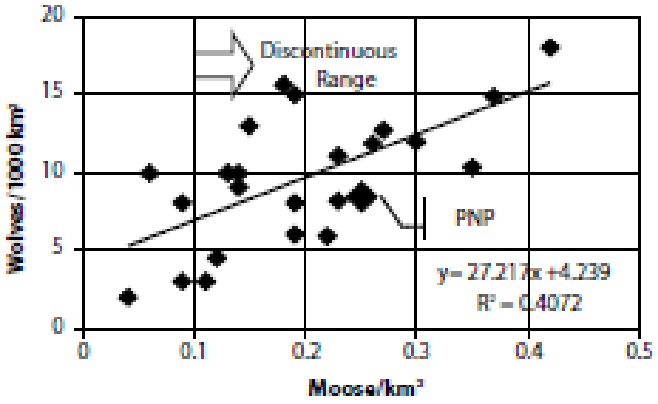

Figure 9. Relationship between moose density and expected wolf density based on studies be Bergerud et al.

+ Insert Before | + Insert After | − Remove Row

Row	Wolf Habitat Index	Moose Density
0	0.12	0
1	0.22	0.0444
2	0.32	0.0889
3	0.42	0.1333
4	0.52	0.1778
5	0.62	0.2222
6	0.72	0.2667
7	0.82	0.3111
8	0.92	0.3556
9	1	0.4

Figure 10. Image of PopDyn lookup table defining relationship between moose density and wolf relative carrying capacity (habitat index).

Finally, researchers (e.g.Messier (1994)) have found that feedback occurs where predation on moose increases both numerically and functionally as wolf density increases (Figure 11). The relationship is somewhat different in low moose-density versus high moose-density habitats, so the lookup curve was adjusted from Messier (1994) to account for most of the variance occurring at relatively low moose and wolf densities. Predation rates on moose are modelled in the lookup table to vary between about 5% and 16% where wolf densities are less than 0.005 wolves/km^2 (Figure 12).

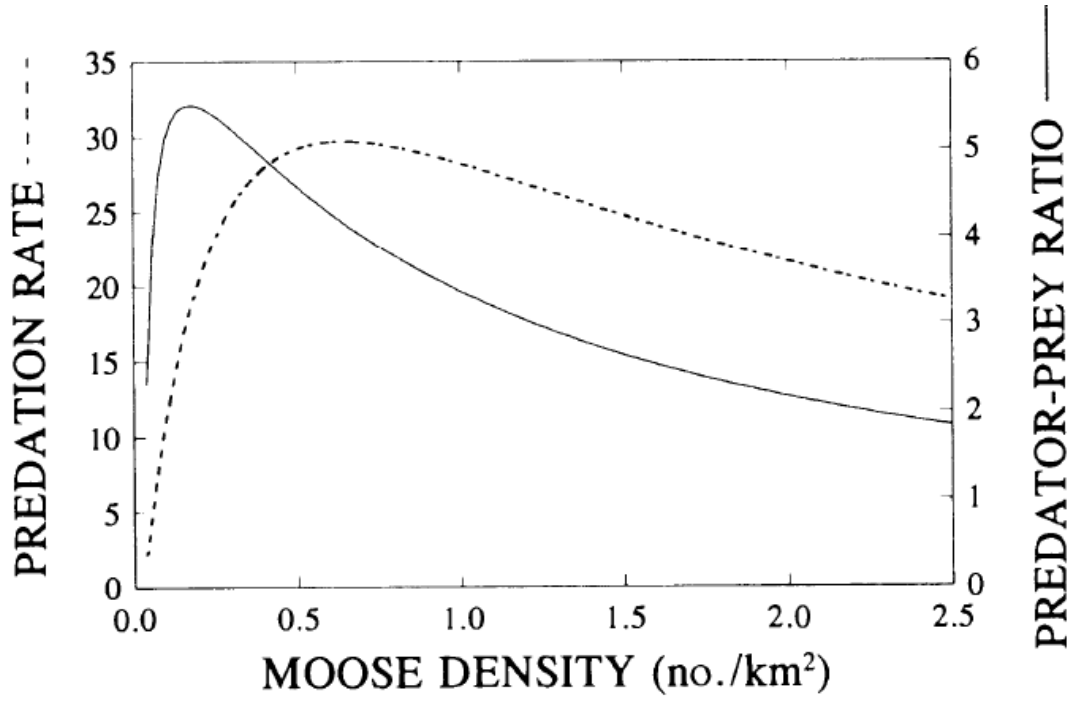

Figure 11. Modelled relationship (from Messier 1994) between moose density and expected predation rate of wolves on moose.

+ Insert Before + Insert After

Row	Wolf Density	Mortality Rate
0	0	0.025
1	0.0026	0.07
2	0.0065	0.2
3	0.0104	0.26
4	0.0143	0.29
5	0.0182	0.3
6	0.026	0.294

Figure 12. Image of PopDyn lookup table relating wolf density to predation rate (mortality) on moose.

Moose Bioclimatic Model

A previously developed moose bioclimatic model was used to predict moose density under changing climate conditions (Rempel 2011).The model was developed by relating climatic and landscape condition to observed moose density across the Province. The large range in current climate conditions from southern to northern Ontario allowed estimation of linear coefficient across a gradient of climatic conditions (Figure 13), which effectively represents a multivariate climate envelope for moose. The model was tested using data not used in model development, and the model performed well, with a slope of observed versus predicted values approaching 1, and a model intercept of 0 (Figure 14). Nonetheless, there was also substantial unaccounted for variance. This model is the basis for predicting a change in moose relative carrying capacity as a function of changing climate and landscape. In northern environments, moose capability is predicted to improve under climate change, whereas it is predicted to decrease in southern environments. Recent observations of moose occurring much further north than where they traditionally occur supports this interpretation.

Model coefficients for biometric regression model predicting moose density as a function of climatic and vegetative landcover variables.

Variable[a]	Model coefficients		Standardized coefficients	*t*	Sig.
	B	Std error	*B*		
Intercept	0.647	0.507		1.28	0.202
YF	0.105	0.032	0.17	3.24	0.001
YF^2	−0.158	0.051	−0.15	−3.09	0.002
MC	0.104	0.034	0.20	3.05	0.002
MC^2	−0.241	0.044	−0.33	−5.51	0.000
AWT	−0.154	0.009	−4.26	−17.60	0.000
AWT^2	−0.006	2.74E−04	−4.38	−20.83	0.000
TCP^2	2.00E−06	1.72E−07	1.52	11.67	0.000
TCP	−0.001	1.37E−04	−1.50	−10.70	0.000
AST	−0.141	0.068	−1.36	−2.07	0.039
AST^2	0.004	0.002	1.31	1.93	0.053

[a] YF is proportion young forest, MC proportion mature conifer, AWT average winter temperature (°C), TCP precipitation during cold period (mm), and AST average summer temperature (°C).

Figure 13. Image of moose bioclimate model coefficients from Rempel (2011).

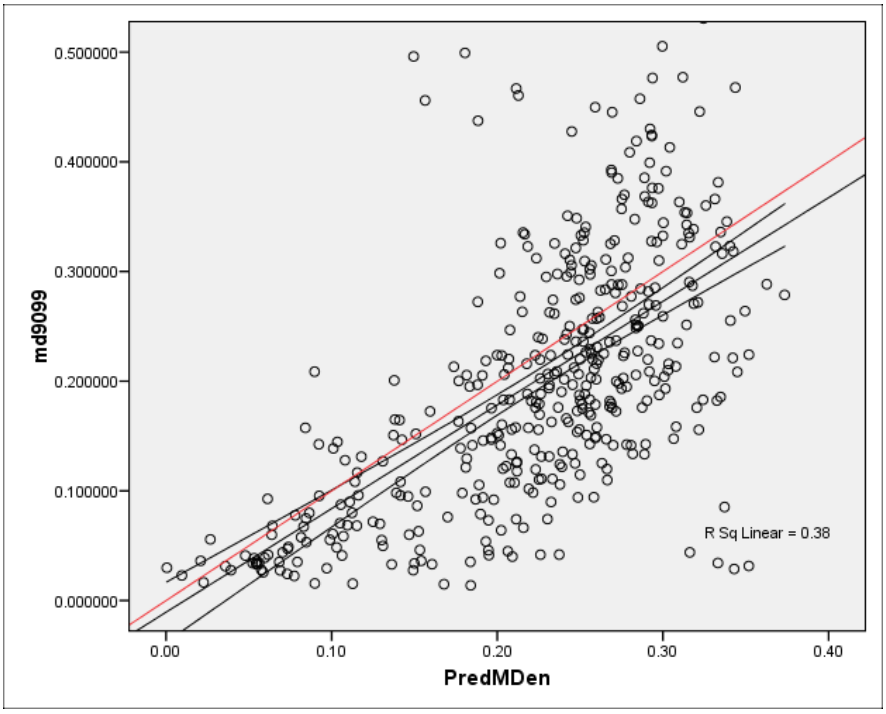

Figure 14. Independent test of the moose bioclimatic model used to predict changes to moose carrying capacity as a function of climate change and forest disturbance (from Rempel (2011)).

Moose-Tick-Climate Relationship

While the bioclimate model is a relatively positive relationship for moose in northern environments, the effect of climate on winter-tick (*Dermacentor albipictus*) and moose is negative, with climate warming resulting in a positive effect on tick survivorship, causing the higher tick loads on moose (Figure 15). This results in coat degradation for moose, and together with winter rains in a relatively warmer winter environment, higher mortality rates (Rempel 2011). This magnitude or effect size of this mortality relationship can be adjusted based on a scaling factor (SF) to accommodate different knowledge or beliefs concerning the negative effects of climate change on moose.

TCP and AWT effects on winter tick[c]		
TCP	TCP/−AWT	D_{wt}
150	6	0.004
200	8.8	0.006
250	12.3	0.008
300	16.7	0.01
350	22.4	0.012
400	30.2	0.014
450	41.3	0.016
500	58.5	0.018
550	88.7	0.02
600	155.8	0.022
650	433.3	0.024

Figure 15. Lookup table from Rempel (2011) specifying effect of total cold-period precipitation (TCP), and average winter temperature (AWT), on Dwt, an index of moose death rate caused by winter tick effects.

Model testing and incorporating latest caribou survey results.

Model testing includes three distinct phases: model verification, calibration, and validation. Model verification involves checking if the model code is performing as expected, and if output using initial default parameters make sense and are within reasonable levels (Figure 16). Verification was accomplished by carefully evaluating various scenario output and checking for inconsistencies or errors.

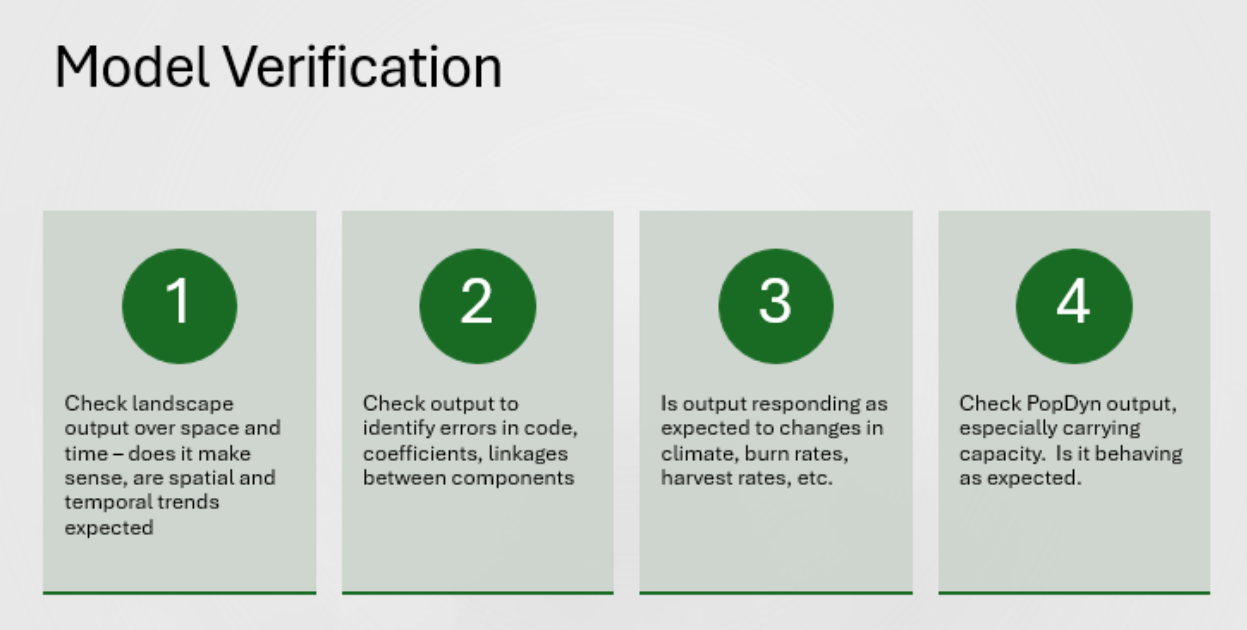

Figure 16. Key considerations in model verification, including 1) landscape output over time, 2) coding errors, 3) response to expected changes, and 4) behaviour of carrying capacity.

Once we were comfortable that the model code is performing correctly, we entered the model calibration stage to carefully explore if model output for a static, present-day landscape is consistent with what is expected based on empirical survey data (Figure 17). For example, is the model replicating observed recruitment and harvest rates, are densities in the range expected, are forests being harvested at known rates, etc.? For a complex simulation model, not every output will exactly match observed data. Calibration is conceptually similar to a least-squares linear regression, where a slope and intercept is estimated to minimize the squared-distance between the observed data and the estimated linear regression (Figure 18). In the case of a complex simulation model, we want to minimize the distance between key observed values on model output, and keep those values within a defined range or tolerance (Figure 18).

Moose harvest mortality and population composition and density provides a key set of calibration targets for the moose model, and these values are available from recent harvest survey data, harvest allocation reports, and population surveys (Figure 19). Harvest rates in the calibration model were adjusted so the model would predict both harvest and composition for a static, present-day landscape, within the tolerance for each statistic. Composition includes adult males: 100 females, and calves per 100 cows.

For caribou, a key calibration statistic is observed cow: calf ratios (calves per 100 cows). Given the multiple factors affecting mortality in the model, it is important that under constant, present-day conditions the model successfully simulates the observed ratio from recent (2023 and 202) caribou survey data, available here. This helped us meet a key project objective to revise the previous 2021 version of the model to incorporate the most recent MNR/MECP survey data.

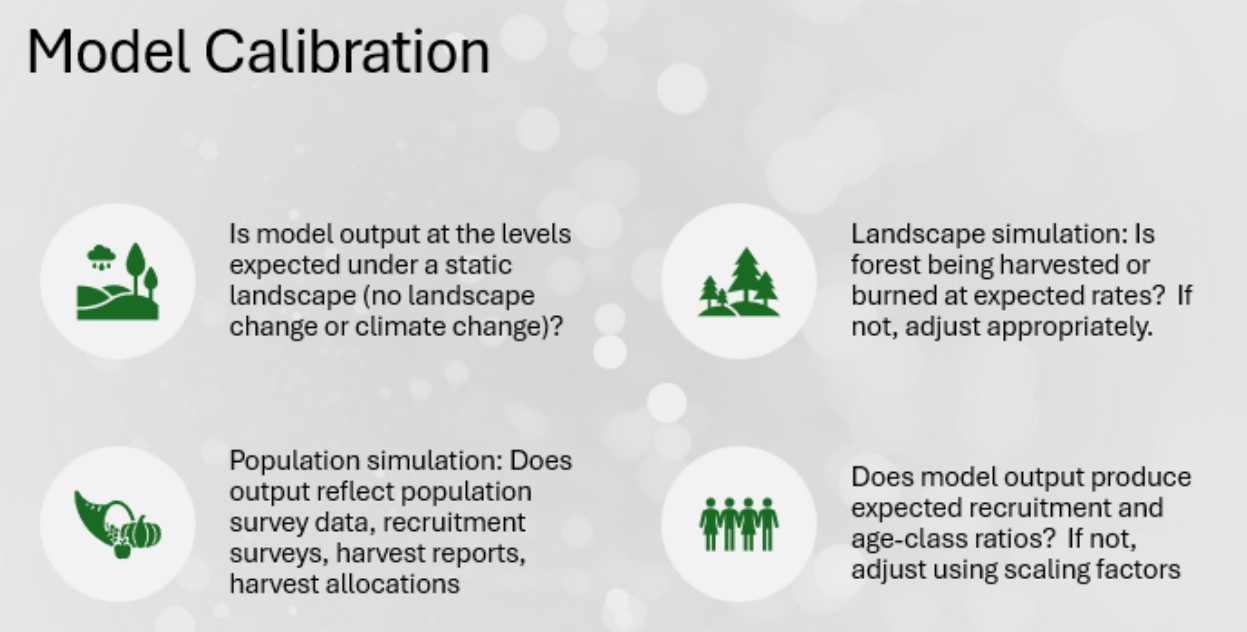

Figure 17. Key considerations in model calibration, including 1) model output under a static landscape, 2) rate of landscape disturbance, 3) does model output reflect population survey data, and 4) does model output produced expected recruitment and age-class ratios.

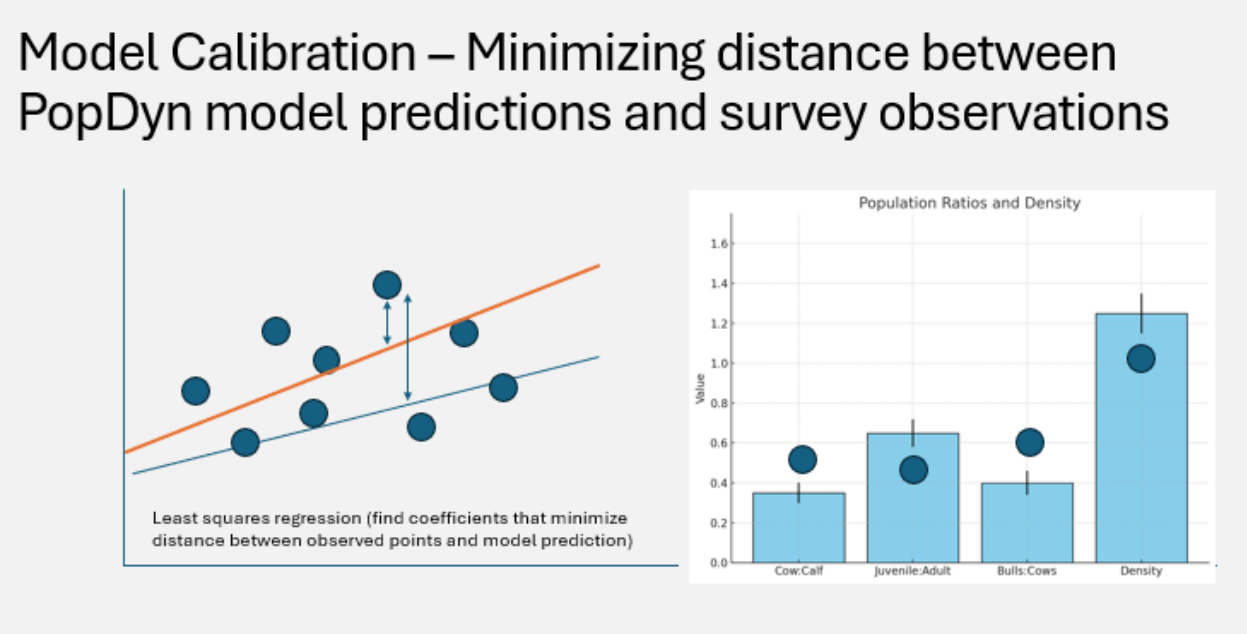

Figure 18. Concept of balancing errors and obtaining best fit to key calibration parameters during model calibration.

Moose Harvest Targets

WMU	Bull	Cow	Calf	% Antlerless	% Antler
2	56%	27%	17%	44%	56%
3	49%	30%	21%	51%	49%
4	54%	32%	14%	46%	54%
01C	83%	13%	4%	17%	83%
16A	75%	18%	7%	25%	75%
16B	72%	20%	7%	28%	72%
Average ->	**65%**	**23%**	**12%**	**39%**	**61%**
SD	**14%**	**7%**	**7%**	**14%**	**14%**

Moose Population Targets

Table. Composition from Aerial Surveys

WMU	Males per 100 females	calves per 100 females
4	61%	35%
16A	87%	48%
16B	77%	40%
1C	86%	42%
Average ->	**77.7%**	**41.0%**
SD	12%	5%

Moose density (2024) for the 7 WMUs - 0.135 moose/km^2

Figure 19. Model calibration targets and range for moose model.

Model Validation

Model validation is conceptually a level higher than calibration. Using statistical model development as a metaphor, consider development of a habitat RSF. The calibration stage is development of the model using model training data, while model validation is testing the model using out-of-sample data that was never seen during model training. In our case, three key model outputs are caribou recruitment, survivorship, and long-term population (λ) trends under the landscape reference model (Figure 20).

Neither survivorship nor λ estimates from recent MNR/MECP surveys or IRAR reports were used in model development, so these are available for model validation purposes.

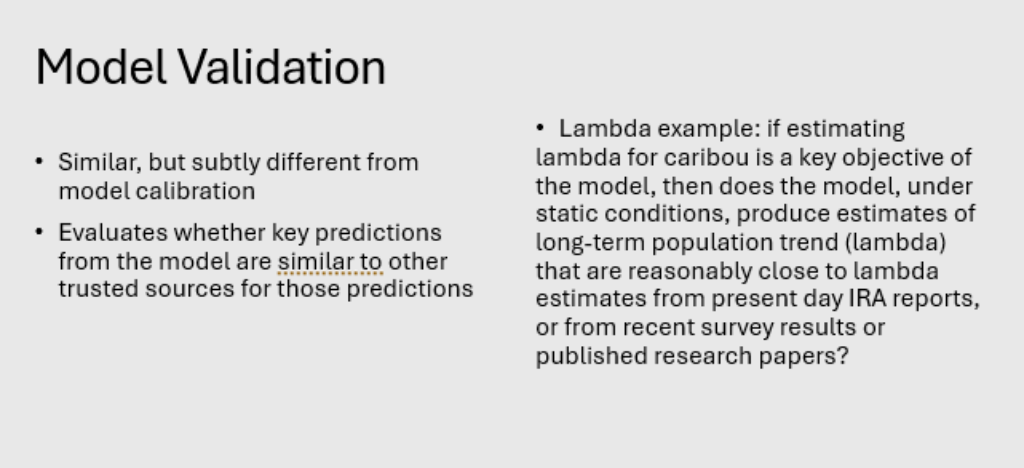

Figure 20. Key concepts in model validation, including matching of lambda estimate to other research.

The average λ value from the most recent MECP caribou surveys for the Berens, Kinloch, and Churchill ranges are given in table 4 of the MECP report (Figure 21, below) under a range of plausible survivorship rates. Under the most likely scenario of harvest occurring at 80% of AAC, and

with climate change under RCP 8.5, λ was estimated as 0.994, and survivorship as 0.865 for the MWC PopDyn model. Recruitment was estimated as 27.6 cows: 100 cows. Based on these values, the MWC model is consistent with the point in time estimates of λ from the MECP survey reports (under assumption that caribou survivorship is moderate (0.85)), and where weighted average of the 3 recruitment estimates (6.7, 18.75. and 32.2 and using n as the weight), is 24.6, and likewise with λ estimates of 0.88, 0.94, and 1.01 for a weighted average of 0.97

An independent estimate of recruitment came from recent survey data and associated analysis submitted to IAAC in support of the Springpole Great Bear Gold project, (WSP 2024). These estimates for 2021 – 2023 estimated recruitment in a study area that included Berens, Kinloch, and Churchill caribou ranges (from table 3 of report) averaged to 21.7, which is similar, but somewhat lower (13.9%) than the MWC model estimate of 27.6, but within acceptable tolerance. Likewise, average λ for this study was 0.964, again somewhat lower than the MWC model estimate of 0.994. These estimates suggest that actual recruitment and λ lies somewhere near the MECP recruitment estimates under the 0.85 survivorship assumption, although future model adjustments might consider increasing wolf mortality rates on young age-class to lower recruitment to better align with recent survey results

Table 8. Population trend estimates (λ) derived using 2023 recruitment estimates and a range of assumed survival rates (low, medium, high) for adult female caribou in the Kinloch Range.

Survival Scenario	S	R	R_{LL}	λ	λ_{LL}	n
Low	0.80	6.7	0	**0.83**	**0.80**	32
Med	0.85	6.7	0	**0.88**	**0.85**	32
High	0.88	6.7	0	**0.91**	**0.88**	32

Table 2. Population growth estimates in the Berens Range

Survival Scenario	S	R	R_{LL}	λ	λ_{LL}	n
Low	0.80	18.75	4.08	**0.88**	**0.82**	59
Med	0.85	18.75	4.08	**0.94**	**0.87**	59
High	0.88	18.75	4.08	**0.97**	**0.90**	59

Table 4. Population trend estimates (λ) derived using 2023 recruitment estimates and a range of assumed survival rates (low, medium, high scenarios) for adult female caribou in the Churchill Range.

Survival Scenario	S	R	R_{LL}	λ	λ_{LL}	n
Low	0.80	32.2	17.5	**0.95**	**0.88**	120
Med	0.85	32.2	17.5	**1.01**	**0.93**	120
High	0.88	32.2	17.5	**1.05**	**0.96**	120

S = assumed survival rate of adult females (Environment Canada, 2008, 2011); R = recruitment rate (calves: 100 adjusted adult females) from the 2023 survey; R_{LL} = lower confidence interval of the recruitment rate from the 2023 survey; λ = estimated population growth rate; λ_{LL} = estimate of population growth calculated using lower confidence interval of the recruitment rate; n = sample size.

Figure 21. Analysis output from MECP 2023 and 2024 survey reports for Kinloch, Berens, and Churchill ranges.

Defining Scenarios:

Given a valid and plausible model of the MWC dynamics, alternative scenarios can be evaluated in terms of potential effectiveness of alternative conservation actions in the context of climate change and natural disturbance. Multiple scenarios were created to explore the scope of options, where

scenarios are defined as a combination of landscape and population dynamic (PopDyn) simulations. For landscape scenarios options include whether or not forest harvest is enabled, and a scaling factor (SF) that specifies the fraction of harvest relative to the plans allowable cut (Figure 22), and the fraction of road building effort relative to the default level. Salvage logging of burned areas can be enabled, with the fraction of burn area salvage logged specified by a SF. Wildfire can be enabled, and a SF specifies the fraction of wildfire relative to the default level, with default level specified by the climate change assumption (no climate change or wildfire under RCP 4.5 or 8.5). To define a scenario with higher fire suppression level than implicitly defined in the HFRZ, a fraction less than 1 could be specified, or in contrast, to define a natural wildfire scenario under no suppression, then a rate higher than the default HFRZ could be specified by using a fraction greater than 1. In the BFOLDS Fire Regime Module the model reproduces the modern, suppression-influenced fire cycle in the intensively protected south by extinguishing small (< 1 ha) fires, resulting in fire return intervals of ~250-400 years, but this can be turned off to represent a natural fire regime without protection, resulting in a natural fire return intervals of ~70-120 years. A recent study by (Malcolm et al. 2025)has challenged how well the fire return intervals BFOLDS mechanistic model represent a natural fire regime, so the Wildfire Settings option can be used to adjust the fire simulation to represent alternative assumptions and observed fire regimes. Such insights can be helpful to develop comparative burn scenarios in ALCES Flow to consider alternative assumptions in the development of conservation options. Finally, an option to disable forest aging can be useful for creating a landscape reference condition.

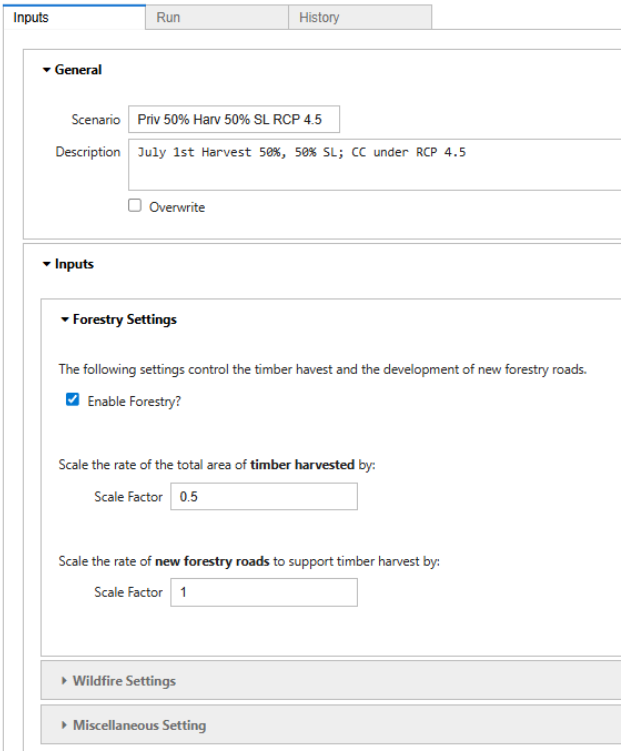

Figure 22. Some of the options available in the user interface for defining a landscape simulation.

Once landscape scenarios have been created, then these can be used as an option for the PopDyn scenarios. In addition to the demographic, vital rate, and harvest parameters used to define the

MWC models, PopDyn options include selecting the landscape scenario to be used for the simulation, and a scale factor specifying level wolf reduction in addition to other mortality factors. Other mortality and fecundity values can also be changed to define a scenario. For example, moose harvest can be increased to represent an attempt to bring down moose population levels, or caribou reproduction could be increased to represent the effect wildlife management options to enhance caribou recruitment levels. More information on PopDyn model specification can be found here.

Scenario Analysis - Results and Discussion:

The Scenario Analysis results reveal how various forest and wildlife management options interact with climate and disturbance regimes to influence caribou persistence across the Red Lake, Trout Lake and Lac Seul FMUs. By operating at a 1 km^2 resolution and reporting harvest area, age-class shifts, land-cover composition and road density, the analysis provides strategic insight into management levers without prescribing exact spatial layouts. Insights from the analysis can support development of alternative harvest scenarios typically developed early in the FMP planning process. Analysis of scenarios can contribute to caribou management from an adaptive management context, where the likelihood of conservation success can be simulated and evaluated before implementation on the ground. Wildlife conservation objectives and relative balance may differ among governments, First Nations, Metis Nations, conservation organizations, and industry, and it is hoped that these types of analyses can lead to informed discussion and assessment of preferred approaches and trade-offs.

To demonstrate the capability of the tool, first, we examined the effect of harvest intensity on mature conifer cover under current wildfire regimes. Harvesting at 100 percent, 80 percent or 50 percent of the annual allowable cut (AAC) all yielded substantially less mature coniferous forest than would be maintained under natural disturbance alone (Figure 23A and B). Note however, that because a SF of 1 was used for the natural disturbance factor, the underlying rate of disturbance implicitly includes fire suppression. Introducing salvage logging, harvesting 50 percent of burned stands instead of healthy stands, did increase the fraction of mature conifer (Figure 23C), but this gain of positive effects for caribou was offset by the additional linear features required for access, raising overall road density and thus representing a negative effect for caribou (Figure 23D).

Next, we examined both the wildlife population and habitat response to these scenarios. At an 80% AAC harvest level, there as an increase in moose and wolf populations (Figure 24A and B), moose carrying (Figure 24C), and a decrease in caribou carrying capacity (Figure 24D), for both current and future wildfire burn rates under the two climate scenarios. The relatively strong response of caribou carrying capacity to climate scenario is likely due to the higher burn rate of conifer causing an increase in disturbed forest. In contrast, when comparing climate scenarios (at 80% vs 50% AAC harvest) that included both a change in wildfire rate and moose carrying capacity based on the bioclimatic model, there was a very strong effect on moose, where stable climate resulted in relatively little increase in moose carrying capacity over time relative to RCP 8.5 climate (Figure 25C), resulting in shallower increase in the moose population (Figure 25A), a much smaller

decrease in the caribou population (Figure 25B), and a lower decrease in caribou carrying capacity (Figure 25D). Harvest level had virtually no effect when comparing stable climate versus climate change.

In turn, caribou respond to natural disturbance and forest management options. Even under the no harvest option, caribou are modelled as declining over time (Figure 26A). This is in part because current caribou recruitment and survivorship rates, as determined through aerial surveys, results in a declining long term population trend, as indicated by λ. There was relatively little difference in projected caribou populations under 80% versus 50% AAC harvest levels. The climate change option has the largest impact on caribou in the model, where under 80% AAC harvest level, a marked decrease in the caribou population occurs under climate change (Figure 26B). Salvage logging had little effect on the caribou population outcome, even though this option resulted in a higher fraction of remaining conifer (Figure 26C). This may in part be a result of higher linear feature densities produced under this scenario, resulting in decreased relative carrying capacity. Finally, the wildlife management scenarios of wolf reduction by 2% and increasing moose harvest by 25% are the only scenarios that resulted in an improvement in long-term persistence of caribou (Figure 26D), where the final population level was about 5% higher than without these options. In terms of caribou response, the model has relatively high sensitivity to wolf density and subsequent predation.

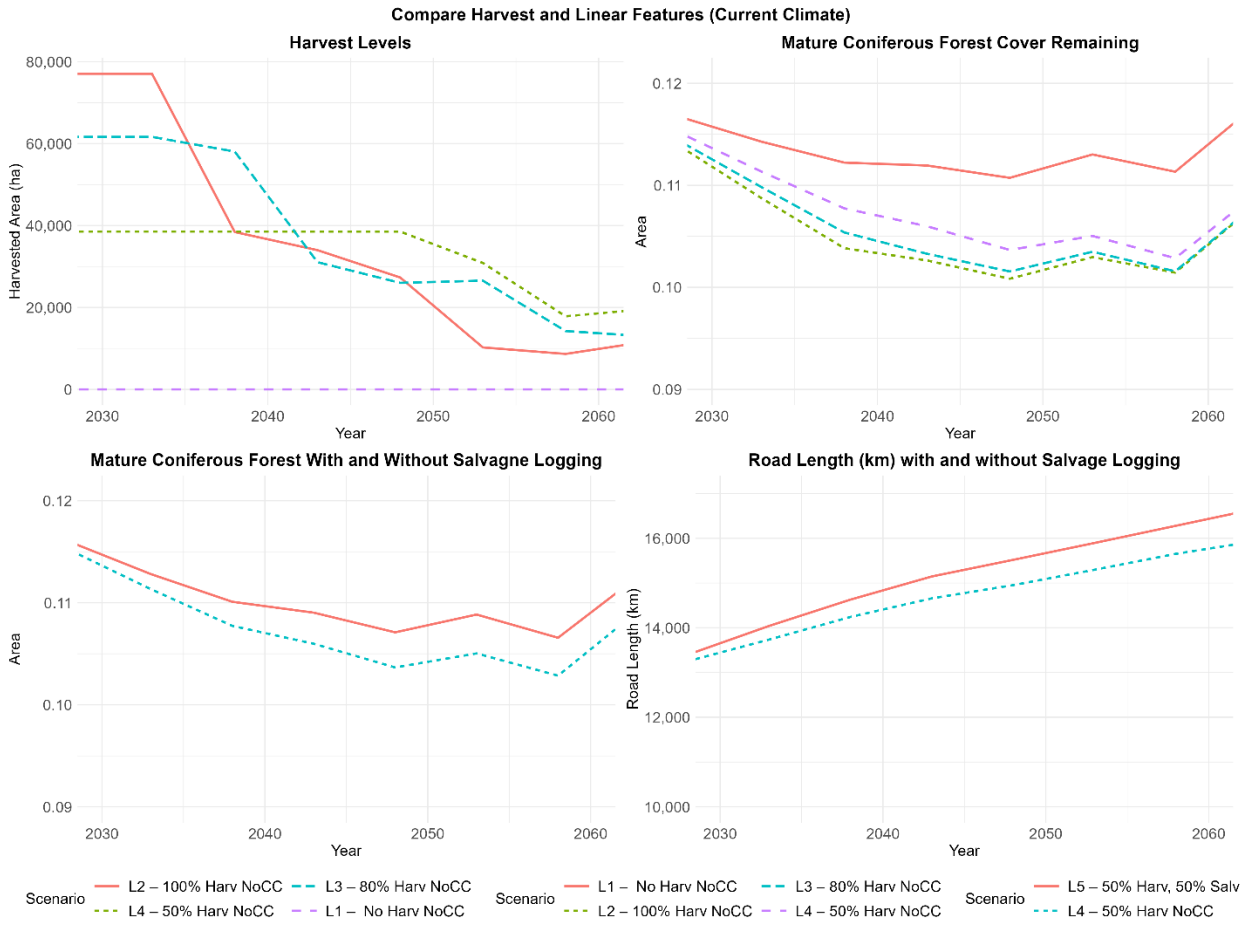

Figure 23. Comparison of (A) forest harvest area, (B) % mature conifer forest remaining (under current climate change) for harvest levels of 100%, 80%, 50% and no harvest (L2, L3, L4, L1)), (C) % mature conifer forest remaining for 50% harvest with 50% salvage logging (L4, L5), and (D) linear feature length for harvest with and without salvage logging (L4, L5).

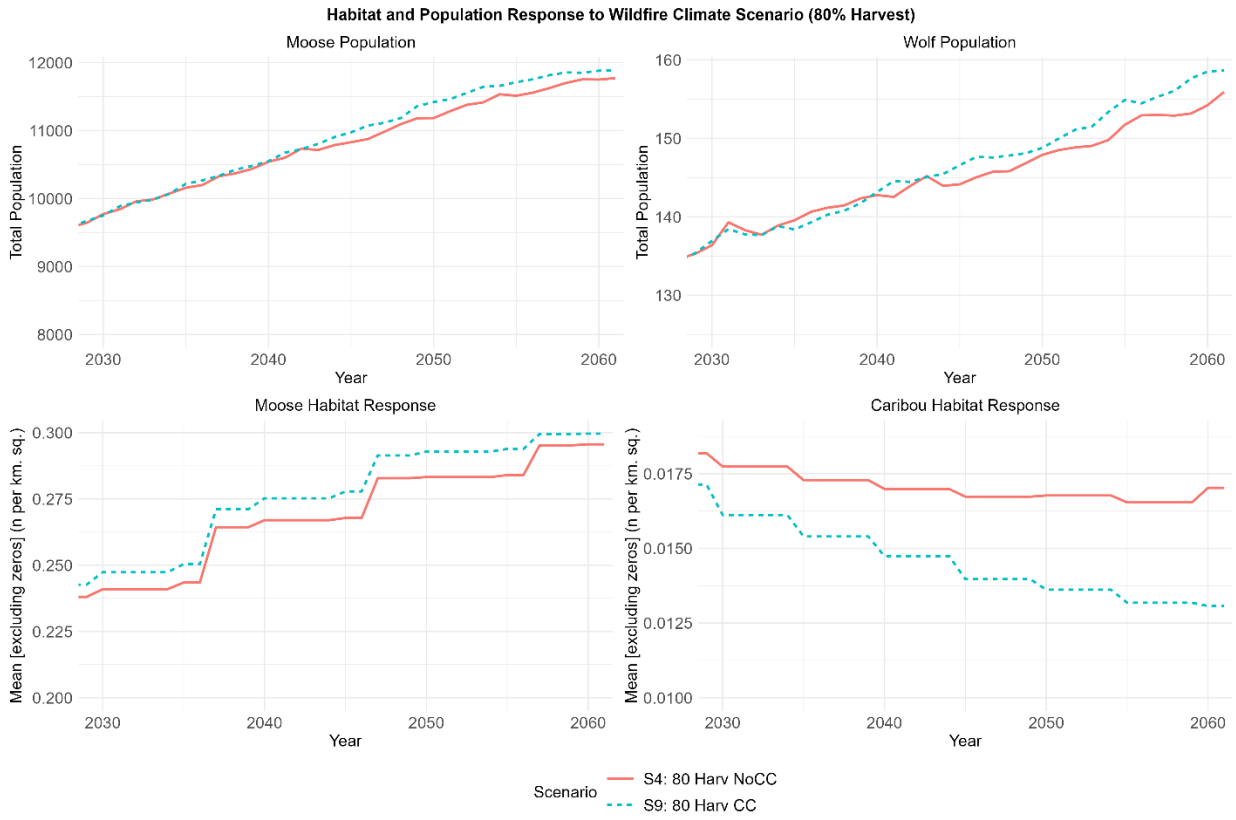

Figure 24. Comparison of habitat and population response to wildfire climate scenarios (80% harvest level) for (A) Moose population, (B) Wolf Population (C) Moose Habitat, and (D) Caribou habitat, for wildfire current climate condition (S4), and future wildfire climate condition (S9). A stable climate condition for moose habitat (S15) is where current climate is used for the moose bioclimatic model.

These results are somewhat pessimistic for caribou, and somewhat in contrast with what the correlative (Environment and Climate Change Canada [ECCC] 2011) model relating recruitment rate to disturbance level might suggest. The simulation model establishes a causal link between level of disturbance, with moose and wolves responding to disturbance and other landscape conditions resulting in changes to predation levels on caribou. The results suggest that within the current range of natural disturbance and forest harvest, additional reduction of harvest from 80% to 50% will have little effect on the caribou population alone, especially in the face of accelerating fire rates. The responses are complex with interacting factors. For example, at current level of disturbance, reducing forest AAC harvest from 80% to 50% may not be completely negative for moose, and consequently might not have a large effect on caribou recruitment rate through increased wolf density and predation rate on caribou calves. A significant uncertainty is the degree to which moose will respond to climate change, as this drive the response of wolves and subsequent effect on caribou recruitment rates. The response of moose and wolves to a shifting climate envelope will drive results of the model, and the response includes more than just rate of wildfire and increased disturbance. From a modelling perspective, this relationship represents a critical uncertainty.

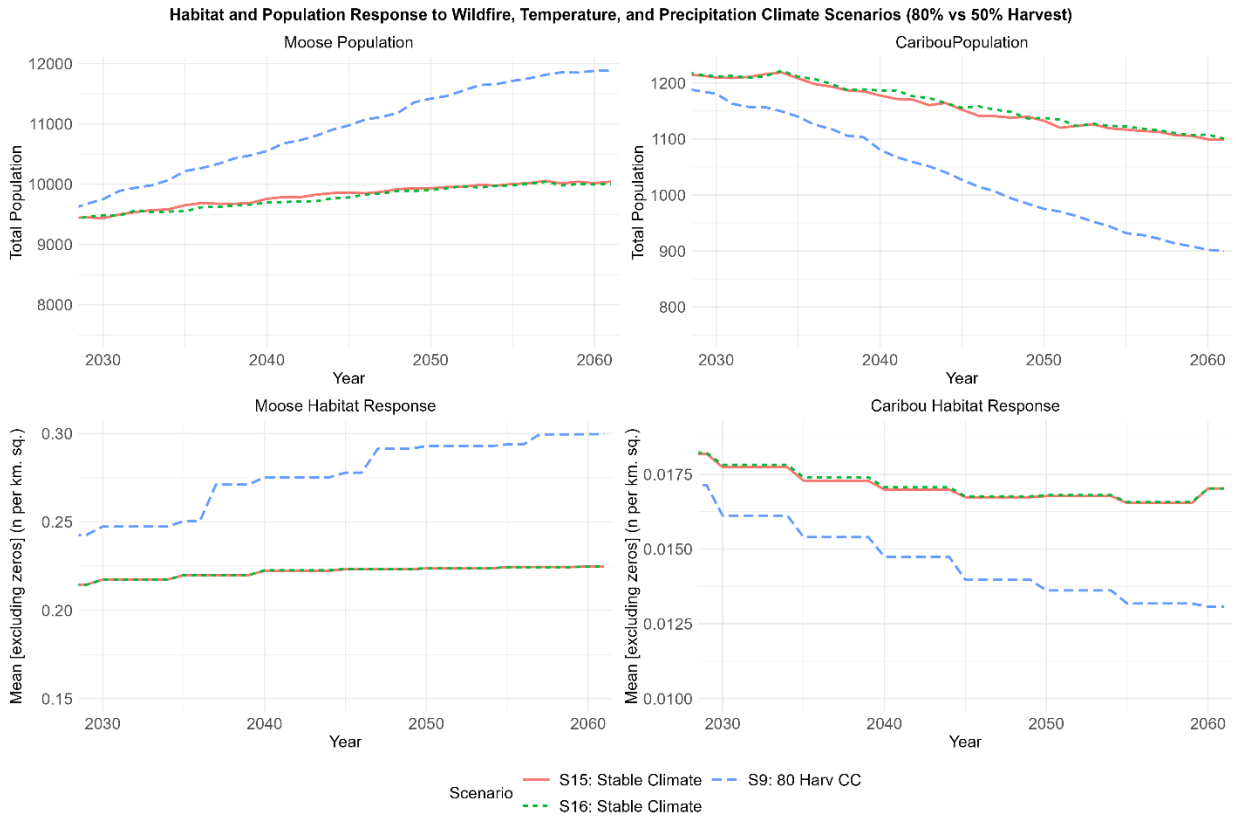

Figure 25. Comparison of moose and caribou population and habitat response to climate scenario options, where climate scenarios affects both wildfire rates and moose habitat. S15 (stable climate, 80% AAC); S16 (stable climate, 50% AAC), S9 (climate changes (RCP 8.5), with 80% AAC).

Leaving more mature conifer on the landscape, such as what would occur from a combination of salvage logging and reduced AAC harvest levels, plus direct wildlife management efforts such as wolf reduction and increased moose harvest levels, appears to have the highest probability of success, given the scenario analysis results. The spatial configuration of harvest could also be important. Developing harvest schedule models that optimize harvest with respect to conservation objectives may be required to better realize the potential benefits of developing forest management plans that consider caribou and other biodiversity objectives. Incorporating more salvage logging opportunities in to FMP harvest plans, however, will likely require more administrative acceptance and a reduction in "red tape" for companies to quickly respond to such harvest opportunities, as time is of the essence if planning to salvage log before insect damage onsets.

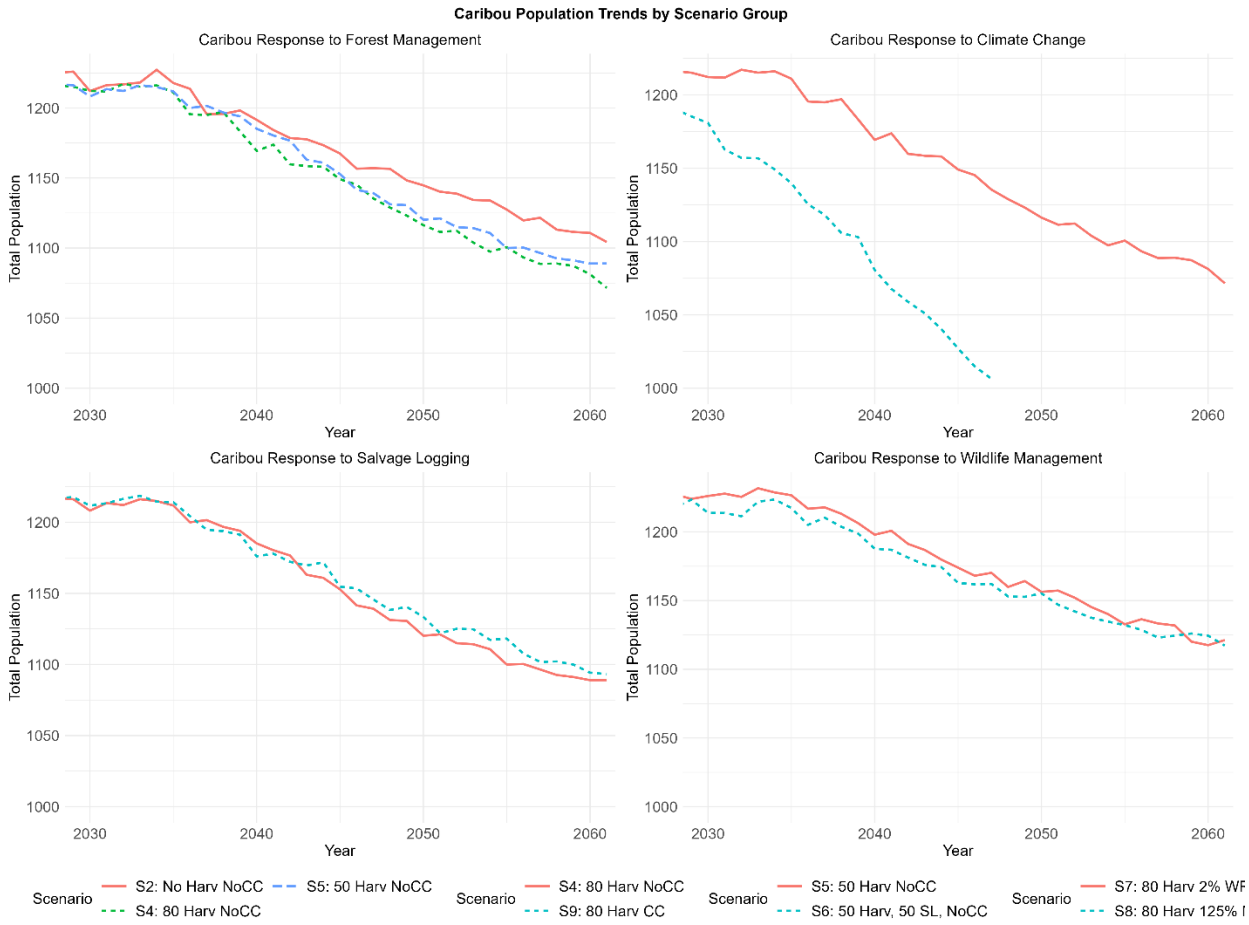

Figure 26. Response of caribou populations forest harvest level, climate change, salvage logging and wildlife management.

From an Indigenous food security perspective, the harvest plans developed to help caribou conservation give no indication of a threat to moose habitat quality, but they appear insufficient to maintain cultural values related to caribou. Any wildlife management plans to improve conditions for caribou, such as increased moose harvest and wolf reduction, should likely involve consultation with First Nation and Metis Nation groups.

Left unaddressed in the study are direct effects of linear features on caribou ecology, such as movement patterns. These are indirectly addressed in the relative habitat quality, RSF based models, which have a strong negative coefficient for linear density. But this does not address movement patterns and barriers, and some other finer scale responses.

Future enhancements to the tool may include ability to import DCHS (or non DCHS) harvest schedules developed through forest estate harvest planning models such as Patchworks or Spatial Stanley. Road building schedules developed through external tools specifically designed to project future road networks could also be imported. This would allow the tool to be somewhat more tactical in nature, and also allow harvest simulations to be better linked to other population dynamic models that required knowledge of more exact placement of harvest blocks and roads.

This report does not provide an exhaustive evaluation of all scenarios possible with the tool, especially those involving climate change options, but rather hightlights results some of the options that the authors considered most interesting. As a group develops conservation, forest, or wildlife management plans, more specific options and and comparsions would likely be required specific to plan scenarios. For example, users could change burn rates to better reflex observed fire regimes. Under annual licensing the MNR and MECP have access to model development, and have the ability to modify the model, define scenarios, and run simulations, while the public viewer allows users to explore and compare the scenarios modelled and presented in this report, including ability to generate specific combinations of scenarios options to output as graphs and raster files for each annual year period for PopDyn simulation results, and 5-year period for Landscape Simulation results. These rasters files can be imported into a GIS so analyses specific to an FMU or other analysis units can be undertaken. Online virtual tutorials will be posted here to assist public users wanting to gain access to the simulation results.

References

Bergerud, A., and J. Elliot. 1986. Dynamics of caribou and wolves in northern British Columbia. Canadian Journal of Zoology 64:1515-1529.

Bergerud, A. T., W. Dalton, H. Butler, L. Camps, and R. Ferguson. 2007. Woodland caribou persistence and extirpation in relic populations on Lake Superior. Rangifer:57-78.

Bernier, P. Y., S. Gauthier, P.-O. Jean, F. Manka, Y. Boulanger, A. Beaudoin, and L. Guindon. 2016. Mapping local effects of forest properties on fire risk across Canada. Forests 7:157.

Boulanger, Y., S. Gauthier, and P. J. Burton. 2014. A refinement of models projecting future Canadian fire regimes using homogeneous fire regime zones. Canadian Journal of Forest Research 44:365-376.

Environment and Climate Change Canada [ECCC]. 2011. Scientific assessment to inform the identification of critical habitat for woodland caribou (*Rangifer tarandus caribou*), boreal population, in Canada: 2011 update. <https://www.registrelep-sararegistry.gc.ca/document/doc2248p/sec2_st_caribou_e.cfm >. Accessed 25 Mar 2021.

Johnson, C. A., G. D. Sutherland, E. Neave, M. Leblond, P. Kirby, C. Superbie, and P. D. McLoughlin. 2020. Science to inform policy: linking population dynamics to habitat for a threatened species in Canada. Journal of Applied Ecology 57:1314-1327.

Malcolm, J. R., J. J. Boan, and J. C. Ray. 2025. Emulation or Degradation? Evaluating Forest Management Outcomes in Boreal Northeastern Ontario. Environmental Management 75:1901-1922.

Messier, F. 1994. Ungulate population models with predation: a case study with the North American moose. Ecology 75:478-488.

Rempel, R. S. 2011. Effects of climate change on moose populations: Exploring the response horizon through biometric and systems models. Ecological Modelling 222:3355 - 3365.

Rempel, R. S., M. Carlson, A. R. Rodgers, J. L. Shuter, C. E. Farrell, D. Cairns, B. Stelfox, L. M. Hunt, R. W. Mackereth, and J. M. Jackson. 2021. Modeling Cumulative Effects of Climate and Development on Moose, Wolf, and Caribou Populations. The Journal of Wildlife Management 85:1355-1376.

WSP. 2024. Report on Caribou Sustainability Metrics for the Springpole Project P4. <https://iaac-aeic.gc.ca/050/evaluations/document/160106 >. Accessed July 2025.