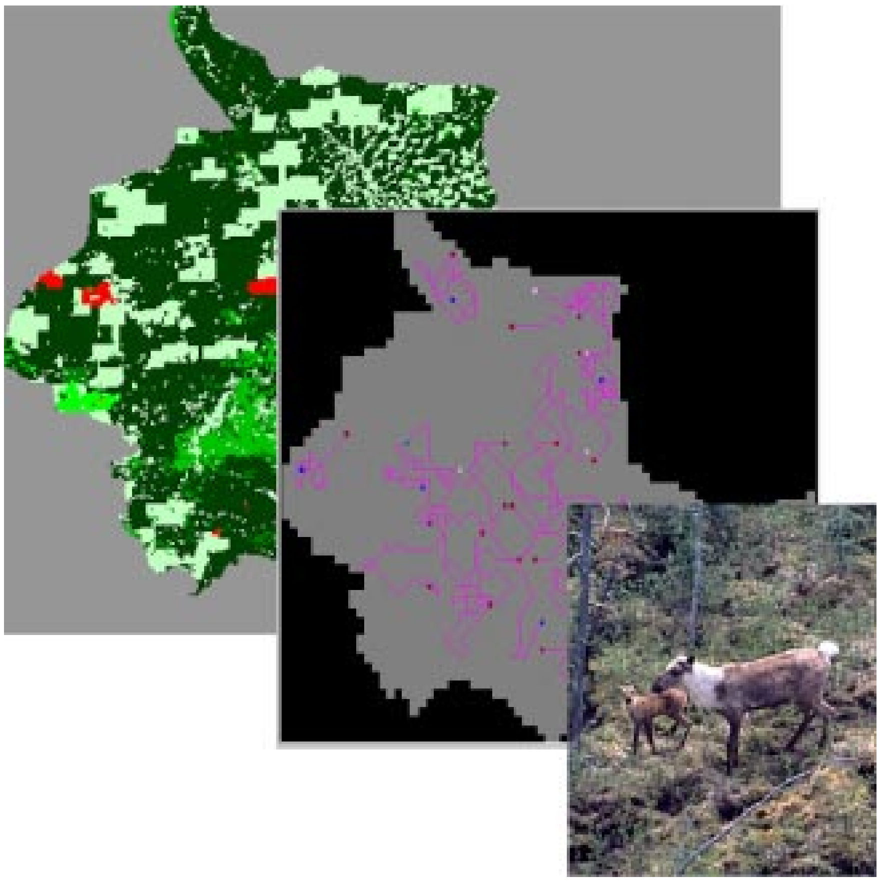
CUMULATIVE EFFECTS AND MOUNTAIN CARIBOU IN WEST-CENTRAL ALBERTA:

AN INDIVIDUAL-BASED AND SPATIALLY EXPLICIT POPULATION MODEL FOR CONSERVATION PLANNING



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28 July, 2000

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INTRODUCTION

Objectives of the model

A computer simulation model was developed to provide an objective and quantitative tool mainly for comparing forest policy options in an attempt to integrate caribou conservation and resource development in west-central Alberta. More specifically, this model was designed to serve the following purposes:

1) Synthesis of existing knowledge;
2) Guidance for efficient collection of relevant field data;
3) Tools for evaluating management scenarios;
4) Biological framework for cumulative effects assessment on caribou herds.

Please note that the strength of models lies in connecting assumptions to predict logical outcomes of interactions, and not so much to mimic reality in detail. Models are fruitful if they stimulate a discussion and learning experience for managers based on the set of assumptions chosen, how components in a system are connected, and the logical outcomes when this system is exposed to a range of management scenarios.

The objective was to have a preliminary model available for planning as early as possible, even if some components currently rely on expert opinion rather than on field data. Subsequent versions of this model will be tested against and updated from most recent research results.

Objectives of this report

This report is providing a detailed description of the first version of a suite of herd-specific caribou management models in west-central Alberta. An evaluation of the model and first conclusions will be presented in a separate research paper.

Background

Concerns about the long-term sustainability of managed, forested ecosystems have resulted in a demand for forest companies to develop Forest Management Plans that incorporate maintenance of non-timber values. Many efforts are now directed at identifying forest practices that conserve biological diversity. Plans to emulate the landscape patterns created by natural disturbance regimes represent a coarse-filter approach to biodiversity management. However, for some species of particular concern, a finer-scale approach to assessing population persistence is necessary.

Woodland caribou *(Rangifer tarandus caribou)* inhabit boreal and montane forests across Canada. For most of their range, woodland caribou are considered to have been in decline for some time, probably due to the combined effects of over-hunting, habitat loss, and habitat fragmentation (e.g. Bergerud 1974, Edmonds and Bloomfield 1984, Mallory and Hillis 1996, Seip 1998, but see also Bradshaw and Hebert 1996).

In 1985, the Alberta Government designated the woodland caribou as threatened in the *Wildlife Act*, making this species of considerable concern to biologists and land managers alike (Edmonds and Bloomfield 1984, Stuart-Smith et al. 1997, Hervieux et al. 1996, Brown and Hobson 1998). In May 2000, the 'Committee on the Status of Endangered Wildlife in Canada' designated woodland caribou in Alberta as threatened (COSEWIC 2000).

To date, there are no Canadian examples of large-scale industrial forestry and caribou co-existing on the same land-base for a prolonged period, and there are concerns about indirect effects of oil and gas exploration (Cumming and Beange 1993). Winter ranges of caribou overlap with areas intended for resource development along the eastern slopes of the Rocky Mountains. As a consequence, special planning zones have been designated for caribou protection (Hervieux et al. 1996, Edmonds 1998). Within these areas, resource development is possible under the condition that the long-term viability of caribou populations is assured (Alberta Energy 1991, WCACSC 1996).

Operationally, many decisions are pressing. How can we integrate resource development and caribou conservation? Previous research on caribou in west-central Alberta identified several different herds, their ranges, and the basics of their ecology (e.g. Edmonds and Bloomfield 1984, Edmonds 1988, Thomas et al. 1996; review in Brown and Hobson 1998). In 1992, the West-central Alberta Caribou Standing Committee was formed with the purpose to develop a regional management strategy for caribou based on the involvement and cooperation of industries, public, and governmental agencies. Because rapid measuring of responses by caribou to development is difficult, the committee identified ecological models, among other research directions, as a priority (WCACSC 1998).

The challenge and opportunity of such a model lies in identifying appropriate scales of resource extraction that will ensure the coexistence of woodland caribou and industrial activity. Ecological systems are subject to natural disturbance and renewal, for example as a consequence of forest fires occurring regularly in west-central Alberta (Andison 1997). Responsible industrial resource development will be successful in integrating long-term caribou conservation if landscape changes are designed at scales that are similar to natural disturbance and if they lie within the natural capacity of caribou populations to absorb environmental change.

GENERAL APPROACH AND MODEL STRUCTURE

Model selection

There are a variety of ecological modelling approaches to management of renewable resources, comparisons of policy options, population viability and risk analysis. These span from differential equations, balance-type simulation models, matrix population models, to individually-based and spatially explicit models (Caughley 1977, Walters 1986, DeAngelis & Gross 1992, Akcakaya 1999). Trade-offs exist between detail and simplicity in these ecological models. We chose an approach that uses individual caribou, allows spatially explicit detail with links to GIS sources, and has a strong focus on key processes that emulate a simple demographic balance-type model.

The modelling platform was based on a decade of work and several software packages created by C. Walters, which was then modified to include specific forestry and animal population modules (Cummings et al. 1998, Demarchi 1998).

Ecological key processes

Declines or conservation concerns are reported from woodland caribou across the continent. The major hypotheses why populations decline are the following (WCACSC 1998):

- *Predation mortality on winter ranges:* Primarily wolves may cause high mortality rates during winter (Bergerud 1974, Cumming et al. 1996, Stuart-Smith et al. 1997, Seip 1998, James 1999). Two mechanisms are proposed:

  (1) *Alternative Prey Hypothesis.* Timber harvesting leads to early successional stages with deciduous shrub, which are major browse items for other ungulates such as moose, elk, and deer. As a result these populations increase, and since they are available year-round, wolf densities will also increase, with the consequence of higher predation on caribou when they visit wintering areas.

  (2) *Spatial Separation Hypothesis:* habitat fragmentation through access roads, seismic lines, or smaller habitat fragments facilitates access of wolves to caribou, thus leading to increased encounter rates and higher predation mortality.

- *Low calf survival:* Recruitment may be critically low because of low calf survival. Main factors are predators (wolves, grizzlies), potentially low pregnancy rates because of poor nutritional condition of females (rarely observed). Occurrence of wolves on calving grounds may be related to increased wolf densities due to landscape changes (see above). Calf survival may also be reduced when females are delayed in reaching optimal calving grounds due to human disturbance during migration (Edmonds and Smith 1991).

- *Limited availability of (or access to) winter food:* Timber harvesting decreases lichen biomass available to caribou if (1) rotation periods are too short, or (2) lichen regeneration is delayed by logging practices (Edmonds and Bloomfield 1984, Cumming et al. 1996, Hervieux et al. 1996). Access to food sources may be inhibited through fragmentation by large cutblocks. Human disturbance may have a similar effect of reducing access to food and disturbing the energy balance of caribou Bradshaw et al. 1997). Sources of direct disturbance may include heavy machinery for exploration, mining, road construction, timber harvesting; hunting; recreational activity such as snowmobiles, frequent air traffic such as helicopters.

- *Climate change:* Loss of calving grounds (or loss of isolation from predators), and increase of deciduous forage on winter ranges with increased predation mortality according to the Alternative Prey Hypothesis (see above). No detailed studies on woodland caribou available to our knowledge.

Note that all of these hypotheses isolate single factors as causes for a possible decline. The following two hypotheses are not based on single factors – any combination of factors could be detrimental. It is rather the density of impacts that has to be kept within acceptable thresholds, and putting effects together in a model are often the only method to anticipate potential conservation problems and evaluate acceptable thresholds for development:

- *Cumulative effects:* Effects of certain management actions may be minor and not even detectable, but can have detrimental effects if changes in a landscape accumulate over time or different types of development occur together.
- *Minimum viable populations ('extinction vortex'):* Small populations are more vulnerable to extinction than larger ones. Any chance event or combination of negative impacts of resource development may lead to further decline or extinction.

Model overview

Ecological systems are immensely complex and need to be simplified in a model. We prioritized the model structure based on available literature, reports, and interviews with local experts.

Our basic approach was to use individual caribou that move over the landscape. These model caribou survive and reproduce according to demographic parameters measured in the study area. Different habitat types and landscape features in the model have a specific suitability (attraction) for caribou and a specific survival probability. Development then alters this suitability and the predation risk to caribou according to specific hypotheses (quantitative relationships), which can be varied by the user. Increased predation risk had been identified as a high concern and was therefore modeled more specifically than other aspects such as carrying capacity. In other words, we are not modelling caribou ecology in detail to recreate all natural patterns but focus on deviations potentially occurring by resource development.

The model uses a GIS-generated raster as a basic landscape layer. This landscape can then be developed, either by simulating industrial activity by using an internal *forest harvest model*, or by importing GIS data that describes such industrial activity over time. Preferences by caribou for different habitat types are determined by a *habitat suitability component.* The *movement component* sets the rules at which caribou move across the landscape. The *population model* is based on the performance of individual caribou and calculates demographic parameters and population trajectories as the main results of the model. Details on these model components are provided in the respective sections below.

Model format

This software runs in a Windows environment and is driven by Visual Basic. An electronic version on CD is available. The instructions for installation and running the program are provided in Appendix 1.

MODEL INPUT

The model currently makes use of a raster based map file that can be generated from GIS data. This allows the user to define the area of concern and the spatial resolution desired. This also allows the model to be used for a wide range of wildlife species and habitat types. The information within this database can be manipulated through a user-friendly interface that allows manual changes. This enables the user to define multiple conservation strategies and to change the attribute values of individual cells. These changes can be used immediately or can be saved to a new map file. This manipulation of data can occur at anytime throughout the forest harvesting simulation allowing for predicted policy changes (e.g., new parks, newly operable forest).

In summary, data input can occur in three basic ways:

- By importing gridded GIS data layers (habitat data, forest harvest data),
- By changing parameters on interactive and user-friendly pop-up windows,
- By changing parameters or quantitative relationships in the program code.

Details on the specific input possibilities are described in the respective sections below.

FOREST HABITAT MODEL

Approach to forest habitat and forest harvesting

The forest habitat and harvesting component of this model is temporal and spatial in nature. The purpose of spatial modelling is to: 1) exhibit site dynamics; 2) allow for a linkage structure (i.e., adjacency); 3) represent patches (i.e., aggregate spatial state data); and 4) store model-specific attributes in an array that can be changed if necessary. This component is the first step in assessing forestry impacts on mountain caribou. The most important aspect of the forest harvesting model is that simulated changes, that occur spatially and temporally on the forested landbase, reflect reality to the accuracy level of the Phase 3 forest inventory data.

Note: *This forest model is a suitable tool to generate a wide range of landscape changes and scenarios, which are necessary to explore the nature of responses by caribou to landscape change. To explore what amount of development will begin to pose problems for caribou persistence, the limits can be pushed to extremes in the model at no environmental cost. This does not mean that such scenarios are actually intended or advisable in reality, and simulations of harvesting are not meant to replace the more detailed planning process of individual companies. The model is fully compatible to process exogenous forest harvest maps that had been created with other software (see p. 10 for details).*

Forest inventory data

The map used in the caribou model has been generated by "gridding" the Phase 3 inventory data for the Redrock, Prairie Creek and Daniel Creek Caribou management zones. The grid size is 200m x 200m (4ha) and the characterization of each stand was calculated as the predominant type within each grid cell. The total map area is 215 720 ha. The following list outlines the data layers used in the model (data layers with an asterisk are internally generated):

a) column number (range: 1 to 357)
b) row number (range: 1 to 295)
c) primary forest species
    - 1 = non-forest
    - 2 = lodgepole pine
    - 3 = white spruce
    - 4 = balsam fir
    - 5 = black spruce
    - 6 = aspen
    - 7 = balsam poplar
    - 8 = larch
    - 9 = non-productive coniferous
    - 10 = non-productive deciduous
    - 11 = bare soil/rock
    - 12 = meadow
    - 13 = water
    - 14 = muskeg
d) road access
    - 0 = no access
    - 1 = near logging road
    - 2 + road persistence time = logging road
e) site index
    - 0 = poor
    - 1 = good
    - 2 = medium
    - 3 = fair
f) elevation (in meters from Digital Elevation Model (DEM))
g) current forest age
h) park/reserve status (used by the model to remove portions of the landscape from harvest permanently or for green-up/adjacency requirements)
i) animal location (not currently used)
j) log hauling route linkage
k) secondary tree species (see “primary forest species” above)
l) third tree species (see “primary forest species” above)
m) fourth tree species (see “primary forest species” above)
n) seismic line development
    - 0 = seismic line not present
    - 1 = seismic line present
o) crown closure class
    - 0 = no crown closure
    - 1 = 6 – 30% crown closure
    - 2 = 31 – 50% crown closure
    - 3 = 51 – 70% crown closure
    - 4 = 71 – 100% crown closure
p) slope (%)
q) aspect (^{o})
r) forest height class
    - 0 = 0 – 6.0m
    - 1 = 6.1 – 12.0m
    - 2 = 12.1 – 18.0m
    - 3 = 18.1 – 24.0m
    - 4 = 24.1 – 30.0m

5 = 30.1+m

s) streams/rivers

0 = no stream/river present

1 = stream/river present

t) yield group (used to specify the potential yield from a particular stand and the particular yield table to be used to estimate wood volume– from Weyerhaeuser Detailed Forest Management Plan)

u) natural subregion (used to predict yield group)

1 = Upper Foothills

2 = Sub Alpine

v) caribou habitat suitability index*

w) maximum snow depth (m) = ((0.1175 * Elevation in meters + 83.641) * 10) / 1000

x) log hauling costs*

y) forest age at the start of a simulation*

z) harvest indicator (distinguishes stands from burned stands)*

aa) regeneration curve followed by yield group (either "Fire Origin" or "Regenerating with Stand Tending" – harvested stands follow Regenerating with Stand Tending curves")

Forest dynamics

In the model, forest harvesting is represented through clearcut logging at the 4-ha. scale. At this scale, each forest stand is treated as homogenous in age and species type. Yield tables (obtained from Weyerhaeuser's Detailed Forest Management Plan) are used to represent the net effects of growth and natural mortality as each stand (cell) ages after cutting or burning. A total of 68 yield curves (34 natural regeneration and 34 regenerating with stand tending) for 17 Yield Groups and 2 Natural Subregions have been utilized[1]. Once harvested, stand age can be reset to zero to account for immediate silvicultural practices or to an age less than zero to account for regeneration delays (succession). Stand height is predicted from the yield tables as well.

The cost and production values (in dollars) that result from harvesting are predicted with a few key parameters. Using results from a road and haul routing and cost calculation routine, each forested cell has costs associated with harvesting it and hauling the logs to the nearest mill. Once a forested cell is chosen for logging, these costs plus cutting costs and net production value (price/m^3 x volume in m^3) are calculated. The cost of harvesting a cell is then the cost/km of building a road to that cell from the nearest road, plus the cost of cutting the timber, plus basic silviculture cost, plus the cost of hauling wood back to the nearest mill location (cost/km x distance). Production value is the net volume of wood obtained during one simulated year of harvest multiplied by the mean price/m^3 of wood. During a simulation, the total area logged and the cost and production totals for all cells harvested within one year, are plotted against the simulation year for visual interpretation of patterns such as "fall-down" and increasing cost as less accessible stands are taken.

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[1] Note: There is a lack of wood volume data at old ages for many stand types. Therefore, Weyerhaeuser's wood volume curves indicate that there is little or no wood volume for stands that are older than 220 – 260 years. If stands are not harvested in a simulation before they reach this falldown then they are not likely to be cut. This, of course, depends on the Annual Allowable Cut and the harvest selection criteria. However, this may result in a false reserve system within the model. If volume data for older stands becomes available then it is suggested that the yield curves used by the model should be updated.

Simulated forest harvesting

Forest harvest schedule generation

The forest harvesting model allows the user to simulate potential harvest schedules. Currently, the user can specify an Annual Allowable Cut (AAC) target and forested stands will be harvested until that AAC is reached. However, as per the requirements in Weyerhaeuser's Caribou Management Strategy, all harvesting will cease if there is more than 20% of the forested landbase that is less than 30 years old.

Cutblock harvest selection can occur in one of the following six ways:

1) oldest stands first
2) sequentially from left to right and top to bottom
3) maximum wood volume first
4) random
5) maximum net value (i.e., maximize production minus cost)
6) township/two-pass system with a specified time period between passes

During preliminary model explorations it appeared that the maximum net value criteria closely mimicked Weyerhaeuser's plans to concentrate harvesting in one contiguous area at a time. It also follows Weyerhaeuser's principle to harvest the remaining passes as quickly as possible in areas that have been previously fragmented by the removal of first pass in a traditional harvest pattern.

Cutblock size can be delineated in one of two ways. First, the user can specify the maximum block size and forest age range. Cutblocks will be delineated in forested stands until they reach the maximum size or until the age range criteria is not met. This results in a layout of similarly sized cutblocks. Second, in an attempt to mimic natural disturbance (i.e., fires and fire size) the user can specify a mean cutblock size and standard deviation around that mean. The cutblock size will follow a lognormal distribution pattern with many cutblocks clustered around the mean with a few very large cutblocks.

The results of the forest harvesting scenario can be saved to an output file with the extension ".fsc". This file can be used to either replay the forest harvest scenario or it can be used by the caribou population model to assess the relative impact that that particular harvesting plan may have on the caribou population.

Input of exogenous forest harvest schedules

Projections of harvest scenarios are complex and different timber companies use their own software to generate harvest scenarios. The model has full flexibility to be applied to harvest schedules that have been generated elsewhere. This allows a user to assess the potential effects that their own scenarios or current forest management plans may have on caribou populations. The harvest schedule must be prepared by the user in a specific way so that it can be read into the model. The following description outlines this process:

> The coordinates of each harvested block must be analogous to the coordinates used in the model. That is, each stand harvested must have a row value that ranges from 1 to 295 and a column number that ranges from 1 to 357.

The text file that the user creates must have an ".sch" file extension and the following structure:

```
caribou.map                    'line 1
12234     35                   'line 2
253       172                  'line 3
138       242                  'line 4
304       57                   'line 5
.              .               'line 6
.              .               'line 7
.              .               'line 8
235                            'line 9
467                            'line 10
295                            'line 11
176                            'line 12
577                            'line 13
.                              'line 14
.                              'line 15
.                              'line 16
```

Line 1 states the map file to be loaded for the simulation. On line 2, the first number indicates the entire number of stands to be harvested during the simulation and the second number indicates the length of the simulation in years. Lines 3 through 8 list the row and column numbers of the stands to be harvested (these must be in the order they are to be harvested during the simulation and must be equal to the number of stands harvested as indicated on line 2). Lines 9 through 16 indicate the number of stands to be harvested during each year of the simulation (the number of lines required here must equal the simulation length as indicated on line 2).

HABITAT SUITABILITY

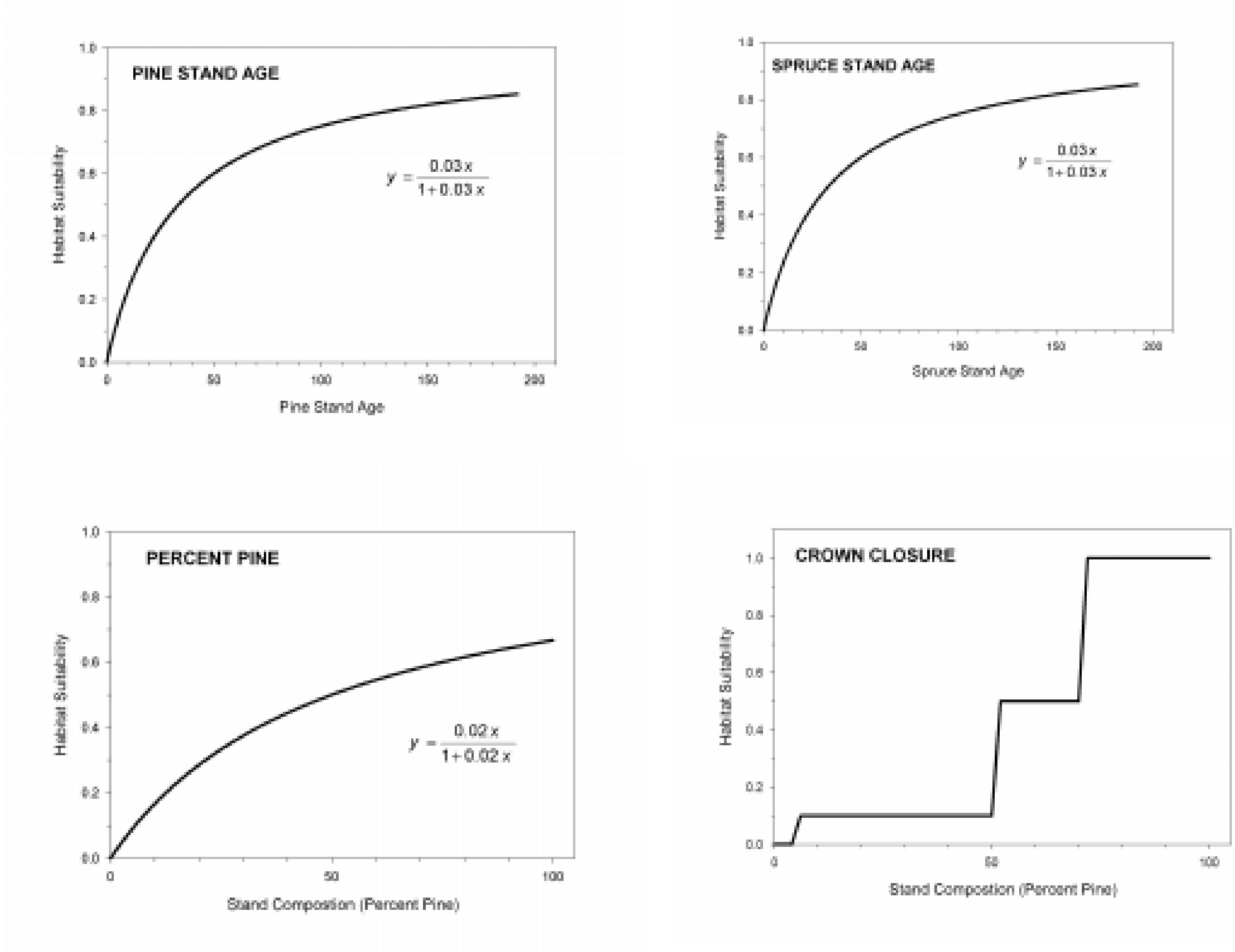
Approach to modelling Habitat Suitability

An intuitive habitat suitability model has been developed for caribou winter range based on interviews with local experts. The habitat suitability is calculated on a per stand basis and consists of several stand metrics. It is important to note that this suitability model must be revised based on current radio telemetry and Global Positioning Systems (GPS) locations. Also, snow accumulation effects on habitat selection and suitability should also be quantified. The suitability values range from a minimum of 0 (i.e., no suitability) to 4 (i.e., maximum suitability). Four is the maximum because each of the four metrics range from 0 to 1 and the suitability is a sum of these four metrics. The calculations of the metrics are described in the following sections.

Factors affecting suitability of forest stands

Lodgepole pine stand age

The lodgepole pine stand age metric is calculated for forested stands that have pine as the primary (34 – 100%) or secondary species (21-50%) only. The value of the lodgepole pine stand age metric varies between 0 and 1. The relationship between age and suitabil-



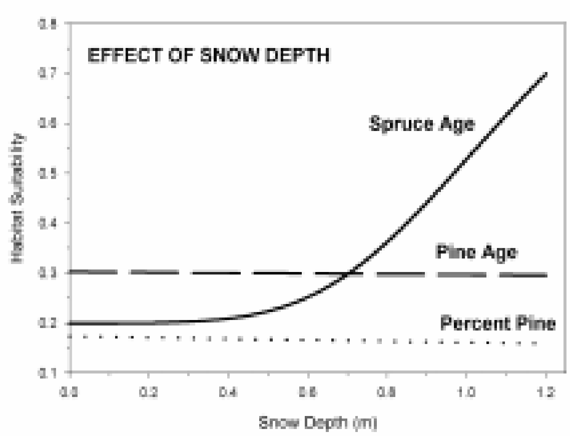


Figure 2: Graphical representation of quantitative relationships defining habitat suitability for woodland caribou in west-central Alberta (see text for explanation). For demonstrating the effect of snowdepth on current suitabilities, an arbitrary level of 0.7 was chosen for all suitabilities prior to this calculation.

ity is described by a modified disc equation. As the age of the stand increases so does the suitability. This, in effect, captures the potential amount of lichen forage that may be present in the stand. The disc equation is as follows:

$$\text{Pine Age Suitability} = \frac{0.03 \text{ x Stand Age}}{1 + 0.03 \text{ x Stand Age}}$$

Percent lodgepole pine

The percent of lodgepole within a stand is calculated based on the mean species percent from Phase 3 inventory data. Percent pine calculations are based on the following table:

	Species Percent		
Species Designation	1^o	2^o	3^o
1^o	100%		
1^o 2^o	65%	35%	
1^o 2^o 3^o	46%	30%	27%

The suitability of pine stands increases with the increasing percentage of pine. The value of the percent pine suitability ranges from 0.2 to 1. This relationship is described by the following disc equation:

$$\text{Percent Pine Suitability} = \frac{0.2 + 0.2 \text{ x Percent Pine}}{1 + 0.2 \text{ x Percent Pine}}$$

White spruce stand age

White spruce stand age suitability is calculated the same as lodgepole pine stand age but only for stands that are primarily or secondarily white spruce. The following equation describes the relationship:

$$\text{Spruce Age Suitability} = \frac{0.03 \text{ x Stand Age}}{1 + 0.03 \text{ x Stand Age}}$$

Crown closure class

The suitability of the five possible crown closure classes have been fixed at the following levels:

CCC0 (no crown closure) = 0.0
CCC1 (6 – 30% crown closure) = 0.1
CCC2 (31 – 50% crown closure) = 0.1
CCC3 (51 – 70% crown closure) = 0.5
CCC4 (71 – 100% crown closure) = 1.0

Effect of snow depth and severe winters on habitat suitability

Increasing snow depth decreases the suitability of lodgepole pine stands and increases the suitability of white spruce stands. As snow accumulates over the winter pine stands become less suitable because it becomes increasingly more difficult for caribou to crater down to terrestrial lichens. The suitability of white spruce stands increases as snow accumulates because the relatively high (compared to lodgepole pine stands) snow interception provides some relief to the caribou from having to crater for forage and arboreal lichens may be more available in these stands. As snow accumulates throughout the winter, the suitability of pine stands is decreased and the suitability of spruce stands increase. During harsh winters (i.e., which occur at a user-defined frequency) the effect of snow is increased by a factor of 2. However, at no time does the suitability of any stand metric become less than zero or greater than 1. The effect of snow is based on the maximum snowfall levels (in meters) in a particular stand. At the beginning of the winter cycle snow depth is 0. Snow levels are calculated as a proportion of this maximum using a logistic curve with a minimum of 0 and a maximum of 1. Maximum snowfall rates occur in the middle of the winter. The following equations describe the calculation of the snow depth effect coefficients:

$$\text{Pine Snow Depth Effect} = (-0.05 \text{ x Current Snow Depth}^2) + (0.0175 \text{ x Current Snow Depth}) + 1$$

$$\text{Spruce Snow Depth Effect} = (3 \text{ x Current Snow Depth}^5) + (2 \text{ x Current Snow Depth}^4)$$

The local habitat suitability (i.e., the current location of the herd) is updated according to current snow depth by summing the following equations and dividing by 4:

$$\text{Current Percent Pine Suitability} = \frac{0.2 + 0.2 \text{ x Pine Snow Depth Effect x Percent Pine Suitability}}{1 + 0.2 \text{ x Pine Snow Depth Effect x Percent Pine Suitability}}$$

$$\text{Current Pine Age Suitability} = \frac{0.03 + 0.2 \text{ x Pine Snow Depth Effect x Pine Age Suitability}}{1 + 0.03 \text{ x Pine Snow Depth Effect x Pine Age Suitability}}$$

$$\text{Current Spruce Age Suitability} = \frac{0.2 + 0.2 \text{ x Spruce Snow Depth Effect x Spruce Age Suitability}}{1 + 0.2 \text{ x Spruce Snow Depth Effect x Spruce Age Suitability}}$$

$$\text{Current Crown Closure Suitability} = \text{Crown Closure Suitability}$$

CARIBOU MOVEMENT

Approach to modelling caribou movement

Our basic approach was to divide a 'caribou year' into two distinctively different seasons. The summer season was strongly simplified and not made spatially explicit, because resource development is planned for winter ranges and there is little potential to alter conditions during summer in the alpine parks through management actions. In winter, caribou move over the winter ranges at weekly time steps.

Movement rules

Migration onto winter range

At the beginning of each winter season herds are randomly placed onto the winter range. The size of the herds depends on a user-specified mean number of cows per herd and a user-specified standard deviation. Herds are then moved around on the winter range as a unit. During each weekly movement there is a chance that individual animals within the herd will die. The mortality rates are age dependent (i.e., cow, yearling, calf) and are also influenced by the calculated predation risk and habitat suitability.

The movement rules used in the model will be tested against and updated from results of weekly radio telemetry and GPS locations of caribou in the field.

Random winter movement on winter range

If the random movement option is chosen by the user then the herd is moved from its current location to a random location. The random location is chosen by first selecting a direction of movement. Then, second, the distance moved is selected from a Poisson distribution of a user-specified mean. This dispersal pattern mimics the weekly movement distances recently exhibited by radio-collared caribou in the study area. That is, most of the weekly movement distances cluster around the mean but occasionally there is a large movement step.

Movement on winter range to best adjacent habitat

The user can choose the option to have the herds move to the best habitat adjacent to their current location. This assumes that the caribou have previous knowledge of the area and will locate the best available habitat. The user specifies a radius (in km) that the herds will search. As a consequence of this option the caribou can get "stuck" in a loop between two very good habitats. In order to more closely mimic the actual movement patterns exhibited by collared caribou the user can set a winter habitat carrying capacity. That is, the user can specify the number of "caribou weeks" a habitat can support within a winter after which the caribou reduce the available forage and are forced to move to other habitats.

CARIBOU POPULATION DYNAMICS

Approach to the population model

Industrial development will alter the properties of the tiles or pixels of this landscape for caribou. In particular, these alterations can affect where caribou will move and what predation risk they experience. For each time step, the survival of each caribou is calculated based on the features over which the caribou moved. Similar to a 'mine sweeper' game, each landscape pixel can have altered survival probabilities depending on the development that had occurred, and the winter survival of caribou will be altered depending on the encounter frequency or length of time spent near industrial development.

Productivity

At the end of each winter the surviving yearlings are added to the cow population. Female calves are produced by the cows and last fall's yearlings (Rettie and Messier 1997) at a user-specified rate (e.g. half of the pregnancy or natality rate measured in the field, which includes both male and female calves).

Seasonal survival

Summer Survival

Initial cow, calf and yearling numbers are specified by the user at the beginning of a simulation. These segments of the population are survived over the summer based on user-specified summer survival rates. The following spring, the number of cows, calves and yearlings surviving the winter are tallied, calves are produced by the surviving cows (see section 3.2), and then they are survived over the summer to the following winter. This process repeats for a user-specified time period (i.e., typically 100 years).

Winter Survival

Winter survival is more complicated than the summer survival process. The winter survival rates are transformed into a weekly survival rate using the following equation:

$$\text{Weekly Survival} = e^{\ln(\text{winter survival rate})/(\text{winter length in weeks})}$$

As the herds are moved around the winter range on a weekly basis (see section 3.4), each animal in the herd is survived to the next movement step based on the weekly survival rate. This survival rate is directly related to the habitat suitability and the predation risk of the local habitat. The maximum weekly survival is updated to reflect the road predation risk, clearcut predation risk and habitat suitability of the local habitat. This is accomplished by the following equation:

$$\text{Updated Weekly Survival} = \text{Weekly Survival} \times \text{Road Predation Risk} \times \text{Clearcut Predation Risk} \times \text{Habitat Risk}$$

The results of this transformation generally translate into a decrease in yearly survival of 2-3% in the habitats with the highest predation risks and the lowest suitabilities.

Effects of industrial development on caribou survival

Predation risk due to roads

Predation risk is directly related to the distance to the nearest roads of the local habitat. That is, the probability of survival on a weekly time-step basis is reduced, linearly, the closer the roads are to the caribou group's current position (Fig. 3, next page). The maximum reduction in survival is specified by the user along with a maximum distance (in km) from a road that this predation risk acts (i.e., any values greater than 1 are truncated to survival=1). The Typically a very small decrease in survival per weekly time-step (i.e., maximum decrease of survival = 0.9985 per week at d=0 km from a road). This small reduction in weekly survival translates into a maximum decrease of 5% per year (winter of 34 weeks) in habitats right next to roads.

$$\text{Road Predation Risk} = \frac{(1 - \text{Road Predation Risk Factor})}{\text{Maximum Road Distance Effect}} \times \text{Distance to nearest road} + \text{Road Predation Risk Factor}$$

Predation risk due to cutblocks

Timber harvesting can create suitable habitat for moose and elk by generating young forests with abundant browse. The user can specify the time period during which cutblocks are suitable habitat for other species. The user can also specify the maximum distance from a cutblock that this effect is felt (i.e., there is no effect beyond this distance). This attempts to mimic the incidental predation risk on caribou by wolves. Similar to the effect of roads, the risk associated with cutblocks increases as the distance from the caribou group to the nearest cutblock decreases. The same equation is used for this function and values range from the cutblock predation risk factor to 1 (i.e., any values greater than 1 are truncated to 1).

$$\text{Clearcut Predation Risk} = \frac{(1 - \text{Clearcut Predation Risk Factor})}{\text{Maximum Clearcut Distance Effect}} \times \text{Distance to nearest clearcut} + \text{Clearcut Predation Risk Factor}$$

Habitat suitability and survival

The habitat suitability is used as an indicator of the survival rates experienced by caribou. This assumes that survival in poor habitat is reduced due to less forage, less nutritional forage, inadequate thermal cover and high snow levels. The values for habitat suitability range from 0 (poor habitat) to 1 (excellent habitat). The weekly risk associated with being in a particular habitat varies linearly from a user specified maximum risk or y-intercept (e.g., 0.99995) in the poorest habitat to 1 in habitat with a suitability of 1. The equation for calculating this factor is as follows:

$$\text{Habitat Suitablity Risk} = (1 - \text{Maximum Habitat Risk}) \times \text{Habitat Suitability} + \text{Maximum Habitat Risk}$$

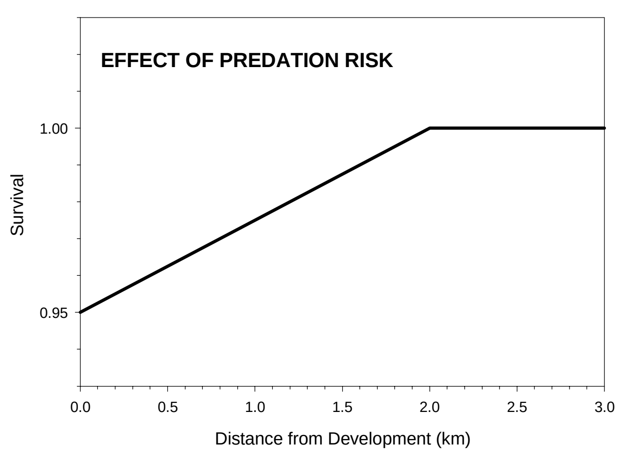


Figure 3: Predation risk in relation to road distance, expressed as a reduction in survival probability. Maximum reduction of survival and effective distance from road can be set by user.

Habitat suitability/capability weekly update

Habitat suitability is updated yearly but the accumulation of snow decreases the suitability of lodgepole pine stands later in winter and increases the suitability of white spruce stands. The suitability is updated based on the time of winter and the snowfall accumulation specific to each time (see 'Habitat Suitability'). Over the winter the importance of white spruce stands increases due to its snow interception properties. Although the forage in these stands may not be optimal, the caribou require thermal cover and small amounts of forage because late in the winter the animals are likely in a negative energy budget situation.

MODEL OUTPUT

Graphic output

Maps of caribou movements and habitat suitability are displayed for each winter (or can be turned of for faster simulations). Some vital demographic statistics such as population size, calves produced, and number of yearlings are plotted over years. The changes in forest dynamics can be followed visually for selected base maps (see Appendix 1 for details). Simulation runs can be paused and the current maps can be saved in their gridded format to an ASCII file (see Appendix 1). Examples of graphics are provided in Appendix 2.

Data output

At the beginning of each simulation a file called “caribou.dat” is created in the default directory. The file records all of the parameter information plus it records the current simulation number, the current year, the cow population size, the yearling population size and the calf population size. This allows the user to graphically, and statistically, compare the outcomes of various policy alternatives. It is very important to rename the file after each simulation because failure to do so will result in the data being overwritten by the next simulation. The following is an example of the file’s output:

```
Forest harvest scenario/schedule =C:\Caribou\NoHarvTest.fsc
Cow summer survival = 0.95
Cow winter survival = 0.9
Calf summer survival = 0.45
Calf winter survival = 0.8
Yearling summer survival = 0.9
Yearling winter survival = 0.85

Productivity: female calves per cow = 0.45
Mean number of cows in herd =  6
Standard deviation of mean number of cows in herd = 1.32

Initial number of cows = 100
Initial number of calves = 27
Initial number of yearlings= 15

Local habitat size in hectares = 100

Wolf/Road predation risk = 0.99995
Maximum road effect distance = 2
Road persistence time = 50

Incidental predation risk = 0.99995
```

```
Maximum clearcut effect distance = 2
Minimum age for good clearcut habitat for alternative prey = 15
Maximum age for good clearcut habitat for alternative prey = 35

Decrease in survival in poor habitat = 0.9995

Winter length in weeks = 34
Severe winter frequency = 0.1
Random movement on winter range =True
Maximum movement distance per week in kilometers = 1

Move to best available habitat on winter range =False
Number of animals a local habitat can support in one winter = 15
Distance (in km) a herd will search for best available habitat = 5

simulation    year          cows          calves        yearlings
 1             1             110           22            26
 1             2             115           28            18
 .             .              .            .             .
 .             .              .            .             .
 .             .              .            .             .
 100           99            132           17            31
 100           100           133           24            12
```


ACKNOWLEDGEMENTS

We thank Fiona Schmiegelow for suggesting this software as a platform for modelling and for initiating contacts between people involved. Steve Cummings and Carl Walters followed our progress with great interest and provided advice.

This model was based on the fieldwork and experience of local caribou experts, and our work would not have been possible without the dedication and advice from Dave Hervieux, Kirby Smith, Jan Ficht-Edmonds, Kent Brown, Dave Hobson, and Bob Wynes. We also thank Luigi Morgantini, Randy Poole, Rick Bonar, Al Kennedy, Lorne Greenhorn, and Dan Gilmore for their information, ideas, and feedback on management practices and potential scenarios and conflict solutions.

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APPENDIX 1: Brief Instructions for Running the Model

Setting up and installing

Run the Setup.exe file.

Starting up the program

Run the Caribou.exe file and press start when prompted.

Viewing Maps

There are two modes of the program: the *Forest Model* and the *Population Model*. Running the Caribou.exe file will bring you into the Forest Model by default. A series of maps are displayed in the upper panel. With the 'Graphics' pull-down menue the number and type of maps on display can be chosen. The menu 'Maps' allows a full-screen view of each map selected, and the colour legend as well as the map cells can be manually changed. Note that the pull-down menu above the colour-legend contains all base maps to be selected for display. All of these maps can be saved at any stage of the simulation in their grid format as ASCII files. Similarly to the base maps, the graphs of specific output variables over time (e.g. hectares logged) can be selected and displayed in the lower panel.

Running the Forest Model

Choose the type of simulation you wish to run from the box at the bottom of the screen. It is possible to run a new simulation, replay saved scenarios, or run externally generated harvest schedules (format described in text). The menu 'Forest' allows the setting of parameters for timber harvesting, forest dynamics, and visual habitat suitability. Habitat maps can be turned off for faster processing, and plotting of values as graphs can be overlaid for direct comparison of successive simulations.

Running the Population Model

From the Forest Model, choose the selection 'Population Model' at the bottom. Note that for faster simulations without map displays, you need to turn off 'Habitat Maps' in the Forest Model before switching to the Population Model. Choose 'Ungulate Model' when prompted. Parameters can be changed in the 'Population' menu. The number of years can be specified on the main screen (note that each simulation will consist of 100 runs of x years). A popup screen will appear by default and inform about current results of the population model. This screen can be turned on or off at will during as simulations are running by pressing ctrl+S or clicking 'Show Population Statistics' in the 'Population' menu (all other settings should not be changed during simulations). Output file is always 'caribou.dat' (see text for detailed format). Save this output file under a different name as it will be overwritten with each new simulation that you start.

APPENDIX 2: Sample Screens for Running The Model

Screen 1: Forest Model (simulation running)

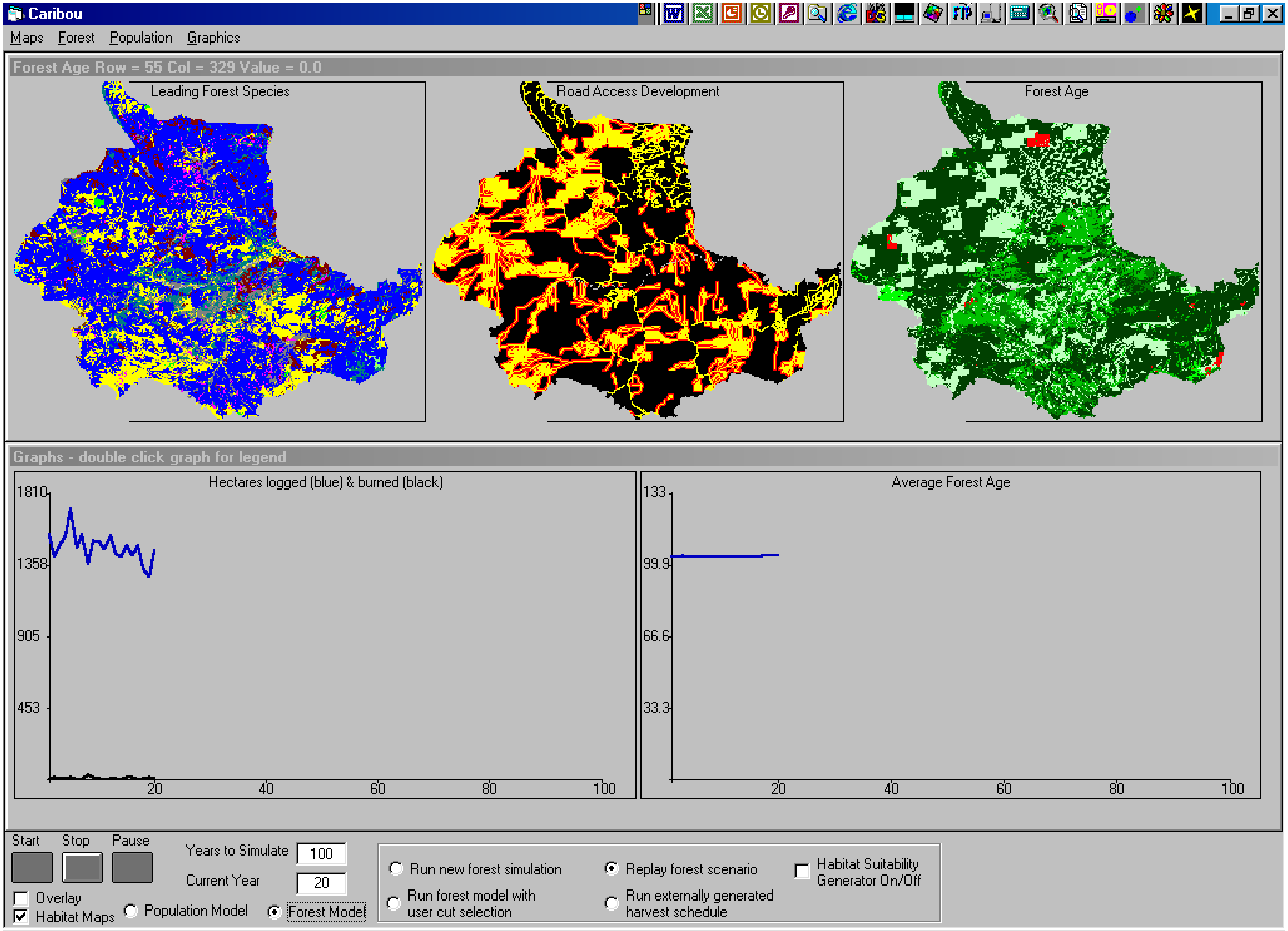
Screen 2: Edit Habitat Maps (forest age)

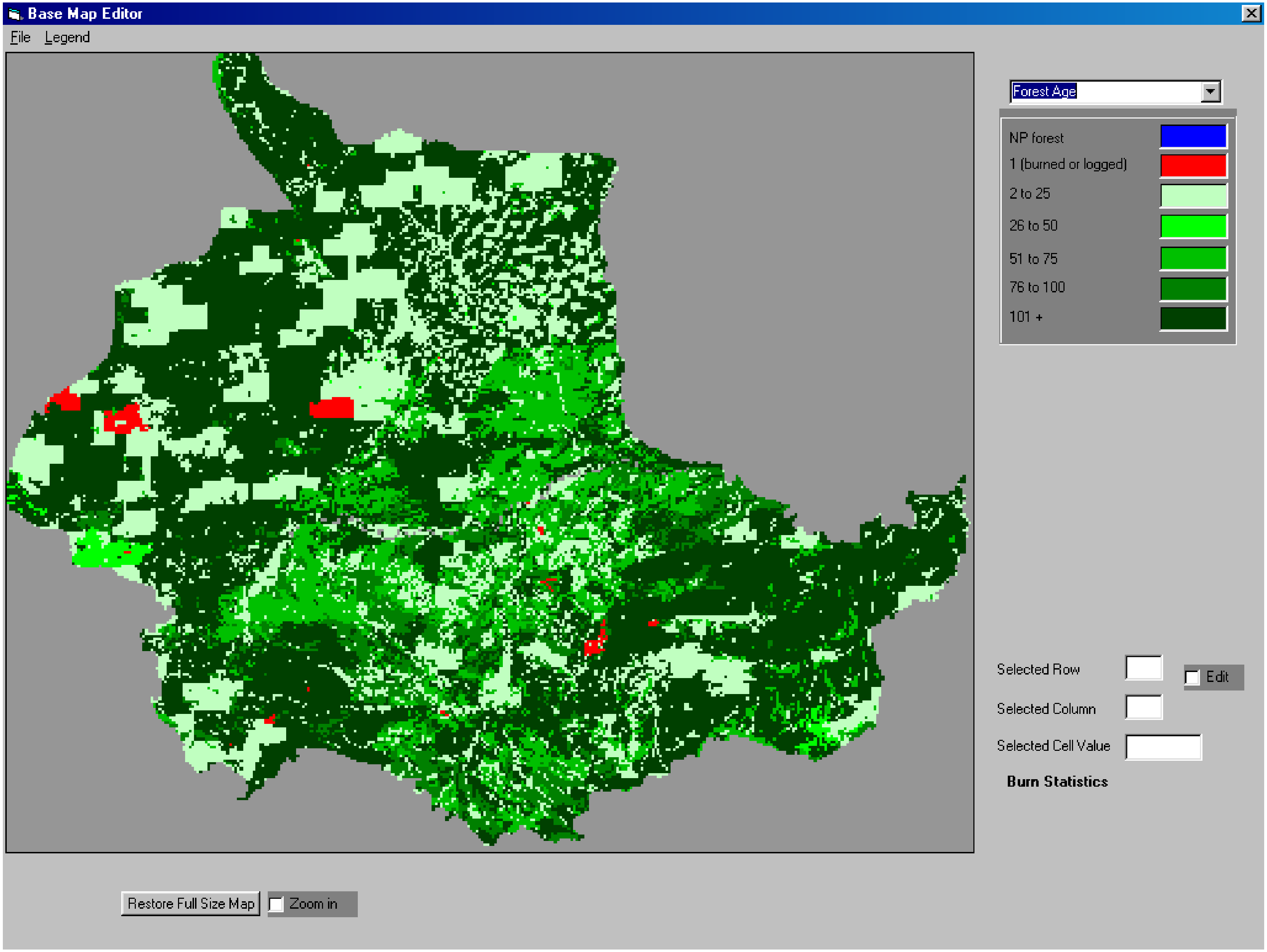
Screen 3: Population Model (simulations running)

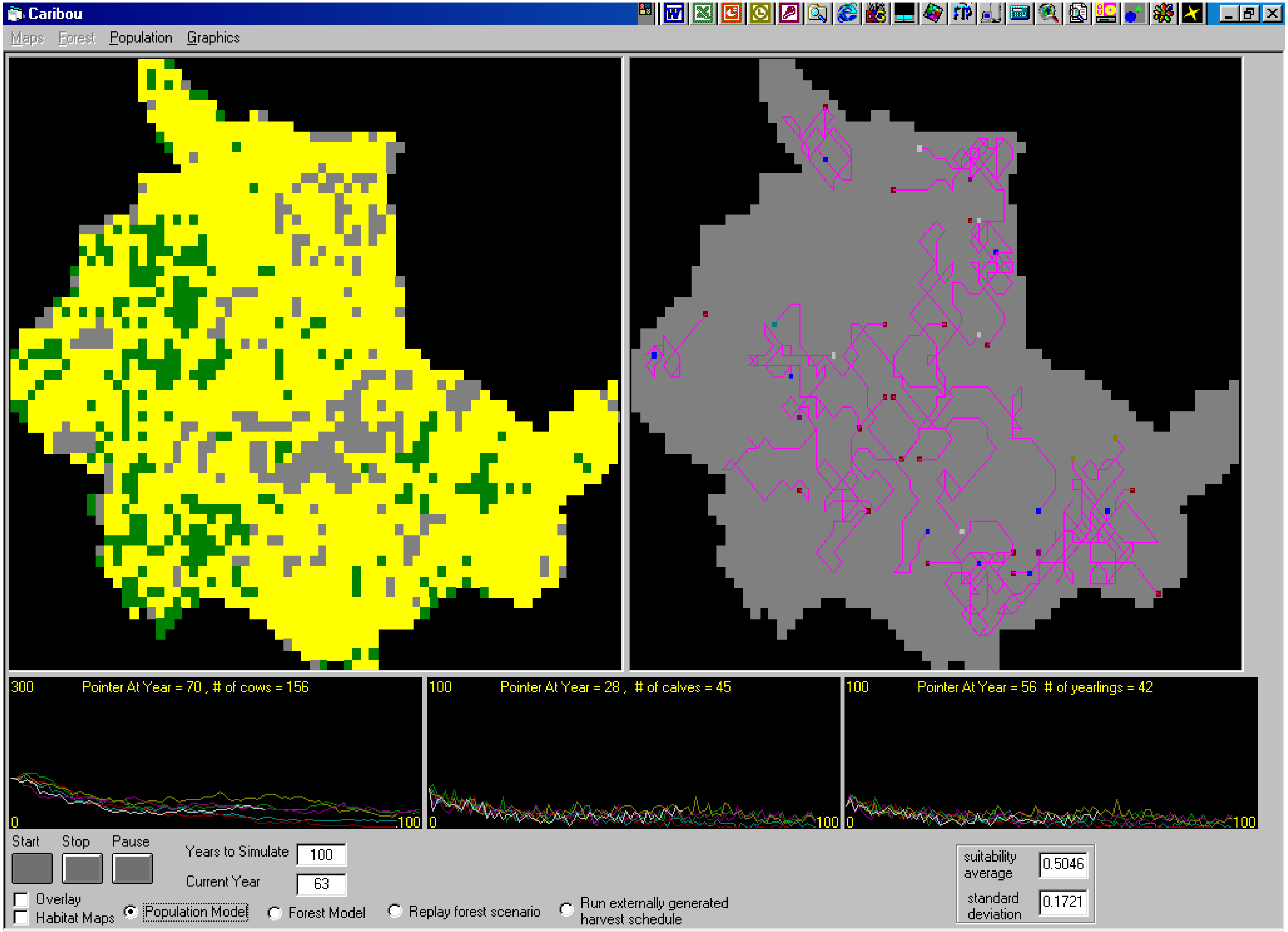
Screen 4: Edit parameters for Ungulate Population Model (pop-up screen)

DISCLAIMER:

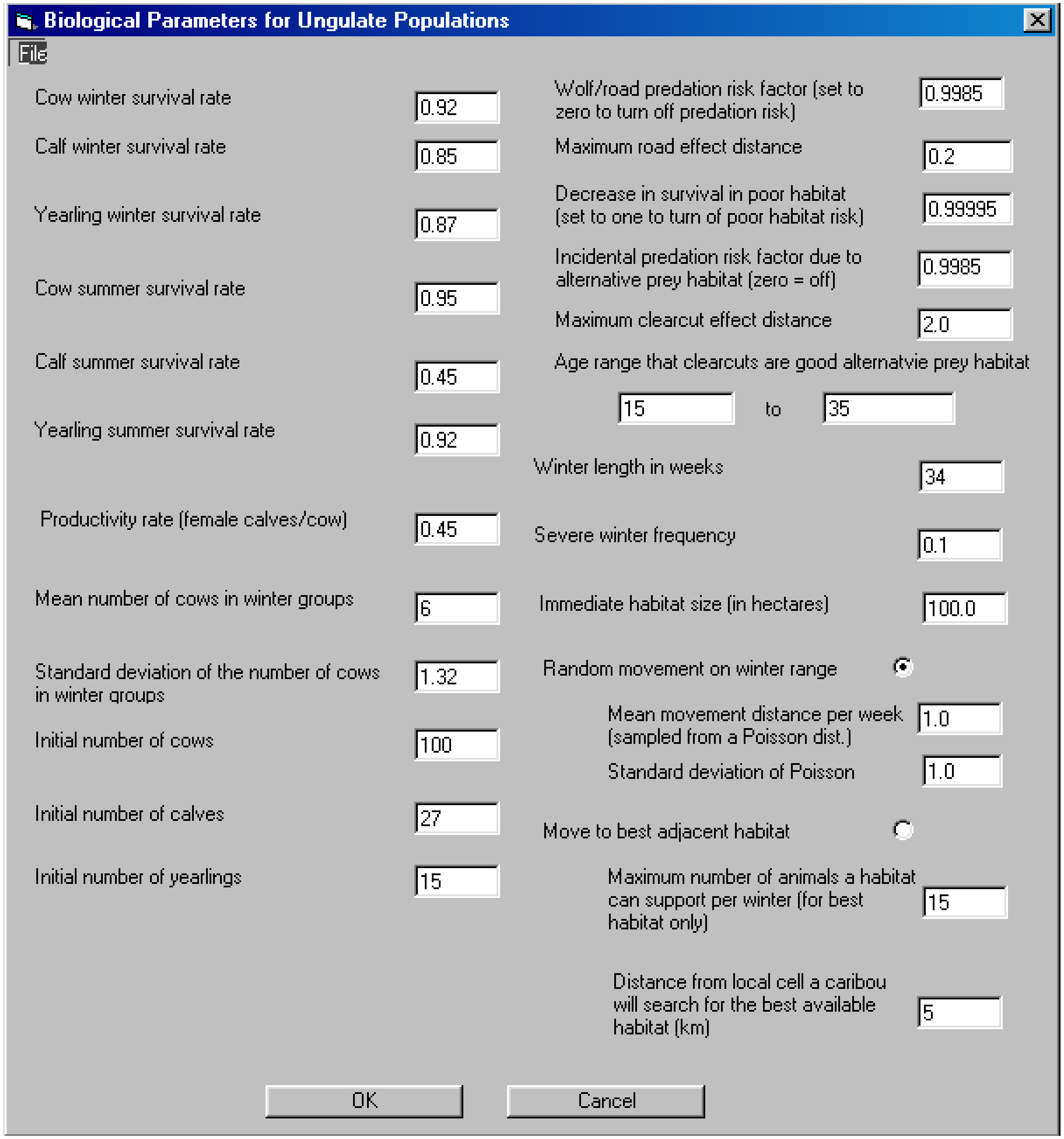
Please note that all of the included illustrations were derived from internal simulations of the model. These are intended to explore the sensitivity of modelled caribou responses to a wide range of hypothetical management scenarios, with the purpose of optimizing management actions for wildlife conservation. The presented illustrations do not represent any intended, planned, or approved development in the area.


Caribou
Maps Forest Population Graphics
Forest Age Row = 55 Col = 329 Value = 0.0
Leading Forest Species
Road Access Development
Forest Age
Graphs - double click graph for legend
Hectares logged (blue) & burned (black)
1810
1358
905
453
20
40
60
80
100
Average Forest Age
133
99.9
66.6
33.3
20
40
60
80
100
Start
Stop
Pause
Years to Simulate
100
Current Year
20
Overlay
Habitat Maps
Population Model
Forest Model
Run new forest simulation
Run forest model with user cut selection
Replay forest scenario
Run externally generated harvest schedule
Habitat Suitability Generator On/Off


Base Map Editor
File
Legend
Forest Age
NP forest
1 (burned or logged)
2 to 25
26 to 50
51 to 75
76 to 100
101 +
Selected Row
Edit
Selected Column
Selected Cell Value
Burn Statistics
Restore Full Size Map
Zoom in



Caribou
Maps Forest Population Graphics
300 Pointer At Year = 70 , # of cows = 156
0
100
100 Pointer At Year = 28 , # of calves = 45
0
100
100 Pointer At Year = 56 # of yearlings = 42
0
100
Start Stop Pause
Years to Simulate 100
Current Year 63
Overlay
Habitat Maps
Population Model
Forest Model
Replay forest scenario
Run externally generated harvest schedule
suitability average 0.5046
standard deviation 0.1721


Biological Parameters for Ungulate Populations
File
Cow winter survival rate
0.92
Calf winter survival rate
0.85
Yearling winter survival rate
0.87
Cow summer survival rate
0.95
Calf summer survival rate
0.45
Yearling summer survival rate
0.92
Productivity rate (female calves/cow)
0.45
Mean number of cows in winter groups
6
Standard deviation of the number of cows in winter groups
1.32
Initial number of cows
100
Initial number of calves
27
Initial number of yearlings
15
Wolf/road predation risk factor (set to zero to turn off predation risk)
0.9985
Maximum road effect distance
0.2
Decrease in survival in poor habitat (set to one to turn of poor habitat risk)
0.99995
Incidental predation risk factor due to alternative prey habitat (zero = off)
0.9985
Maximum clearcut effect distance
2.0
Age range that clearcuts are good alternatvie prey habitat
15
to
35
Winter length in weeks
34
Severe winter frequency
0.1
Immediate habitat size (in hectares)
100.0
Random movement on winter range
Mean movement distance per week (sampled from a Poisson dist.)
1.0
Standard deviation of Poisson
1.0
Move to best adjacent habitat
Maximum number of animals a habitat can support per winter (for best habitat only)
15
Distance from local cell a caribou will search for the best available habitat (km)
5
OK
Cancel