Management and Conservation Article

Determining Sustainable Levels of Cumulative Effects for Boreal Caribou

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ABSTRACT Direct and indirect effects of industrial development have contributed, in part, to the threatened status of boreal ecotype caribou (*Rangifer tarandus caribou*) in Alberta and Canada. Our goal was to develop a model that would allow managers to identify landscape-scale targets for industrial development, while ensuring functional habitat for sustainable caribou populations. We examined the relationship between functional habitat loss resulting from cumulative effects of natural and anthropogenic disturbance, and the rate of population change (λ) for 6 populations of boreal caribou in Alberta, Canada. We defined functional habitat loss according to 2 variables for which we had a priori reasons to suspect causative associations with λ: 1) percentage area of caribou range within 250 m of anthropogenic footprint, and 2) percentage of caribou range disturbed by wildfire within the last 50 years. Multiple regression coefficients for both independent variables indicated significant effects on λ. The 2-predictor model explained 96% (R^2) of observed variation in λ among population units ($F_{2,3} = 35.2$, $P = 0.008$). The model may be used to evaluate plans for industrial development in relation to predicted wildfire rates and goals for caribou population growth rates. (JOURNAL OF WILDLIFE MANAGEMENT 72(4):900–905; 2008)

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Of particular importance to wildlife management are questions of thresholds to habitat loss, either natural or anthropogenic, associated with declines of wildlife populations. In the long term, populations are expected to persist with habitat change when the total extent of change falls within the range of natural variation in the environment to which individuals are adapted. Populations may not persist if habitat changes exceed those historically experienced by the species. A habitat threshold can therefore be defined as the point at which habitat change, either in frequency, intensity, or extent, exceeds levels for which individuals are adapted, thus leading to population decline or local extinction.

Knowledge of habitat thresholds will help us to manage cumulative effects—the sum of incremental effects on wildlife resulting from the combined influences of anthropogenic and natural disturbances—and permit development of natural resources with acceptable levels of risk to species conservation. To achieve this, we must understand the relationship between one or more measures of population vigour (e.g., survival, reproduction, rate of increase, probability of persistence) and habitat change (e.g., habitat loss and fragmentation), which would likely require an experiment whereby several populations or subpopulations of the species in question, each subject to differing amounts of habitat change, are compared. An expression describing the above relationships (a multivariate function in the case of cumulative effects) could then be explored to identify tolerable thresholds of anthropogenic and natural disturbances.

In Alberta, 2 ecotypes of woodland caribou (*Rangifer tarandus caribou*) are recognized (Edmonds 1988): the migratory mountain ecotype inhabits mountains and foothills in west-central Alberta, whereas the nonmigratory boreal ecotype is generally found in peatland habitats throughout central and northern Alberta (Fig. 1). Boreal ecotype caribou are believed to be declining throughout most of their range in North America (Ferguson and Gauthier 1992, Mallory and Hillis 1998, Gray 1999, Dzus 2001, McLoughlin et al. 2003), and both ecotypes are currently listed as "threatened" by the Committee on the Status of Endangered Wildlife in Canada (2002). We believe the recent (<60 yr) addition of large-scale anthropogenic disturbances (e.g., agriculture, forestry, peat mining, oil, gas, and pipeline development) has played a role in generating population declines in northern Alberta because caribou have historically coexisted with both wildfire and predators.

Research on Alberta's monitored caribou populations has shown that caribou avoid, by $\geq$250 m, areas of industrial

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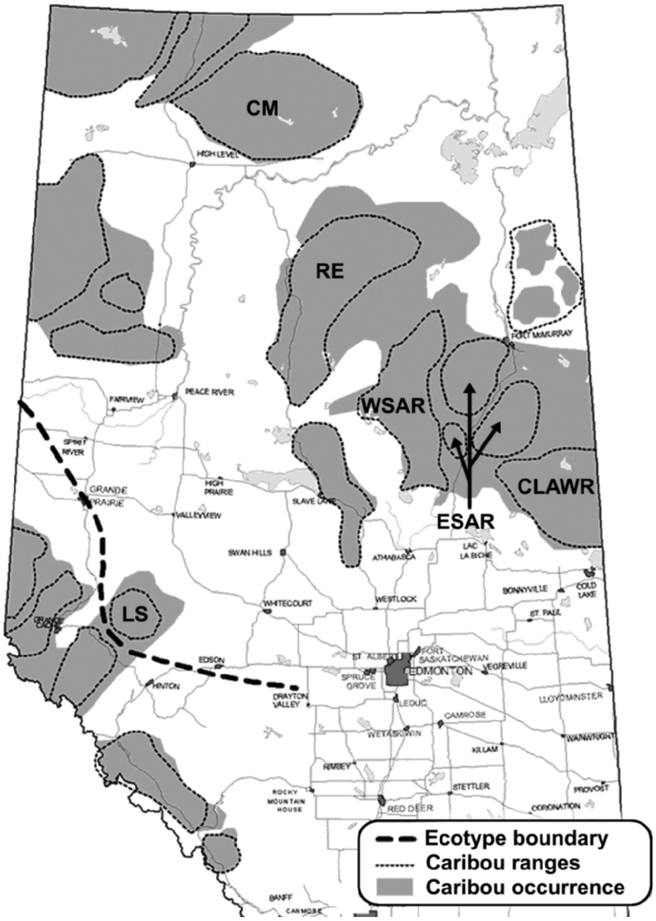

Figure 1. Approximate areas of woodland caribou occurrence between 1993 and 2001 in northern Alberta, Canada. Approximate ranges of the 6 boreal caribou populations studied include the following: east side of the Athabasca River (ESAR), west side of the Athabasca River (WSAR), Little Smoky River (LS), Cold Lake Air Weapons Range of the Royal Canadian Air Force (CLAWR), Caribou Mountains (CM), and Red Earth (RE) caribou ranges. Boundaries of boreal and mountain ecotypes of woodland caribou in Alberta are delineated. Unstudied caribou ranges are outlined but not labelled.

activity, including roads, geophysical exploration (seismic) lines, pipelines, electrical transmission line rights-of-way, oil and gas wellsites, and cutblocks (Smith et al. 2000, Dyer et al. 2001, Oberg 2001). In addition, Dyer (1999) demonstrated that roadways act as partial barriers to caribou movements. These results support the notion that anthropogenic disturbances can result in functional habitat loss for caribou. We also have data suggesting that avoidance of industrial linear features by caribou may be linked to an enhancement of the functional response (i.e., search time, hunting efficiency, and kill rates) of caribou predators such as wolves (*Canis* spp.) using linear features (James 1999, James and Stuart-Smith 2000, Smith 2004). Other aspects of increased anthropogenic disturbance such as hunting and poaching, vehicle collisions, and noise disturbance could also reduce the amount of functional habitat and place additional stress on the population.

Recent research in Alberta has also shown that boreal caribou, which feed primarily on lichens (*Cladina* spp. and *Cladonia* spp.) and prefer stands of old forest, generally avoid recently burned areas, likely as a result of reduced lichen biomass for 40 years postfire (Bradshaw et al. 1995, Anderson 1999, James 1999, Rettie and Messier 2000, Dunford et al. 2006). McLoughlin et al. (2003) found that the Caribou Mountains population in northern Alberta has declined at an alarming rate since 1995 subsequent to 2 major fires in 1988 and 1995 that cumulatively burned 48% of the range. Wildfire could affect caribou in several ways, including habitat loss and change, habitat avoidance, reduced survival or reproduction, direct mortality associated with flame and smoke, and increased predation.

Our goal was to develop a landscape cumulative effects model for boreal caribou in Alberta, Canada. The model needed sufficient power to evaluate the probability of caribou population survival while reviewing industrial development plans within boreal caribou range. We examined the relationship between functional habitat loss and the geometric mean rate of caribou population change (λ). Rate of population change is the amount by which the population must be multiplied to give the population size in the next time unit (assuming the population has a stable age structure). For example, if $\lambda = 1.1$ the population will grow by 10% annually and more than double in 8 years.

STUDY AREA

The study area encompassed 6 year-round boreal caribou ranges in northern Alberta (Fig. 1): the east side of the Athabasca River (ESAR), west side of the Athabasca River (WSAR), the basin of the Little Smoky River (LS), the Cold Lake Air Weapons Range of the Royal Canadian Air Force (CLAWR), the Caribou Mountains (CM), and Red Earth (RE). Elevation ranged between 250 m and 1,450 m in the study area, with little topographic variation within ranges except in CM (elevation 300–1,000 m). Black spruce (*Picea mariana*) and tamarack (*Larix larcina*) dominated fens and bogs. Uplands were dominated by white spruce (*Picea glauca*), jack pine (*Pinus banksiana*), and lodgepole pine (*Pinus contorta*). Bradshaw et al. (1995) provide a detailed description of the landscape typical of boreal caribou range in Alberta. The study areas were variable with respect to current amounts of disturbance, both from wildfire and anthropogenic sources (Table 1).

METHODS

We monitored 330 female caribou ($\bar{x}$ = 27.1 F/caribou range/yr, SD = 7.9) by aerial telemetry between 1993 and 2001, under the auspices of the Boreal Caribou Committee and the West Central Alberta Caribou Standing Committee (these committees are now jointly known as the Alberta Caribou Committee of Alberta [ACC]). The monitoring generated approximately 141,000 caribou locations for use in our study (see McLoughlin et al. 2003 for telemetry-sampling protocol).

We developed the boundaries of each caribou range by 1) generating home range polygons for each individual radio-collared caribou in each range, using biweekly or monthly

Table 1. Estimated number of caribou, rates of population change (λ), geometric variance (s^2), number of annual surveys (yr), hectares of kernel home range (range), percentage of range within 250 m of industrial features (%IND), and percentage of range naturally disturbed within the past 50 years (%BURN) for 6 boreal caribou populations in Alberta, Canada, 1993–2001.

Herd[a]	Caribou	λ	s^2	Yr	Range	%IND	%BURN
WSAR	200	1.012	1.162	8	7,780	51.5	8.0
ESAR	480	0.980	1.178	7	8,129	54.1	19.9
LS	80	0.902	1.031	2	2,512	88.4	1.5
CM	400	0.952	1.334	6	13,216	31.7	48.2
RE	250	0.892	1.254	5	10,523	67.8	29.2
CLAWR	350	1.003	1.126	3	7,752	31.6	26.0

[a] WSAR = west side of the Athabasca River, ESAR = east side of the Athabasca River, LS = Little Smoky River, CM = Caribou Mountains, RE = Red Earth, CLAWR = Cold Lake Air Weapons Range of the Royal Canadian Air Force.

locations from all years of study (1993–2001 for ESAR, WSAR, and LS; 1995–2001 for RE and CM; and 1998–2001 for CLAWR) and then 2) merging all home range polygons together to create a range map that gave equal weight to each individual. To calculate individual home ranges, we used the 95% fixed kernel technique with least squares cross-validating to determine bandwidths (Silverman 1986; Worton 1989*a*, *b*, 1995), because this was the least biased method available (Seaman and Powell 1996, Seaman et al. 1999). We conducted home range calculations and merging of ranges using the Animal Movement extension (Hooge and Eichenlaub 1997) in ArcView 3.2®.

Functional Habitat Loss

We defined functional habitat loss according to 2 landscape variables for which we had a priori reasons to suspect associations with λ for caribou populations in northern Alberta: 1) percentage of caribou range within 250 m of anthropogenic disturbances (%IND) and 2) percentage of caribou range naturally disturbed by recent (≤50 yr) wildfires (%BURN).

We identified the actual disturbed area, or footprint, of anthropogenic disturbances at the end of the study period in each caribou range using spatial data updated from classified IRS-1C panchromatic images (taken between 1998 and 2000) with 5.8-m spatial resolution (resampled to 5 m) for the province of Alberta (Resource Data Division, Alberta Sustainable Resource Development, unpublished data). We buffered footprints by 250 m, merged them to remove overlap, and calculated them as a percentage of area of the caribou herd's range.

We determined percentage of habitat burned within the past 50 years for each caribou range at the end of the study period from polygons of class E fires (i.e., >200 ha) obtained from Alberta Sustainable Resource Development (Resource Data Division, Alberta Sustainable Resource Development, unpublished data). Fires <200 ha were not consistently reported, and we presumed their presence or absence to have unknown but substantial error. We merged wildfire polygons to remove any overlap within the past 50 years.

The 2 landscape factors were not spatially exclusive of one another (e.g., some burned areas were within 250 m of an industrial feature). Anthropogenic and wildfire disturbances occurred continuously throughout the study, and we quantified them at the end of the study period. We conducted all spatial analyses used to define our independent variables, including buffering of anthropogenic features, using ArcView.

Rate of Population Change (λ)

We determined our dependent variable, λ, for each population using methods presented in McLoughlin et al. (2003) based on annual evaluations of adult female survival and recruitment from 1993 to 2001. For each range, we determined λ for the entire study period as the geometric mean of annual estimates of λ (Caughley 1977, McLoughlin et al. 2003). We do not refer to this rate as the finite rate of population increase because we estimated it for the entire study period from an average of annual λ estimates.

We examined annual estimates of λ with casewise diagnostics to identify outliers with undue influence on the regression. We initially screened the 1997–1998 Red Earth survey as an outlier with standardized residuals >3 standard deviations from the mean of annual λs. This datum was the largest annual λ (1.299) and was also an outlier within the Red Earth data. Further analysis with the DfFit measure of influence determined that this annual survey was highly influential on the regression, and we therefore excluded it from further analyses. We conducted all statistical tests with SPSS 11.5 (SPSS Inc., Chicago, IL).

Model Statistics

Many statistical methods could be used to examine relationships between λ and the 2 landscape variables. A primary factor in model selection was its simplicity in management application and interpretation. We performed a multiple regression of λ and the independent variables using SPSS, according to the following equation:

$$\hat{Y}_i = b_0 + b_1 X_{1i} + b_2 X_{2i} \qquad (1)$$

where $\hat{Y}$ is our estimate of λ, b_0 is our estimate of the y-intercept, and b_1 and b_2 are estimated multiple regression coefficients for the independent variables (Zar 1999). The 6 herds were the data points for the multiple regression ($n = 6$). We assumed that estimates of λ were independent across herds. The 6 herd estimates of λ had unequal sampling (no. of survey yr) and variance (Table 1); therefore, the inverse of

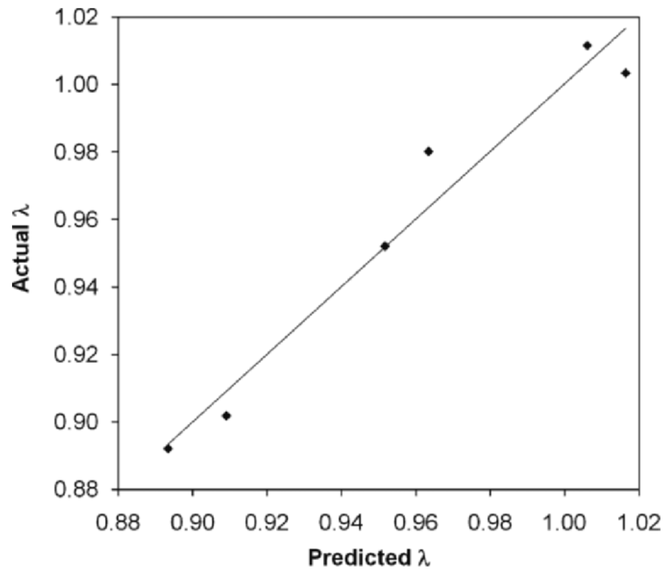

Figure 2. Actual rates of population change (actual λ) for the studied boreal caribou populations in Alberta, Canada, 1993–2001, versus predicted rates of population change (predicted λ) from the regression model. The model predicts rates of population change based on 2 variables: percentage habitat within 250 m of industry and percentage habitat disturbed by wildfire within the past 50 years.

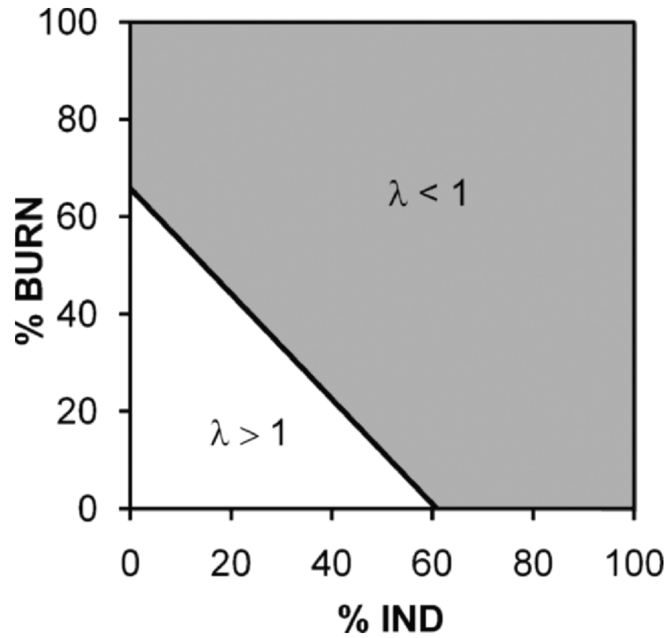

Figure 3. Predicted habitat threshold for sustainable (λ = 1.0) boreal caribou populations in Alberta, 1993–2001, as defined by percentage habitat within 250 m of industrial features (%IND) and percentage habitat disturbed by wildfire within the past 50 years (%BURN).

geometric variance in λ for each herd was used to weight the data using a weighted least squares method. Assumptions of noncollinearity among the 2 independent variables were satisfied during preliminary analyses ($F_{1,4} = 3.6$, $P > 0.10$, $R^2 = 0.47$).

We ranked 3 candidate models by Akaike's Information Criterion (AIC): %IND, %BURN, and %IND with %BURN. Due to the low sample size ($n = 6$) relative to model parameters (K; i.e., n/K < 40), we used the corrected AIC formula (AIC_c; Anderson et al. 2000). We calculated AIC_c weights (w_i) and used them to identify the most parsimonious model (Anderson et al. 2000).

RESULTS

Calculations of the rates of population change (λ) indicated that 4 of 6 monitored populations declined during our study, during which caribou were exposed to extensive industrial footprint (Table 1). On average, 54.2% of the habitat of monitored caribou populations was within 250 m of industrial features (%IND; Table 1), although specific proportions varied considerably among populations (SD = 21.8). Percentage of habitat burned within the past 50 years (%BURN) was generally much lower ($\bar{x} = 22.1\%$, SD = 16.6; Table 1).

The 2-predictor model (%IND with %BURN) had the highest AIC_c weight ($w_i = 0.920$), and explained 95.8% (R^2) of observed variation in λ among herds ($F_{2,3} = 35.21$, $P = 0.008$; Fig. 2). Multiple regression coefficients for both independent variables indicated significant effects on λ (Table 2). We tested range size for each herd as a covariate but it was nonsignificant ($t_2 = 1.11$, $P = 0.383$; Table 1). When we included the identified outlier in estimating average λ for Red Earth, the regression was insignificant ($F_{2,3} = 5.40$, $P = 0.101$, $R^2 = 0.783$) but had a similar constant (1.129) and coefficients (−0.00229 b_1, −0.00176 b_2), indicating that inclusion or exclusion of the outlier did not influence our general interpretations of the model.

Table 2. Nonstandardized multiple regression coefficients (b), standard errors, statistic (t), and probabilities for terms in the regression model. Percentage habitat within 250 m of industrial features (%IND) and percentage habitat naturally disturbed within the past 50 years (%BURN) explained the rates of population change for 6 boreal caribou populations in northern Alberta, Canada, 1993–2001.

Model term	b	SE of b	t (df = 3)	P
Intercept (b_0)	1.192	0.030	39.51	<0.001
%IND (b_1)	−0.00315	0.00038	−8.27	0.004
%BURN (b_2)	−0.00292	0.00052	−5.64	0.011

DISCUSSION

The multiple regression model described can be used to prescribe or evaluate cumulative natural and anthropogenic habitat change in relation to goals for caribou population growth rates. The habitat threshold defined with this management tool is not one number, but rather a combination of 2 landscape variables to predict sustainability of a caribou population (Fig. 3), which results in a flexible model that can be applied to ranges with different disturbance histories and development pressures. Likewise, future levels of landscape change on individual ranges (due to industrial development and wildfire) can be examined independently or in combination for their influence on caribou population growth. Expectations of reclamation, reforestation, and forest succession can be incorporated into this evaluation.

Using extrapolation, our model predicts sustainable caribou populations at a maximum of 61% of the range within 250 m of industrial development (x-intercept; Fig. 3) or at a maximum of 66% naturally disturbed (y-intercept; Fig 3). Future research could test these 2 thresholds if caribou populations could be monitored in landscapes disturbed solely by fire or by industry. Unfortunately, there are no boreal caribou ranges in Alberta without a substantial level of industrial development. In contrast, with essentially no wildfire disturbance in the last 50 years and extremely high industrial development, the LS range could be compared with other ranges with various levels of industrial development and essentially no wildfire disturbance. Both axis intercepts occur outside of the range of data points in our study; therefore, they should be interpreted cautiously.

It is clear that for some caribou ranges in Alberta, past landscape management practices and fire history will make it exceedingly difficult to recover populations based on habitat restoration alone. Reversing caribou population declines by restoring functionally lost habitat will require an enormous effort, both in time and money. Because linear features (seismic lines, roads, and pipelines) represent >90% of the industrial footprint in most ranges, it is likely that anthropogenic lines will need to be substantially reduced or restored to stabilize ($\lambda = 1.0$) declining populations. Increasing functional habitat may partially be achieved through an active program of line reclamation, and the ACC is currently pursuing a pilot program to evaluate methods to speed restoration of old and unused industrial infrastructure to functional habitat. However, enhanced reclamation is unlikely to be sufficient; new and innovative industrial methods will also be required to limit the loss of functional habitat at time of development. For example, new methods exist for using narrow (1.5–2.5 m wide) meandering seismic lines, instead of the traditionally wide (8-m) straight lines, which apparently take longer to restore. Similarly, some types of oil and gas well sites can be produced using remote monitoring techniques, reducing or eliminating roadway construction. Application of these types of industrial practices will likely be required by all industrial sectors to conserve caribou habitat throughout the province (Boreal Caribou Committee 2001).

Although there is good evidence to support the assumption that caribou avoid industrial developments by $\geq$250 m (Smith et al. 2000, Dyer et al. 2001, Oberg 2001), the truth or accuracy of this assumption need not be proven to proceed with a model that uses a distance of 250 m. We view this distance term within the model as an index to track cumulative effects of industrial development. Evidence of caribou avoidance suggests that the sum of actual industrial footprint area would underestimate its effect on caribou. By including a zone of influence around the footprint we recognize the exponential impact of a small footprint on adjacent habitat function.

In addition to managing industrial footprint, risk of large-scale wildfires must be managed with respect to caribou habitat. Caribou habitat in northern Alberta is predominately lowland bog and fen dominated by species such as black spruce and tamarack. These areas are primarily nonmerchantable for pulp or timber, so past fire suppression in the region has been minimal. Managing stochastic wildfire disturbance rates is not an easy, or perhaps possible, task. Common methods to reduce wildfire risk such as large fire-breaks, road infrastructure, maintaining younger forest age, and managing for deciduous tree species are all contraindicated for caribou management and maximizing functional habitat. Developing detailed wildfire response plans and extensive mitigation and restoration plans that are spatially specific to each caribou range is probably the most a manager can realistically do to reduce wildfire risk. If one accepts that wildfires are inevitable, management of industrial development rates must be conservative so that a variety of potential wildfire disturbance events will not result in exceeding the calculated cumulative effects threshold for a sustainable caribou population. Likewise, forecasts of λ into the future should include an allowance for disturbances by fire, either by planning for stochastic events or taking account of long-term average natural disturbance rates.

There are 2 major concerns with our methods. 1) We used an average rate of population change (with associated variance) instead of a known finite rate of increase and 2) the landscape continued to be disturbed during the study. It is difficult to examine the influence of landscape changes on population sustainability at any point in time (i.e., finite rate of increase) due to the lag of landscape effects and population structure effects on recruitment and survival. It is therefore critical to identify a period of study that is long enough to obtain a representative estimate of the rate of population change but short enough to minimize any significant on-going changes in the landscape.

Basing wildlife management policy on correlative analysis, such as that we proposed, must be approached with caution. Correlation does not always imply causation. Causation may be invoked, however, if correlational evidence is accompanied by plausible dependencies between supposed causes and outcomes (Romesburg 1981). We believe that population growth rates of boreal caribou in northern Alberta have a plausible dependency on functional habitat loss resulting from wildfire or industrial footprint through habitat alienation and changing predator–prey dynamics (James 1999, James and Stuart-Smith 2000, Dyer et al. 2001, Dunford et al. 2006). Managers intending to use similar habitat threshold models must develop a thorough understanding of the mechanisms influencing population growth rates in their system and be comfortable in distinguishing causation from correlation.

MANAGEMENT IMPLICATIONS

We view the regression formula and its application in management of industrial activity and wildfire disturbance as an exercise in adaptive management. Managers should use the model conservatively because we do not know how long these cumulative effects will persist, and lower population growth rates may lag behind industrial development or wildfire disturbance rates. Likewise, long-term changes in the ecosystem, such as global warming, could reduce the accuracy of our model. Population stability ($\lambda = 1.0$) in most cases should not be a management target because it leaves no room for error in the cumulative effects model, nor does it leave room for natural fluctuations in climate and predation pressure. As new information is obtained for caribou populations, our approach to evaluating the impacts of industrial development and wildfire on caribou conservation will be refined.

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