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Climate change and woodland caribou in Northwestern Ontario: a risk analysis

Gerald D. Racey

Ontario Ministry of Natural Resources, Northwest Science and Information, RR#1 25th Sideroad, Thunder Bay, Ontario, Canada, P7C 4T9 (gerry.racey@mnr.gov.on.ca)

Abstract: Woodland caribou (*Rangifer tarandus caribou*) range occupancy and populations have declined in northwestern (NW) Ontario over the last 100 years primarily due to human-induced factors. Recovery efforts are underway to halt this decline by reducing risk factors. Climate forecasts suggest a 4–5 °C increase in May–August mean temperature over the next century with little change in precipitation. Resulting increases in extreme weather events and increased fire weather severity will likely increase the amount of forest burned, reduce the area of older forest, alter distribution and abundance of forest tree species and plant communities, and increase abundance of alternate prey. The reduced amount of older forest preferred by caribou will be in greater demand by the forest industry leading to more conflict over ecological and economic values. Most of these factors will increase risk to caribou survival. Although forests may experience enhanced productivity, forest management practices will try to adapt harvest, regeneration, silviculture and fire management practices to both maintain economic benefits and increase the ability of forests to sequester carbon. The interaction of climate-induced forest change and forest management practices adds uncertainty to caribou conservation efforts at the southern edge of its current range. This uncertainty reinforces the need for a precautionary approach to forest management, increased research and monitoring effort, sustained emphasis on caribou recovery, and careful rationalization of restoration efforts where greatest opportunities for success may be realized.

Key words: boreal, climate change, forest-dwelling, forest management, *Rangifer*, recovery, weather.

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Introduction

Over the past 100 years, the range occupied by woodland caribou (*Rangifer tarandus caribou*) in NW Ontario has receded northward (Racey & Armstrong, 2000). This decline has been attributed to many factors (Bergerud, 1974; Darby *et al.*, 1989; Cumming, 1998; Racey & Armstrong, 2000), most of which are direct or indirect effects of human activity and development. These factors include logging, land clearing, fire, disease and parasites associated with white-tailed deer (*Odocoileus virginianus*) range expansion, predation, hunting and human disturbance. Predation risk, as influenced by multiple biological and physical factors, is considered by many biologists to be the most important ecological variable in all seasonal distributions of caribou rather than forage supplies (Bergerud, 1996). There is certainly interaction among factors contributing to caribou decline (Racey & Armstrong, 2000).

The Committee on the Status of Endangered Wildlife in Canada officially listed Woodland Caribou - Boreal Population as a Threatened species in May 2000 (Thomas & Gray, 2001). Ontario has taken steps to officially designate forest-dwelling woodland caribou as a threatened species based on recommendations in a provincial status report (Harris, 1999). These designations impose responsibility for recovery planning to ensure forest-dwelling woodland caribou do not become endangered (National Recovery Working Group, 2001). Recovery planning is underway in Ontario, incorporating policy, education, research, and management objectives.

Since the 1980s, the government of Ontario has supported efforts to understand and modify forest management practices to mitigate adverse consequences for caribou (Cumming, 1992; Racey & Armstrong, 1996; Greig & Duinker, 1997; Armstrong, 1998; Euler, 1998; OMNR, 1999a; Racey *et al.*, 1999). Ontario's Crown Forest Sustainability Act (Statutes of Ontario, 1994) and Ministry of Natural Resources strategic direction statement (OMNR, 2000) set ecological sustainability as a cornerstone for all other resource management objectives. Sustainable resource management planning has generally not regarded climate as a factor despite recognition that weather patterns and climate influence forest pattern and composition (Thompson *et al.*, 1998; Flannigan & Weber, 2000) and likely caribou distribution and abundance (Thompson, 2000). Despite significant efforts to minimize risk by increasing the number and size of protected areas (OMNR, 1999b), emulating natural disturbance patterns (OMNR, 2001), conserving habitat value for caribou, (Racey *et al.*, 1999) and trying to ensure natural processes important to caribou continue to operate; climate change may alter the very natural processes we are attempting to emulate and conserve.

The connection between caribou and climate is obscure and managers and policy-makers question how climate change will impede recovery efforts. They also express concern that even if climate change effects are real, measurable impacts on caribou populations, range occupancy or habitats may only be detectable over decades. More important, climate change may affect the nature, magnitude and consequences of the interaction between physical and biological variables, changing the ecological context of caribou habitat and the entire approach to caribou conservation and recovery efforts. Climate change scenarios also add uncertainty by creating an environment substantially different from that under which current scientific knowledge was generated and applied.

Climate change context

Climate projections based on General Circulation Models (GCMs) (Boer *et al.*, 1992; McFarlane *et al.*, 1992) suggest NW Ontario will experience mean increases in air temperature of 4–5 °C with no significant change in growing season precipitation (Parker *et al.*, 2000). The largest reduction in precipitation will occur from north of Lake Superior west to Manitoba. Temperature differences (Table 1) will be more pronounced in spring and early summer (Wotton *et al.*, 2003). Higher temperatures will increase evapotranspiration and lead to drier soils (Parker *et al.*, 2000). Extreme weather events are expected to be more frequent (Frances & Hengeveld, 1998; Parker *et al.*, 2000) and will likely be expressed as heavier but less frequent rainfall events and severe thunderstorms. These less frequent but heavier rainfall events will be less efficient at recharging soil moisture than lighter more frequent rainfall events (Francis & Hengeveld, 1998). The severe weather projections include a 30% increase in lightning activity (6% for every 1 °C rise in average temperature), increased moisture moving to the higher latitudes with potential increases in mid-latitude winter snowfall, and the potential for an increase in extreme wind events associated with storm activity (Frances & Hengeveld, 1998).

Table 1. Monthly temperature differences (ΔT) and precipitation ratios (P_{2090}/P_{2000}) for northwestern Ontario GCM grid cells for 2 future decades using the year 2000 (1995–2004) as a baseline (adapted from Wotton *et al.*, 2003).

Month	Northwestern Ontario 50.1°N by 93.75°W			
	2040		2090	
	ΔT (°C)	P2040/ P2000	ΔT (°C)	P2090/ P2000
April	3.0	1.19	6.5	1.60
May	2.1	1.08	6.2	1.05
June	2.9	0.79	6.5	0.87
July	2.5	1.00	4.4	0.83
August	2.4	0.94	4.3	0.80
September	1.8	0.93	4.2	1.07

Climate change projections suggest the most pronounced increase in fire weather severity is expected in the extreme northwest and south-central regions of Ontario (Parker *et al.*, 2000). Assuming current fire management efforts, Ontario may experience a 30% increase in number of escaped fires by 2040 and a 80% increase by 2090, largely attributed to increased receptivity of fuels to ignition sources (Wotton *et al.*, 2003), a higher frequency and severity of drought years (Simard, 1997) and an extension of the fire season by as much as 25 days (Wotton & Flannigan, 1993). In addition to lightning-caused fires, an estimated 26% increase in human-caused fires is anticipated (Wotton *et al.*, 2003). Overall, by 2090 a conservative estimate of an 80% increase in the average annual area burned (Wotton *et al.*, 2003) is expected in the zone of intensive fire management (Fig. 1d).

A 3.5 °C mean temperature increase may shift the climatic range of species 100–500 km to the north (Parker *et al.*, 2000). Major shifts in forest species and plant communities have occurred in the past (DeHayes *et al.*, 2000). However, there is a tendency for plant species to migrate singly rather than as intact plant

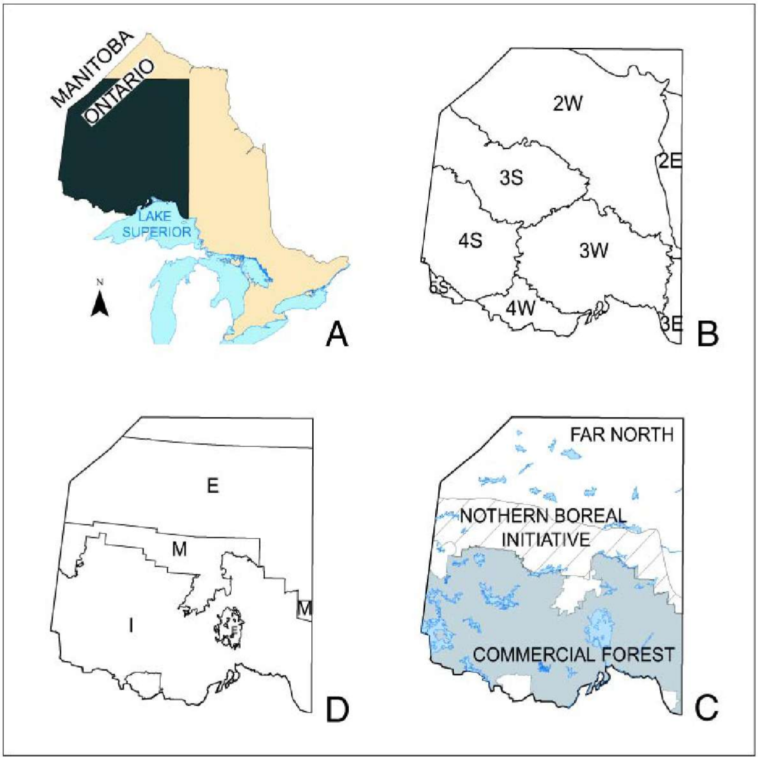

Fig. 1. Administrative and ecological context of the northwestern Ontario study area: a) study area within Ontario; b) ecoregions of Ontario; c) forest management context; and d) major fire management zones prior to 2004 (extensive [E], Intensive [I], measured [M]).

adjust to changing climate and its associated environmental stresses. Forest management practices intended to increase carbon storage could become a critical component of national efforts to reduce greenhouse gas emissions and slow the rate of climate change (Parker *et al.*, 2000). Additional effort will likely be applied to the management and regeneration of declining stands (Parker *et al.*, 2000) and extensive artificial regeneration efforts to assist migration of tolerant genotypes (Mackey & Sims, 1993). Forest management for carbon sequestration may encourage longer rotation periods (balanced against fire interval), planting of fast growing genotypes, partial cutting systems, artificial rather than natural regeneration, control of competing vegetation to make more light, nutrients and water available, thinning and fertilization (Parker *et al.*, 2000).

Some authors forecast an expansion of white-tailed deer range and reduction in caribou and moose (*Alces alces*) range associated with climate change (Thompson *et al.*, 1998). Meningeal worm (*Parelaphostrongylus tenuis*) infection rates will most likely increase as a result of warmer summers and lengthening of the frost-free period in autumn, combined with a documented northward extension of deer range and altered range and abundance of terrestrial gastropods (Greifenhagen & Noland, 2003).

communities (Peters, 1990). If anticipated climate changes are realized, trees that begin growing in the next decade will mature in a climate substantially different from today (Parker *et al.*, 2000). The forest prairie ecotone of NW Ontario will see some of the largest relative changes in vegetation, and in regions where fire is expected to increase in frequency, fire adapted tree species will be favored (Parker *et al.*, 2000). In the extreme case where the fire interval is shorter than the age to sexual maturity of tree species, jack pine forests in NW Ontario may be replaced by grasslands or aspen parklands (Schindler, 1998). With increases in extreme storm events and heavier snowfalls (Francis & Hengeveld, 1998) there is an associated potential for increases in snow and wind damage. Forest disturbance caused by insects and disease may increase in frequency or intensity due to climate trends. Outbreaks of spruce budworm (*Choristoneura fumiferana* Clem.), jack pine budworm (*Choristoneura pinus pinus* Freeman), and forest tent caterpillar (*Malacosoma disstria* Hubner) are likely to increase in areas with warmer, drier growing seasons like NW Ontario (Fleming & Volney, 1995).

The focus of forest management is expected to

This report is a synthesis of existing climate change literature pertinent to NW Ontario and central Canada augmented by a limited modelling exercise. I examine current and projected climatic trends as they might affect risk factors associated with woodland caribou survival. I speculate how these changes might influence the prospects for caribou persistence on the landscape and how managers may adapt their approach to caribou conservation.

Study area

The NW Ontario study area (Fig. 1a) is characterized mainly by provincial ecoregions 4S, 3W, 3S and 2W (Crins, 2000) (Fig. 1b) of the boreal shield ecozone. Each ecoregion has a set of climatic, physical and

Table 2. Modelled (150 yr) change in forest composition and caribou habitat availability (with forest management) under 3 projected levels of wildfire. Forest response in terms of older (≥ 80 yr) jack pine (Pj old), black spruce (Sb old), and mixed upland conifer (Conmx old). Caribou refuge (caribou habitat) and winter habitat availability were estimated based on forest composition and age class. The third model run (80% increase) was only able to find a feasible solution through elimination of most environmental constraints such as maintenance of 10% old growth.

Analysis area	Forest unit class	Change (%) 30% increase in area burned per yr	Change (%) 50% increase in area burned per yr	Change (%) 80% increase in area burned per yr
4S	Pj old	12	-9	-91
	Sb old	-22	-24	-69
	ConMx old	-45	-49	-36
	Caribou habitat	-8	-12	-89
	Caribou winter habitat	-3	-8	-94
3W & 3S[a]	Pj old	7	-1	-98
	Sb old	-5	-16	-99
	ConMx old	-4	-17	-99
	Caribou habitat	0	0	-96
	Caribou winter habitat	1	2	-95

[a] Models for this analysis area only captured the northern portion of 3W and made available for harvest only those forests currently licensed for forest management.

biological properties that help distinguish them from other ecoregions. Ecoregions reflect forest vegetation soil and climate relationships and are used to stratify the land for biodiversity conservation, and land use planning. There is a strong relationship between these ecoregions and major climatic gradients. Within these ecoregions, forest and wetland plants are organized in well-defined community types (Sims *et al.*, 1989; Harris *et al.*, 1996; Racey *et al.*, 1996), many of which are directly associated with habitat value for caribou, deer or moose (Racey *et al.*, 1989).

Administratively, the study area consists of 3 zones: the most southerly is subject to commercial forestry and reflects most of the human presence in NW Ontario; the far north has no anticipated forest management activity and in between is an area where new economic development opportunities are sought under the Northern Boreal Initiative (NBI) (Fig. 1c). Fire management effort varies among these zones and prior to 2004 this effort was termed intensive (each fire receives initial attack and sustained suppression effort), measured (fires receive initial attack and escaped fires are assessed for their potential impacts and appropriate suppression actions are formulated within program capacity), and extensive (fires only monitored and no suppression action taken unless life or property is at risk) (Fig. 1d).

Historically, the forests and associated flora and fauna of NW Ontario have developed under a natural fire regime (Heinselman, 1971; 1981). Fire cycles, within the current management environment are estimated at 248 yr (4S), 389 yr (3W), 120 yr (3S) and 154 yr (2W) (Frech, 1998). Forest management recognizes the historic and natural forest condition within these ecoregions as a benchmark against which sustainability is assessed (OMNR, 1996).

Methods

I examined existing literature describing recent weather trends, projected climate change and associated impacts in NW Ontario and central Canada to extract inferences and arguments pertaining to risk factors relevant to woodland caribou. I analysed these risk factors within a framework based on a functional definition of habitat, i.e., habitat provides refuge from predation and disease while also providing essential resources for survival and reproduction. I then tabled potential changes and impacts under categories of forest attributes, disease, predation pressure, compensatory forest management practices and thermal stress. I assumed that risk to caribou increased if the refuge value of habitat was reduced.

I used Ontario's Strategic Forest Management Model (OMNR, 2002a) to examine the potential impact of a predicted increase in annual area burned by wildfire as a result of climate change. I modelled 2 forest management - succession scenarios, assuming factors such as forest succession and non-fire disturbance agents remain relatively constant. I then used

Table 3. Modelled (150 yr) forest composition change under 4 levels of fire, and without forest management on all or part of ecoregions 3S, 3W, and 4S. Forest response is reported for older jack pine stands ≥ 100 yr (Pj old), older black spruce stands ≥ 110 yr (Sb old), and older mixed conifer stands ≥ 110 yr (Conmx old).

Analysis area	Forest unit class	Change (%) 30% increase in area burned per yr	Change (%) 80% increase in area burned per yr	Change (%) Gradual increase[a]
3S	Pj old	-16	-40	-40
	Sb old	-26	-55	-43
	Conmx old	-27	-57	-48
3W	Pj old	+36	-17	-18
	Sb old	-22	-48	-37
	Conmx old	-22	-49	-37
4S	Pj old	-9	-28	-22
	Sb old	-26	-55	-41
	Conmx old	-23	-50	-43

[a] Modelled under a gradual increase from 0% (yr 1–50) to 30% (yr 51–70) to 80% (yr 71–150).

the model outputs to quantify changes in forest cover attributes relevant to habitat quality.

Modelled forest composition with forest management
Existing forest models featuring forest dynamics, harvest, fire and silviculture were obtained from the provincial *Forest Resource Assessment Project*. These models have been used to assess forest resources for the *State of the Forests* report (OMNR, 2002b). The 2 models, corresponded approximately to provincial ecoregions 4S, and upper portions of 3W and 3S. In these models, forest harvest was fixed at levels agreed under the *Ontario Forest Accord*. A 150 yr simulation was run, within which the only change from the base models was the area burned by wildfire which was adjusted to correspond approximately to 2040 and 2090 projections made by Wotton *et al.* (2003). For each model run the percent change in older conifer forest types was determined as well as the approximate area represented as preferred caribou habitat and winter habitat (Racey *et al.*, 1999).

Modelled forest composition without forest management
Three existing, generalized natural dynamics forest models featuring only forest dynamics and fire for ecoregions 3S, 4S, and 3W were used to estimate potential changes in forest composition with increased occurrence of fire assuming no forest management takes place. These base models were used to estimate modelled bounds of natural variation in NW Ontario (Ride *et al.*, 2004). A 150 yr simulation was run, within which the only change from the base models was the area burned by wildfire which was adjusted to correspond approximately to 2040 and 2090 projections made by Wotton *et al.* (2003). For each model run, 12 in all, the number of hectares of forest types by age class at the end of the modelling period was recorded.

Results

Modelled forest composition showed a substantial reduction in older conifer forest types with (Table 2) and without (Table 3) forest management. In the presence of forestry and fire management, stands with desirable attributes for caribou habitat were reduced 8–12% in 4S but did not change in the northern portions of 3W and 3S where a large portion of the modelled forest was not considered available for harvest. The *Forest Resource Assessment* models were unable to find a feasible solution in trying to meet wood supply commitments and environmental constraints with an 80% increase in area burned per year (Table 2). In this case, the constraints on maximum silvicultural investment and 10% old growth maintenance had to be eliminated along with other assumptions in order to maintain wood products flow resulting in virtual elimination of older forest components and caribou habitat potential. Therefore, results of a 50% increase in annual area burned was recorded for comparison purposes. In the absence of forest and fire management and within the most realistic gradual increase scenario, best estimates of changes in forest composition suggest an 18–48% reduction in older conifer forest depending on species and ecoregion (Table 3).

A risk-analysis framework (Table 4) applied to direct and indirect consequences of climate change suggests that most will tend to increase risk to woodland caribou survival in the study area. Of the 14 risk categories assessed, 10 clearly increased risk, 1 reduced risk, 1 was uncertain, and 2 are assumed to increase risk but may actually reduce risk if alternate assumptions are more important than currently

Table 4. Risk analysis framework to examine the potential impacts of climate change on risk to woodland caribou in northwestern Ontario; mechanisms and risk are synoptic and have value primarily for supporting future debate, investigation and analysis.

Category	Factor	Factors affected directly by climate	Theoretical mechanism for impact on woodland caribou	Risk[a]
Forest Attributes	Proportion of older forest	Wildfire frequency	Reduced area in large patches of older, conifer dominated forest reduce ability of caribou to separate themselves spatially and temporally from predators.	++
	Proportion of conifer forest	Wildfire frequency and intensity		++
	Size of patches of older forest	Wildfire frequency		++
	Forest community distribution	Growing season length, growing season precipitation drought frequency	Relative distribution and abundance of browse producing stands influences alternate prey species abundance or distribution.	?
	Forest stand mortality	Insect infestation rates and frequency of severe wind or snow events	Blowdown and breakage of trees impedes travel and visibility while increasing fire risk.	+
Disease	Distribution of alternate hosts and carriers	Winter severity, snow depth, snow-free period (deer range expansion)	If extreme winter weather frequency is enough to minimize deer range expansion and fire frequency, fire intensity and drought cycles are significant enough to depress gastropod populations, *P. tenuis* may not increase risk in study area. Otherwise risk increases.	+/-
Predation Pressure	Numbers of alternate prey	Suitable habitat for moose, white-tailed deer	Increased area covered by early successional forests increases moose and deer numbers inducing a functional response by wolves and coyotes (increased predator numbers).	+
	Distribution of Alternate prey	Wildfire frequency and distribution, winter severity, winter temperatures, snow depth, extreme weather events	Fire will increase early successional habitats beneficial to moose and deer but will reduce older forest components necessary for coping with extreme winter weather events. Deer and moose both respond to severe winter weather conditions concentrating in most suitable habitats. Caribou refuge habitats with low abundance of alternate prey will become smaller and less abundant.	+
	Predator efficiency	Winter severity, winter temperatures, snow depth, extreme weather events	Extreme weather favors caribou more than moose and deer. Heavy snow years may also concentrate deer and wolves that prey on them yielding a spatial separation from caribou. Longer growing season and increased forest disturbance could increase black bear abundance and caribou encounters.	+
Compensatory Forest Management Practices	Harvest levels	No direct climate effect	If wood flow is maintained despite increased fire losses, there will be increased pressure on older forest components	+
	Age of stands harvested	No direct climate effect	Shorter rotations for upland stands will reduce effective time period for larger areas of older forest to provide for caribou habitat	+
	Intensified silviculture activities	No direct climate effect	Increased forest productivity may reduce terrestrial lichen abundance and distribution in mature and developing stands. Increased road construction and maintenance may support predator mobility across landscape. Competition control to enhance conifer crop tree growth may enhance refuge value	+ /-
	Fire Suppression Effort	No direct climate effect	Increased fire suppression efforts to maintain wood supply may also help maintain older conifer forest components important for maintaining caribou. Resources available for managing wildfire activity may or may not change proportionate to fire risk.	-
Thermal Stress	Thermal stress	Spring and summer temperature extremes	Despite increased ambient temperatures, caribou have abundant access to environments with water-moderated temperatures and ready access to water for consumption.	+

[a] ++ large increase in risk, + higher risk, - lower risk, ? unknown change in risk, +/- increased risk assumed but may be reduced risk if alternate assumptions are more important than presently thought.

thought. These projections, generated by inference from findings in published literature, are intended as testable hypotheses for future debate, investigation and analysis. There is no implied level of accuracy or precision.

Discussion

Modelled climate change projections are generalized over large areas and demonstrate substantial continental variation. They suggest northeastern Ontario may not warm as dramatically as NW Ontario, and the climate may become drier towards the Manitoba border (Parker *et al.*, 2000). The size, location, unique biophysical landscape and projected climate response of NW Ontario justifies its role as a unique study area for examining the implications of climate change on woodland caribou.

Conservation of woodland caribou depends on maintaining risk factors at levels compatible with maintaining range occupancy. The objective for conserving caribou landscapes subject to forestry is to maintain a continuous supply of suitable, mature, year-round habitat distributed both geographically and temporally across the landscape in such a manner as to ensure permanent range occupancy (Racey *et al.*, 1999). This objective recognizes that woodland caribou have evolved to cope with a naturally dynamic boreal forest that includes predators. The premise behind this objective is that the overall forest landscape provides refuge from predators and disease. The landscape provides a context for relative abundance and distribution of predators, availability and distribution of alternate prey species, escape opportunities and separation from disease agents. It also provides a context for caribou forage opportunities. Factors that change the forest landscape in a manner that increases risk, reduce the likelihood that caribou range occupancy can be maintained. Considerable interaction among factors is expected, and this interaction is likely to be complex. It is also likely that some factors have both positive and negative implications for caribou. Speculation on relative importance of one factor over another and the consequences for caribou survival can only be made within the context of existing, incomplete scientific understanding supplemented by logical inferences to "fill-the-gaps."

Forest attributes

Forest modelling results

Forest modelling suggests a major shift in forest composition leading to a future forest with less area in older, conifer dominated forests which currently characterize landscapes that contain woodland caribou. These older conifer forest types are an important component of both winter and summer caribou habitat. The reduction in older forest usually results in a landscape dominated by younger stands of hardwoods and jack pine. This general shift in age class structure and forest species composition is presumed to increase risk by reducing the refuge value of the landscape. However, spatial arrangement or pattern of forest types is generally recognized as important for refuge value (Racey *et al.*, 1999). Especially important are large contiguous areas of relatively old conifer forest associated with lichen-rich woodlands, shallow-soil dominated forests and forested peatland complexes. Although the model results are not spatially explicit, an increase in number of escaped fires will not only change the proportion of young and old forest, it will also likely reduce the number and extent of large contiguous tracts of older conifer dominated forest. It is anticipated that the reduction in availability of older forest will increase public pressure for social and economic trade-offs with caribou conservation, due to the need to maintain flow of wood to the forest products industry. These trade-offs will likely result in increased forest fragmentation because forest companies will have to apply greater selectivity to access wood in specific age classes (the forest models suggest most stands must be harvested at 65–75 years of age to maintain wood flow), and with high-quality fiber attributes. Collectively, the potential reduction in the proportion of larger tracts of older conifer forest, and an increase in forest landscape fragmentation could result in a biologically significant reduction in caribou refuge value across the landscape.

In ecoregions 3S and upper 3W, the reductions in conifer forest were not as great as ecoregion 4S, attributed in part to the fact there was no expectation for the models to "generate" wood from the NBI area. Under this scenario, there was a minor increase in caribou habitat availability. However, in the foreseeable future, there will be demand for wood products from this area and the projections for caribou habitat and older conifer forest may be more similar to the results for 4S. As this area represents the "heart" of current occupied caribou range, the potential combined impacts of forest harvest and increase in area burned might have substantial negative impacts on forest types that serve to provide caribou with refuge from predators. The combined effects of increased fire under an 80% increase in area burned scenario and the effects of a forest products driven management system essentially eliminated the older conifer forest and virtually all caribou habitat potential. If such a scenario actually occurs and there are no dramatic changes in forest product demand or economic expectations, managers will have to make the tough choice between caribou survival and the maintenance of the forest industry as we now know it. However, if sustainable forest management adapts thoughtfully to the changing climatic and ecological context, a suitable balance may be struck among harvest levels, natural disturbance and habitat values that could sustain caribou on a managed landscape. A comprehensive ecosystem-based approach to management of the forest landscape may be essential for the survival of both caribou and the forest industry.

Inferences should be tempered with caution. Many factors, singly and in combination, contribute to the fire regimes demonstrated in NW Ontario (Li, 2000). The estimates of change in forest cover and age class presented here are considered conservative, recognizing the crude fire-change estimates of Wotton *et al.* (2003) which did not account for increased lightning activity and other weather pattern phenomena that would also contribute to increased fire activity. Estimates of the increase in area burned are for northern Ontario, but the increase for NW Ontario is expected to be greater than northeastern Ontario. In addition, these estimates were for the zone of intensive fire management that represents only a portion of the caribou range in NW Ontario. The remainder of the forest might be expected to exhibit even greater increases in area burned. Risk to caribou would increase at least in proportion to, and possibly exponentially with the amount of area disturbed by fire and logging.

The general relationship between forest cover, age class and caribou is thought to be fairly well understood (Racey *et al.*, 1999). Wildfire has a direct impact on temporal expression and use of habitat by woodland caribou (Schaefer & Pruitt, 1991). However, indirect implications of climate change for habitat relationships may be reflected in successional relationships (Kenkel *et al.*, 1998) and silvicultural practices (OMNR, 1997) that are likely to respond to ecologically and commercially significant changes in the composition and productivity of forests (Reed & Desanker, 1992).

Forest community types and distribution

Changes in forest plant communities are difficult to forecast because they relate to a multitude of factors and interactions such as frequency and intensity of wildfire, rates of nutrient cycling, growing season length and growing season precipitation. The greatest risk to caribou, independent of changes to the broad forest cover and age class distribution, is a general increase in shrub or herb richness of sites. Greater occurrence of desirable moose browse species in mature forest communities may make the landscape more desirable for moose, leading to an increase in abundance of alternate prey for wolves.

Generally, forest conditions sampled in ecoregion 3S (Racey, 2001), home to some of the healthiest populations of woodland caribou in NW Ontario (Racey & Klich, 2003), suggest a higher proportion of low-diversity vegetation community types. Among the species most conspicuous in their absence are beaked hazel (*Corylus cornuta*), mountain maple (*Acer spicatum*), balsam fir (*Abies balsamea*) and pin cherry (*Prunus pensylvanica*), which tend to be major contributors to browsable biomass for moose elsewhere in NW Ontario (Rempel *et al.*, 1997a). A possible explanation for the reduced occurrence of some of the more herb and shrub rich vegetation types as described by (Sims *et al.*, 1989) is the aggressive fire regime exhibited within the ecoregion (Racey, 2001), particularly on shallow or deep sandy soils. While increased growing season length may favor herb and shrub growth, the potential increase in fire frequency and intensity may discourage these species at the landscape level. Climate change may also disrupt the expected occurrence and structure of vegetation types due to the tendency for species to migrate singly rather than as intact plant communities (Peters, 1990). If, at the landscape level, climate change favors the development of browse producing species, an increase in mixed forest conditions and a reduction in the frequency and distribution of low-diversity stands normally used by caribou, increased risk would be expected. On the other hand, if increased fire frequency, intensity and drought cycles maintain the proportion of lower-diversity forest types exhibited, then the level of risk associated with abundance and distribution of forest community types may not change much.

Disease

The primary disease agent of concern with climate change is *P. tenuis*. This parasite is fatal to caribou (Trainer, 1973), is carried by white-tailed deer and uses terrestrial gastropods as intermediate hosts. Deer range in NW Ontario has fluctuated widely over the past 70 years, most likely due to among-year variation in winter severity. In the study area, white-tailed deer range in 2003 approximates range extent in the 1940s (J. Van den Broek, pers. comm.) but was greatly reduced between the late 1960s through to the 1980s. These range expansions correspond to 2 general warming trends separated by a cooling trend. Biologists speculate that white-tailed deer range will continue to expand under a warmer climate. But winter severity is a major limiting factor for white-tailed deer (Hepburn, 1959) partly attributed to over-winter condition but mostly due to their susceptibility to predation (DelGiudice *et al.*, 2002). Climate change scenarios for increased snowfall and bigger storm events especially in middle and higher latitudes (Francis & Hengeveld, 1998), combined with a reduction in the proportion of older conifer forest suggest that white-tailed deer may continue to be limited by sporadic severe winter conditions.

Little is known of the ecological requirements of the gastropod intermediate hosts for *P. tenuis.* However, in Newfoundland, Ball *et al.* (2001) found that infection rates of *Elaphostrongylus rangiferi* in caribou had a positive correlation with mean annual minimum temperature, and a negative correlation with mean summer temperatures. The risk of infection increased with moderate summer temperatures suitable for the activity and infection of gastropod intermediate hosts and by mild winters with little snow that extended the transmission period. It is possible that hotter, drier conditions and severe fire events projected with climate change, particularly on the very shallow, sandy soils common in NW Ontario may not be conducive to either the abundance or the activity of intermediate host gastropods.

As white-tailed deer populations are able to recover more quickly than caribou when suitable conditions prevail, and as there is great uncertainty regarding the response of terrestrial gastropods, I suggest that risk to caribou may increase provided terrestrial gastropod populations are not significantly inhibited by the occurrence of drought, intense fire, and shallow and dry soils in the study area.

Predation

Ontario caribou managers believe that direct and indirect causes of increased predation pressure, as described by Bergerud (1974; 1996), Bergerud *et al.* (1984) and Seip (1992) are a highly significant factor in caribou decline. Caribou cope with predators through range use and habitat selection at various spatial scales (Rettie & Messier, 2000; 2001; Johnson *et al.*, 2002). We assume predator numbers in existing woodland caribou-occupied forest ecosystems will respond to increased availability of alternate prey such as white-tailed deer or moose. Increased predator numbers will place caribou at risk. The degree of risk will depend on the size of increase in predator numbers in response to the available ungulate prey and the increase in predator efficiency. It is the number and distribution of alternate prey that is expected to respond to climate-induced environmental changes.

In the absence of hunting, moose respond positively to younger forest resulting from both logging and natural disturbances (Rempel *et al.*, 1997b). The frequency of forest disturbance and area of disturbed forest is expected to increase under the modelled climate change scenario and the proportion of older forest is expected to decrease. However, even with lower hunting pressure in northern wildlife management units, moose populations have not responded in the more northern portions of the managed forest in Ontario (McKenney *et al.*, 1998).

Increased proportion of younger forests as a result of increased fire activity may favor some aspects of moose habitat quality. However, moose may actually decline in some parts of their range because of changes in landscape structure (Thompson *et al.*, 1998). Cursory examination of forest stand composition and structure in the NBI area suggests that the aggressive fire regime experienced in the past may actually maintain forest conditions less desirable to moose because of a reduction in some preferred browse species such as white birch (*Betula payrifera)*, red-osier dogwood (*Cornus stolonifera)*, mountain maple, and serviceberry (*Amalanchier* sp.) (Racey, 2001). It is uncertain if increasing the intensity and frequency of fires in this system will reduce or enhance the quality of moose habitat in the manner described by Rempel *et al.* (1997b), but I suggest that it is more likely that moose browse production will increase through an increase in younger, hardwood and shrub–dominated forest types. The increased proportion of disturbed forest, shrub-rich forest, and a longer growing season may also increase mast availability for black bears *(Ursus americanus)* and increase the length of time black bears are active. Increased activity periods may increase encounter rates with caribou calves.

An additional factor may be the incidence of heat stress imposed by increasing frequency of hot spring and early summer conditions. Moose begin to experience thermal stress at 14 °C with full open-mouth panting at 20 °C (Renecker & Hudson, 1986; 1990). This may be particularly significant in spring and early summer when the greatest increases in temperature are expected and may increase the number of days each year when moose are exposed to heat sufficient to depress foraging activity and weight gain as described by Renecker & Hudson (1986). Increased spring and summer temperatures would be expected to add stress to moose populations at the southern edge of their range. This may provide a small mitigating factor affecting some alternate prey within caribou range.

Winter habitat selection tends to be associated with larger contiguous tracts of older conifer forest and major wetland complexes (Racey & Klich, 2003), likely in response to lower risk of predation (Rettie & Messier, 2000). Modeled forest composition shows a decline in older conifer forest which may increase the evenness of moose distribution, and reduce the size and extent of old forest patches that provide limited refuge for caribou. Even if the absolute increase in alternate prey and predators is lower than forecast, the reduction of refuge and more even distribution of predators may increase risk to caribou by increasing encounter probabilities. I believe this is a very important risk factor unless countered by an increase in winter severity.

Deep snow, crusting conditions and severe weather may negatively impact white-tailed deer populations by concentrating wintering herds, increasing susceptibility of deer to predation (Fuller, 1991) and imposing nutritional constraints (DelGiudice *et al.*, 2002). The degree to which white-tailed deer contribute to abundance of alternate prey may not be significant if wintering herds are highly concentrated or if they are subject to periods of increased predator or weather-related mortality. It is unlikely that white-tailed deer winter habitat overlaps substantially with the forest types described by Ahti & Hepburn (1967) or Racey *et al.* (1989).

Compensatory forest management practices

Forest management practices are expected to adapt to increased fire frequency, increased forest disease, altered nutrient cycling and to maximize carbon storage in the boreal forest. Parker *et al.* (2000) suggest that managing species on relatively short rotations may be preferable for upland tree species. They also suggest the potential use of partial cutting systems, greater emphasis on artificial regeneration, and further analysis of the net benefits of thinning and fertilization. Shorter rotations would combine with fire to reduce the amount of older forest on the landscape. Efforts to increase forest or site productivity may have negative impacts on terrestrial lichen availability on shallow or sandy soils that normally support abundant terrestrial lichen communities (Sims *et al.*, 1989; Racey *et al.*, 1989) by increasing canopy closure of crop trees and herbaceous species thus reducing exposure to sunlight, one of the most important requirements for lichen establishment and growth (Ahti & Hepburn, 1967; Johnson, 1981). Some resource managers are concerned that the increased road networks and road maintenance periods associated with more harvesting activity or intensified silvicultural approaches may also increase the movement or effectiveness of predators in caribou range thus increasing risk in a manner similar to that suggested by Dyer *et al.* (2001) or James (2000). With the exception of increased fire protection effort, most compensatory forest management practices will increase expected risk to caribou.

Thermoregulation

Experimental evidence on caribou shows measured physiological response to heat at temperatures of 35 °C and above (Yousef & Luick, 1975). With the increasing frequency of warm days, the number of days per year caribou might have to devote to minimizing heat stress will also increase. Rosenmann & Morrison (1967) suggested that caribou have good capacity for heat resistance when water is available. The abundant lakes, rivers and wetland complexes associated with summer habitats in NW Ontario offer abundant free water, aquatic refuge and water-cooled environments to assist caribou in coping with heat stress. Risk to caribou may increase if high temperatures are combined with human or predator disturbance, causing caribou to remain active during warm weather.

Conclusions

Climate change as described in current projections will almost certainly increase risk to woodland caribou survival in NW Ontario. Many of the factors that contribute to increased risk likely apply similarly to other jurisdictions such as Manitoba and northeastern Ontario. Much uncertainty remains, not only in the projections for climate change, but in the response of forest and wildlife communities to climate change. At the same time as our appreciation of this uncertainty grows, land use and resource management decisions (wood supply commitments, forest harvest, regeneration efforts and desired future forest condition in terms of forest pattern and composition) are being made under current assumptions of forest dynamics and wildlife habitat relationships. The time frame for climate change to have an impact on current assumptions is probably less than the time required to realize the outcomes of our current management decisions. If we are to maintain our commitment to conserve woodland caribou in NW Ontario, a sustained emphasis on caribou recovery conservation efforts must be precautionary, practical, responsive and visionary.

Precautionary

We must live with the uncertainty of modelled projections and recognize that they may be wrong. But we must err on the side of caution and develop management responses to higher-risk scenarios. Conversely we should develop plausible management alternatives for high risk caribou populations under the assumption that our climate change evaluation may be incorrect.

Practical

Management approaches based on the "best science" and augmented by precautionary assumptions need to be designed and implemented across the managed landscape. These approaches must be integrated across the disciplines of forestry, wildlife management, and sociology. Practical solutions must not pit caribou against all other development opportunities which, in a "take-it-or-leave-it" alternative may not favor caribou. The ultimate survival of both caribou and the forest industry may depend on a reasoned and adaptive ecosystem-based approach to management of the forest landscape.

Responsive (adaptive)

Measurable indicators of success for woodland caribou conservation, and indicators of desired future forest condition need to be established. Suitable measures of woodland caribou population health should be regularly monitored in order to determine, at the earliest opportunity, if conservation efforts have been successful or if additional or modified mitigation measures are required. Effectiveness should be evaluated at the landscape or "ecosystem" scale consistent with caribou range use in a dynamic boreal forest. Rigorous scientific investigation of the changing ecological context of caribou conservation is crucial.

Visionary

Bold approaches may be required to manage the relationship between various ecological, social and economic values represented in Ontario's boreal forest. These approaches may have to seriously examine societal response to threatened species, the role of the forest industry, and the notion of forest sustainability under plausible climate change scenarios. Managers have never before faced prospects of such systematic and far-reaching changes in the ecological context for the renewable resources and social benefits they try to sustain. Risk-taking is an important component of any visionary approach, including sustained recovery efforts on high-risk populations and the possible abandonment of populations that have no hope of maintenance even if climate change predictions and their negative impacts are wrong.

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