Biological Conservation 232 (2019) 238–252

Contents lists available at ScienceDirect

Biological Conservation

journal homepage: www.elsevier.com/locate/biocon

Conservation through co-occurrence: Woodland caribou as a focal species for boreal biodiversity

C. Ronnie Drever[a,*], Chantal Hutchison[b], Mark C. Drever[c], Daniel Fortin[d], Cheryl Ann Johnson[e], Yolanda F. Wiersma[f]

[a] The Nature Conservancy, Suite 308 - 100 Gloucester Street, Ottawa K2P 0A4, ON, Canada
[b] Department of Biology, McGill University, 1205 Docteur Penfield, Montreal H3A 1B1, QC, Canada
[c] Department of Forest and Conservation Sciences, University of British Columbia, 2424 Main Mall, Vancouver, British Columbia, V6T 1Z4, Canada
[d] Département de biologie, Université Laval, Pavillon Alexandre-Vachon, 1045, av. de la Médecine, Québec G1V 0A6, QC, Canada
[e] Environment Canada and Climate Change, Science and Technology, 1125 Colonel By Drive, Ottawa K1A 0H3, ON, Canada
[f] Department of Biology, Memorial University, St. John's A1B 3X9, NL, Canada

ARTICLE INFO

Keywords:
Woodland caribou
Boreal population
Systematic conservation planning
Species richness
At-risk mammals
At-risk birds
Canada

ABSTRACT

Understanding how conservation of woodland caribou, an at-risk species for which large undisturbed areas are often proposed to maintain viable populations, can contribute to conservation of boreal biodiversity is an important consideration for an ecosystem warming at twice the global average and experiencing rapid resource development. We assess the focal or 'umbrella' value of the boreal population of woodland caribou for conservation of mammalian and avian richness (n = 432) in the boreal region of Canada by (i) evaluating co-occurrence of caribou distribution with that of boreal mammals (n = 102), birds (n = 330), at-risk mammals (n = 11) and at-risk birds (n = 47); and (ii) conducting systematic conservation planning using MARXAN software to identify minimum representative and complementary reserve networks, comprised of planning units deemed large enough (10,000 km^2) for persistence of terrestrial wildlife, both at the extent of boreal caribou distribution and the entire boreal region. While boreal caribou overlap with the range of 90% of boreal birds and mammals, area-efficient networks representative of boreal diversity focus on species-rich areas south of caribou distribution and other areas that contain relatively small-ranged species. A similar pattern occurs when the MARXAN analysis focused only on caribou distribution, i.e. representative networks are preferentially located on southern herd ranges. However, this situation differs markedly to include large areas within the distribution of caribou if anthropogenic footprint on the landscape is considered as a constraint on reserve design. Efforts to sustain boreal caribou offer considerable opportunities to conserve diversity of co-occurring mammals and birds, including areas of the relatively more disturbed caribou southern ranges that have irreplaceable value in an efficient and representative pan-boreal network of reserves. The high focal value of boreal caribou for animal diversity should be considered when making decisions and policy choices about how to best allocate conservation efforts across its extensive distribution.

1. Introduction

As high-latitude ecosystems, boreal forests are experiencing rapid increases in annual mean temperature, in some regions at twice the rate of the global average (Hartmann et al., 2013). In combination with anthropogenic land use, these changes are altering the composition and structure of boreal forests around the world and testing the resilience of this ecosystem and its inhabiting people (Gauthier et al., 2015). Since the persistence of large mammals is a useful indicator for effective efforts to conserve biodiversity (Morrison et al., 2007), we examine how conservation planning for the boreal population of woodland caribou (*Rangifer tarandus caribou,* hereafter 'boreal caribou'), an at-risk, forest-dwelling ecotype experiencing declines throughout North America (COSEWIC, 2014), can influence efforts to conserve boreal biodiversity more generally.

The northward recession of caribou distribution in North America matches the 20th century expansion of the physical footprint of industrial forest development (Schaefer, 2003; Vors et al., 2007). The

* Corresponding author.
E-mail addresses: cdrever@tnc.org (C.R. Drever), chantal.hutchison@mail.mcgill.ca (C. Hutchison), Mark.Drever@canada.ca (M.C. Drever), daniel.fortin@bio.ulaval.ca (D. Fortin), Cheryl-Ann.Johnson@canada.ca (C.A. Johnson), ywiersma@mun.ca (Y.F. Wiersma).

https://doi.org/10.1016/j.biocon.2019.01.026
Received 19 November 2018; Received in revised form 22 January 2019; Accepted 25 January 2019
Available online 20 February 2019

principal threats to persistence of forest-dwelling boreal caribou include habitat loss and increased predation, the latter likely facilitated by road building (Dickie et al., 2017), forest harvesting and other activities that create early seral habitat beneficial for competitive ungulate species (Gagné et al., 2016). The increase in abundance of competitive species thereby increases caribou mortality by higher consequent abundance of wolves and other predators (Festa-Bianchet et al., 2011), that is, apparent competition (Holt, 1977).

Due to the association between forest disturbance and caribou decline, conservation of large interconnected areas is often proposed as necessary for the persistence of caribou (Courtois et al., 2007). If efforts to conserve boreal caribou include the protection of large forest areas from industrial activities, it is instructive to understand the value of these actions for conservation of other species by assessing how representative reserve networks overlap with caribou distribution and thereby protect boreal caribou alongside the larger suite of boreal biodiversity.

Systematic conservation planning addresses the question of how best to allocate limited resources to build optimal reserve networks that meet a set of conservation objectives while minimizing costs (Margules and Pressey, 2000). The reserve network is optimally designed with consideration for biodiversity over the entire area, using the principle of complementarity. The complementarity principle requires design of reserve networks to optimize how individual sites ('planning units') are complementary to each other and together best represent species not found at other sites, thereby generating a reserve design that is greater than the sum of the parts. We use the optimality framework generated by MARXAN software (Ball et al., 2009) to evaluate the degree to which complementary representation of richness of boreal mammals and birds might strategically overlap with caribou distribution across the 57 local populations (ranges) identified by Environment Canada (2011) (Fig. 1). Our assumption is that high priority sites for reserves identified by MARXAN can include the most biodiverse areas in the boreal for the taxa analyzed. This assumption rests on the notion that the 'minimum site set' problem the MARXAN algorithm seeks to solve will, by design, focus on planning units with the highest richness. We focus on a minimum set of complementary sites to gain insight into how spatial patterns of species distributions should influence an efficient network and protected areas design at the biome level. In addition, examining how an optimal reserve network in caribou distribution overlaps with the different boreal populations can help to determine which ranges might be associated with priority sites, and therefore have similar value as above for biodiversity conservation throughout the distribution of boreal caribou. Our analysis does not specifically address how the present system of boreal protected areas fits with our findings, although we expect the work can be useful in this regard.

Our objectives were to evaluate co-occurrence of the distribution of boreal caribou with (i) mammals, birds, and at-risk mammals and birds, and (ii) efficient, complementary reserve networks, identified through systematic conservation planning, that represent the full suite of boreal mammals and birds, in the boreal region in its entirety as well as in boreal caribou distribution. A comparison between the entire boreal region and that of caribou alone allows insight into both the umbrella value of caribou as well as what is not conserved, on the basis of spatial overlap, by efforts to conserve boreal caribou. Our focus was on minimum, representative and complementary networks of reserves, comprised of areas large enough to do so effectively (i.e., 10,000 km^2). This scale of planning was chosen as it is consistent with minimum reserve area required by terrestrial mammals so that reserves do not lose species due to insularization (Gurd et al., 2001) and larger than the minimum dynamic reserve area estimated for major classes of boreal plant communities (Leroux et al., 2007).

While caribou conservation also includes strategies such as silviculture to maintain conifer dominance (Fortin et al., 2011; Courtois et al., 2008), predator control (Hervieux et al., 2014) or other stewardship and management activities (e.g. Cornwall, 2016), our focus is on the role of large conservation areas and the degree to which a representative and efficient reserve network can overlap the distribution of woodland caribou. In addition, we focus on at-risk species to identify possible simultaneous opportunities for recovery planning of multiple mammals and birds (Environment and Climate Change Canada, 2018). We target mammals and birds because management strategies for effective protection of woodland caribou are of similar spatial and temporal magnitude, in contrast to insects or fungi (Kerr, 1997). Moreover, relative to birds and mammals, there is little variation in richness of amphibians and reptiles across the boreal region or the distribution of woodland caribou (Warman et al., 2004).

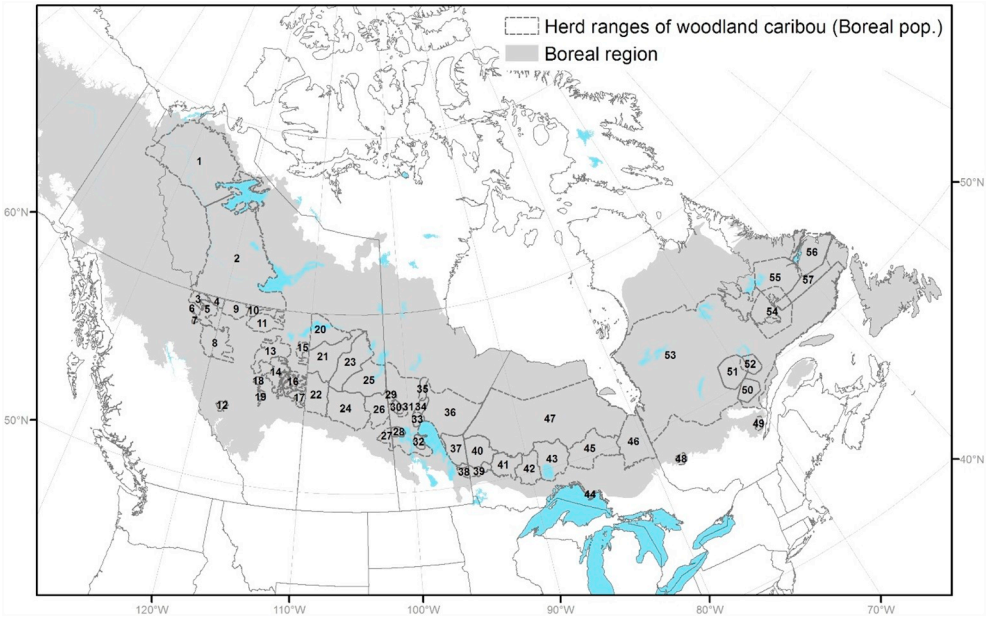

Fig. 1. Boreal region of Canada (Brandt, 2009) and herd ranges of the Boreal population of woodland caribou. Numbers indicate herd names: 1-Northwest Territories North, 2-Norwest Territories South, 3-Maxhamish, 4-Calendar, 5-Snake-Sahtahneh, 6-Parker, 7-Prophet, 8-Chinchaga, 9-Bistcho, 10-Yates, 11-Caribou Mountains, 12-Little Smoky, 13-Red Earth, 14-West Side Athabasca River, 15-Richardson, 16-East Side Athabasca River, 17-Cold Lake, 18-Nipisi, 19-Slave Lake, 20-Davy-Athabasca, 21-Clearwater, 22-Primrose-Cold Lake, 23-Highrock-Key, 24-Smoothstone-Wapawekka, 25-Steephill-Foster, 26-Suggi-Amisk-Kississing, 27-Pasquia-Bog, 28-The Bog, 29-Kississing, 30-Naosap, 31-Reed, 32-North Interlake, 33-William Lake, 34-Wabowden, 35-Wapisu, 36-Manitoba, 37-Atikaki-Bernes, 38-Owl-Flinstone, 39-Sydney, 40-Bernes, 41-Churchill, 42-Brightsand, 43-Nipigon, 44-Costal, 45-Pagwachuan, 46-Kesgami, 47-Far North, 48-Val-d'Or, 49-Charlevoix, 50-Pipmuacan, 51-Manouane, 52-Manicougan, 53-Quebec, 54-Lac Joseph, 55-Red Wine Mountain, 56-Mealy Mountain, 57-Labrador.

2. Methods

2.1. Richness mapping

We developed a spatial dataset of extent of occurrence for mammal (n = 102) and bird (n = 330) species in Canada's boreal region based on Warman et al. (2004). Warman et al. (2004) determined presence of common and listed species in terrestrial Canada by overlaying digitized range maps on a grid composed of 10,000 km^2 hexagonal 'planning units' and counting as present any species with range intersecting the planning unit. Warman et al. (2004) relied on Ridgely et al. (2003) for bird distributions. We updated mammal distributions by overlaying range maps from Patterson et al. (2007). We also updated the data on at-risk mammals and birds based on distributions of species listed as Endangered, Threatened or Special Concern by the Committee on the Status of Endangered Wildlife in Canada (COSEWIC) using range maps digitized from recent species-specific assessment reports available at the Public Registry for Species at Risk (Government of Canada, 2017). We relied on Environment Canada (2011) for range information of boreal woodland caribou (Fig. 1). We clipped this grid to the boreal boundaries mapped by Brandt (2009) and removed all water bodies larger than 10,000 km^2 (Fig. 2). The clipping produced a set of 680 planning units at the extent of the boreal region, some with varying sizes along the perimeter of the study region or large lakes.

2.2. Systematic conservation planning

We used MARXAN v. 2.43 (Ball et al., 2009) to map cost-efficient reserve networks that represent all the species in our dataset. MARXAN is an optimization tool widely used in systematic conservation planning to identify spatial reserve networks that meet pre-set biodiversity goals while minimizing 'cost' (see below for goal-specific definitions of cost). In other words, MARXAN seeks to solve the minimum set problem of reserve design: what is the minimum number of sites necessary to represent all species at the least cost? As mentioned, MARXAN uses complementarity as a key design principle, i.e. planning units complement each other well if the species they contain are different, so in combination the planning units that compose the reserve network together achieve comprehensive representation in an efficient manner. The software finds optimal reserve networks by running a user-defined number of iterations aimed at minimizing the following objective function where trade-offs among feature penalties, spatial design and cost are considered:

$$\text{Objective function} = \sum \text{Planning units Cost} + \text{BLM} \sum \text{Planning units Boundary} + \sum_{\substack{\text{Conservation} \\ \text{Feature}}} \text{SPF} \times \text{Feature penalty} \quad (1)$$

where BLM is the Boundary Length Modifier and SPF is the Species Penalty Factor (see explanation below).

MARXAN seeks to minimise the cost of all the planning units included in the reserve network while incorporating penalties on solutions that do not reach the set target for all the conservation features (Feature Penalty, weighted by Species Penalty Factor, SPF). We programmed MARXAN to meet the following targets for all mammal or bird species ('conservation features' in MARXAN lexicon):

$$\sum_{i=1}^{N_f} x_i r_{ij} = 1, \forall \textit{ species } j \quad (2)$$

where the control variable x_i has value 1 for selected planning units and 0 for planning units not selected, and r_{ij} is an area-weighted occurrence of species j in site i. In principle, the reserve network should represent every mammal and bird species at least once (i.e. there is at least one planning unit worth of each species). By area-weighted, we mean that the occurrence matrix was normalized by the size of a planning unit (i.e. 10,000 km^2). We chose an area-weighted approach to compensate for the bias towards planning units on the perimeter which have smaller areas from being clipped by the boreal boundary.

The cost component of Eq. (1) has three parts. First, there is a penalty associated with each planning unit in the network. We programmed two different penalties for this component: i. area, where the cost of a planning unit is its geographic size in ha, and ii. landscape condition, where the cost of a planning unit is the percent of the planning unit area covered by human and industrial footprint (Fig. 2). To estimate the footprint of industrial disturbances, we used Global Forest Watch Canada (2014) 'access' dataset, a binary dataset of disturbed or undisturbed areas derived from Landsat (TM and ETM) satellite images by delineating all visible infrastructure and other industrial activities with a 500-m buffer (cf. Pasher et al., 2013).

The second component is the penalty for targets not being met, the

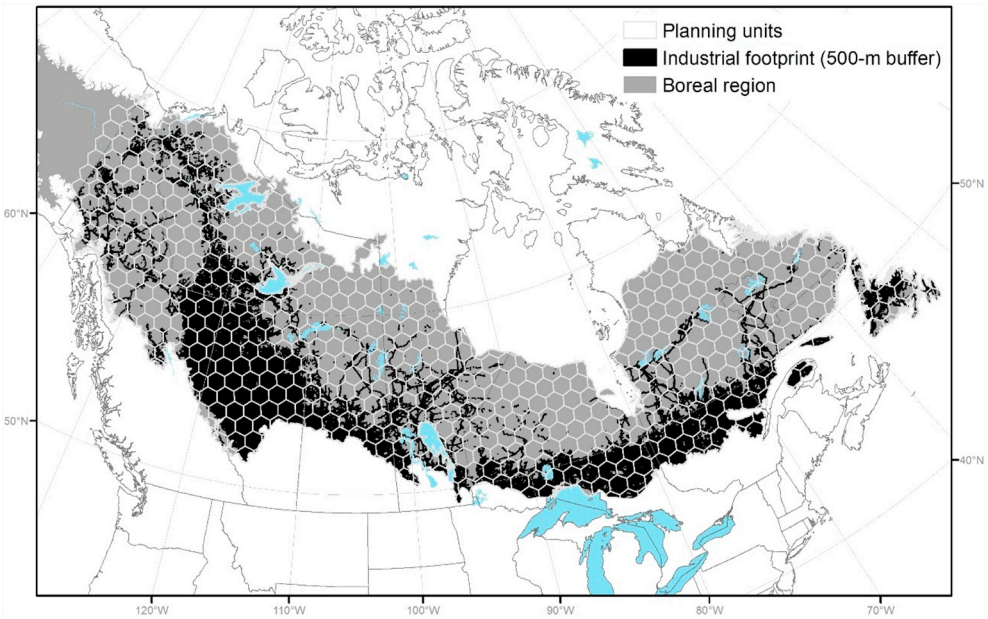

Fig. 2. Planning units and landscape condition as characterized by 500-m buffered footprint of human and industrial activity ('access'; Global Forest Watch Canada, 2014) in the Boreal region of Canada.

species penalty factor (SPF). We set SPF = 100 for all scenarios as this number is on the same order of the number of features (in this case, species) and for which the number of missing targets is at a minimum. Because we were interested in how caribou distribution overlapped with boreal mammal and bird diversity broadly, we did not modify the SPF by species. If we wanted to evaluate how caribou distribution overlapped with a particular species or group of species within the boreal set, we could have set the SPF differently for individual species. However, such an analysis was outside the scope of this paper. The third component of cost is a penalty associated with the shape or clumping of the reserve network, controlled by the Boundary Length Modifier (BLM). We set BLM = 0, meaning the algorithm ignored boundary length, based on the assumption that the large size of individual planning units is effective for biodiversity conservation and that compactness is not critical for reserve design given our research question and national scale of analysis.

We assessed the value of planning units in the overall reserve network design by examining how many times a given planning unit was included in the minimization solution. Planning units included in ≥90% of all runs (n = 200 with 1,000,000 iterations each) were deemed to have high value for representation in the boreal region because they were crucial to meeting the goal of all species having to be present in at least 10,000 km^2. We also mapped the 'best solution' (Nicolson et al., 2010), i.e. the one with the lowest value of the objective function and that represents the most efficient solution. Our aim was to evaluate whether high value areas occurred within the distribution of boreal caribou, and if so, where. This approach allowed us to understand how boreal-wide species diversity relates to that found only in boreal caribou distribution, which comprises approximately half of the boreal region (Environment Canada, 2012). A second analysis using the same representation targets as the first focused exclusively on the planning units that intersected the distribution of boreal caribou (n = 359), to understand in which ranges high-value areas occur for efficient representation of diversity of boreal mammals and birds.

3. Results

3.1. Distribution of mammal and avian diversity in Canada's boreal

Our biodiversity data (n = 432) showed a strong latitudinal gradient of richness throughout Canada's boreal region (Fig. 3). This pattern was apparent for both mammals (Fig. 3a) and birds (Fig. 3b). The 90% decile of total species richness occurred along a 200–500 km-band along southern boreal edge of Ontario to Alberta (Fig. 3c), while the 10% decile occurred along a 100–600 km-band of the northern boreal extent of Newfoundland and Labrador, Quebec and the Northwest Territories.

The distribution of boreal caribou contained 389 species or 90% of mammals (n = 95) and birds (n = 294) found in the boreal. The highest species richness (90% decile) occurred along the southern extent of caribou distribution in Alberta, Saskatchewan and Manitoba, while the lowest richness occurred in northern Quebec, coastal Labrador and the northern extent of caribou distribution in the Northwest Territories' Great Bear Lake region (Fig. 3c).

The distribution of at-risk mammals (n = 11; Fig. 4a) and birds (n = 47; Fig. 4b) varied across boreal Canada, with the highest richness (90% decile) for both taxa occurring in the southern edge of boreal Alberta, Manitoba, and Quebec (Fig. 4c). Thirty-seven of the 57 caribou ranges contained at least 10 at-risk mammals and birds. The lowest richness (10% decile) followed the same spatial northern pattern as for all species combined. Richness of at-risk taxa in caribou distribution was highest (90% decile) in the Charlevoix and Owl-Flinstone ranges (15 and 14 species, respectively) and lowest (10% decile, five species) in northern extents of the Quebec, Northwest Territories North and Northwest Territories South ranges.

3.2. Systematic conservation planning

In the first scenario, in which planning units had area-based costs, most planning units were selected with low frequency (< 10% of all runs) and planning units of high importance for a representative network (i.e. selected in ≥90% of all runs) occurred principally on the southern fringe of the boreal region from British Columbia to the island of Newfoundland (Fig. 5a). This scenario also included several planning units in the northern boreal extent, on the western shore of Hudson Bay, as well as in the Northwest Territories north of Great Bear Lake and Yukon-Alaska border region near the Old Crow flats. Areas of high selection by MARXAN intersected caribou distribution in the following herd ranges: Charlevoix, Owl-Flintstone and the Northwest Territories North. The best-fit solution (i.e. the reserve design that best met our representation target at the least cost) comprised 46 planning units covering approximately 17 M ha (Fig. 5a).

Twenty species did not meet the areal representation target, with < 10,000 km^2 in the reserve network identified as the best solution by MARXAN. This situation was due to the species having < 10,000 km^2 of range intersecting the boreal study area. These species were principally birds with small range overlap with the southern extent of the boreal region (e.g. Yellow-throated Vireo (*Vireo flavifrons*), Green-backed heron (*Butorides virescens*), Cinnamon Teal (*Spatula cyanoptera*)) or one of three mammals (Eastern red bat (*Lasiurus borealis*), Plains pocket gopher (*Geomys bursarius*) and Olive-backed pocket mouse (*Perognathus fasciatus*)) in the same situation. The planning units containing these species were selected in nearly all MARXAN runs and best-fit solutions, indicating a high degree of irreplaceability (a measure of the likelihood that a site will be required to represent each species in a planning region). Similarly, the planning units in the northern boreal extent chosen with high frequency corresponded to areas that contain rare species, such as Whooping Crane (*Grus americana*) in northern Alberta.

In the second scenario, in which cost was set by the percent of each PU covered by human and industrial footprint (landscape condition or "access"; Fig. 2), a different pattern emerged. While most planning units selected at high percentage by MARXAN also occurred on the southern fringe of the boreal region or the same high-frequency areas in the northern edges of study area selected in the first scenario (Fig. 5b), large areas were also selected with moderate frequency in the northern boreal, some within caribou distribution in Northwest Territories, Saskatchewan, Manitoba, Ontario, Quebec and Labrador. The best-fit solution in this scenario covered more area than the first, 59 M ha over 103 planning units.

When we constrained the analysis to caribou distribution and evaluated scenarios with area (Fig. 6a) or landscape condition (Fig. 6b) as cost, a similar pattern emerged to the analysis of the entire boreal region, i.e. MARXAN selected planning units principally along the southern extent of boreal caribou distribution, for instance, in the Val-d'Or, Charlevoix and Little Smoky ranges, as well as several planning units along the northern extent of caribou distribution in the Northwest Territories North herd. Using a cost function based on landscape condition indicated many areas in northern Ontario and Quebec also have value as part of a representative, complementary network of reserves in caribou distribution. The best-fit solution in these scenarios covered 35 M ha and 41 planning units (area-based cost) and 60 M ha and 68 planning units (landscape condition-based cost).

4. Discussion

Our findings indicate an area-efficient minimum reserve network that is representative of boreal birds and mammals in Canada should include the relative species-rich areas at the region's southern extent alongside northern areas that contain rare species found only there – areas that generally do not overlap with the distribution of boreal caribou. However, this pattern differs considerably when landscape

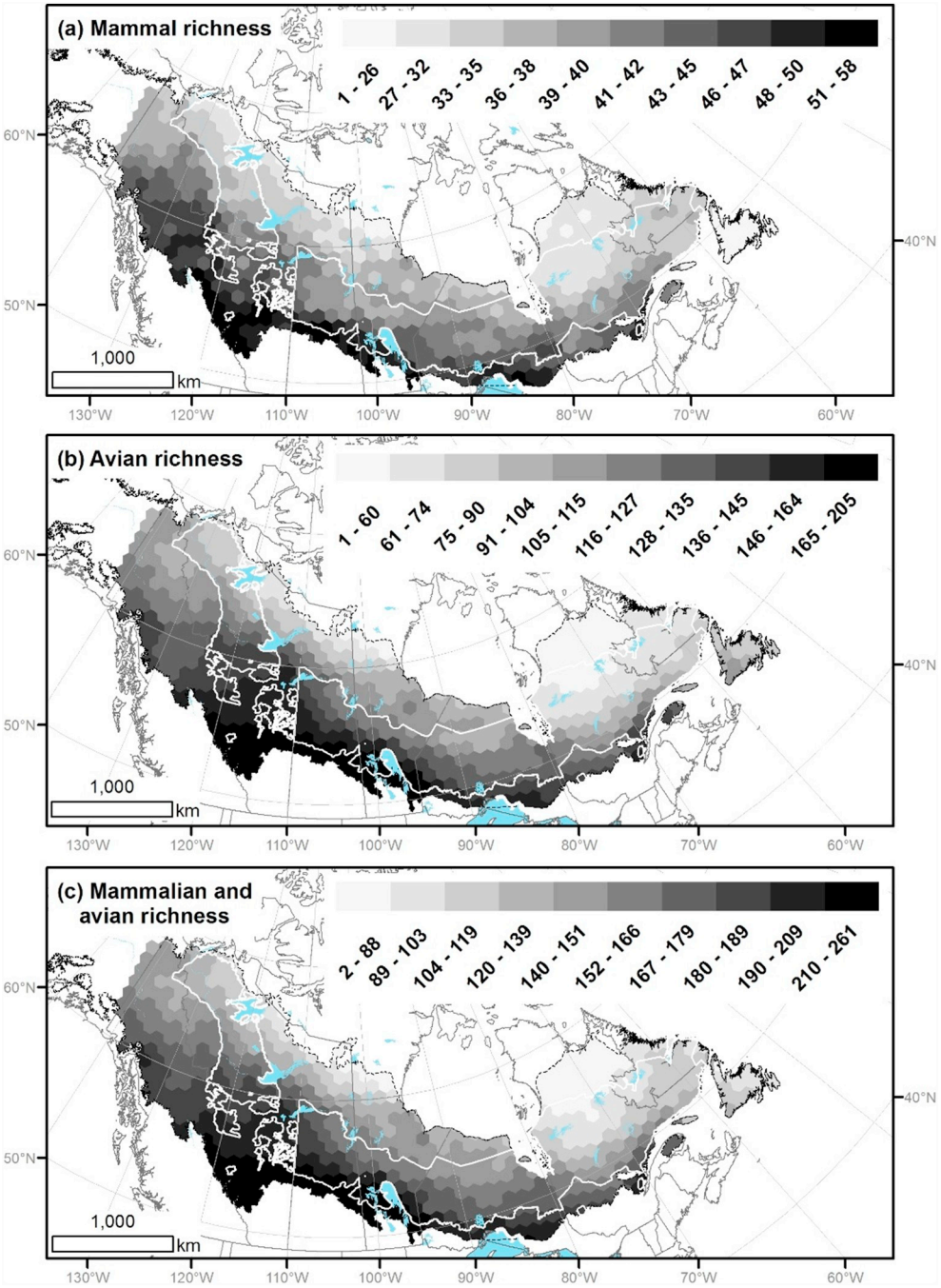

Fig. 3. Distribution of mammalian and avian richness in Canada's boreal region (data shown in deciles). White lines indicate the distribution of boreal caribou.

condition, as estimated by percent of industrial footprint in each planning unit, is considered as a cost on network design so that areas with low footprint are preferentially chosen. In this case, caribou distribution, especially in Ontario and Quebec, becomes important as part of a representative network for boreal avian and mammalian diversity. This finding, in conjunction with i. the fact that boreal distribution includes 90% of boreal bird and mammal species, ii. 65% of the 57 ranges in Canada's distribution of boreal caribou contain areas with > 10 mammals or birds considered at-risk, offering abundant opportunities to simultaneously conserve caribou and other imperilled fauna, and iii. Recent evidence that forest management practices aimed at maintaining caribou habitat can directly benefit other boreal fauna (Bichet et al., 2016), suggest that woodland caribou in Canada, like other mammals with wide public appeal (Di Minin and Moilanen, 2014), has high value as an umbrella species for boreal biodiversity.

Our finding that an efficient allocation of complementary reserves requires sites throughout the southern edge of boreal Canada is consistent with other studies and likely a consequence of the latitudinal diversity gradient. Warman et al. (2004) determined that irreplaceability was highest in southern Canada and a minimum set of sites to represent 793 species of various taxa was mostly along the southern extent of the International Boundary between USA and Canada. A meta-analysis (Andrew et al., 2014) examining studies of reserve networks in boreal Canada found sites in southern Canada are predominately selected by approaches that rely on systematic conservation planning. Given our findings, the ongoing northward recession of boreal caribou distribution by 34 km per decade (Schaefer, 2003) may be decreasing the representation value of caribou for diversity across the boreal

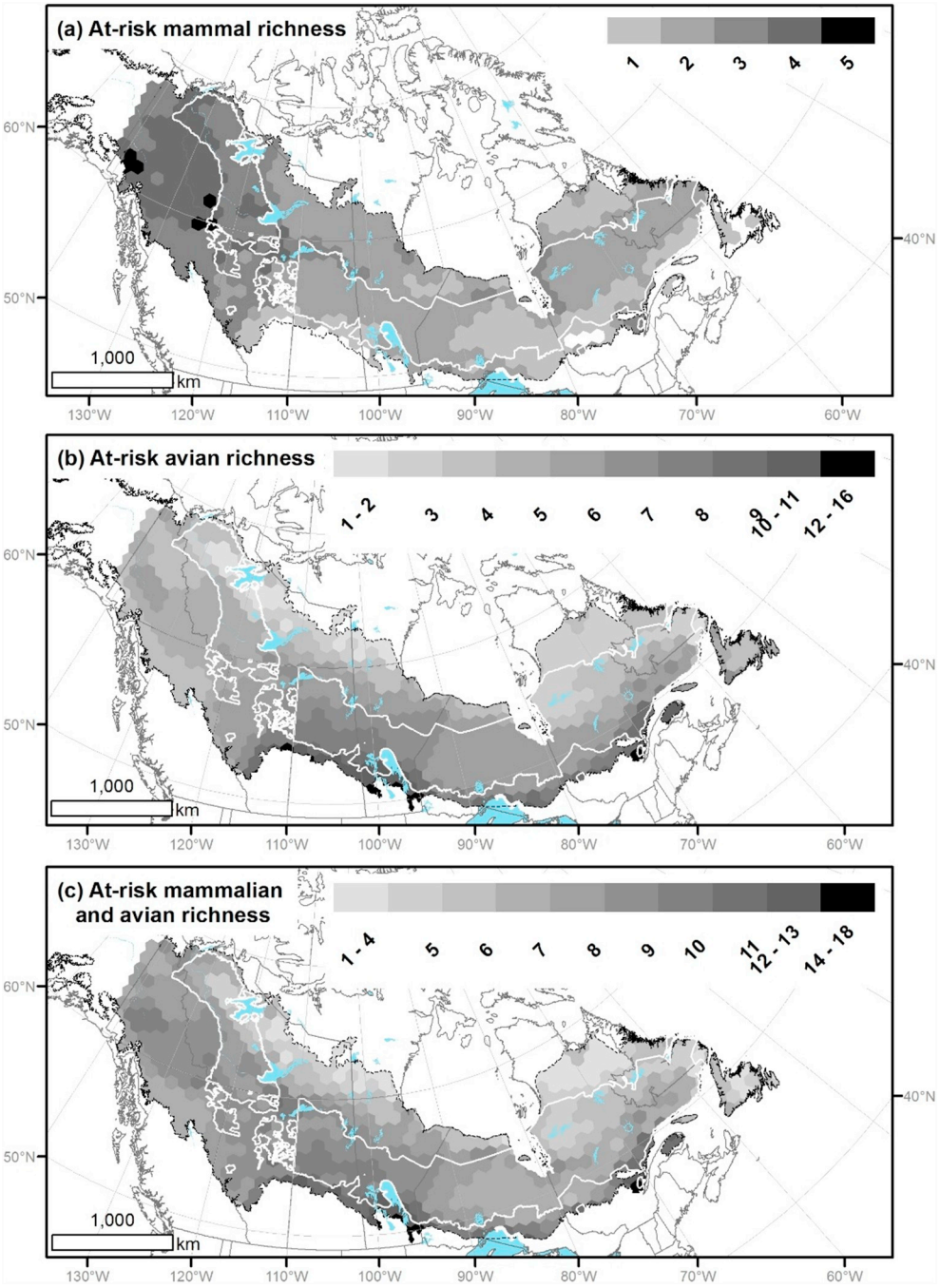

Fig. 4. Distribution of species richness of at-risk mammal and bird species in Canada's boreal region (data shown in deciles). White lines indicate the distribution of boreal caribou.

region. This situation underscores the value of not abandoning conservation efforts in the southern portion of the distribution. Irrespective of caribou outcomes, large-landscape conservation in these areas stands to improve prospects for the widest variety of boreal mammals and birds.

When considering the areas encompassed by caribou distribution and the 90% of the boreal mammal and bird species contained therein, we found high value for representation of boreal diversity in the Northwest Territories North herd, especially when landscape condition was included in the cost function. This range also has a high occurrence of at-risk mammals in its northwestern extent, providing opportunities for planning and conservation of multiple species with populations in jeopardy of extirpation or extinction.

Our analyses also indicate southern herds such as Charlevoix, Val-d'Or or Little Smoky have considerable value as part of a representative reserve network, a finding that did not change upon consideration of the impacted state of their ranges. Species in these ranges are found in no other areas of the boreal region (e.g. Bighorn sheep (*Ovis canadensis*); Black-throated blue warbler (*Setophaga caerulescens*)). The relatively high value of southern herds for boreal diversity should be accounted for by planners and managers when making triage decisions about allocation of scarce resources for caribou conservation. These decisions often imply abandoning efforts in the south where human disturbance footprint is expansive for a focus on northern ranges where conflicts with resource use are presently relatively lower and in which herds have higher probabilities of population persistence (e.g. Wilson

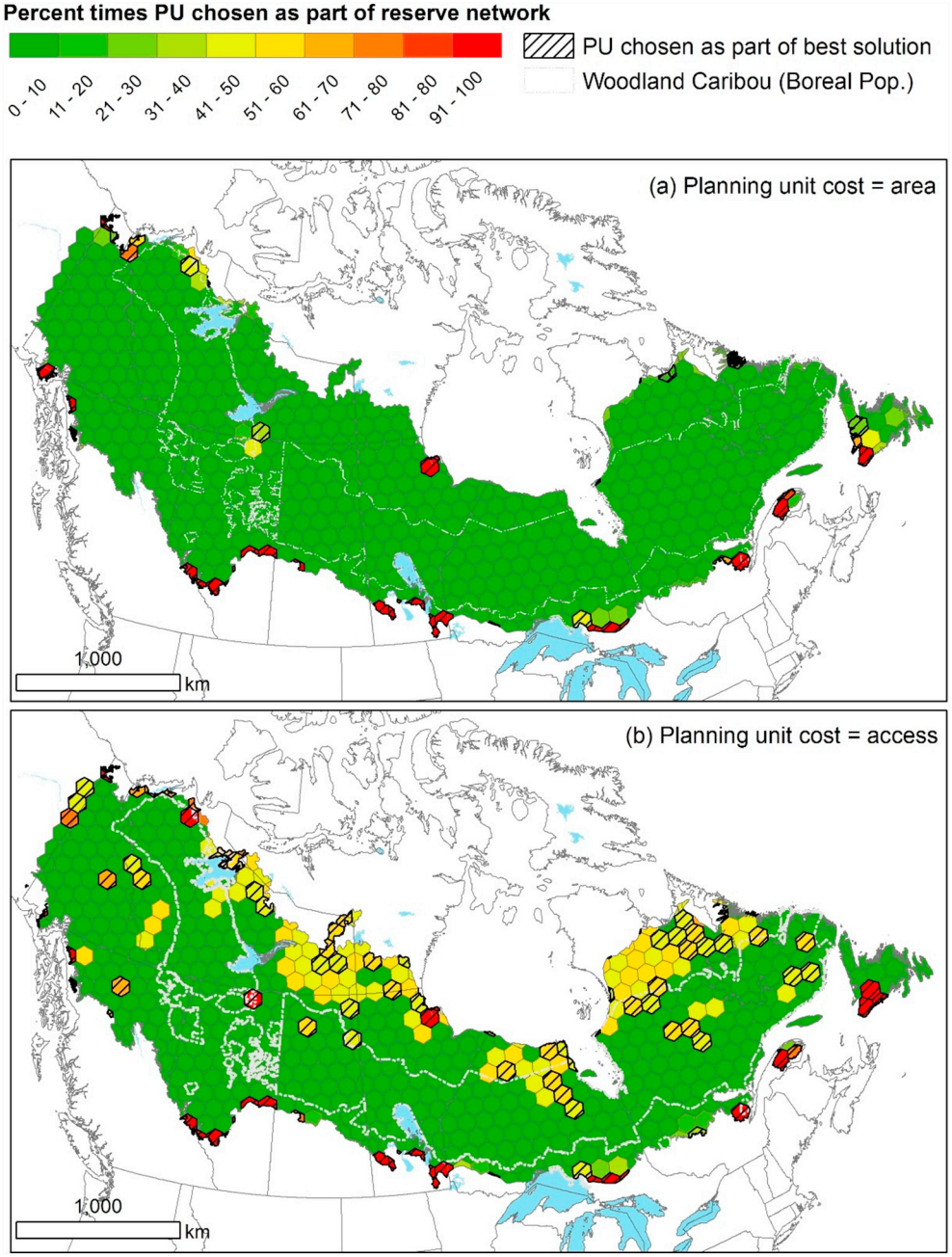

Fig. 5. Percent of times that planning units (PU) were chosen in optimal MARXAN solutions or selected in the best solution for a boreal-wide representative reserve network under two conditions: (a) PU cost set to area of each planning unit; and (b) PU cost function set as percent of PU area under industrial footprint ('access'). Gray dashed lines indicate the distribution of boreal caribou.

et al., 2011; Schneider et al., 2010). Recognizing the relatively poorer condition of many southern herds and that species richness is only one consideration in a complex process of decision-making regarding where to efficiently allocate conservation efforts, our observations indicate northern herds that represent at-risk species and southern herds that represent areas of high local species diversity should be considered priority sites that can optimize the strategic value of woodland caribou recovery for boreal-wide conservation.

Our approach has potential limitations. First, our reserve design is likely scale-dependent, either related to the size of the planning units (Kunin, 1997) or scale of input data (Rouget, 2003). We assume this scale dependence can be accounted for by choosing a spatial grain deemed large enough for persistence, i.e. our results provide an ecologically motivated scale for which caribou might act as a focal species for other taxa. This assumption is based on the ecological rationale for our planning unit size, i.e. it is larger than the area required for a reserve to not 'lose' mammal species due to habitat insularization in eastern Canada (2700 km^2; Gurd et al., 2001), the minimum size of effective reserves across Canada (3140 km^2; Wiersma et al., 2004) or the estimated minimum dynamic area for spruce forests in northwest Canada (3407 km^2; Leroux et al., 2007). Second, species richness does not necessarily capture the full biodiversity of any given area. Using relative abundance data would certainly be a valuable complementary approach. That said, richness remains a useful (and often the only available) proxy for biodiversity and captures dimensions of composition. To the best of our knowledge, relative abundance data or information on beta-diversity for all our focal taxa are simply not available at the scale of the boreal. Thirdly, identification of high value areas

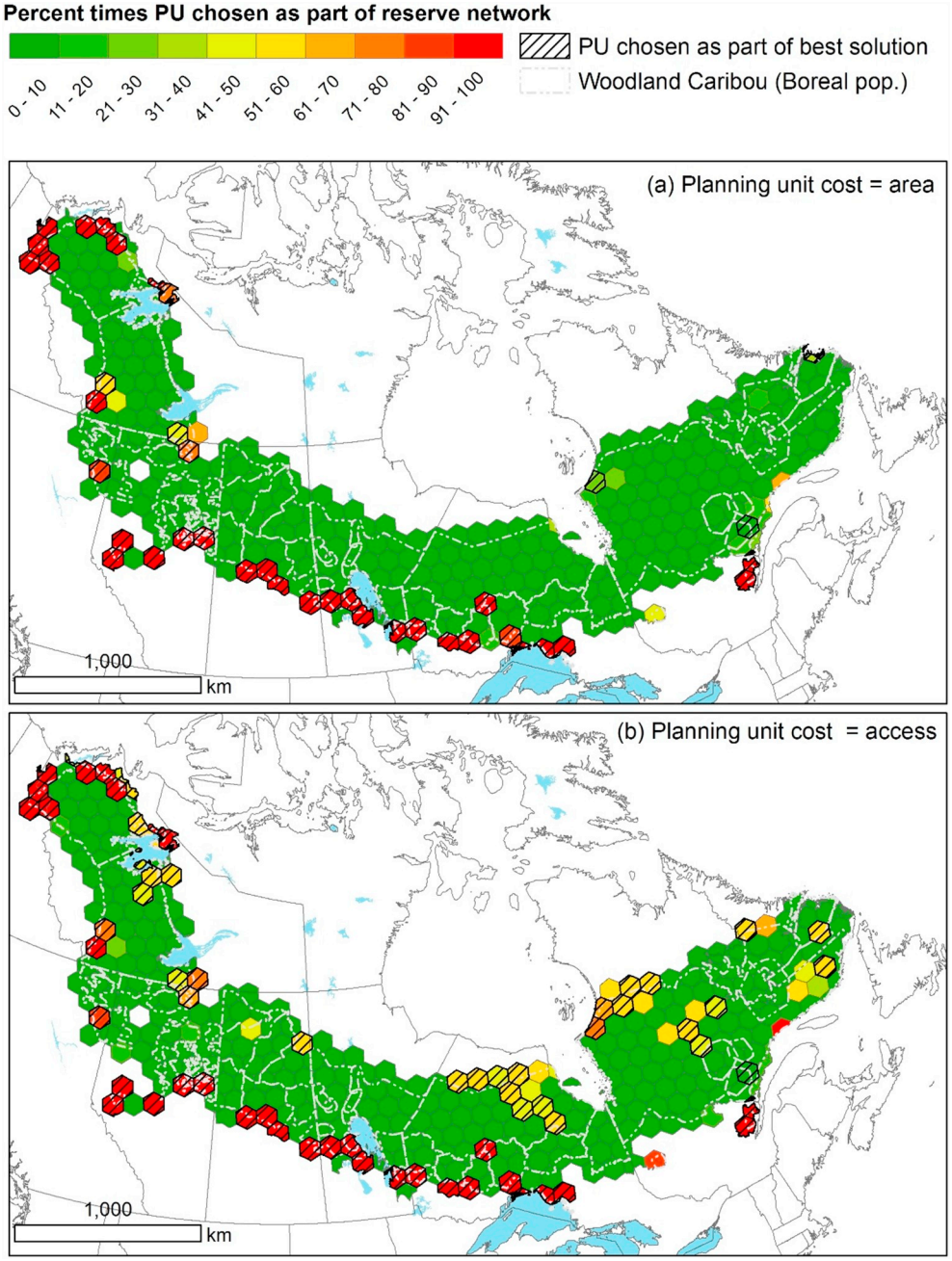

Fig. 6. Percent of times that planning units (PU) were chosen in optimal MARXAN solutions or selected in the best solution for a representative reserve network in the distribution of boreal caribou under two conditions: (a) PU cost set as area of each planning unit; and (b) PU cost function set as area under industrial footprint ('access').

in MARXAN is based on the probability of species presence in a planning unit. However, the species may be rare in a given planning unit, as species are typically not equally abundant throughout their ranges (Brown et al., 1995). Focusing on only the portion of high priority areas within caribou range may not capture the uneven distribution of intraspecific abundances, and thus miss areas where abundances are greatest, habitat suitability is optimal, or species-specific conservation measures may be most effective. Lastly, we examined only a minimum set of sites that includes at least only one site for a given species – this minimum network makes no assumption of adequacy for effective or lasting conservation of the species therein. Such a network would probably be larger and cover more sites than our minimum set and so provide planners with certainty the network could sustain component species in the long term. That said, our work is meant to identify how general spatial patterns of boreal diversity should be considered in the design of actions for caribou recovery at the broad scale of its distribution.

In conclusion, using a minimum viable area that allows for wildlife persistence as our unit of interest, we demonstrate caribou can have high representative value for boreal diversity, species at-risk and for range-restricted species in the southern edge of its distribution. While we acknowledge species richness should not be the only indicator for identifying high priority sites for conservation, we find evidence the extirpation of caribou from the southern boreal may be limiting its effectiveness as a focal species, reinforcing the need to prevent further recession due to anthropogenic pressure.

Acknowledgements

Thanks to Leanna Warman for providing initial data regarding bird and mammal distributions in Canada. Additional bird range data were provided by NatureServe in collaboration with Robert Ridgely, James Zook, The Nature Conservancy - Migratory Bird Program, Conservation International - CABS, World Wildlife Fund - US, and Environment Canada - WILDSPACE. Funding was provided in part by The Nature Conservancy.

Data accessibility

All GIS layers and MARXAN model results generated for this study are available as shapefiles or tables from the corresponding author upon request.

Appendix A. Species list

Notes: Threat status under the Committee on the Status of Endangered Wildlife in Canada (COSEWIC): SC = Special Concern: TH = Threatened; EN = Endangered. If indicated as 'no' in caribou co-occurrence, species has a range that does not intersect the distribution of the Boreal population of woodland caribou.

Birds

Common name	Scientific name	COSEWIC status	Caribou co-occurrence
Alder Flycatcher	*Empidonax alnorum*		
American Avocet	*Recurvirostra americana*		
American Bittern	*Botaurus lentiginosus*		
American Black duck	*Anas rubripes*		
American Coot	*Fulica americana*		
American Crow	*Corvus brachyrhynchos*		
American Dipper	*Cinclus mexicanus*		
American Golden-plover	*Pluvialis dominica*		
American Goldfinch	*Carduelis tristis*		
American Kestrel	*Falco sparverius*		
American Pipit	*Anthus rubescens*		
American Redstart	*Setophaga ruticilla*		
American Robin	*Turdus migratorius*		
American Tree sparrow	*Spizella arborea*		
American White pelican	*Pelecanus erythrorhynchos*		
American Wigeon	*Anas americana*		
American Woodcock	*Scolopax minor*		
Arctic Tern	*Sterna paradisea*		
Atlantic Brant	*Branta bernicla*		
Baird's Sandpiper	*Calidris bairdii*		
Baird's Sparrow	*Ammodramus bairdii*	SC	
Bald Eagle	*Haliaeetus leucocephalus*		
Bank Swallow	*Riparia riparia*	TH	
Barn Swallow	*Hirundo rustica*	TH	
Barred Owl	*Strix varia*		
Barrow's Goldeneye	*Becephala islandica*		
Barrow's Goldeneye (Eastern population)	*Becephala islandica*	SC	
Bay-breasted Warbler	*Dendoica castanea*		
Belted Kingfisher	*Ceryle alcyon*		
Bicknell's Thrush	*Catharus bicknelli*	TH	
Black Scoter	*Melanitta nigra*		
Black Swift	*Cypseloides niger*	EN	
Black Tern	*Chlidonias niger*		
Black-and-white Warbler	*Mniotilta varia*		
Black-backed Woodpecker	*Picoides arcticus*		
Black-bellied Plover	*Pluvialis squatarola*		
Black-billed Cuckoo	*Coccyzus erythopthalmus*		
Black-billed Magpie	*Pica pica*		
Blackburnian Warbler	*Dendroica fusca*		
Black-capped Chickadee	*Parus atricapillus*		
Black-crowned night heron	*Nycticorax nycticorax*		
Black-headed grosbeak	*Pheuticus melanocephalus*		No
Blackpoll warbler	*Dendroica striata*		
Black-throated blue warbler	*Dendroica caerulescens*		
Black-throated green warbler	*Dendroica virens*		
Blue grouse	*Dendragapus obscurus*		
Blue jay	*Cyanocitta cristata*		
Blue-winged teal	*Anas discors*		
Bobolink	*Dolichonyx oryzivorus*	TH	
Bohemian waxwing	*Bombycilla garrulus*		
Bonaparte's gull	*Larus philadelphia*		
Boreal chickadee	*Parus hudsonicus*		
Boreal owl	*Aegolius funereus*		
Brewer's blackbird	*Euphagus cyanocephalus*		
Brewer's sparrow	*Spizella breweri*		
Broad-winged hawk	*Buteo platypterus*		
Brown creeper	*Certhia americana*		

Brown thrasher	*Toxostoma rufum*		
Brown-headed cowbird	*Molothrus ater*		
Buff-breasted sandpiper	*Tryngites subruficollis*	SC	
Bufflehead	*Bucephala albeola*		
Burrowing owl	*Athene cunicularia*	EN	No
California gull	*Larus californicus*		
Calliope hummingbird	*Stellula calliope*		
Canada goose	*Branta canadensis*		
Canada warbler	*Wilsonia canadensis*	TH	
Canvasback	*Aythya valisineria*		
Cape may warbler	*Dendroica tigrina*		
Cassin's finch	*Carpodacus cassinii*		No
Cedar waxwing	*Bombycilla cedrorum*		
Chestnut-backed chickadee	*Parus rufescens*		No
Chestnut-collared longspur	*Calcarius ornatus*	TH	No
Chestnut-sided warbler	*Dendroica pensylvanica*		
Chimney swift	*Chaetura pelagica*	TH	
Chipping sparrow	*Spizella passerina*		
Cinnamon teal	*Anas cyanoptera*		No
Clark's grebe	*Aechmophorus clarkii*		
Clark's nutcracker	*Nucifraga columbiana*		
Clay-colored sparrow	*Spizella pallida*		
Cliff swallow	*Hirundo pyrrhonota*		
Common goldeneye	*Bucephala clangula*		
Common grackle	*Quiscalus quiscula*		
Common loon	*Gavia immer*		
Common merganser	*Mergus merganser*		
Common moorhen	*Gallinula chloropus*		
Common nighthawk	*Chordeiles minor*	TH	
Common poorwill	*Phalaenoptilus nuttalii*		
Common raven	*Corvus corax*		
Common snipe	*Gallinago gallinago*		
Common tern	*Sterna hirundo*		
Common yellowthroat	*Geothlypis trichas*		
Connecticut warbler	*Oporornis agilis*		
Cooper's hawk	*Accipiter cooperii*		
Dark-eyed junco	*Junco hyemalis*		
Dickcissel	*Spiza americana*		No
Double-crested cormorant	*Phalacrocorax auritus*		
Downy woodpecker	*Picoides pubescens*		
Dunlin	*Calidris alpina*		
Dusky flycatcher	*Empidonax oberholseri*		No
Eared grebe	*Podiceps nigricollis*		
Eastern bluebird	*Sialia sialis*		
Eastern kingbird	*Tyrannus tyrannus*		
Eastern meadowlark	*Sturnella magna*	TH	
Eastern phoebe	*Sayornis phoebe*		
Eastern screech owl	*Otus asio*		No
Eastern wood-pewee	*Contopus virens*	SC	
Eskimo Curlew	*Numenius borealis*	EN	
Evening grosbeak	*Coccothraustes vespertinus*	SC	
Ferruginous hawk	*Buteo regalis*	TH	No
Field sparrow	*Spizella pusilla*		No
Forster's tern	*Sterna forsteri*		
Fox sparrow	*Passerella iliaca*		
Franklin's gull	*Larus pipixcan*		
Gadwall	*Anas strepera*		
Glaucous gull	*Larus hyperboreus*		
Golden eagle	*Aquila chrysaetos*		
Golden-crowned kinglet	*Regulus satrapa*		
Golden-crowned sparrow	*Zonotrichia atricapilla*		
Golden-winged warbler	*Vermivora chrysoptera*	TH	No
Grasshopper sparrow	*Ammodramus savannarum*	SC	No
Gray catbird	*Dumetella carolinensis*		
Gray jay	*Perisoreus canadensis*		
Gray-cheeked thrush	*Catharus minimus*		
Great blue heron	*Ardea herodias*		
Great crested flycatcher	*Myiarchus crinitus*		
Great gray owl	*Strix nebulosa*		
Great horned owl	*Bubo virginianus*		
Greater scaup	*Aythya marila*		
Greater white-fronted Goose	*Anser albifrons*		
Greater yellowlegs	*Tringa melanoleuca*		
Green-backed heron	*Butorides striatus*		
Green-winged teal	*Anas crecca*		
Gyrfalcon	*Falco rusticolus*		
Hairy woodpecker	*Picoides villosus*		
Hammond's flycatcher	*Empidonax hammondii*		No
Harlequin duck	*Histrionicus histrionicus*		
Harlequin duck (eastern population)	*Histrionicus histrionicus*	SC	

Harris' sparrow	*Zonotrichia querula*	SC	
Hermit thrush	*Catharus guttatus*		
Herring gull	*Larus argentatus*		
Hoary redpoll	*Carduelis hornemanni*		
Hooded merganser	*Lophodytes cucullatus*		
Horned grebe	*Podiceps auritus*	SC	
Horned lark	*Eremophila alpestris*		
House wren	*Trogiodytes aedon*		
Hudsonian godwit	*Limosa haemastica*		
Indigo bunting	*Passerina cyanea*		
Killdeer	*Charadrius vociferus*		
Lapland longspur	*Calcarius lapponicus*		
Lark bunting	*Calamospiza melanocorys*		No
Lark sparrow	*Chondestes grammacus*		No
Lazuli bunting	*Passerina amoena*		No
Le conte's sparrow	*Ammodramus leconteii*		
Least bittern	*Ixobrychus exilis*	TH	
Least flycatcher	*Empidonax minimus*		
Least sandpiper	*Calidris minutilla*		
Lesser snow goose	*Chen caerulescens*		
Lesser yellowlegs	*Tringa flavipes*		
Lewis' woodpecker	*Melanerpes lewis*	TH	
Lincoln's sparrow	*Melospiza lincolnii*		
Loggerhead shrike	*Lanius ludovicianus*		
Loggerhead shrike (eastern)	*Lanius ludovicianus migrans*	EN	
Loggerhead shrike (prairie)	*Lanius ludovicianus excubitorides*	TH	
Long-billed curlew	*Numenius americanus*	SC	No
Long-billed dowitcher	*Limnodromus scolopaceus*		
Long-eared owl	*Asio otus*		
Magnolia warbler	*Dendroica magnolia*		
Mallard	*Anas platyrhynchos*		
Marbled godwit	*Limosa fedoa*		
Marsh wren	*Cistothorus palustris*		
McCown's longspur	*Calcarius mccownii*	TH	No
Merlin	*Falco columbarius*		
Mew gull	*Larus canus*		
Mountain bluebird	*Sialia currucoides*		
Mountain chickadee	*Parus gambeli*		
Mourning dove	*Zenaida macroura*		
Mourning warbler	*Oporornis philadelphia*		
Nashville warbler	*Vermivora ruficapilla*		
Northern flicker	*Colaptes auratus*		
Northern goshawk	*Accipiter gentilis*		
Northern harrier	*Circus cyaneus*		
Northern hawk owl	*Surnia ulula*		
Northern mockingbird	*Mimus polyglottos*		
Northern oriole	*Icterus galbula*		
Northern parula	*Parula americana*		
Northern pintail	*Anas acuta*		
Northern pygmy-owl	*Glaucidium gnoma*		
Northern rough-winged swallow	*Stelgidopteryx serripennis*		
Northern saw-whet owl	*Aegolius acadicus*		
Northern shoveler	*Anas clypeata*		
Northern shrike	*Lanius excubitor*		
Northern waterthrush	*Seiurus noveboracensis*		
Northern wheatear	*Oenanthe oenanthe*		
Northwestern crow	*Corvus caurinus*		No
Oldsquaw	*Clangula hyemalis*		
Olive-sided flycatcher	*Contopus borealis*	TH	
Orange-crowned warbler	*Vermivora celata*		
Orchard oriole	*Icterus spurius*		No
Osprey	*Pandion haliaetus*		
Ovenbird	*Seiurus aurocapillus*		
Pacific loon	*Gavia pacifica*		
Pacific-slope flycatcher	*Empidonax difficilis*		No
Palm warbler	*Dendroica palmarum*		
Peale's peregrine falcon	*Falco peregrinus pealei*	SC	
Peregrine falcon	*Falco peregrinus*	SC	
Philadelphia vireo	*Vireo philadelphicus*		
Pied-billed grebe	*Podilymbus podiceps*		
Pileated woodpecker	*Dryocopus pileatus*		
Pine grosbeak	*Pinicola enucleator*		
Pine siskin	*Carduelis pinus*		
Pine warbler	*Dendroica pinus*		
Piping plover (*melodus* subspecies)	*Charadrius melodus*	EN	No
Piping plover (*circumcinctus* subspecies)	*Charadrius melodus*	EN	
Prairie falcon	*Falco mexicanus*		No
Purple finch	*Carpodacus purpureus*		
Purple martin	*Progne subis*		
Red crossbill (*percna* subspecies)	*Loxia curvirostra*	EN	

Red crossbill	*Loxia curvirostra*		
Red phalarope	*Phalaropus fulicaria*		
Red-breasted merganser	*Mergus serrator*		
Red-breasted nuthatch	*Sitta canadensis*		
Red-breasted sapsucker	*Sphyrapicus ruber*		No
Red-eyed vireo	*Vireo olivaceus*		
Redhead	*Aythya americana*		
Red-headed woodpecker	*Melanerpes erythrocephalus*	TH	
Red-naped sapsucker	*Sphyrapicus nuchalis*		
Red-necked grebe	*Podiceps grisegena*		
Red-necked phalarope	*Phalaropus lobatus*	SC	
Red-shouldered hawk	*Buteo lineatus*		
Red-tailed hawk	*Buteo jamaicensis*		
Red-throated loon	*Gavia stellata*		
Red-winged blackbird	*Agelaius phoeniceus*		
Ring-billed gull	*Larus delawarensis*		
Ring-necked duck	*Aythya collaris*		
Rock ptarmigan	*Lagopus mutus*		
Rose-breasted grosbeak	*Pheuticus ludovicianus*		
Ross' gull	*Rhodostethia rosea*	TH	No
Rough-legged hawk	*Buteo lagopus*		
Ruby-crowned kinglet	*Regulus calendula*		
Ruby-throated hummingbird	*Archilochus colubris*		
Ruddy duck	*Oxyura jamaicensis*		
Ruddy turnstone	*Arenaria interpres*		No
Ruffed grouse	*Bonasa umbellus*		
Rufous hummingbird	*Selasphorus rufus*		No
Rufous-sided towhee	*Pipilo erythrophthalmus*		No
Rusty blackbird	*Euphagus carolinus*	SC	
Sabine's gull	*Xema sabini*		
Sandhill crane	*Grus canadensis*		
Savannah sparrow	*Passerculus sandwichensis*		
Say's phoebe	*Sayornis saya*		
Scarlet tanager	*Piranga olivacea*		
Sedge wren	*Cistothorus platensis*		
Semipalmated plover	*Charadrius semipalmatus*		
Semipalmated sandpiper	*Calidris pusilla*		
Sharp-shinned hawk	*Accipiter striatus*		
Sharp-tailed grouse	*Tympanuchus phasianellus*		
Sharp-tailed sparrow	*Ammodramus caudacutus*		
Short-billed dowitcher	*Limnodromus griseus*		
Short-eared owl	*Asio flammeus*	SC	
Siberian tit	*Parus cinctus*		
Smith's longspur	*Calcarius pictus*		
Snow bunting	*Plectrophenax nivalis*		
Snowy owl	*Nyctea scandiaca*		
Solitary sandpiper	*Tringa solitaria*		
Solitary vireo	*Vireo solitarius*		
Song sparrow	*Melospiza melodia*		
Sora	*Porzana carolina*		
Spotted sandpiper	*Actitus macularia*		
Sprague's pipit	*Anthus spragueii*	TH	
Spruce grouse	*Dendragapus canadensis*		
Stellar's jay	*Cyanocitta stelleri*		
Stilt sandpiper	*Calidris himantopus*		
Surf scoter	*Melanitta perspicillata*		
Surfbird	*Aphriza virgata*		
Swainson's hawk	*Buteo swainsoni*		
Swainson's thrush	*Catharus ustulatus*		
Swamp sparrow	*Melospiza georgiana*		
Tennessee warbler	*Vermivora peregrina*		
Three-toed woodpecker	*Picoides tridactylus*		
Townsend's solitaire	*Myadestes townsendi*		
Townsend's warbler	*Dendroica townsendi*		
Tree swallow	*Tachycineta bicolor*		
Trumpeter swan	*Cygnus buccinator*		
Tundra swan	*Cygnus columbianus*		
Turkey vulture	*Cathartes aura*		
Upland sandpiper	*Bartramia longicauda*		
Varied thrush	*Ixoreus naevius*		
Vaux's swift	*Chaetura vauxi*		No
Veery	*Catharus fuscescens*		
Vesper sparrow	*Pooecetes gramineus*		
Viginia rail	*Rallus limicola*		
Violet-green swallow	*Tachycineta thalassina*		
Wandering tattler	*Heteroscelus incanus*		
Warbling vireo	*Vireo gilvus*		
Western bluebird	*Sialia mexicana*		No
Western grebe	*Aechmophorus occidentalis*	SC	
Western kingbird	*Tyrannus verticalis*		No

Western meadowlark	*Sturnella neglecta*		
Western screech owl	*Otus kennicottii*		No
Western tanager	*Piranga ludoviciana*		
Western wood-pewee	*Contopus sordidulus*		
Whimbrel	*Numenius phaeopus*		
Whip-poor-will	*Caprimulgus vociferus*	TH	
White-breasted nuthatch	*Sitta carolinensis*		
White-crowned sparrow	*Zonotrichia leucophrys*		
White-rumped sandpiper	*Calidris fuscicollis*		
White-throated sparrow	*Zonotrichia albicollis*		
White-throated swift	*Aeronautes saxatalis*		
White-winged crossbill	*Loxia leucoptera*		
White-winged scoter	*Melanitta fusca*		
Whooping crane	*Grus americana*	EN	
Willet	*Catoptrophorus semipalmatus*		
Williamson's sapsucker	*Sphyrapicus thyroideus*		No
Willow flycatcher	*Empidonax traillii*		
Wilson's phalarope	*Phalaropus tricolor*		
Wilson's warbler	*Wilsonia pusilla*		
Winter wren	*Troglodytes troglodytes*		
Wood duck	*Aix sponsa*		
Wood thrush	*Hylocichla mustelina*	TH	
Yellow rail	*Coturnicops noveboracensis*	SC	
Yellow wagtail	*Motacilla flava*		
Yellow warbler	*Dendroica petechia*		
Yellow-bellied flycatcher	*Empidonax flaviventris*		
Yellow-bellied sapsucker	*Sphyrapicus varius*		
Yellow-billed cuckoo	*Coccyzus americanus*		
Yellow-billed loon	*Gavia adamsii*		
Yellow-breasted chat	*Icteria virens*	EN	No
Yellow-headed blackbird	*Xanthocephalus anthocephalus*		
Yellow-rumped warbler	*Dendroica coronata*		
Yellow-throated vireo	*Vireo flavifrons*		No

Mammals

Common name	Scientific name	COSEWIC status	Caribou co-occurrence
American badger	*Taxidea taxus*	SC	
American beaver	*Castor canadensis*		
American black bear	*Ursus americanus*		
American marten	*Martes americana*		
American mink	*Mustela vison*		
American pika	*Ochotona princeps*		
American porcupine	*Erethizon dorsatum*		
American red squirrel	*Tamiasciurus hudsonicus*		
American water shrew	*Sorex palustris*		
Arctic fox	*Alopex lagopus*		
Arctic ground squirrel	*Spermophilus parryii*		
Arctic hare	*Lepus arcticus*		
Arctic shrew	*Sorex arcticus*		
Big brown bat	*Eptesicus fuscus*		
Bighorn sheep	*Ovis canadensis*		
Bobcat	*Lynx rufus*		
Brown lemming	*Lemmus lemmus*		
Bushy-tailed wood rat	*Neotoma cinerea*		
Chestnut-cheeked vole	*Microtus xanthognathus*		
Collared lemming	*Dicrostonyx torquatus*		
Collared pika	*Ochotona collaris*		
Columbian ground squirrel	*Spermophilus columbianus*		
Cougar	*Felis concolor*		
Coyote	*Canis latrans*		
Dall's sheep	*Ovis dalli*		
Deer mouse	*Peromyscus maniculatus*		
Dusky shrew	*Sorex obscurus*		
Eastern chipmunk	*Tamias striatus*		
Eastern cottontail	*Sylvilagus floridanus*		
Eastern pipistrelle	*Pipistrellus subflavus*		
Eastern Wolf	*Canis lupus lycaon*	TH	
Fisher	*Martes pennanti*		
Franklin's ground squirrel	*Spermophilus franklinii*		
Gapper's red-backed vole	*Clethrionomys gapperi*		
Gaspé shrew	*Sorex gaspensis*		No
Golden-mantled ground squirrel	*Spermophilus lateralis*		
Gray wolf	*Canis lupus*		
Gray fox	*Urocyon cinereoargenteus*	TH	
Gray or black squirrel	*Sciurus carolinensis*		
Grizzly bear	*Ursus arctos*	SC	
Hairy-tailed mole	*Parascalops breweri*		
Heather vole	*Phenacomys intermedius*		
Hoary bat	*Lasiurus cinerus*		

Hoary marmots	*Marmota caligata*		
Keen's Long-eared bat	*Myotis keenii*		
Least chipmunk	*Eutamias minimus*		
Least weasel	*Mustela nivalis*		
Little brown bat	*Myotis lucifugus*	EN	
Long-eared bat	*Myotis evotis*		
Long-legged bat	*Myotis volans*		
Long-tailed vole	*Microtus longicaudus*		
Long-tailed weasel	*Mustela frenata*		
Lynx	*Lynx lynx*		
Marten (Newfoundland)	*Martes americana atrata*	TH	No
Masked shrew	*Sorex cinereus*		
Meadow jumping vole mouse	*Zapus hudsonius*		
Meadow vole	*Microtus pennsylvanicus*		
Moose	*Alces alces*		
Mountain goat	*Oreamnos americanus*		
Mule deer	*Odocoileus hemionus*		
Muskox	*Ovibos moschatus*		
Muskrat	*Ondrata zibethicus*		
Northern bog lemming	*Synaptomys borealis*		
Northern flying squirrel	*Glaucomys sabrinus*		
Northern grasshopper mouse	*Onychomys leucogaster*		No
Northern pocket gopher	*Thomomys talpoides*		
Olive-backed pocket mouse	*Perognathus fasciatus*		No
Pigmy shrew	*Microsorex hoyi*		
Plains pocket gopher	*Geomys bursarius*		No
Polar bear	*Ursus maritimus*	SC	
Prairie vole	*Microtus ochrogaster*		
Raccoon	*Procyon lotor*		
Red bat	*Lasiurus borealis*		No
Red fox	*Vulpes vulpes*		
Red-backed vole	*Clethrionomys rutilus*		
Richardson's ground squirrel	*Spermophilus richardsonii*		
Richardson's water vole	*Arvicola richardsoni*		
River otter	*Lontra canadensis*		
Rock vole	*Microtus chrotorrhinus*		
Short-tailed shrew	*Blarina brevicauda*		
Silver-haired bat	*Lasionycteris noctivagans*		
Singing vole	*Microtus miurus*		
Small-footed bat	*Myotis leibii*		
Smokey shrew	*Sorex fumeus*		
Snowshoe hare	*Lepus americanus*		
Southern bog lemming	*Synaptomys cooperi*		
Star-nosed mole	*Condylura cristata*		
Striped skunk	*Mephitis mephitis*		
Thirteen-lined ground squirrel	*Spermophilus tridecemlineatus*		
Tundra vole	*Microtus oeconomus*		
Ungava lemming	*Dicrostonyx hudsonius*		
Wapiti	*Cervus elaphus*		
Western jumping vole mouse	*Zapus princeps*		
White-tailed deer	*Odocoileus virginianus*		
White-tailed jack rabbit	*Lepus townsendii*		
Wolverine	*Gulo gulo*	SC (West); EN (East)	
Wood bison	*Bison bison athabascae*	TH	
Woodchuck	*Marmota monax*		
Woodland caribou	*Rangifer tarandus caribou*		
Woodland caribou (boreal population)	*Rangifer tarandus*	TH	
Woodland caribou (Gaspe population)	*Rangifer tarandus*	EN	No
Woodland jumping vole mouse	*Napaeozapus insignis*		

References

Andrew, M.E., Wulder, M.A., Cardille, J.A., 2014. Protected areas in boreal Canada: a baseline and considerations for the continued development of a representative and effective reserve network. Environ. Rev. 22, 135–160.

Ball, I.R., Possingham, H.P., Watts, M., 2009. Marxan and relatives: software for spatial conservation prioritisation. In: Moilanen, A., Wilson, K.A., Possingham, H.P. (Eds.), Spatial Conservation Prioritisation: Quantitative Methods and Computational Tools. Oxford University Press, Oxford, UK.

Bichet, O., Dupuch, A., Hébert, C., Le Borgne, H., Fortin, D., 2016. Maintaining animal species assemblages through single-species management: the case of threatened caribou in boreal forest. Ecol. Appl. 26, 612–623.

Brandt, J.P., 2009. The extent of the North American boreal zone. Environ. Rev. 17, 101–161.

Brown, J.H., Mehlman, D.W., Stevens, G.C., 1995. Spatial variation in abundance. Ecology 76, 2028–2043.

Cornwall, W., 2016. To save caribou, Alberta wants to fence them in. Science 353, 333.

COSEWIC, 2014. COSEWIC Assessment and Status Report on the Caribou *Rangifer tarandus*, Newfoundland Population, Atlantic-Gaspésie Population and Boreal Population, in Canada. Committee on the Status of Endangered Wildlife in Canada, Ottawa (xxiii + 218 pp.). www.registrelep-sararegistry.gc.ca/default_e.cfm.

Courtois, R., Ouellet, J.P., Breton, L., Gingras, A., Dussault, C., 2007. Effects of forest disturbance on density, space use, and mortality of woodland caribou. Écoscience 14, 491–498.

Courtois, R., Gingras, A., Fortin, D., Sebbane, A., Rochette, B., Breton, L., 2008. Demographic and behavioural response of woodland caribou to forest harvesting. Can. J. For. Res. 38, 2837–2849.

Di Minin, E., Moilanen, A., 2014. Improving the surrogacy effectiveness of charismatic megafauna with well-surveyed taxonomic groups and habitat types. J. Appl. Ecol. 51, 281–288.

Dickie, M., Serrouya, R., McNay, R.S., Boutin, S., 2017. Faster and farther: wolf movement on linear features and implications for hunting behaviour. J. Appl. Ecol. 54, 253–263.

Environment and Climate Change Canada, 2018. Action Plan for the Woodland Caribou (Rangifer tarandus caribou), Boreal Population, in Canada – Federal Actions. Species at Risk Act Action Plan Series Environment and Climate Change Canada, Ottawa (vii + 28 pp).

Environment Canada, 2011. Scientific assessment to inform the identification of critical habitat for woodland caribou (*Rangifer tarandus caribou*), boreal population. In: Canada: 2011 Update. Ottawa, Ontario, Canada, (102 pp).
Environment Canada, 2012. Recovery Strategy for the Woodland Caribou (*Rangifer tarandus caribou*), Boreal population, in Canada. Species at Risk Act Recovery Strategy Series Environment Canada, Ottawa (xi + 138 pp).
Festa-Bianchet, M., Ray, J.C., Boutin, S., Côté, S.D., Gunn, A., 2011. Conservation of caribou (Rangifer tarandus) in Canada: an uncertain future. Can. J. Zool. 89 (5), 419–434.
Fortin, D., Hébert, C., Légaré, J.-P., Courbin, N., Swiston, K., Hodson, J., LeBlanc, M.-L., Dussault, C., Pothier, D., Ruel, J.-C., Couturier, S., 2011. Partial harvesting in old-growth boreal forests and the preservation of animal diversity from ants to woodland caribou. In: Wallace, E.B. (Ed.), Woodlands: Ecology, Management and Conservation. Nova Science Publishers, Inc, Hauppauge, NY, USA.
Gagné, C., Mainguy, J., Fortin, D., 2016. The impact of forest harvesting on caribou-moose-wolf interactions decreases along a latitudinal gradient. Biol. Conserv. 197, 215–222.
Gauthier, S., Bernier, P., Kuuluvainen, T., Shvidenko, A.Z., Schepaschenko, D.G., 2015. Boreal forest health and global change. Science 349, 819–822.
Global Forest Watch Canada, 2014. Canada Access 2010 Dataset. Available at: http://globalforestwatch.ca/node/198.
Government of Canada, 2017. Species at Risk Public Registry. Available at: http://www.registrelep-sararegistry.gc.ca/search/SpeciesSearch_e.cfm.
Gurd, D.B., Nudds, T.D., Rivard, D.H., 2001. Conservation of mammals in eastern North American wildlife reserves: how small is too small? Conserv. Biol. 15, 1355–1363.
Hartmann, D.L., Klein Tank, A.M.G., Rusticucci, M., Alexander, L.V., Brönnimann, S., Charabi, Y., Dentener, F.J., Dlugokencky, E.J., Easterling, D.R., Kaplan, A., Soden, B.J., Thorne, P.W., Wild, M., Zhai, P.M., 2013. Observations: atmosphere and surface. In: Stocker, T.F., Qin, D., Plattner, G.-K., Tignor, M., Allen, S.K., Boschung, J., Nauels, A., Xia, Y., Bex, V., Midgley, P.M. (Eds.), Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.
Hervieux, D., Hebblewhite, M., Stepnisky, D., Bacon, M., Boutin, S., 2014. Managing wolves to recover threatened woodland caribou in Alberta. Can. J. Zool. 92, 1029–1037.
Holt, R.D., 1977. Predation, apparent competition, and the structure of prey communities. Theor. Popul. Biol. 12, 197–229.
Kerr, J.T., 1997. Species richness, endemism, and the choice of areas for conservation. Conserv. Biol. 11, 1094–1100.
Kunin, W.E., 1997. Sample shape, spatial scale and species counts: implications for reserve design. Biol. Conserv. 82, 369–377.
Leroux, S.J., Schmiegelow, F.K., Lessard, R.B., Cumming, S.G., 2007. Minimum dynamic reserves: a framework for determining reserve size in ecosystems structured by large disturbances. Biol. Conserv. 138, 464–473.
Margules, C.R., Pressey, R.L., 2000. Systematic conservation planning. Nature 405, 243–253.
Morrison, J.C., Sechrest, W., Dinerstein, E., Wilcove, D.S., Lamoreux, J.F., 2007. Persistence of large mammal faunas as indicators of global human impacts. J. Mammal. 88, 1363–1380.
Nicolson, D.J., Lötter, M., Lieberknecht, L., Wells, R., Gerhartz, J.L., Ban, N.C., Ardron, J.A., 2010. Interpreting and Communicating Outputs. In: Ardron, J.A., Possingham, H.P., Klein, C.J. (Eds.), Marxan Good Practices Handbook. Pacific Marine Analysis and Research Association, Victoria, pp. 165. www.pacmara.org, Version 2.
Pasher, J., Seed, E., Duffe, J., 2013. Development of boreal ecosystem anthropogenic disturbance layers for Canada based on 2008 to 2010 Landsat imagery. Can. J. Remote. Sens. 39, 42–58.
Patterson, B.D., Ceballos, G., Sechrest, W., Tognelli, M.F., Brooks, T., Luna, L., Ortega, P., Salazar, I., Young, B.E., 2007. Digital Distribution Maps of the Mammals of the Western Hemisphere, Version 3.0. NatureServe, Arlington, Virginia, USA.
Ridgely, R.S., Allnutt, T.F., Brooks, T., McNicol, D.K., Mehlman, D.W., Young, B.E., Zook, J.R., 2003. Digital distribution maps of the birds of the western hemisphere, version 1.0. NatureServe, Arlington, Virginia, USA.
Rouget, M., 2003. Measuring conservation value at fine and broad scales: implications for a diverse and fragmented region, the Agulhas plain. Biol. Conserv. 112, 217–232.
Schaefer, J.A., 2003. Long-term range recession and persistence of caribou in the taiga. Conserv. Biol. 17, 1435–1439.
Schneider, R.R., Hauer, G., Adamowicz, W.L., Boutin, S., 2010. Triage for conserving populations of threatened species: the case of woodland caribou in Alberta. Biol. Conserv. 143, 1603–1611.
Vors, L.S., Schaefer, J.A., Pond, B.A., Rodgers, A.R., Patterson, B.R., 2007. Woodland caribou extirpation and antropogenic landscape disturbance in Ontario. J. Wildl. Manag. 71, 1249–1256.
Warman, L.D., Forsyth, D.M., Sinclair, A.R.E., Freemark, K., Moore, H.D., Barrett, T.W., Pressey, R.L., White, D., 2004. Species distributions, surrogacy, and important conservation regions in Canada. Ecol. Lett. 7, 374–379.
Wiersma, Y.F., Nudds, T.D., Rivard, D.H., 2004. Models to distinguish effects of landscape patterns and human population pressures associated with species loss in Canadian national parks. Landsc. Ecol. 19, 773–786.
Wilson, H.B., Joseph, L.N., Moore, A.L., Possingham, H.P., 2011. When should we save the most endangered species? Ecol. Lett. 14, 886–890.