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Science-informed policy decisions lead to the creation of a protected area for a wide-ranging species at risk

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Abstract

Protected areas are needed to conserve nature and biodiversity worldwide. The province of Québec (Canada) recently established a large wilderness area affording significant habitat protection for boreal woodland caribou (*Rangifer tarandus caribou*), a wide-ranging species at risk. We describe a decision support framework combining ecological modeling with socioeconomic constraints that ultimately led to the creation of this protected area. Multiple criteria were used to identify candidate protected areas for boreal caribou. These had to be large in size (>10,000 km^2) and located in regions where available high-quality habitat was threatened by development pressures. Candidate areas also had to contribute substantively to the maintenance of functional habitat connectivity, be exempt from major industrial developments and recent fires, and required evidence of recent use by caribou. Five candidate protected areas emerged from this exercise. Key regional stakeholders were consulted, thereby strengthening advocacy for land designation, and boundaries were refined through their input, which helped further reduce socioeconomic conflicts. This process involved difficult compromises, but eventually led to the legal designation on March 4, 2021 of a new protected area for boreal caribou known as the Caribous-Forestiers-de-Manouane-Manicouagan. We show how our science-informed decision support framework was instrumental in the success of this endeavor, and describe the obstacles overcame in the process, so that other jurisdictions may draw from this experience in their efforts to achieve similar conservation goals.

KEYWORDS

connectivity, habitat protection, habitat suitability, *Rangifer tarandus*, wilderness areas, woodland caribou

1 | INTRODUCTION

Animals may range across broad areas to acquire widely dispersed resources, access seasonal habitats, and find mates (Bell, 1991; Clobert et al., 2012). However, the availability of wildlife habitat is often precluded by natural or human obstacles, which can negatively influence the population dynamics of wide-ranging species, especially those living in highly disturbed landscapes (Stevens et al., 2018). Numerous large mammal species have suffered drastic population declines, primarily due to the growing encroachment of human activities (Benítez-López et al., 2010; Ceballos & Ehrlich, 2002; Morrison et al., 2007). For example, the grizzly bear (*Ursus arctos*) range in the contiguous United States has contracted to only 2%–5% of its historical distribution (Mattson & Merrill, 2002), and conservation of this species is believed to largely depend on the protection of vast natural spaces occupied by few people. Some large mammal populations suffer from increased predation risk arising from habitat alteration (DeCesare et al., 2010), the advent of new pathogens (Edmunds et al., 2016), global warming (Rondinini & Visconti, 2015), or outright persecution from humans (Musiani & Paquet, 2004). In the face of such adverse trends, many authors have urged for prompt and efficient protection of wide-ranging mammals and their habitat (Morrison et al., 2007; Ripple et al., 2015).

Well-managed protected areas remain one of the most effective ways to protect biodiversity worldwide (Geldmann et al., 2013; Naughton-Treves et al., 2005). The International Union for Conservation of Nature (IUCN) defines protected areas as "clearly defined geographical spaces [...] dedicated to the long-term conservation of nature, ecosystem services, and cultural values." As of May 2021, protected areas and other area-based conservation measures occupied 22.5 million km^2 or 16.6% of Earth's land surface (UNEP-WCMC & IUCN, 2021; https://www.protectedplanet.net, accessed February 9, 2022). Countries subscribing to the Aichi Targets of the United Nations Convention on Biological Diversity committed to protect 17% of their terrestrial and inland water areas by 2020 (https://www.cbd.int/sp/targets, accessed February 9, 2022). More recently, participants at the 2021 London G7 meeting on climate and the environment committed to protect 30% by 2030 (https://www.g7uk.org, accessed February 9, 2022).

Although biodiversity conservation is a key value for subscribing countries, protected areas often compete for space with other land uses such as agriculture, logging, mining, and oil and gas extraction (Sayer et al., 2013). Multiple stakeholders are involved in land-use planning, from private landowners to industrial corporations, and from local to regional, national, and Indigenous governments. In this context, science-based solutions are often subordinate to socioeconomic interests (Hebblewhite, 2017). Nevertheless, many countries and sub-national governments have endeavored to increase protected areas coverage following endorsement of the Aichi Targets in 2010. While some efforts aim to protect rare or threatened ecosystems, others aim to stem the decline of particular species. In Canada, for example, widespread declines in boreal populations of woodland caribou (*Rangifer tarandus caribou*, hereafter boreal caribou) spurred its designation as a threatened species under the Species at Risk Act (SC, 2002). Boreal caribou are considered an umbrella species for a range of organisms associated with mature and old-growth forest conditions in the boreal biome (Bichet et al., 2016). Resource extraction activities such as forest harvesting, oil and gas production, and associated road network development are the primary drivers of widespread declines of boreal caribou in Canada, be it through direct habitat loss or indirectly through their influence on the structure of large mammal communities (Festa-Bianchet et al., 2011). One mechanism by which anthropogenic disturbances influence boreal caribou demography is through habitat-driven apparent competition (Wittmer et al., 2007). By benefiting alternate prey, specifically moose (*Alces alces*) and deer (*Odocoileus* spp.), and their common predators (usually gray wolf *Canis lupus*, black bear *Ursus americanus* and grizzly bear), anthropogenic disturbances increase predation risk on caribou (Seip, 1992). Consequently, the protection of large undisturbed landscapes was identified as a key management action to ensure conservation of this species in Canada (Environment Canada, 2012). In 2015, with a view to reaching the Aichi target, the provincial government of Québec, Canada, selected boreal caribou as a surrogate species for the establishment of a large protected area. At that time, 147,493 km^2 (9.75%) of mainland Québec was protected, and identifying a large protected area tailored to the needs of boreal caribou constituted a major step forward for the conservation of this species at risk.

In this study, we describe the steps that led to the establishment of a >10,000 km^2 protected area for boreal caribou in Québec called Caribous-Forestiers-de-Manouane-Manicouagan. We highlight the pivotal role of a decision support framework in this outcome. Steps included: (1) integration of scientific results at early stages of planning, (2) use of multiple criteria—namely size, geographic location, habitat suitability, and functional connectivity, as well as socioeconomic and geophysical constraints—to generate multiple scenarios for protection, (3) validation of candidate areas using independent datasets on population distribution and connectivity, and (4) consultation with key stakeholders to identify and refine protected area boundaries. Although we focus on the science that led to the identification of a protected area designed to meet boreal caribou habitat requirements, we also describe the socioeconomic conditions that were necessary to achieve its formal designation. Our intent is to share experience and highlight obstacles encountered during the process so that other jurisdictions may be better equipped to accomplish similar conservation projects in human-altered landscapes.

2 | CRITERIA FOR THE IDENTIFICATION OF CANDIDATE PROTECTED AREAS

2.1 | Size

Protected areas under IUCN Criteria Ib (Wilderness Areas sensu Dudley, 2008) aim to protect the long-term ecological integrity of large natural areas undisturbed by significant human activity, maintain ecological and evolutionary processes as well as ecosystem services, and buffer ecosystems against the impacts of climate change. When designed to protect a particular wildlife species, protected areas need to meet the minimum space requirements of that targeted species or population. More than 70% of protected areas in the world are <10 km^2 (data from www.protectedplanet.net, accessed February 9, 2022). These relatively small parcels of protected land may be appropriate for the conservation of small-bodied animals with limited mobility, or to increase connectivity in highly fragmented landscapes (Cantú-Salazar & Gaston, 2010), but they may be insufficient for wide-ranging large mammal species. As a case in point, boreal caribou typically occupy areas of at least 10,000–15,000 km^2 (Courtois et al., 2004), sometimes up to 40,000 km^2 and more (Johnson et al., 2020), as they rely on vast areas to access high-quality resources away from predators. Overly small protected areas may be ineffective, as their large perimeter-to-area ratio renders them more susceptible to the effects of surrounding land-use practices (Hansen & DeFries, 2007). Courbin et al. (2009) showed that boreal caribou were more likely to encounter wolves in small protected forest blocks (covering 2300 km^2 in total) due to the adjacency of roads and logged areas, two landscape attributes favoring wolf numerical and functional responses. A minimum size requirement of 10,000–15,000 km^2 is considered a reasonable guideline to allow maintenance of a stable boreal caribou population over the long term (e.g., Environment Canada, 2012). Therefore, our first criterion for the identification of a protected area that could act as an IUCN Criteria Ib Wilderness Area for boreal caribou was a minimum size of 10,000 km^2. We recognize that this size is on the low-end of caribou requirements; however, earlier work has shown that contiguous high-quality areas ≥10,000 km^2 were virtually absent in the southern part of the boreal caribou distribution in Québec (Groupe de mise en oeuvre sur les aires protégées de l'équipe de rétablissement du caribou forestier au Québec [GMO], 2012), mostly due to sustained pressure from the timber industry over the last decades (Courtois et al., 2004).

2.2 | Habitat quality and geographic location

In principle, protected areas should contain resources of sufficient quality and quantity to allow for the complete life cycle of focal species to occur within their bounds. In contrast, Joppa and Pfaff (2009) found that most protected areas around the world were situated so as to avoid areas of potential conflict with other land users (e.g., in remote or less populated regions, at high elevations or on steep terrain). Authors like Myers et al. (2000) have argued that protected areas should be concentrated where high-quality habitat already exists for focal species, irrespective of human footprint. In Québec, a large portion of boreal caribou distribution overlaps with areas of higheconomic value for industrial activity, particularly timber harvesting (Figure 1). A protected area designed to safeguard suitable boreal caribou habitat from human activities would thus be of particular benefit in the commercial forest, where development pressures are significantly greater and large patches of undisturbed forest are increasingly scarce. However attempts to protect such areas are more likely to provoke opposition from stakeholders, whose activities stand to be affected. Conversely, habitat quality for boreal caribou declines at higher latitudes as the relatively dense boreal forest transitions into taiga (Liu et al., 2002). Consequently, creating a protected area far to the north would reduce the likelihood of land use conflict, but would entail protecting relatively poor habitat, with less threats from which to protect it. We resolved this tradeoff by ensuring that candidate protected areas were identified in a study area that straddled the northern limit of merchantable timber in Québec's boreal forest (Figure 1). Within this broad region, we sought to identify the highest quality areas for boreal caribou habitat protection.

2.3 | Connectivity

Connectivity among high-quality areas has been shown to increase the effectiveness of small- to medium-sized protected areas in supporting populations of wide-

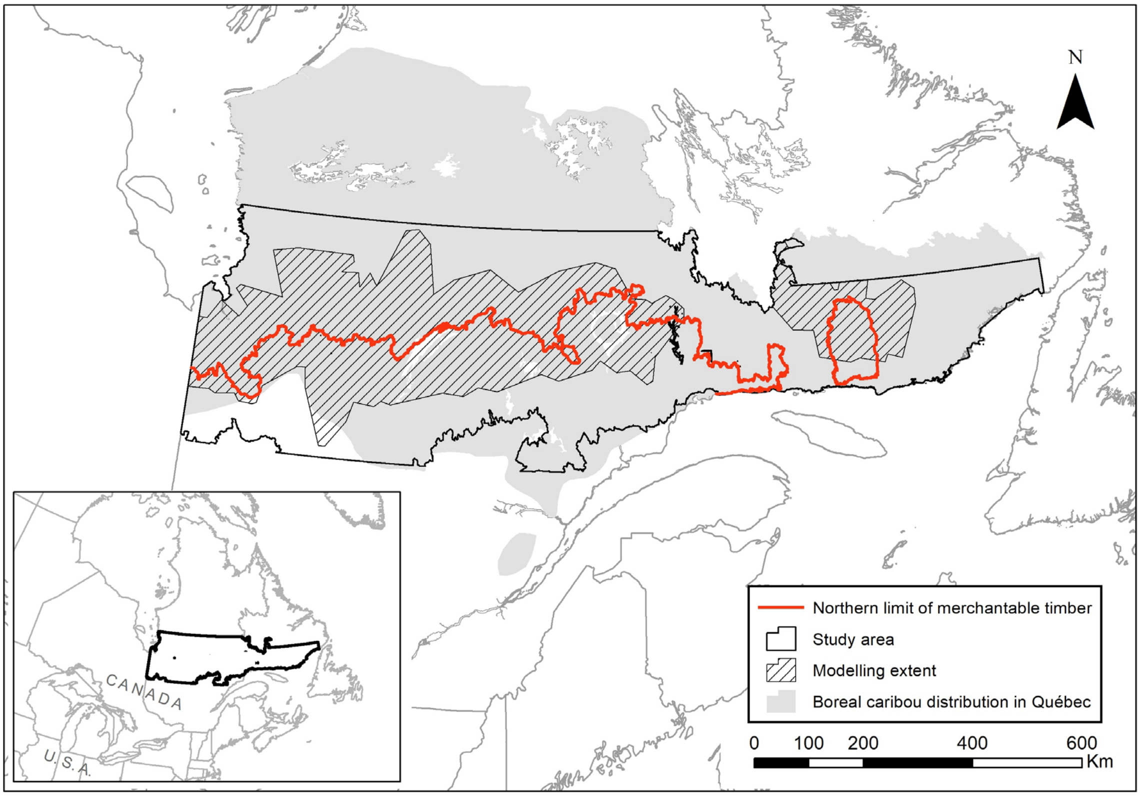

FIGURE 1 Area in Québec, Canada, where we monitored GPS-collared boreal caribou to identify candidate protected areas. The commercial and noncommercial forests were separated by the northern limit of merchantable timber (red line), and we only included individuals that used areas both above and below this limit in our analyses ($n = 55$ out of 178 individuals). The modeling extent (used to evaluate resource selection functions) included all individual annual home ranges, and excluded areas in Labrador and Ontario (hashed polygon). Parameters of the final fitted model were used to generate predictions across the whole study area (black polygon). The distribution of boreal caribou in Québec is also shown in gray

ranging species (Santini et al., 2016), including caribou (Bauduin et al., 2020). Landscape connectivity is defined as the degree to which landscapes facilitate or impede the movement of organisms among resource patches (Taylor et al., 1993). Effective functional landscape connectivity accommodates the behavioral ecology of focal species (Tischendorf & Fahrig, 2000), thereby facilitating the movements of individuals among suitable areas within and between protected areas. At a broad scale, the connectivity of protected areas may facilitate gene flow (Coulon et al., 2004) and increase population resilience to environmental and demographic stochasticity (Lande, 1993). At more local scales, connectivity facilitates movement of individual caribou among suitable patches in their search for food, cover, and reproductive mates (O'Brien et al., 2006). Disturbance can hinder functional landscape connectivity for caribou, particularly anthropogenic features such as roads and trails, which are seldom crossed by boreal caribou (Leblond et al., 2011). Our final selection criterion for candidate protected areas therefore involved maximizing connectivity both within and between protected areas and other suitable habitats at the landscape scale.

3 | METHODS

3.1 | Decision support framework

As described previously, we used multiple criteria pertaining to size, geographic location, habitat suitability, and connectivity to identify potential protected areas for boreal caribou. We combined these criteria within a science-informed decision support framework that also considered socioeconomic and geophysical constraints such as industrial development projects and recently burnt areas (Figure 2). The framework was implemented in a sequential fashion.

First, we identified large swaths of highly suitable habitat (i.e., >10,000 km^2) from habitat selection analyses performed on a large sample of GPS-collared caribou occupying a region that included areas of high economic value. This enabled the identification of coarsely defined areas where candidate protected areas would be situated. We then encircled patches of highly suitable habitat within these regions to form the preliminary boundaries of candidate protected areas. Second, we assessed the

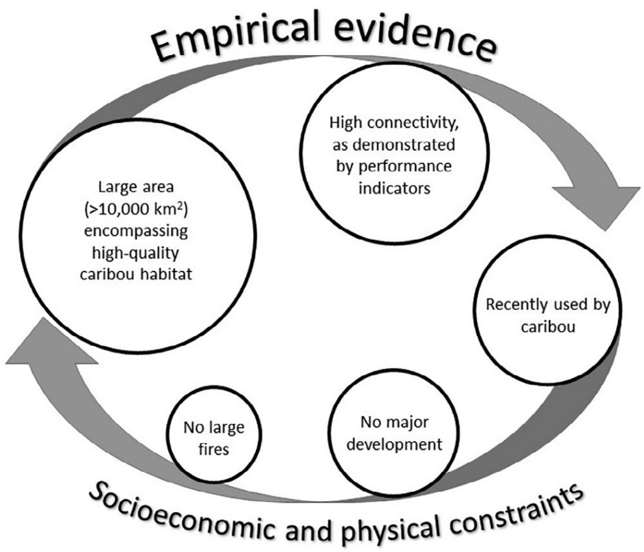

FIGURE 2 Schematic representation of the science-informed decision support framework used to identify candidate protected areas for boreal caribou in Québec, Canada

relative contribution of candidate protected areas to functional landscape connectivity by using complementary metrics of network performance derived from spatial graph theory. Third, we evaluated independent evidence of recent use by caribou from multiple datasets to corroborate the locations of candidate protected areas. Last, we identified potential impediments to the creation of candidate protected areas by compiling all potential socioeconomic constraints within their bounds as well as areas recently burned by major wildfires.

We completed this work in our capacity as members of the recovery committee for boreal caribou in Québec (GMO, 2012), an independent group of experts providing science-based advice to the Québec government. We provided our complete assessment to the government, which then presented our work to key stakeholders during topical regional workshops. Participants included provincial agencies, Indigenous and local communities, industries, environmental nongovernmental organizations, and landowners. These consultations helped bolster social acceptability, and allowed the government to meet the goals of the Convention on Biological Diversity which advocates "full and effective participation […] of indigenous and local communities […] and relevant stakeholders in the establishment and management of new protected areas" (https://www.cbd.int/, accessed February 9, 2022).

3.2 | Study area

The study area spanned >465,000 km^2 of the boreal forest of Québec, Canada (Figure 1). This vast area encompassed 68.9% of boreal caribou distribution in the province. Overlapping the northern limit of merchantable timber, it comprised both commercial and noncommercial forests. We centered our analyses in this area to meet our location criterion, that is, establish a protected area in a region where large (≥10,000 km^2) areas encompassing high-quality habitat for boreal caribou were available. The study area was dominated by black spruce (*Picea mariana*) stands with an understory of mosses and terrestrial lichens (Robitaille et al., 2015). The main disturbances were wildfire and forest harvesting, the latter only occurring in the commercial forest. A few mines, settlements, and hydroelectric powerlines also occurred within the study area, but their footprint was small relative to forest harvesting. The climate was characteristic of the boreal biome. Other large mammals in the study area included moose, gray wolf, and black bear.

3.3 | Caribou data

We used GPS telemetry data to characterize habitat selection by boreal caribou in the study area. We sampled 178 radio-collared adult female caribou monitored across 4 regions: 55 individuals from the Jamésie region (Nottaway, Assinica, and Témiscamie populations; 2004–2012; Rudolph et al., 2017), 64 from the Saguenay – Lac-Saint-Jean region (Pipmuacan, Portneuf, and Lac des Coeurs populations; 2004–2012; Leclerc et al., 2019), 37 from the Côte-Nord region (Eastern and Western Manicouagan populations; 2005–2012; Fortin et al., 2013), and 22 from the Minganie region (2012–2013; St-Laurent et al., 2021). From this data set, we only kept individuals that used the area of interest during a given year, that is, areas both above and below the northern limit of merchantable timber. This generated a final sample of 113 individual years from 55 collared individuals. Additional details on the monitoring of animals are available in Appendix 1.

3.4 | Ethical statement

Captures and manipulations of caribou were performed by experienced field personnel of the Ministère des Forêts, de la Faune et des Parcs du Québec (MFFP). Captures were performed without the use of anesthetic. Manipulations lasted on average 20 min and never more than 30 min to minimize stress on the animals. These manipulations were performed in strict accordance with the recommendations of the Canadian Council on Animal Care, under the following animal welfare committees' certificates: Jamésie, MFFP certificates CPA-04-005,

TABLE 1 Habitat variables used to identify candidate protected areas for boreal caribou in Québec, Canada

Variable type	Name	Description	% Availability (SD)[a]	% Use (SD)[b]
Forested cover types	Deciduous/mixed/regeneration	Mature mixed and deciduous stands (50–90 years old), as well as regenerating conifer, mixed, and deciduous stands (10–30 years old)	1.3 (1.2)	0.8 (2.2)
	Conifer 10%–25% cover	Mature and old conifer stands (50–120 years old) of cover 10%–25%	11.2 (6.2)	14.4 (9.6)
	Conifer 26%–40% cover	Mature and old conifer stands (50–120 years old) of cover 26%–40%	17.8 (7.4)	23.9 (13.1)
	Conifer 41%–60% cover	Mature and old conifer stands (50–120 years old) of cover 41%–60%	21.4 (12.5)	22.5 (13.9)
	Conifer ≥61% cover	Mature and old conifer stands (50–120 years old) of cover ≥61%; islands	5.9 (3.3)	5.9 (6.2)
Naturally open areas	Water	Water bodies (lakes and major rivers)	11.6 (6.5)	4.6 (6.5)
	Open no vegetation	Open areas without vegetation (e.g., rock fields, screes and outcrops)	0.5 (1.7)	0.3 (1.2)
	Wetland	Bogs and fens	6.1 (10.2)	6.4 (11.8)
	Open woodland	Open lichen, moss, or shrub woodlands	0.5 (0.6)	0.7 (1.8)
Disturbance	Natural disturbance	Natural disturbance; dominated by wildfires, but also includes windthrows and insect outbreaks	21.4 (13.6)	19.6 (22.6)
	Human disturbance	Anthropogenic disturbance; dominated by cutblocks, but also includes roads, powerlines, and settlements	2.3 (2.9)	0.9 (1.8)
Topography	Elevation	Elevation (km)		
	Elevation^2	Elevation^2		
	Slope	Slope (°)		
Distance to roads	Distance to roads	Distance to the closest paved or forest road (km), truncated at 1.25 km		

[a]Availability (%) represents the proportion of random locations found in each land cover type, on average across individuals ($n = 55$).
[b]Use (%) represents the proportion of GPS locations found in each land cover type, on average across individuals.

06-00-27, 07-00-04, 2011-03, and 2012-03; Saguenay–Lac-Saint-Jean, Université du Québec à Rimouski certificate 36-08-67; Côte-Nord, Université Laval certificate 2008026-3; Minganie, CPA-2012–12 and CPA-2013-02.

3.5 | Habitat suitability

We used this large sample of satellite telemetry data to develop resource selection functions (RSF; Manly et al., 2002). We used RSF model predictions as a proxy for caribou habitat suitability (see, e.g., Hansen et al., 2001), and assumed that areas selected by caribou served to fulfill their biological requirements (e.g., safe refuge, foraging opportunities), thereby entailing fitness advantages. For our purposes, we defined suitable areas as those containing the top-ranking RSF scores in the study area.

First, we generated a modeling extent by combining the annual home ranges of all individuals during all years. We generated annual home ranges with Minimum Convex Polygons. We then removed areas that fell outside of Québec (i.e., in Labrador and Ontario) because we lacked environmental data for these regions. Within the resulting extent, we tested several candidate models (available in Appendix 1) describing habitat selection at the third order of selection (sensu Johnson, 1980), using different sets of variables including land cover types, topographic indices, and distance to roads (Table 1). We extracted land cover types from a map generated by Bélanger et al. (2008), which combined information from two independent data sources, one above and one below the northern limit of merchantable timber. We considered five forested cover types, four naturally open areas, and natural and human disturbances (Table 1). The region was dominated by coniferous stands, although stem density tended to decrease with latitude. We therefore differentiated mature conifer stands based on canopy cover, with values ranging from 10% to 25%, 26%–40%, 41%–60%, and ≥ 61%. Due to the rarity of deciduous and mixed forest stands and the tendency of boreal caribou to avoid these stand types (e.g., Courbin et al., 2009), we combined them with regenerating stands in a single category. We chose "conifer 41%–60% cover" as the reference category, because it was the most available land cover type (21% of the sampled landscape) with a use/availability ratio close to 1 (1.05; Table 1). Land cover types used significantly more than this category ($\beta > 0$ with 95% confidence interval [95% CI] excluding 0) were considered selected by boreal caribou. We truncated road distances to 1.25 km based on Leblond et al. (2011), who found that behavioral avoidance by boreal caribou was imperceptible beyond this threshold. We identified the most parsimonious model with Akaike's information criterion corrected for small sample sizes (AIC_c). All candidate models included individual and year as random effects. All variables had variance inflation factors ≤ 1.61, indicating no multicollinearity issue (Graham, 2003). We used k-fold cross-validation to validate the most parsimonious RSF model (Boyce et al., 2002).

We derived normalized RSF scores (i.e., predicted values rescaled between 0 and 1) from the most parsimonious model to predict relative probabilities of caribou occurrence across the complete study area (black polygon in Figure 1) at a 100 × 100 m resolution. Because our minimal size criterion for protected areas was 10,000 km^2, we estimated the relative probability of occurrence of each cell by averaging RSF scores of all cells within 10,000 km^2 (i.e., within a 56.4-km radius). This neighborhood analysis allowed us to portray the broad-scale environment surrounding each cell, helping identify areas surrounded by high-quality habitat (e.g., interior forests away from dense road networks). This served the purpose of homogenizing RSF scores in neighboring cells, thereby reducing the impact of small-scale disturbances. We reclassified the resulting values into deciles, and identified the top ≥80th percentile of RSF scores as being the most suitable locations for candidate protected areas. Then, we evaluated the same RSF model at the scale of 100 × 100 m pixels to identify areas within these broad regions that were most suitable to caribou at a local scale. We used results from this analysis to draw the preliminary contours of candidate protected areas.

3.6 | Connectivity

We used spatial graph theory to evaluate functional landscape connectivity for boreal caribou in the study area (Urban & Keitt, 2001). Habitat patches took the form of discrete nodes connected by least-cost paths spanning a resistance matrix identical in spatial extent to the study area used to assess habitat suitability. Nodes corresponded to merged patches of land cover types selected by boreal caribou, as identified by the most parsimonious RSF model (e.g., O'Brien et al., 2006). Due to the large size of our study area and to facilitate computations, habitat patches had to be contiguous over at least 5 km^2 to be considered as nodes. Each node was weighted by the sum of the RSF scores of its cells. We based matrix resistance values on the results of the best RSF model, with the most strongly avoided variables generating the most resistance. To do so, we assigned to each 100 × 100 m cell of the study area the inverse value of its RSF score.

We used Graphab v. 2.2.3 (Foltête et al., 2012) to compute least-cost paths between adjacent nodes (i.e., sharing a Voronoi boundary). Nodes linked by paths >9 km in length were considered functionally isolated. This threshold value represents the maximum net displacement of individual caribou in a single day (95th percentile; expressed as a seasonal weighted average; Rudolph, 2015). For reference purposes, we also report least-cost path analyses using maximum lengths of 4 (maximum daily net displacement in winter) and 15 km (maximum daily net displacement in spring; Appendix 2). Finally, we constructed minimum planar graphs representing weighted nodes and least cost paths weighted by their cumulative cost.

We assessed the relative contribution of candidate protected areas to global network connectivity by removing them one at a time from the available habitat pool (i.e., leave-one-out procedure) and subsequently calculating three complementary metrics. First, we measured the equivalent connectivity (EC) of the network at-large to assess the quality-weighted area of connected habitat across the network (Saura et al., 2011). We then iteratively removed each protected area and measured the resulting change in EC (or ΔEC) to assess the relative contribution of each (Rayfield et al., 2016). This indicator reflects both internode and intranode connectivity and the dispersal capacity of our focal species. Second, we measured the mean shortest path length between all pairs of nodes, again iteratively excluding protected areas, to assess the role of each in facilitating connectivity between pairs of indirectly connected habitat nodes throughout the study area (hereafter mean path length [MPL] Minor & Urban, 2008). This indicator reflects the relative importance of each candidate protected area as a stepping stone in the broader landscape context. Last, we counted the number of disconnected network elements (i.e., independent clusters of interconnected habitat patches) that resulted from the removal of each candidate protected area relative to the reference landscape. This metric reflected the degree to which inter-patch connectivity depended on individual candidate protected areas. Performance of candidate protected areas in terms of overall contribution to landscape connectivity was derived from the sum of individually rescaled connectivity metrics ($0 \leq x \leq 1$). See Appendix 3 for more details on the calculation of network performance metrics.

Complementary spatial and statistical analyses were performed in ArcGIS 10 (ESRI Inc., Redlands, California), the Geospatial Modeling Environment tool (spatialecology.com), and R v. 3.4.3 (R Core Team, 2017).

3.7 | Evidence of recent use by caribou

In preparation for the public consultations that would help identify the most socially acceptable protected area among our list of candidates, we sought to collect empirical evidence suggesting recent use by boreal caribou in each area. We leveraged the large satellite telemetry dataset serving to develop the RSFs as evidence of recent use of candidate protected areas by boreal caribou, collating supplementary information to complement these data. Most of this complementary information came from boreal caribou monitoring reports published by the Québec Government in various regions of Québec between 2009 and 2019 (available on https://mffp.gouv.qc.ca/, accessed February 9, 2022). We also considered caribou snow track networks observed during winter aerial surveys (1999–2005) as evidence of recent use by caribou because these data covered a large portion of the study area (Fortin et al., 2008). Areas indicating recent use by caribou based on multiple sources of information were considered stronger candidates than areas with only a single source or no evidence of recent use. Sufficient data on the demography of caribou populations across our study area was unavailable, and therefore could not be used to further refine this assessment.

3.8 | Socioeconomic and geophysical constraints

We sought to identify potential impediments to the establishment of a protected area. Information on major resource extraction projects within candidate protected areas was provided by provincial authorities. Areas with no foreseen industrial development were considered more likely to receive legal designation than those with one or multiple planned or ongoing projects. Last, we used high-resolution (≥0.1 ha) wildfire maps provided by the MFFP to verify the locations of recent fires in the study area. We subsequently transmitted this information to the Québec government who then conveyed our findings to various stakeholders during multiple consultations. We summarize the outcomes of these consultations in the Section 4.4 below.

TABLE 2 Parameter estimates (β) and lower and upper bounds of the 95% confidence intervals (CIs) of the habitat variables composing the most parsimonious resource selection function assessing habitat selection by boreal caribou in Québec, Canada

Variable	β	Lower	Upper
Land cover types[a]			
Deciduous/mixed/regeneration	−0.69	−1.12	−0.25
Conifer 10%–25% cover	0.32	0.07	0.57
Conifer 26%–40% cover	0.37	0.14	0.59
Conifer ≥61% cover	−0.06	−0.32	0.20
Water	−1.46	−1.81	−1.11
Open no vegetation	−0.23	−0.66	0.20
Wetland	−0.08	−0.27	0.11
Open woodland	1.15	0.67	1.63
Natural disturbance	−0.73	−0.97	−0.50
Human disturbance	−0.50	−0.90	−0.10
Topography			
Elevation (km)	3.36	−0.14	6.85
Elevation^2	−3.78	−6.75	−0.80
Slope (°)	−0.01	−0.03	0.02
Distance to roads			
Distance to roads (km)	1.34	0.83	1.85

[a]We used Conifer 41%–60% cover as the reference category.

4 | RESULTS

4.1 | Habitat suitability

Resource selection by boreal caribou was best explained by a model combining land cover types, topography, and distance to roads. This model was robust to cross-validation with an average r_s of 0.99 ($p < .01$) across 10 iterations. Boreal caribou showed selection for relatively low-density coniferous forest (10%–25% and 26%–40% cover) as well as open woodlands (Table 2). Their use of dense coniferous forests (≥61% cover) was proportional to their use of the reference category. They used deciduous, mixed, and regenerating stands, water bodies, and all types of disturbance less than the reference

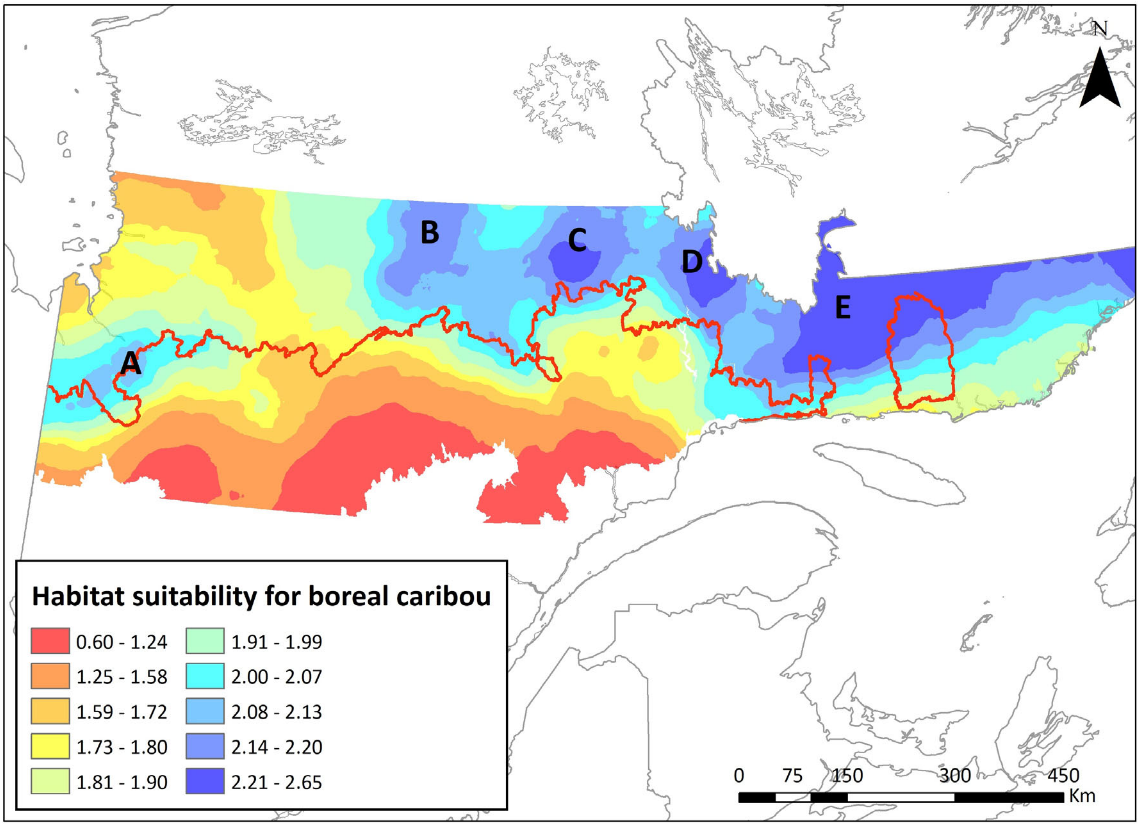

FIGURE 3 Habitat suitability for boreal caribou in Québec, Canada, determined using context-dependent resource selection functions (RSF; cell-wise averages within a 10,000-km^2 area). We reclassified RSF scores into deciles, and identified the top ≥80th percentile as being the most suitable areas for boreal caribou. This analysis highlighted five areas where candidate protected areas should be placed: (a) Grasset, (b) Emmanuel, (c) Manouane-Manicouagan, (d) Opocopa, and (e) Romaine. The northern limit of merchantable timber is shown with a red line

category. They also selected areas far from roads and at intermediate elevations (Table 2).

We used the parameters of the fitted model to predict habitat suitability for boreal caribou across the study area. We identified five broad regions where protected areas for boreal caribou could be considered based on those with the highest RSF scores (≥80th percentile; Figure 3). These regions were named after dominant water bodies as follows (from west to east): Grasset (A), Emmanuel (B), Manouane-Manicouagan (C), Opocopa (D), and Romaine (E; see Figure 3). Candidate protected areas were further refined by enclosing all highly suitable areas based on the results of a local-scale RSF (Figure 4).

At this early stage, it became evident that two of the candidate protected areas were located too far north and excluded the commercial forest (Emmanuel and Opocopa; see Figure 4). We kept these candidate protected areas in our analyses for comparison purposes, but they were never presented to stakeholders for formal consideration because they did not meet our geographic location criterion (i.e., they would not grant protection to areas currently coveted by industry).

4.2 | Connectivity

Conifer forests of 10%–25% and 26%–40% cover were selected by boreal caribou and were thus classified as habitat nodes in the connectivity analysis. We also classified conifer forests of 41%–60% cover (the reference category) as habitat nodes because they were highly available in the landscape and used substantially by caribou (Table 1). Although open woodlands were selected by caribou, given their scarcity and scattered distribution in the study area (relative abundance = 0.5%; mean patch size = 13.4 ha), we considered it unlikely that these land cover types would offer sufficient protective refuge to qualify as connectivity nodes. They were therefore assigned to the heterogeneous matrix along with other forested cover types, exposed environments, natural and human disturbances, and areas within 1.25 km of a road. Nonetheless, given that our cost surface consisted of the inverse of RSF model predictions, least cost paths were more likely to pass through open woodlands than through less favored land cover types.

The final constructed graph comprised 1319 nodes ranging in size from 5 to 27,280 km^2, (median = 10.8 km^2),

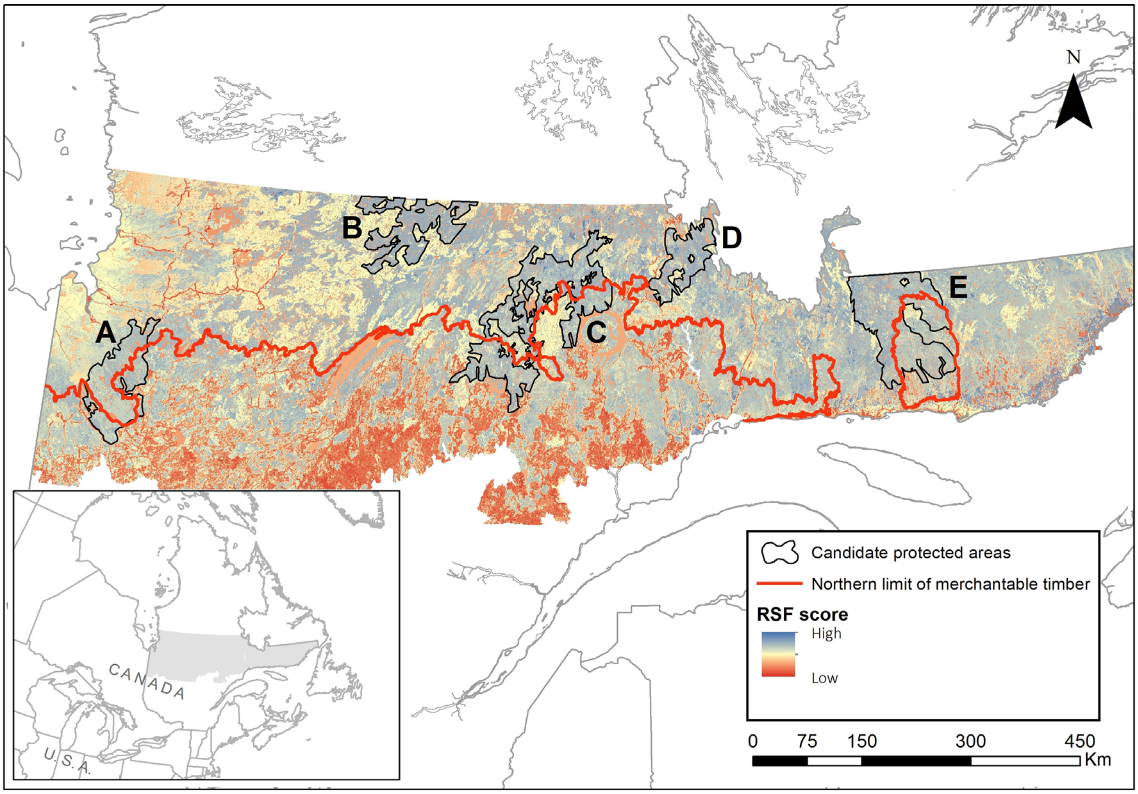

FIGURE 4 Preliminary contours of candidate protected areas for boreal caribou in Québec, Canada, drawn by enclosing patches of highly suitable habitat as determined by local-scale resource selection functions (RSF). Candidate protected areas were (a) Grasset, (b) Emmanuel, (c) Manouane-Manicouagan, (d) Opocopa, and (e) Romaine

linked by 2108 least-cost paths across the study area (Appendix 2). Analyses performed using maximum link distances of 4 and 15 km generated 1517 and 2467 least-cost paths, respectively (Appendix 2). The five candidate protected areas varied in terms of connectivity attributes, as determined by the complementary network performance indicators (Table 3). Manouane-Manicouagan exhibited the best overall performance, followed by Romaine and Emmanuel.

4.3 | Caribou presence and socioeconomic constraints

The GPS locations of the 55 individuals that we used to model habitat selection overlapped a large proportion of the candidate protected areas Grasset, Manouane- Manicouagan, and Romaine (>94.8%; Table 4). These areas, along with Opocopa, also showed recent evidence of caribou use as determined by aerial survey reports (2009–2019) and snow track networks (1999–2005). In contrast, virtually no data existed to confirm caribou presence in Emmanuel. Candidate protected areas Opocopa, Emmanuel, and Grasset had between 10% and 25% of their area covered by mining claims, compared with ≤1.5% for the other two. While analyses were being conducted, a new pipeline and railroad were planned in Opocopa, a mine and access road were planned in Emmanuel, and a major hydroelectric complex was under construction in Romaine (Table 4).

4.4 | Prioritization and identification of a final protected area

Three of the five candidate protected areas that we identified using our decision support framework were presented to stakeholders: Grasset, Manouane-Manicouagan, and Romaine. The two other candidate protected areas were set aside because they were entirely outside the commercial forest, where threats to boreal caribou were less immediate. Candidate protected areas were presented by government officials during multiple consultations in all relevant administrative regions of Québec. Whereas the contours of the candidate protected areas shared with stakeholders were based on the results of our modeling exercise, over the course of 3 years and many discussions, several modifications to these boundaries were introduced to address

TABLE 3 Network performance (connectivity) of candidate protected areas for boreal caribou in Québec identified using a science-informed decision support framework

Candidate protected area	Change in equivalent connectivity (ΔEC)	Change in mean path length (ΔMPL)	Change in number of independent clusters (ΔClust)	Global performance
A—Grasset	62,332	0.1755	4	1
B—Emmanuel	376,604	1.0509	6	3
C—Manouane-Manicouagan	1,059,172	2.8752	17	5
D—Opocopa	340,676	1.8880	4	2
E—Romaine	863,764	3.2974	5	4

Note: Higher values indicate better performance. With a global rank of 5, the Manouane–Manicouagan was the best performing of the candidate protected areas, indicating that it made the greatest contribution to network connectivity within the study area. See Appendix 3 for more details on the calculation of network performance metrics.

TABLE 4 Socioeconomic constraints and conservation potential of candidate protected areas for boreal caribou in Québec, Canada, identified using a science-informed decision support framework

Candidate protected area	Average RSF score (SD)	Most recent evidence of caribou use	Percentage of the area covered by telemetry data (%)	Percentage of the area covered by mining claims (%)	Percentage of the area in commercial forest (%)	Major industrial developments planned
A—Grasset	2.23 (0.50)[a]	2003 = 16 networks, 117 ind.	98.2	24.5	37.9	—
B—Emmanuel	2.36 (0.67)	None	1.2	11.1	0.0	Mine, road
C—Manouane-Manicouagan	2.33 (0.53)	2014 = 39 networks, 697 ind.	94.8	1.5	45.4	—
D—Opocopa	2.35 (0.61)	2014 = 13 networks, 52 ind.	8.1	10.0	0.0	Pipeline, railroad
E—Romaine	2.29 (0.56)	2012 = 22 networks, 156 ind.	96.4	<0.1	42.0	Hydroelectric complex

Abbreviation: RSF, resource selection function.
[a]For comparison purposes, the minimum and maximum RSF scores in the study area were − 1.72 and 3.57, respectively.

local concerns or economic interests (e.g., timber harvest management plans, mineral claims). At this stage, areas recently burned by major wildfires were also excluded from candidate protected area boundaries. Such changes naturally modified the initial characteristics of the areas first identified with our framework. Ultimately, a modified version of the Manouane-Manicouagan candidate protected area that mitigated the impacts of boreal caribou habitat protection on forestry, mining, and hydroelectric potential was recommended (Figure 5). Notwithstanding a significant reduction in size compared with its initial form (10,193 km^2 compared to 15,964 km^2), this new area showed high boreal caribou habitat suitability (average RSF score: 2.23; SD: 0.54) and high connectivity, maintaining its first rank among all other candidate protected areas while establishing protection for 4590 km^2 of previously-allocated commercial forest (see Appendix 4 for supplementary analysis comparing the final protected area to candidate and randomly generated protected areas). This area became known as the Caribous-Forestiers-de-Manouane-Manicouagan protected area, and was legally protected by the Québec Government in March 2021.

5 | DISCUSSION

Our objective for this study was to describe the process that led to the establishment of a large protected area for boreal caribou in a geographic region with conflicting socioeconomic and conservation interests. Our approach employed criteria pertaining to size, geographic location, habitat suitability, functional connectivity, and the feasibility of different scenarios considering multiple socioeconomic and geophysical constraints across a wide swath of boreal forest (>465,000 km^2). The successful identification of this large protected area draws from our

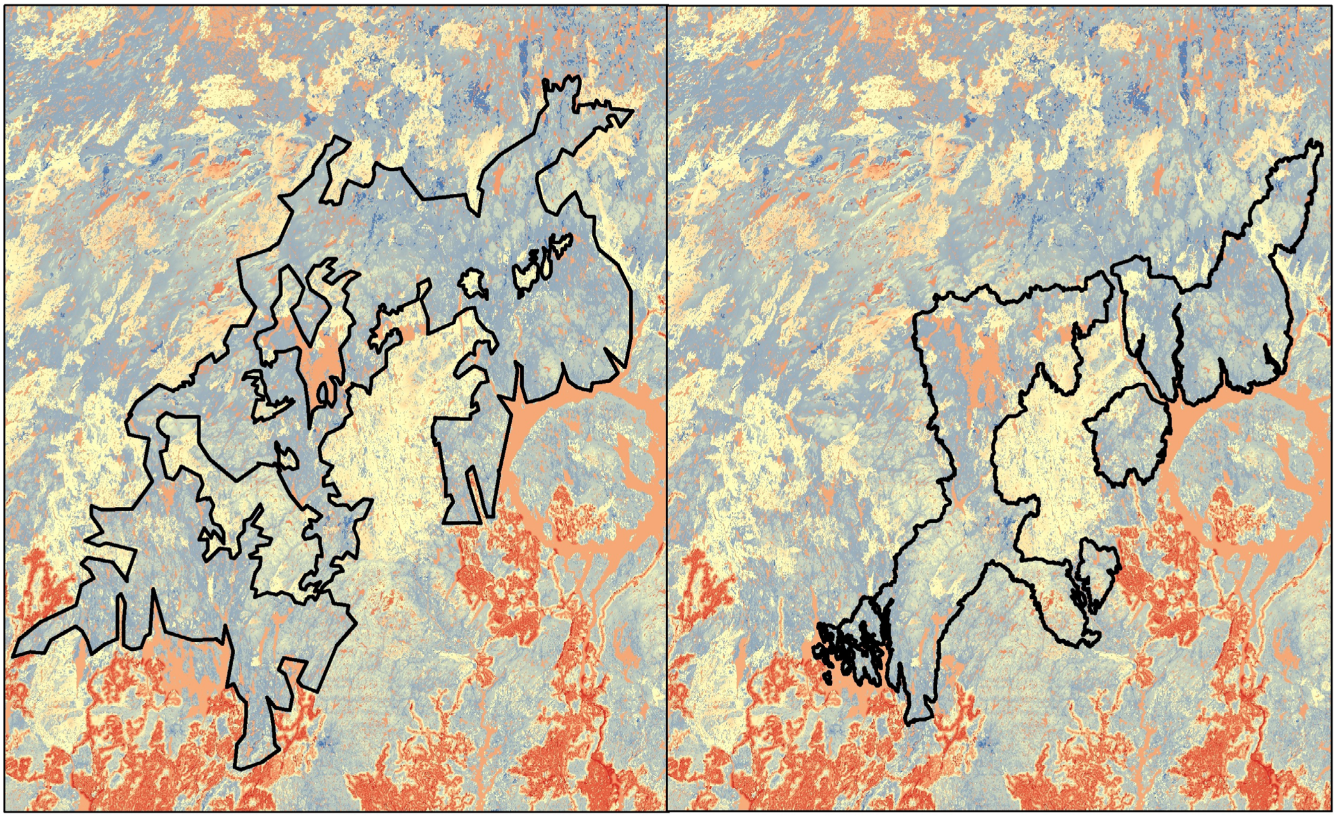

FIGURE 5 On the left—The Manouane-Manicouagan candidate protected area (15,964 km^2), which received the greatest support from our science-informed decision support framework, and which was presented during consultation workshops with key stakeholders along with other protection scenarios. On the right—The caribous-Forestiers-de-Manouane-Manicouagan protected area (10,193 km^2), officially designated by the Québec Government on March 4, 2021

integration of multiple criteria pertaining to boreal caribou requirements, including the use of complementary datasets, the integration of empirical results at early stages of planning, and consideration for logistical and socioeconomic constraints.

5.1 | The benefits of a new protected area

The comprehensive nature of our decision support framework increased the likelihood that we would succeed in identifying a protected area meeting the requirements of boreal caribou in terms of size and habitat quality, while mitigating conflicts with other land users. Enforced land protection through official designation will help maintain a large tract of mature coniferous forest for boreal caribou, and curtail the creation of anthropogenic disturbances that increase predation risk (DeCesare et al., 2010). Other taxa, including rare and endangered species, should likewise benefit from this protection (Bichet et al., 2016). Some sources of anthropogenic disturbance will persist in the protected area until they are actively or naturally restored, but these disturbances currently occupy a very small portion of the identified protected area (<1%). The edges of the protected area could also be susceptible to land-use practices outside of its boundaries (Hansen & DeFries, 2007), and as such, we recommend the enactment of habitat protection and other mitigation measures in areas surrounding the protected area to limit edge effects and maintain connectivity at the landscape scale. Nevertheless, it should provide sufficient core habitat as functional refuge from industrial activities to improve local boreal caribou survival (Courbin et al., 2009).

Protection of caribou in Canada is a multifaceted challenge with important sociopolitical ramifications (Palm et al., 2020). For instance, Hebblewhite (2017) convincingly articulated that the protection of boreal caribou habitat was likely delayed by the substantial socioeconomic costs of protecting its critical habitat, estimated at >150 billion $CAD in Alberta alone. Because of this, few attempts have been made to slow the decline of boreal caribou populations since their inclusion on the Species at Risk Act in 2002 (Ray, 2014). Instead, disturbances have continued to increase in most boreal caribou population ranges across Canada during this period (Environment and Climate Change Canada, 2017). The creation of the Caribous-Forestiers-de-Manouane-Manicouagan protected area is a significant step in the right direction, a much-needed political action for the protection of boreal caribou in Canada where *status quo* has been the norm.

5.2 | Will it be enough?

Simply put, no. The creation of one protected area will not suffice in meeting the goals of the recovery strategy for boreal caribou, which is to achieve self-sustaining local populations in all ranges throughout their current distribution (Environment Canada, 2012). Therefore, although the Caribous-Forestiers-de-Manouane-Manicouagan protected area will undoubtedly become a cornerstone for boreal caribou conservation in northern Québec, it will not address the continued decline of caribou populations elsewhere in Québec and Canada. Rather, sustained efforts will be required across a wide geographic area. This could include the creation of new protected areas. In the southern part of the boreal caribou distribution where habitat disturbance is most prevalent, there may not remain sufficient large pristine areas to consider significant land protection. In these areas, short-term population management actions such as predator control or maternal penning may help safeguard caribou populations until sufficient habitat renewal has taken place through a combination of active and passive restoration efforts (e.g., Serrouya et al., 2019).

Several authors have demonstrated the importance of protected area networks to improve biodiversity conservation (e.g., Geldmann et al., 2013; Naughton-Treves et al., 2005), but we must also recognize the limitations of geographically fixed protected areas in a changing world (Hoffmann, 2022; Walther et al., 2002). Rapid changes in climatic conditions are expected under global warming (Intergovernmental Panel on Climate Change, 2013). Wildfires are predicted to increase in frequency and severity in most boreal regions of Canada (Price et al., 2013), and species range shifts are expected to occur at a significantly faster rate (Chen et al., 2011). In our exercise, we partially alleviated the potential impacts of climate change by ensuring that identified protected areas were sufficiently large to withstand stochastic disturbance events such as local to moderate-scale wildfires (Lande, 1993). Others have integrated climate change forecasts into their reserve designs (Bauduin et al., 2020).

We also note that the capacity of this new protected area to maintain a healthy boreal caribou population remains to be determined. Caribou are a long-lived species that typically sustain high rates of calf mortality (Bergerud, 1980), meaning that several years will need to pass before such an assessment can be made. We hope that its modest size relative to suggested minimum requirements for boreal caribou (10,000–15,000 km^2) will in part be countered by its high connectivity to other suitable areas. Unfortunately, there was very little social appetite for the protection of a much larger area, illustrating the gap that can often exist between conservation science (i.e., our proposed candidate protected area) and practice (i.e., the smaller, officially designated protected area).

5.3 | Conclusion

The Caribous-Forestiers-de-Manouane-Manicouagan protected area was officially announced by the Québec Government in late 2017, and legally protected on March 4, 2021 under the Natural Heritage Conservation Act. With a size of 10,193 km^2, it became the second-largest protected area to partially overlap the commercial forest in Québec. In comparison, the other 4380 protected areas in the region had an average size of 22.5 km^2. Our study showcases a success story for the protection of biodiversity in Canada, and highlights the importance of science-driven decision support frameworks. Our framework could be used to identify the next large protected area in Québec, or could be adapted with little effort to other conservation contexts. Its primary elements include: (i) integrating scientific results at the onset of planning, (ii) considering multiple criteria, both ecological and socioeconomic, in the identification of candidate areas to ensure that protection scenarios are both effective and realistic, (iii) validating protection scenarios using independent data sets, and (iv) including key stakeholders in the decision process to garner their support and resolve potential conflicts.

Much effort and dedication were required to bring this project to fruition. Changing the land-use and tenure framework of more than 10,000 km^2 of Québec's boreal forest involved many stakeholders, and required commitment, lengthy discussions, and compromises. Whereas we emphasize the critical elements of success that underpinned this endeavor, our few sentences fail to underscore the many lengthy consultations that ultimately led to the final boundaries of the recommended protected area. We hope that our work will inspire other jurisdictions to pursue biodiversity conservation and habitat protection, and that our study will serve as an example of what people can achieve by working together to promote the conservation of species at risk.

AUTHOR CONTRIBUTIONS

Mathieu Leblond, Tyler Rudolph, and Dominic Boisjoly were responsible for different analyses. Mathieu Leblond led the writing of the article. All authors conceived the ideas, designed the methodologies, contributed substantively to drafts, and gave their final approval for publication.

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CONFLICT OF INTEREST

The authors declare no conflicts of interest.

DATA AVAILABILITY STATEMENT

This study uses data on the distribution of a species at risk, obtained under restricted data sharing agreements. Partial data and scripts can be made available upon request.

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SUPPORTING INFORMATION

Additional supporting information can be found online in the Supporting Information section at the end of this article.

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