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à Rimouski

EFFET DE LA PROTECTION DE L'HABITAT DU CARIBOU SUR L'APPROVISIONNEMENT EN BOIS

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EFFECT OF CARIBOU-ORIENTED MANAGEMENT ON WOOD SUPPLY AND HABITAT QUALITY

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RÉSUMÉ

Ce travail cherche à évaluer s'il est possible de trouver un équilibre entre l'approvisionnement en bois et la probabilité relative de présence du caribou de l'Atlantique-Gaspésie, un écotype en voie de disparition situé dans la région de la Gaspésie. L'aménagement forestier au Québec cherche à établir le niveau maximum de récolte de matière ligneuse tout en assurant aucune réduction dans l'approvisionnement, en ayant-majoritairement recours à des régimes de futaie régulière. Toutefois, ces traitements sylvicoles, combinés à la densification du réseaux routiers, sont reconnus pour avoir contribué à un déclin des populations de caribous, passant d'environ 1 000 individus dans les années 1950 à environ 34 individus en 2020. Afin de trouver l'équilibre entre la récolte et la qualité de l'habitat, l'étude a utilisé le simulateur de croissance ARTEMIS pour tester 16 scénarios sur un horizon de 50 ans pour évaluer les effets de la coupe forestière sur l'habitat du caribou, incluant 15 scénarios d'aménagement en plus du scénario de référence correspondant au statu quo (*business-as-usual*, BAU). En appliquant une fonction de sélection des ressources aux sorties des simulations ARTEMIS, les résultats montrent que la probabilité relative de présence du caribou diminue au cours des 50 prochaines années sous le BAU. Dans ce scénario, la probabilité relative de présence du caribou passe de 0,15 en 2017 à 0,12 en 2067, principalement en raison des jeunes parterres de coupe et de l'expansion du réseau routier. À l'inverse, la stratégie la plus efficace pour la restauration de l'habitat a été l'application de la coupe de jardinage par pied d'arbre (SL_P2) dans les zones à l'intérieur de son aire de répartition du caribou, combinée à un retrait complet des routes. Cette combinaison a environ triplé la probabilité relative de présence du caribou dans l'aire de répartition. Les résultats mettent en évidence ce compromis : l'atteinte d'un habitat avec de grandes probabilités d'occurrence du caribou est associée à une légère diminution des volumes récoltés. Les scénarios ayant le plus d'impact sur la probabilité d'occurrence ont entraîné des pertes de récolte de bois variant de 2% à 9%. Cependant, la stratégie SL_P2 s'est imposée comme le meilleur compromis, proposant l'approvisionnement en bois le plus élevé parmi les différentes alternatives cherchant à augmenter la qualité de l'habitat du caribou. Ces résultats démontrent que, bien que les changements sylvicoles aient des effets positifs, ils demeurent insuffisants en l'absence de retrait des routes. En conclusion, le mémoire soutient que le rétablissement de l'habitat de cette population en voie de disparition repose sur un changement de paradigme vers une restauration active, dans laquelle la fermeture des routes doit être considérée comme une exigence opérationnelle centrale plutôt qu'une mesure secondaire.

Mots clés: caribou de l'Atlantique-Gaspésie, simulations de croissance ARTEMIS, déclassement des routes, traitements sylvicoles, compromis d'approvisionnement en bois, restauration de l'habitat

ABSTRACT

This research tries to find the balance between the wood supply and the relative probability of caribou occurrence (RPOC) of Atlantic-Gaspesie caribou, an endangered ecotype found in the Gaspesie region. Forest management in Quebec tries to find the maximum harvesting level that can be sustained over a very long horizon, generally using even-aged systems. However, these silvicultural treatments, along with extensive road networks, contributed to the decline in caribou populations from 1,000 individuals in the 1950s to approximately 34 animals by 2020. To determine the balance point, this study applied the ARTEMIS forest growth simulator to test 16 scenarios, including 15 caribou-oriented management scenarios along with the current business-as-usual (BAU) strategy, over a 50-year horizon. By employing a resource selection function (RSF) on outputs of ARTEMIS growth simulations, the results underscore that under BAU, which uses clear-cutting, RPOC will decline gradually over the next 50 years. The RPOC in this scenario was observed to decrease from 0.15 in 2017 to 0.12 by 2067, mainly shaped by young cutblocks and the spread of the road network. In contrast, the most successful strategy for habitat restoration was the application of selection cutting (SL_P2) in sensitive zones inside the caribou range combined with 100% road removals. This combination approximately tripled the RPOC in sensitive zones. The outcomes highlight a necessary trade-off: achieving high-quality habitat is associated with the lowering of harvesting volumes. The best scenarios yielded timber harvest losses ranging from 2% to 9%. However, the SL_P2 strategy appeared as a middle ground, proposing the highest wood supply across the alternative caribou-oriented options while still providing a relatively better long-term habitat. These results provide evidence that while silvicultural shifts are positive, they are suboptimal without intense road rehabilitation. This thesis concludes that the habitat recovery of this endangered population relies on a paradigm shift toward active restoration which considers road decommissioning as a central operational requirement rather than a secondary measure.

Keywords: ARTEMIS growth simulations, Atlantic-Gaspesie caribou, habitat restoration, road decommissioning, silvicultural treatments, wood supply trade-offs

TABLE OF CONTENTS

ACKNOWLEDGEMENTS ix

RÉSUMÉ xi

ABSTRACT xiii

TABLE OF CONTENTS xv

LIST OF TABLES xvii

LIST OF FIGURES xix

LIST OF ABBREVIATIONS AND ACRONYMS xxi

LIST OF SYMBOLS xxv

CHAPTER 1
GENERAL INTRODUCTION 1

1.1 PROBLEM STATEMENT 2

1.2 LITERATURE REVIEW 4

1.2.1 Introduction to caribou and its Atlantic-Gaspesie population . . 4

1.2.2 History of forest management and creation of associated road networks in Gaspesie 5

1.2.3 Efforts to conserve caribou 6

1.2.4 Concern over implementation of caribou recovery plan 8

1.2.5 Integrated simulation studies 9

1.2.6 ARTEMIS: Forest growth simulator 10

1.2.7 Caribou habitat model 17

1.2.8 TRIAD zoning approach 19

1.3 OBJECTIVES OF THE WORK 20

1.3.1 Research questions 21

1.3.2 Research objectives 22

1.3.3 Hypotheses 22

CHAPTER 2
EFFECT OF CARIBOU-ORIENTED MANAGEMENT ON WOOD SUPPLY AND HABITAT QUALITY IN EASTERN CANADA 23
2.1 ABSTRACT 24
2.2 INTRODUCTION 25
2.3 METHODOLOGY 28
2.3.1 Study area 28
2.3.2 Methods 30
2.4 RESULTS 47
2.4.1 RPOC under BAU 47
2.4.2 Effects of alternative management strategies on RPOC 47
2.4.3 Mapping RPOC 51
2.4.4 Effect of forest management scenarios on wood supply 53
2.5 DISCUSSION 58
2.5.1 Modulation of silvicultural treatments 58
2.5.2 Inclusion of dynamic road component in the simulation 59
2.5.3 RPOC in caribou range and management strata 60
2.5.4 Effect on total harvest volume 61
2.5.5 Implementation of an optimal scenario 63
2.5.6 Limitations and scope 64
2.6 CONCLUSION 65
GENERAL CONCLUSION 67
ANNEX I 71
ANNEX II 79
REFERENCES 81

LIST OF TABLES

1 The number of permanent sample plots in each forest management unit (FMU) and the plots measured between 2017 and 2021 kept for modeling purposes 30

2 A functional grouping of forest disturbance and silvicultural intervention codes used in Quebec's public forest inventory system. Codes are categorized by management intensity (Intensive, Extensive), disturbance origin (Natural), and other intervention types 35

3 Land cover classes used in the resource selection function (RSF) model, defined by cover type, treatment history, and stand age 36

4 Land use stratification: number of sample plots and area by strata . . . 39

5 Potential vegetation types identified in the Gaspesie, associated silvicultural treatment methods, and their respective treatment return intervals 40

6 Maximum annual area allocated by silvicultural treatment type (ha) across different scenarios, including treatment codes. The area for clearcutting with protection of regeneration and soils (CPRS) remained fixed in all scenarios. In contrast, the areas for shelterwood and selection cutting in the constrained 1 and 2 were variable and could exceed the baselines set in the current business-as-usual and conservation scenarios 41

7 Caribou habitat restoration zones in the caribou range, including zone codes and respective area in hectares, representing critical habitat, predator management, and peripheral habitat zones 42

8 Forest and road management decisions used to construct the different scenarios. Each combination of forest and road management possibilities are used, leading to 16 scenarios 45

9 Temporal patterns in timber harvest volume (m^3/yr) in reference to the 2017-2027 business-as-usual (BAU) harvest volume. Values indicate the absolute change in harvest volume and the corresponding percentage shift (in parentheses) for six forest management strategies across five 10-year intervals from 2017-2027 to 2057-2067. Positive values represent increase and negative value represent decrease in harvest volume compared to the initial BAU. Strategies include: BAU (business-as-usual), CONS (conservation), SW (shelterwood), and SL (selection). Management intensity is denoted by intervention area: P1 denotes the predator management zone, and P2 comprises both the predator management and peripheral habitat zones making SW_P1: shelterwood cutting in P1, SW_P2: shelterwood cutting in P2, SL_P1: selection cutting in P1, SL_P2: selection cutting in P2. The CONS scenario is baseline alternative management. The BAU scenario is current forest management strategy 57

10 Landcover types, topography variables and linear features considered in the different candidate models of resource selection functions used to evaluate habitat selection patterns of the 41 Atlantic-Gaspésie caribou monitored between 2013 and 2016 75

11 Candidate models considered in the model selection exercise aiming at characterizing habitat selection patterns of 41 Atlantic-Gaspésie caribou between 2013 and 2016 in Québec, Canada. Each group of variables is described in Table 10 76

12 Coefficients (β) and 95% confidence interval (95% CI) [lower bound: upper bound] of the most parsimonious model describing habitat selection patterns of caribou based on the telemetry monitoring of 41 caribou between 2013 and 2016. Coefficients for which the 95% CI did not overlap zero are considered to have a significant influence on caribou behaviour. Results of the k-fold cross validation (Spearman correlation coefficient, $r_s \pm$ SD) are presented 77

13 Rules for assigning cover types (Conifer, Mixed wood, Broadleaf) from simulated basal area by species group 79

14 Topography variables and linear features used in previously defined resource selection function 79

15 Land use category classification used in simulations, adapted from Ecoforest management maps 80

LIST OF FIGURES

1 ARTEMIS-2009 work flow (Fortin et al., 2022) 12

2 Location of the permanent sample plots and the three Forest Management Units (FMU: 11161, 11262, and 11263) in Gaspesie 29

3 Schematic diagram of the integration framework linking ARTEMIS-2009 forest simulations with the resource selection function (RSF) model to generate relative probability of caribou occurrence values 34

4 Schematic workflow illustrating the spatial integration of protected areas with conservation and protection scenarios, using sequential overlay and clipping of critical (CHZ), predator management (PMZ), and peripheral (PHZ) habitat zones by the study area 44

5 Results of application of resource selection function (RSF) on ARTEMIS forest growth simulator. Results are computed using 1,000 Monte Carlo simulations of 208 permanent sample plots for 50 simulation years. (a) Relative probability of caribou occurrence across landcover types; boxes depict the interquartile range (IQR), the central horizontal line represents the median, and whiskers scale to the 95% confidence interval, with individual simulation realizations shown as randomly selected 50 jittered points. (b) Response to nearest road distance (m) 48

6 Distribution and projection of relative probability of caribou occurrence in Gaspesie. (a) Density plot showing the gamma distribution of the relative probability of caribou occurrence, (b) Projected forecast of the mean relative probability of caribou occurrence from 2017 to 2067 with the 95% confidence interval across the simulation period 49

7 Scenario-based projections of the relative probability of caribou occurrence (2017-2027) under multiple forest management and road decommissioning strategies. Left panel maps symbolize the extent of management across five spatial scales: (A) the entire study area, (B) caribou range, (C) conservation strata (protected area + critical habitat zone), (D) sensitive wood production strata (predator management zone + peripheral habitat zone), and (E) general wood production strata. The multi-figure layout displays the forecasted mean relative probability of occurrence across three road management decisions: (a) No road removal, (b) 50% road removal, and (c) 100% road removal 52

8 Spatiotemporal pattern of mean relative probability of caribou occurrence of optimal forest management strategies under each road decommissioning scenarios (2017-2067). The maps portray the empirical Bayesian kriging based spatial interpolation of mean relative probability of caribou occurrence for: (a) SL_P1 under no road removal, (b) SL_P2 under 50% road removal, and (c) SL_P2 under 100% road removal . . 54

9 Projected impacts of forest management strategies on timber harvest and standing volume (2017-2067). (a) Total annual harvest volume (m^3/ha) is sum of timber harvest aggregated in 10-year intervals. (b) Forecast of standing volume (m^3/ha). (c) Trade-off analysis between caribou habitat quality and wood supply across 16 management scenarios. The scatterplots demonstrate the 50-year average relative probability of occurrence (habitat quality) against the 50-year average timber harvest (m^3/yr; wood supply). Error bars capture the standard error with 95% confidence intervals estimated from the 1000 Monte Carlo realizations. Color bars depicts specific forest management strategies: BAU (business-as-usual), CONS (conservation), SW (shelterwood), and SL (selection). Management intensity is denoted by intervention area: P1 denotes the predator management zone, and P2 comprises both the predator management and peripheral habitat zones making SW_P1: shelterwood cutting in P1, SW_P2: shelterwood cutting in P2, SL_P1: selection cutting in P1, SL_P2: selection cutting in P2. The CONS scenario is baseline alternative management. The BAU scenario is current forest management strategy 56

LIST OF ABBREVIATIONS AND ACRONYMS

AAC	Annual allowable cut
AIPL	Intensification of timber production area (*Aire d'intensification de la production ligneuse*)
ATV	All-terrain vehicle
BA	Basal area
BAU	Business-as-usual
BFEC	Office of the chief forester (*Bureau du forestier en chef*)
BIC	Bayesian information criterion
BR	Burn / wildfire
CAD	Canadian dollar
CAPSIS	Computer-aided projection for strategies in silviculture, a software platform for forestry modellers
CHZ	Critical habitat zone
CI	Confidence interval
CJ	Selection cut (*Coupe de jardinage*)
CJMSCR	Selection cutting after 2004
CONS	Conservation scenario
COSEPAC	Committee on the status of endangered wildlife in Canada (*Comité sur la situation des espèces en péril au Canada*)
COSEWIC	Committee on the status of endangered wildlife in Canada
CP	Partial cut (*Coupe partielle*)
CPI	Irregular shelterwood cut *(Coupe progressive irrégulière*)
CPR	Shelterwood cut (*Coupe progressive régulière*)
CPRS	Clearcut with protection of regeneration and soils *(Coupe avec protection de la régénération et des sols)*

CPRS_U	Uniform clearcut with protection of regeneration and soils *(Coupe uniforme avec protection de la régénération et des sols)*
CT	Total cut / clearcut (*Coupe totale*)
DBH	Diameter at breast height
DEG	Cleaning / weeding (*Dégagement*)
DR0	Road dismantling at 0%
DR50	Road dismantling at 50%
DR100	Road dismantling at 100%
EBK	Empirical bayesian kriging
EBM	Ecosystem-based forest management
EC	Commercial thinning (*Éclaircie commerciale*)
ECA	Equivalent connected area
ECJ	Selection cut (periodical cuts in uneven-aged stands)
EL	Mild insect epidemic (*Épidémie légère*)
EPC	Precommercial thinning (*Éclaircie précommerciale*)
ES	Severe insect epidemic (*Épidémie sévère*)
FMU	Forest management unit
FRI	Forest resource inventory
GPS	Global positioning system
HD	Height–diameter relationship, used to estimate tree volume in growth models
HRZ	Habitat restoration zone
HSI	Habitat suitability index
HSMs	Habitat suitability models
ID	Identifier
IQR	Interquartile range

ITBM	Individual tree-based model
LANDIS	Landscape disturbances and succession forest model
M and F	Male and female
MCP	Minimum convex polygon
MFFP	Ministry of forests, wildlife and parks (*Ministère des forêts, de la faune et des Parcs*)
MFWP	Ministry of forests, wildlife and parks (*Ministère des forêts, de la faune et des parcs*)
MRNF	Ministry of natural resources and forests (*Ministère des ressources naturelles et des forêts*)
NH	No harvest
NSERC/CRSNG	Natural sciences and engineering research council of Canada (*Conseil de recherches en sciences naturelles et en génie du Canada*)
P	Plantation
P1	Protection strategy one
P2	Protection strategy two
PAFIT	Tactical integrated forest management plan (*Plan d'aménagement forestier intégré tactique*)
PHZ	Peripheral habitat zone
PMZ	Predator management zone
PSPs	Permanent sample plots
RCPs	Representative concentration pathways
RE2	Black spruce moss potential vegetation
RE3	Black spruce sphagnum potential vegetation
RPOC	Relative probability of caribou occurrence
RR	Scarification and reforestation (*Regarni de régénération*)
RSF	Resource selection function

SARA	Species at risk act
SD	Standard deviation
SELES	Spatially explicit landscape event simulator
SFM	Sustainable forest management
SL	Selection cutting
SSF	Step selection functions
SW	Shelterwood cutting
TBE	Spruce budworm (*Tordeuse des bourgeons de l'épinette*)
UQAR	Université du Québec à Rimouski
VIF	Variance inflation factor
ZOI	Zone of influence

LIST OF SYMBOLS

A_{ijk}, B_{ijk}	General parameters of the height and volume equations (where B_{ijk} specifically relates to the form coefficient or taper)
acc_{ijk}	The diameter increment (in cm) of a tree
B	Total number of Monte Carlo realizations or bootstrap replicates; larger B gives more stable estimates
dhp_{ijk}	The diameter at breast height (in cm or m depending on the formula)
dr_{ijk}	The response variable representing the number of millimeters a recruit's diameter exceeds the threshold
$\boldsymbol{e}$	Euler's number ($\approx$ 2.718), base of natural logarithms, used in functions like e^x
E_m	Expected value under the bootstrap model for variance estimators
$\hat{E}_m$	Estimated expected value under the bootstrap model
g_{iks}	A vector of explanatory variables used to predict abundance
h_{ijk}	The total height (in m) of a tree
$\boldsymbol{k}$	Number of parameters in a candidate model, important for penalizing model complexity
logit	The linear logit transformation used in logistic regression: $\text{logit}(p) = \ln\left(\frac{p}{1-p}\right)$, converting probability to a range from $-\infty$ to $+\infty$
m_{ijk}	A binary response variable indicating if tree j in plot i dies (1) or survives (0) during interval k
$\boldsymbol{n}$	Sample size, e.g., number of plots or caribou
$P(y \mid x)$	The relative probability of caribou occurrence at a specific location, conditional on environmental variables x

r_{iks}	The number of recruits (stems reaching ≥ 9.1 cm) for species group s
r_s	Spearman rank correlation coefficient for predictive accuracy, ranging from -1 (perfect negative) to 1 (perfect positive)
u_i, u_{ik}	Random effects for the plot and for the interval, respectively
V_d	Design-based variance estimator
$\hat{V}_d$	Estimated design-based variance
V_m	Model-based variance
$V_{md,CORR}$	Hybrid estimator of difference for model and sampling uncertainty
x_{ijk}	A vector of explanatory variables used to predict survival, growth, and initial size
y_{ijk}	The gross merchantable volume (in dm^3) of a tree
α	Value used in the decay function for road response: $\exp(-\alpha/\text{distance})$; larger α means faster decay with distance
β	Statistical coefficients representing the influence of environmental variables on caribou behavior; positive β increases relative probability of caribou occurrence, negative β decreases it
γ	A vector of estimated parameters (coefficients)
$\mathbf{\Delta BIC}$	Change in Bayesian information criterion; smaller BIC indicates better balance of fit and complexity
Δt_{ik}	The duration of the interval (fixed at 10 years for standard model use)
ϵ_{ijk}	The residual error term
μ_{BS}	Bootstrap mean estimator
μ_{iks}, μ_{ijk}	The expectation (mean) of the distributions
μ_y	Estimate of the population mean from observed data
$\hat{\mu}_y$	Estimated population mean from observed data

$\hat{\mu}_{y,b}$	The mean of the realized bootstrap replicate estimates
π	The geometric constant Pi
π_{ijk}	The mortality probability of a tree
π_{iks}	The probability of detecting at least one recruit
$\sigma^2_{plac}, \sigma^2_{int}$	Variances used in the normal distributions for the plot and interval random effects
ϕ	The probability mass function of a negative binomial distribution
ω	The dispersion parameter, which acts as a variance estimator

CHAPTER 1

GENERAL INTRODUCTION

The boreal forest accounts for nearly 30% of the world's total forest cover (Gauthier et al., 2023; Kneeshaw et al., 2011). Globally, this ecosystem supports almost half of the world's remaining natural and near-natural forests (Burton et al., 2010; Gauthier et al., 2015). The boreal forest has substantial ecological value because it supports numerous species (Kuuluvainen and Nummi, 2023), and plays an important role in global climate regulation (Gauthier et al., 2015; Kuuluvainen and Nummi, 2023). Two-thirds of the forests in the boreal region are subject to active management (Gauthier et al., 2023). Historically, forest management was mainly centered on optimizing wood production via sustained yield management, utilizing clear-cutting and age-class regulation to maintain a stable chain of timber supply (Girona et al., 2023a; Perrow and Davy, 2002). Conversely, public and scientific concerns regarding loss of biodiversity and the ecological impacts of intensive silviculture have shifted the paradigm towards ecosystem-based forest management (EBM) (Franklin, 1996; Lindenmeyer and Franklin, 2002; Schneider et al., 2021). The main aim of EBM is to sustain and restore healthy and resilient ecosystems by narrowing the difference between natural and managed forest ecosystems. This assures the long-term provision of numerous ecosystem functions and services, which in turn result into social and economic benefits (Gauthier, 2009). Through this framework, the principles of sustainable forest management (SFM) could achieve a balance between biodiversity conservation, timber supply, and wildlife habitat preservation (Chen et al., 2016).

1.1 PROBLEM STATEMENT

The conservation of woodland caribou (*Rangifer tarandus caribou*), a vulnerable species under Canada's Species at Risk Act (SARA), is a significant concern for sustainable forestry in the Canadian boreal zone (COSEWIC, 2002; Environnement Canada, 2012; SARA, 2002). Caribou populations have been declining throughout several regions, a trend that is closely connected to the direct and indirect effects of human-induced habitat loss and fragmentation (Dickie et al., 2017; Dussault et al., 2012; Dyer et al., 2001; Fortin et al., 2015; Hins et al., 2009; Leblond et al., 2013; Leclerc et al., 2012; Muhly et al., 2015; Mumma et al., 2019; Polfus et al., 2011; Rudolph et al., 2017, 2012; Schaefer, 2003; Skarin et al., 2015; St-Pierre et al., 2022; Vors et al., 2007; Weir et al., 2007). In Gaspesie, forest management practices are considered as the main reasons for the decline of the caribou population. Caribou need large, undisturbed areas of mature and old-growth forests (Rudolph et al., 2017; Yemshanov et al., 2022), and high-elevation habitats for winter foraging (Caouette, 2024). Forest harvest activities and road creation have degraded its essential habitat (Caouette, 2024). Formation of newly generated seedlings and saplings after harvesting fosters high densities of alternative prey species such as moose (*Alces alces*), white-tailed deer (*Odocoileus virginianus*) and snowshoe hare (*Lepus americanus*), which leads to increasing predation risk on caribou through apparent competition (MFFP, 2021).

Conservation measures for caribou such as restricting harvesting activities and setting aside large patches of caribou habitat could significantly reduce wood supply, which often implies the relocation of timber extraction to more distant locations or increase return time of harvesting (Yemshanov et al., 2020). These adjustments increase the cost of timber supply (Yemshanov et al., 2020). Previous studies often utilize optimization models to evaluate trade-offs between timber harvest and wildlife conservation goals (Gustafson et al., 2006; Johnson and Scheurman, 1977; McDill et al., 2016; McKenney et al., 1998; Öhman, 2000; Tóth and McDill, 2008). For example, these

analyses highlighted that relocating or deferring the harvest plan to protect habitat can increase the delivered timber unit price (Yemshanov et al., 2020) and that regulating spatial constraints, such as modulating forestry practices and removing road structures in caribou habitat mosaics, results in quantifiable reductions in potential wood harvest volume (McKenney et al., 1998). Moreover, while alternative silvicultural systems like shelterwood and selection systems are generally recommended inside caribou home ranges as beneficial conservation systems when compared to clear cut systems, these methods yield lower wood supply per hectare (Nadeau Fortin et al., 2016). This paradox means that trying to stick to clear cut systems might jeopardize caribou habitat so much that it makes the whole process ecologically unsustainable.

Provided the isolated and endangered status of the Atlantic Gaspesie caribou population, along with the region's socio-economic dependence on forestry, quantitative analysis of the consequences of conservation measures is vital (Équipe de rétablissement du caribou de la Gaspésie, 2018). Policy and decision makers need a robust understanding of the effect of caribou-oriented management on wood supply to implement restoration policies effectively (Armstrong, 1998; Yemshanov et al., 2020). The importance of anthropic disturbances in eastern Canada requires integrated planning, especially since timber harvesting is considered the most important agent of habitat change up to 2050 (St-Laurent et al., 2022). Estimating the trade-offs associated with reduced harvesting area, habitat management, and road restoration is critical, as this is the only means local managers can control to maintain habitat quality while ensuring sustainable timber provisioning in the long term (St-Laurent et al., 2022).

1.2 LITERATURE REVIEW

1.2.1 Introduction to caribou and its Atlantic-Gaspesie population

The caribou of North America and reindeer of Eurasia fall under the single species *Rangifer tarandus* (Équipe de rétablissement du caribou de la Gaspésie, 2018). In North America, four subspecies are typically identified based on morphological criteria: the Peary caribou (*Rangifer tarandus pearyi*), the Grant's caribou (*Rangifer tarandus granti*), the Barren-ground caribou (*Rangifer tarandus groenlandicus*), and the woodland caribou (*Rangifer tarandus caribou*) (Banfield, 1961).

The woodland caribou (*Rangifer tarandus caribou*) is the only subspecies found in Quebec (Équipe de rétablissement du caribou de la Gaspésie, 2018). However, biologists distinguish populations based on ecotypes, which reflect genetic, morphological, and behavioral adaptations to specific local environments. The three distinct ecotypes are recognized in Québec: 1. Migratory Caribou: This ecotype resides in the taiga and tundra of northern Quebec. It is characterized by large groups that undertake long seasonal migrations (e.g., the Rivière-aux-Feuilles and Rivière George herds) (Gouvernement du Québec, 2024). 2. Forest-dwelling (Boreal) Caribou: This ecotype is mostly sedentary and exist in the boreal forest band between the 49th and 55th parallels (Gouvernement du Québec, 2024). It usually lives in low abundance (1-5 caribou/km^2) and forms small groups to escape predation (Bastille-Rousseau et al., 2012; Brown et al., 2003; Faille et al., 2010; Wilson et al., 2019). 3. Mountain Caribou: This ecotype is found in mountains and migrates to high altitudes (Gouvernement du Québec, 2024). In Eastern Canada, this ecotype is comprised of only two populations: the Torngat Mountains and the Atlantic-Gaspesie populations (Environnement et Changement climatique Canada, 2022; Équipe de rétablissement du caribou de la Gaspésie, 2018). Genetic studies suggest that, while these ecotypes are included in the same subspecies, there is notable genetic differentiation. The Atlantic-Gaspesie population, especially,

is genetically distinct and isolated from other caribou populations in Quebec (MFFP, 2021).

The Atlantic-Gaspesie caribou population is the remnant of the population that formerly inhabited the south shore of the St. Lawrence River, expanding into the Maritime provinces (Équipe de rétablissement du caribou de la Gaspésie, 2018; MFFP, 2021). The population has exhibited a substantial decline, decreasing from an estimated 700–1,500 individuals in the 1950s to not more than 100 individuals in recent years (MFFP, 2021; Moisan, 1957), with a 2020 estimate of nearly 34 individuals (Morin and Lesmerises, 2020). The Gaspesie caribou lives in the high plateaus of the Gaspesie National Park and periphery, particularly the Chic-Chocs, Mount Albert, Mount Logan and McGerrigle mountains (Équipe de rétablissement du caribou de la Gaspésie, 2018). Their winter diet depends largely on mature and over-mature fir (*Abies balsamea*) and spruce spp., along with alpine tundra (Mosnier, 2002; St-Laurent et al., 2009). A key element of their winter diet is arboreal lichen (Rivard, 1978), which is predominant in mature forests (Mosnier et al., 2003). Their diet extends to ground vegetation such as ferns, herbs, and shrubs (Christopherson et al., 2019).

1.2.2 History of forest management and creation of associated road networks in Gaspesie

Forestry practices in Gaspesie shifted from partial harvesting to industrial management practices, leading to significant changes in the landscape over the last century (MRNF, 2015). Before European colonization in the pre-industrial era, the repercussion of indigenous populations on the forest was very low. From the mid-16th to the late 18th century, Europeans harvested trees for firewood and construction (MRNF, 2015). Commercial forestry started in the 19th century with selective logging, targeting certain high-value species like *Pinus* spp., *Thuya occidentalis*, and large spruce for naval construction and lumber. These selective forest management practices retained

the forest canopy somewhat unaltered (MRNF, 2015). The pulp and paper industry in the early 20th century led to the harvesting of smaller trees and a larger range of species. This phase also led to the introduction of the first important forest road networks (Pinna et al., 2009). Although the Gaspesie National Park was established in 1937, logging and mining extended within its boundaries for decades. It was just after 1977, following the implementation of the Parks Act, that logging was completely prohibited inside the park (Équipe de rétablissement du caribou de la Gaspésie, 2018). For that reason, industrial forestry concentrated in the peripheral zones surrounding the park, leading to a very high density of forest roads in its outskirts (Gaudry, 2013). In the management unit 111-61 alone, the forest road network occupies over 15,293 km, with the physical right-of-way filling approximately 31,534 ha (about 5% of the unit's total area) (MRNF, 2015). Since the mid-20th century, forest management switched to intensive practices consisting of mainly clear-cutting (typically referred to as cutting with protection of regeneration and soils, or CPRS). This reshaped the landscape from a structure largely consisting of mature conifers to younger, regenerating stands with an increased deciduous component (Boucher et al., 2006; Pinto et al., 2008; Girona et al., 2023b).

1.2.3 Efforts to conserve caribou

A legal habitat was declared in 1993 under the Regulation on Wildlife Habitats to protect the caribou from mining and forestry interventions (Équipe de rétablissement du caribou de la Gaspésie, 2018). This area was broadened in 2011 to span the caribou's range (Équipe de rétablissement du caribou de la Gaspésie, 2018). Actions are further directed by sequential recovery plans. The recent 2019–2029 Recovery Plan aims to restore habitat components favorable for population survival and to reverse the decline and increase the number of individuals. This plan consists of 12 measures and 35 distinct actions (Équipe de rétablissement du caribou de la

Gaspésie, 2018). Past forest management decisions are identified as key cause of habitat degradation leading to caribou decline (Festa-Bianchet et al., 2011; Vors et al., 2007). Thus, tactical integrated forest management plans (*plan d'aménagement forestier intégré tactique*, PAFIT) have been adjusted since 1999 to include forestry practices within the caribou's range that limit the impacts to its habitat (Équipe de rétablissement du caribou de la Gaspésie, 2018). The most recent plans (2013-2018, extended) include a 2,056 km^2 area adjacent to the Gaspesie National Park and divides the territory into specific management zones (MRNF, 2013); A) Conservation Zone: Timber harvesting is not allowed in this section to protect the best remaining caribou habitats. More recently, interim measures expanded the area withdrawn from harvest to cover the core of the range, totaling approximately 2,033 km^2 (MFFP, 2021). B) Management zone: In zones where forestry is allowed, treatments vary based on altitude to isolate caribou from predators (black bear/coyotes) and alternative prey (moose) (Équipe de rétablissement du caribou de la Gaspésie, 2018; MRNF, 2015). Habitats at high altitude ($>$ 700 m) are regulated to preserve mature and over-mature softwood stands crucial for arboreal lichen growth (winter food) (MRNF, 2015). Only uneven-aged management (selection cutting) is allowed. Clear-cutting is restricted. The purpose is to keep 100% irregular stand structure and 0% young stands (0-20 years) (MRNF, 2015). It is directed to control the regeneration of early seral stages (hardwoods and berry bushes) that attract moose, bears, and coyotes (apparent competition) (MRNF, 2015). Irregular shelterwood cutting is given priority over clear-cutting (CPRS) to maintain cover. Hardwood stems must be thinned during tending operations to conserve conifer-dominated stands (MRNF, 2015). The caribou recovery team suggests not including intensification of timber production areas (*aire d'intensification de la production ligneuse*, AIPL) in the caribou range to mitigate clashes with conservation needs (Équipe de rétablissement du caribou de la Gaspésie, 2018). Current guidelines limit the use of exotic species in AIPLs to a maximum of 5% of the region (MRNF, 2023). The government has introduced pilot projects (2023-2024)

for the Gaspesie and Charlevoix populations to test caribou-oriented strategies. These include focusing on limiting the disturbance levels to 35% in habitat restoration zones (HRZ) (Gouvernement du Québec, 2024). Stricter rules apply to retain large blocks of conservation massifs and areas of biologically sensitive habitat to maintain connectivity and critical attributes (Gouvernement du Québec, 2024). Projects like the Vallières-de-Saint-Réal protected area are being promoted to safeguard critical habitat.

1.2.4 Concern over implementation of caribou recovery plan

Moreau and Guénette (2015) highlights the probable effects of the second recovery plan of Quebec government for the caribou. The authors proposed that while conservation is necessary, the proposed strategies such as the need to retain a maximum 35% habitat disturbance rate (Gouvernement du Québec, 2024), could impose costs on the forestry sector as compared to the conservation benefits. According to the authors, Quebec's forest industries were already facing problems with a drop in 40% in annual harvest between 2000 and 2013 (Direction du développement de l'industrie des produits du bois, 2005, 2015). Adopting the 35% disturbance ceiling would further reduce allowable cut and net harvest. The plan could cut annual harvest by approximately 3 million cubic meters. Since the forest industry does not generally harvest 100% of the allowable cut, the probable loss in harvest is assessed at 1.3 million cubic meters per year. Moreau and Guénette (2015) stress that factors apart from forestry such as climate change, forest fires, insect epidemics, and hunting also influence population decrease. Protecting habitat frequently drive harvesting into distant or sub optimal areas, increasing transportation and infrastructure costs. For example, in the Cold Lake caribou range (Alberta), preserving caribou habitat increased the timber unit cost by 2 CAD per cubic meter (Yemshanov et al., 2020).

1.2.5 Integrated simulation studies

Simulation studies that join forest growth simulators with wildlife habitat models are important tools for analyzing the trade-offs between timber production and conservation goals. These studies commonly utilize optimization models to program harvests over extensive planning horizons (e.g., 50, 100 years) (Johnson and Scheurman, 1977; Martin et al., 2017; McDill and Braze, 2000; McDill et al., 2002; McDill et al., 2016) under spatial and temporal limitations established for wildlife protection (St-Laurent et al., 2022; Yemshanov et al., 2020; Yemshanov et al., 2022). This approach interfaces the gap between forestry activities and their biological significance for wildlife. Brown et al. (2007) employed a procedure by applying a resource selection function to outputs of Patchworks, a stochastic optimization model that spatially allocates forest harvesting over a 120-year management horizon. This integration allowed them to foresee that management strategies with definite caribou constraints resulted in better probabilities of caribou occurrence than baseline courses of action. Muhly (2016) used SELES to simulate future forest harvesting and road infrastructure, connecting these outputs to a statistical model of disturbance to caribou habitat assessment model. This enabled the evaluation of how future forestry scenarios would impact disturbance density relative to federal thresholds. The application of a resource selection function model to simulator outputs acknowledges a key limitation of static habitat modelling: lack of consideration of forest structure over time. Whitman et al. (2017) and Ruppert et al. (2016) showed that using dynamic disturbance simulations produced different habitat quality landscapes than static simulations. Consequently, coupling caribou habitat model with simulators offers a quantitative foundation for ranking alternative management scenarios (Brown et al., 2007; Leblond et al., 2011).

1.2.6 ARTEMIS: Forest growth simulator

ARTEMIS-2009 was developed by Fortin and Langevin (2010) for the Quebec Ministry of Natural Resources (*Ministère des Ressources Naturelles et des Forêts*, MRNF). It is a stochastic, individual-tree growth simulator that is currently being used in Quebec for strategic management decisions. Unlike stand-level yield tables, ARTEMIS simulates forest dynamics by modeling individual trees and aggregates predictions at the plot level over 10-year intervals (Fortin et al., 2022). It is implemented on the CAPSIS platform (Dufour-Kowalski et al., 2012). The system is composed of four dynamic sub-models (mortality, growth, recruitment, and recruit size) and two static sub-models (height and volume) (Fortin et al., 2007, 2009a) (Figure 1). The model was calibrated using data from permanent sample plots for the 25 most common potential vegetation types found in the forests of Quebec (Fortin and Langevin, 2010).

1.2.6.1 Mortality sub-model

The mortality sub-model is a dynamic module that simulates the probability of an individual tree dying within a 10-year growth interval. It is a generalized linear model that is based on a stochastic approach to facilitate an estimate of computational error. The model assumes that the response variable follows a Bernoulli distribution and employs an complementary log-log (clog-log) link function to represent explanatory variables linearly (McCullagh, 2019). The mortality sub-model is given by Fortin et al. (2008):

$$m_{ijk} \sim Bernoulli(\pi_{ijk}) \tag{1}$$

$$\pi_{ijk} = 1 - e^{-e^{\mathbf{x}_{ijk}\boldsymbol{\beta} + ln(\Delta t_{ik})}} \tag{2}$$

Where m_{ijk} is the binary response variable: 1 if tree j in plot i dies during interval k, and 0 if it survives. π_{ijk} is the mortality probability of a tree. $\mathbf{x}_{ijk}$ is a vector of explanatory variables. $\boldsymbol{\beta}$ is a vector of estimated parameters that weight the influence of each explanatory variable. Δt_{ik} is the duration of the interval (fixed at 10 years for standard model use).

The vector of explanatory variables typically includes the species group, diameter at breast height, competition index, merchantable basal area (m^2/ha), merchantable stem density (stems/ha), merchantable quadratic mean diameter (cm), interval duration in years, partial cut occurrence, spruce budworm (TBE) defoliation, mean annual temperature (^{o}C) and precipitation (mm) (1971–2000 normals) to determine the survival. The model efficiently accommodates the time-dependent attribute of mortality, enabling it to consider natural senescence (aging), competition-based mortality, and the effect of external stresses such as insect outbreaks or post-harvesting exposure.

1.2.6.2 Diameter growth sub-model

It is a linear mixed-effects model which includes a correlation structure. The model uses the natural logarithm of the diameter increment to achieve normality for the residual error terms which in turn retain biological coherence and manage data variance. The diameter growth sub model is given by:

$$ln(acc_{ijk} + 1) = \mathbf{x}_{ijk}\boldsymbol{\beta} + u_i + u_{ik} + \epsilon_{ijk} \tag{3}$$

Where acc_{ijk} is the diameter increment (cm) of tree j in plot i during interval k. $\mathbf{x}_{ijk}$ is a vector of explanatory variables. u_i is a random effect for the plot, following a normal distribution N(0, $\sigma_p lac^2$). u_{ik} is a random effect for the interval, following a normal distribution N(0, $\sigma_i nt^2$). ϵ_{ijk} is the residual error term, adjusting for intra-tree correlation over time.

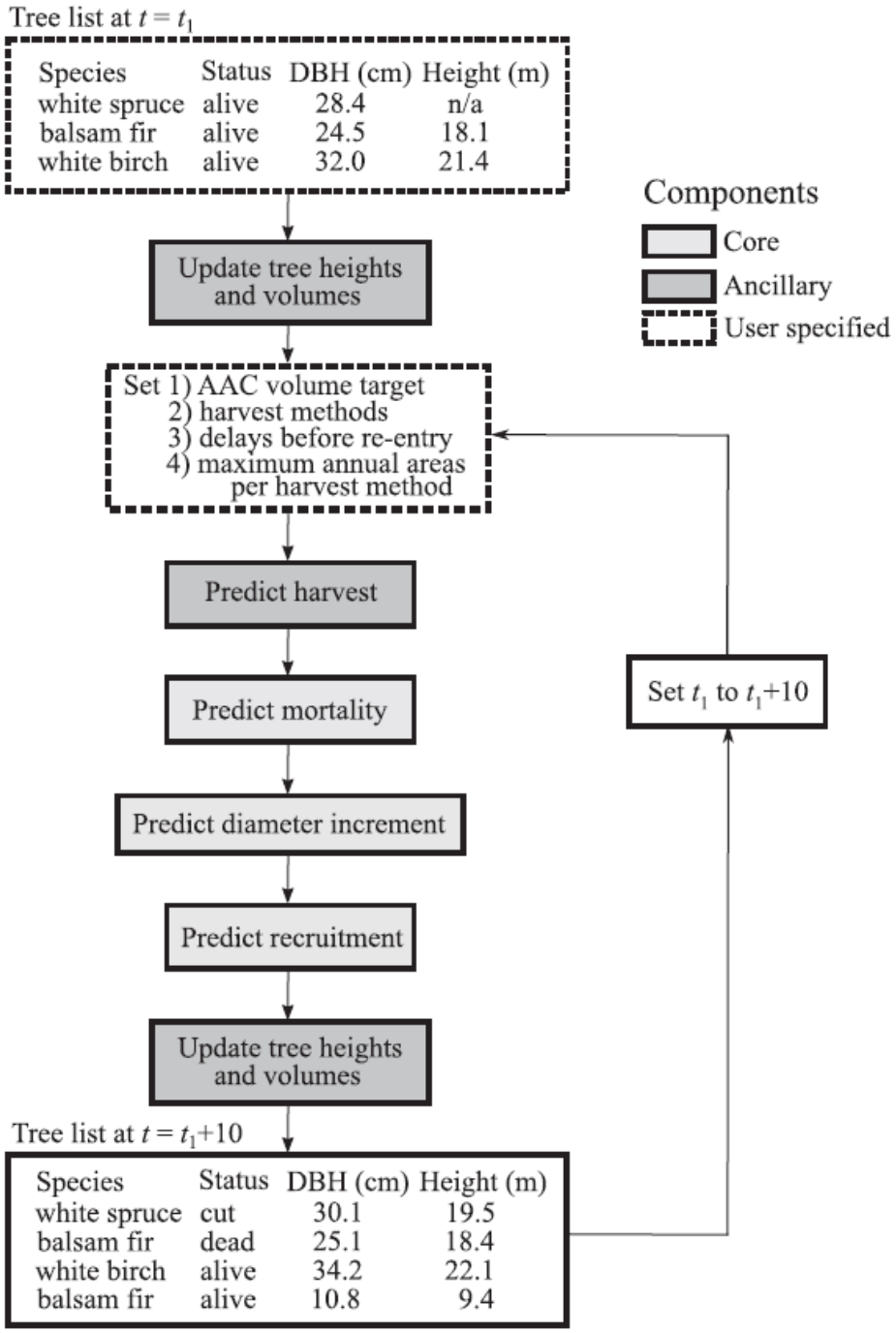


Figure 1. ARTEMIS-2009 work flow (Fortin et al., 2022)

The fixed effects variables include the species group, diameter at breast height, merchantable basal area (m^2/ha) of the plot, interval duration in years, partial cut occurrence, spruce budworm (TBE) defoliation, mean annual precipitation (mm) (1971–2000 normals) to predict growth. The mixed effects (random effects) are part to consider unobserved variability and correlations distinct to the plot and the growth interval.

1.2.6.3 Recruitment sub-model

It is one of the dynamic components that predicts the number of new stems simulating the minimum diameter threshold of 9.1 cm within a 10-year growth interval. The model treats recruitment as a two-step process: first, predicting the probability that recruitment occurs using a Bernoulli distribution, and second, predicting the number of recruits if it does using a negative binomial distribution. The recruitment sub-model given by:

$$Pr(r_{iks}) = \begin{cases} 1 - \pi_{iks} & \text{if } r_{iks} = 0 \\ \pi_{iks} \cdot \varphi(r_{iks} - 1 \mid \mu_{iks}, \omega) & \text{if } r_{iks} > 0 \end{cases} \tag{4}$$

$$\pi_{iks} = \frac{e^{\mathbf{x}_{iks}\boldsymbol{\beta}}}{1 + e^{\mathbf{x}_{iks}\boldsymbol{\beta}}}, \quad \mu_{iks} = e^{\mathbf{g}_{iks}\boldsymbol{\gamma}} \tag{5}$$

Where r_{iks} is the number of recruits (stems reaching ≥ 9.1 cm) for species group s in plot i at the end of interval k. π_{iks} is the probability of detecting at least one recruit for species group s in plot i at the end of interval k. φ is the probability mass function of a negative binomial distribution. This distribution is employed to model the count of recruits because it deals with data where the variance is higher than the mean (over-dispersion). μ_{iks} is the expected abundance (mean) of the negative binomial distribution, depicting the number of recruits given that recruitment has occurred. ω is dispersion parameter, which acts as a variance estimator for the recruit abundance.

π_{ik} and $\mathbf{g}_{iks}$ are the vectors of explanatory variables used to predict occurrence and abundance respectively. $\boldsymbol{\beta}$ and $\boldsymbol{\gamma}$ are vectors of estimated parameters (coefficients) specific to each potential vegetation type. $r_{iks} - 1$ is a term used because the abundance part of the model is based on there being at least one recruit; it models the extra recruits beyond the first one. The explanatory variables used in the recruitment sub-model vectors are species group, interval duration in years, merchantable basal area (m^2/ha), merchantable density (stems/ha), partial cut occurrence, mean annual temperature (^{o}C) and precipitation (mm) (1971–2000 normals).

1.2.6.4 Diameter of recruited tree sub-model

The diameter of the recruited tree sub-model is a dynamic element that maps an initial diameter to new stems at the time they pass the merchantable threshold of 9.1 cm. Since recruits do not all enter the tree list at exactly 9.1 cm, this model makes certain that the simulated diameter distribution of new trees is biologically realistic. The model captures the number of millimeters a recruit's diameter is greater than the 9.1 cm threshold. Based on the diameter distributions, the predictor variable is modeled applying a Gamma distribution with a log link function:

$$dr_{ijk} \sim Gamma(\mu_{ijk}, \omega) \tag{6}$$

$$\mu_{ijk} = exp(\mathbf{x}_{ijk}\boldsymbol{\beta}) \tag{7}$$

Where dr_{ijk} is the response variable, representing the number of millimeters exceeding the 9.1 cm DBH threshold for recruit j in plot i at the end of interval k. Gamma ($\mu_{ijk,\omega}$) is the probability distribution assigned to the response variable. The Gamma distribution is used for modeling continuous, positive size increments that are skewed. μ_{ijk} is the expectation (mean) of the distribution, which is linked to the

explanatory variables using an exponential function. ω is the dispersion parameter, which represents the variance or spread of the diameters around the predicted mean. $\mathbf{x}_{ijk}$ is a vector of explanatory variables that influence the initial size of the recruit. $\boldsymbol{\beta}$ is a vector of estimated parameters (coefficients) specific to the potential vegetation type. The explanatory variables used in the recruitment sub-model vectors are species group, interval duration in years, merchantable basal area (m^2/ha), merchantable quadratic mean diameter of the plot, partial cut occurrence, mean annual temperature (^{o}C) and precipitation (mm) (1971–2000 normals).

1.2.6.5 Height sub-model

The height sub-model is a static component that estimates the total height of the 20 most abundant commercial tree species in Quebec's public forests. Unlike dynamic models which forecast change over time, this model estimates height based on the tree's current physical attributes and its environmental context. The model is developed as a linear mixed-effects model to consider for variations between different forest stands. The underlying mathematical structure is given by (Fortin et al., 2009a):

$$h_{ijk} = 1.3 + A_{ijk} \ln(dhp_{ijk} + 1) + B_{ijk}(\ln((dhp_{ijk}))^2) + \epsilon_{ijk} \tag{8}$$

Where h_{ijk} is the total height (in meters) of tree j in plot i at the end of interval k. A constant of 1.3 meters expressing standard breast height. dhp_{ijk} is the diameter at the breast height of the tree (measured in m). The addition of 1 to the diameter inside the logarithmic maintains mathematical consistency when the diameter is very small. A_{ijk} and B_{ijk} are general parameters of the equation. It is hypothesized that these parameters are actually driven by linear functions of explanatory variables (like temperature, basal area, and drainage). By expanding A_{ijk} and B_{ijk} into these particular environmental variables and including an error term ϵ_{ijk} can be generalized to the population.

1.2.6.6 Volume sub-model

The volume sub-model is a static component applied to estimate the gross merchantable volume of every single tree. Like the height model, it is a linear mixed-effects model that determines volume at a certain point of time based on the physical dimensions of the tree. The model infers the gross merchantable volume (from a 15 cm stump to a 9 cm top diameter) using the following underlying model formulation given by (Fortin et al., 2007):

$$y_{ijk} = -A_{ijk} + B_{ijk}\frac{\pi \cdot dhp_{ijk}^2 \cdot h_{ijk}}{40} + \varepsilon_{ijk} \tag{9}$$

Where y_{ijk} is the gross merchantable volume (in dm^3) of tree j in plot i at the end of interval k. dhp_{ijk} is the diameter at breast height (1.3 m) of the same tree (cm), h_{ijk} is the height of the same tree (m), $-A_{ijk}$ and B_{ijk} are the general parameters of the model, and ϵ_{ijk} is the residual error term. $-A_{ijk}$ is a negative constant depicting the non-merchantable top portion of the tree (the tip of the cone) that must be subtracted. B_{ijk} is the form coefficient, or taper of the stem. The term $\pi \cdot dhp_{ijk}^2 \cdot h_{ijk}$ represents the geometric volume of a cylinder (dm^3) calculated from the tree's diameter at breast height (in cm) and total height (in m). The estimation of B_{ijk} is therefore related to the taper or the form coefficient of the stem. The parameter A_{ijk}, conceptually, represents the non-merchantable portion of the stem. However, it is impossible to estimate the values of the general model parameters for each tree.

The ARTEMIS forest growth simulator asserts considerable potential for linking with caribou habitat models, allowing the forecast of future habitat conditions. Because ARTEMIS is an individual tree-based model fit for simulating complex stand dynamics, it can provide realizations of the vegetation attributes required to compute habitat suitability for the woodland caribou. Caribou habitat quality is closely tied to stand-level characteristics.

ARTEMIS contains a harvest sub-model fit for simulating different forest management practices, accounting for tree removal and the growth and mortality of residual stems (Fortin, 2014a; Melo et al., 2017). It enables researchers to test whether silvicultural treatments retain canopy cover and habitat conditions over time, while also anticipating long-term stand dynamics under climate change using temperature and precipitation inputs (MRNF, 2015; Nadeau Fortin et al., 2016). Therefore, ARTEMIS can also be used for landscape planning by upscaling its stand-level outcomes to address wider management requirements (Fortin et al., 2022), which is critical for caribou management.

1.2.7 Caribou habitat model

Researchers employ multiple modeling approaches to quantify habitat quality and connectivity for woodland caribou.

1.2.7.1 Resource selection functions (RSFs)

These are statistical models (often mixed-effect logistic regressions) which assess the relative probability of caribou occurrence (RPOC) by comparing environmental and geographical variables at locations utilized by caribou (GPS telemetry points) relative to random available locations (Manly et al., 2002). RSFs are typically multi-scale, quantifying selection at both the broad landscape level (home range) and fine local level (forest stand) (Leblond et al., 2011; Whitman et al., 2017). RSFs identify differences between simple space use (time spent in an area) and resource selection (preference) (Johnson, 1980; Manly et al., 2002). This approach translates forest inventory maps into continuous RPOC values, which in turn supports comparisons between historical and future caribou occurrences (Leblond et al., 2011; St-Laurent et al., 2022). In a recent study, when an RSF model was applied to LANDIS-II, it produced RPOC in future scenarios up to 2100 (St-Laurent et al., 2022). These simulations accounted for

the impacts of multiple factors such as climate change, fire regimes and commercial timber harvesting (St-Laurent et al., 2022) on caribou occurrence. The RSF models are capable of integrating non-linear responses to anthropogenic factors including the decay distance to roads (Carpenter et al., 2010), which allows the model to assess the changes in avoidance behaviour of caribou in relation to the distance from the disturbance (St-Laurent et al., 2022).

1.2.7.2 Habitat suitability index (HSI) models

These models label scores (0 to 1) to forest stands supported by life history needs, including the presence of food (lichen) or cover (Brooks, 1997; Yemshanov et al., 2020), for example, preferred winter habitat is frequently observed using forest resource inventory (FRI) data to position mature jack pine or black spruce stands (Boan et al., 2013). However, the performance of these scores is frequently influenced by anthropogenic disturbances; habitat capacity score may be punished or attributed high tolerance scores in areas in proximity to roads or recently harvested cutblocks to capture increased predation risk and functional habitat loss (Yemshanov et al., 2020).

1.2.7.3 Habitat effectiveness and zone of influence (ZOI)

This technique assesses the actual capacity of a landscape to support caribou by coupling the impacts of anthropogenic disturbance with the species' response pattern (Anderson et al., 2002). While a standard system may detect a stand as high-quality as a function of vegetation, its effectiveness is lowered if it falls within the zone of influence of anthropogenic features, which is the extent where caribou density is significantly lowered due to avoidance (Anderson et al., 2002). To estimate this, it uses buffers (e.g., 500 m) around features like roads and cutblocks to take into account caribou avoidance response and functional habitat loss (Mackey et al., 2023).

1.2.7.4 Graph theoretic and connectivity models

These models consider the landscape as a web of nodes (habitat patches), which indicate isolated habitat fragments or refugia, and links, which trace potential movement routes between them (Ruppert et al., 2016; Yemshanov et al., 2022). These models enable researchers to assess functional connectivity, estimating the permeability of the landscape derived from caribou movement and their behavioral tolerance to traversing through disturbed matrix environments (Ruppert et al., 2016). Metrics particularly equivalent connected area (ECA) estimates the measure of reachable habitat, by incorporating individual patch size with the maximum probability of efficient movement between them (Ruppert et al., 2016).

1.2.7.5 Step selection functions (SSFs)

These are advanced conditional regression frameworks used to assess fine-scale movement choices (steps) by analyzing actual movement, the linear segments between successive GPS relocations, to a set of random alternative paths originating from the same starting point (Leblond et al., 2016; Therneau, 2015). This approach offers a high-resolution, process-based understanding of how animals cross fragmented environments, determining whether specific anthropogenic or natural features support smooth movement or act as semipermeable barriers that induce energetically demanding detours (Leblond et al., 2016).

1.2.8 TRIAD zoning approach

The TRIAD zoning approach, initially developed by Seymour and Hunter (1992), segments forested landscapes into three well defined management zones: intensive production, extensive management, and unmanaged ecological reserves, to optimize

competing socioeconomic and conservation objectives (Burton, 1995; Nitschke and Innes, 2005). The intensive management zone adopts intensive silviculture and genetically improved plantations to optimize timber yield per hectare, an approach that can minimize reduction for wood supply caused by the allocation of protected areas (Bell et al., 2000). The extensive management zone sandwiched between two zones, where prescribed "closer to nature" silviculture replicates natural disturbance patterns to provide integrated advantages such as wildlife habitat and watershed conservation followed by medium harvest levels (Palik et al., 2020). Finally, ecological reserves are strictly preserved to protect natural states, sustain viable populations of sensitive species, and acts as reference standard to influence ecosystem management in other zones (Montigny and MacLean, 2006). Research in New Brunswick has illustrated that expanding the coverage of land under intensive management can double long-term softwood harvest while simultaneously permitting for the expansion of reserves to safeguard old-growth habitats (Montigny and MacLean, 2006). Current modifications of the TRIAD model include functional connectivity and multi-scale interaction between its zones and it utilizes strategic nodes of future-adapted species to improve resilience at large scale against the uncertainty of climate change and shifting disturbance patterns (Craven et al., 2016; Gömöry et al., 2020; Messier et al., 2019).

1.3 OBJECTIVES OF THE WORK

This work is motivated by the urgent need for continuous knowledge concerning the relationship between caribou and their habitat as well as efficiency of various habitat management measures. As highlighted by Government of Quebec (2024) and Gaspesie caribou recovery committee (2018), such data-driven insights are necessary for informed decision-making. This thesis, therefore, aims to quantify the effect of caribou-oriented management on wood supply in Gaspesie by ranking various management scenarios. By integrating the bigger picture of regulations proposed by the government of Quebec for

Atlantic Gaspesie caribou with forest management planning, this research will provide insights for developing optimized strategies that support long-term caribou recovery while mitigating negative impacts on timber harvest.

1.3.1 Research questions

A. Primary research question

What is the quantitative effect of diverse caribou habitat protection scenarios on the sustainable timber harvest and future habitat quality within the forest management units of Gaspesie region?

B. Specific Research Questions

1. How can the dynamics of road distance be captured within the harvest scheduling of cutblocks within the ARTEMIS growth model to account for operational constraints and caribou habitat avoidance?
2. How do caribou-oriented management strategies (such as silvicultural modulation and road decommissioning) influence future caribou habitat quality and the regional wood supply?
3. How does even-aged system (e.g., clear-cutting) and continuous cover/extensive system (e.g., selection or shelterwood cutting), control the trade-off between wood supply and caribou habitat quality?
4. How does the addition of road decommissioning strategies (ranging between 0 and 100% removal) into the modeling framework modify the predicted RPOC across the landscape relative to silvicultural changes alone?

1.3.2 Research objectives

The main aim of this study was to quantify the effect of several caribou habitat protection scenarios on the sustainable timber harvest within the Gaspesie region. To achieve this, the specific focus was on developing a method for applying caribou-oriented forest management decisions and road management decisions into the ARTEMIS model to estimate the wood supply and caribou habitat quality. The first specific objective was to integrate dynamics of road distance to the harvest scheduling of cutblocks in ARTEMIS. The second specific objective sought to link the output of ARTEMIS, specifically forest structure and evolving road proximity, to caribou habitat model to predict the landscape and specific management strata level RPOC.

1.3.3 Hypotheses

Caribou prefer the area managed under continuous cover/extensive management (such as selection or shelterwood cutting) than those under even-aged management (such as clear-cutting). Because they retain the mature and suitable forest structures suitable for caribou. This change in management practices decrease timber harvesting when management choices favor a higher caribou habitat quality. To understand these dynamics, we hypothesized that combining extensive silvicultural treatments with road decommissioning, will significantly increase the RPOC. Extensive treatments conserve essential canopy cover and restrict the expansion of early-seral vegetation which favors alternative prey, while road decommissioning restricts predator access into these habitats (Lochhead et al., 2022; Nadeau Fortin et al., 2016). We predict these collective strategies will significantly improve RPOC within caribou range, though at the cost of a reduction in the regional wood supply.

CHAPTER 2

EFFECT OF CARIBOU-ORIENTED MANAGEMENT ON WOOD SUPPLY AND HABITAT QUALITY IN EASTERN CANADA

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2.1 ABSTRACT

Forest management practices and associated road networks have been identified as key factors for the decline of the Atlantic-Gaspesie caribou population. A range of measures have been considered for conservation of their habitat. In this study we tested 16 scenarios combining different forest management options (i.e. business-as-usual, conservation, shelterwood, and selection cutting) with road decommissioning strategies (i.e. 0%, 50%, and 100% removal). A total of 208 plots were simulated over a 50-year horizon using the ARTEMIS growth model, and the outputs were coupled with a resource selection function to obtain the evolution of the relative probability of caribou occurrence (RPOC). Results showed that the business-as-usual forest management strategy is unable to increase the RPOC. In contrast, scenarios that favor selection cutting or shelterwood systems, combined with 100% road removal tripled the RPOC in the caribou range relative to business-as-usual conditions. These improvements in habitat quality are related to decrease in timber harvest volumes, though these declines vary with the conservation strategies. While these harvest constraints cause a marginal loss in wood supply in our trade-off analysis, it seems to be an ecological necessity for population viability. The restoration of the endangered Atlantic-Gaspesie caribou habitat demands a paradigm shift from passive conservation to active restoration requiring both silvicultural modulation and road network decommissioning.

Keywords: Atlantic-Gaspesie caribou, habitat restoration, resource selection function, road decommissioning, silvicultural treatments, wood supply trade-offs

2.2 INTRODUCTION

Atlantic-Gaspesie caribou is one of the four ecotypes that are found in Quebec. It is found on the south shore of the St Lawrence river, and is genetically distinct from the other populations (Mosnier et al., 2003; Ouellet et al., 1996; St-Laurent et al., 2009). There is a general agreement on the fact that the caribou population decline was induced by past forest management decisions (Gouvernement du Québec, 2022; McLoughlin et al., 2003). A number of measures have been proposed to help caribou populations recover, including conservation of their habitat, minimizing human-induced disturbances, and mitigating factors such as predators and climate change that contribute to their decline (Environment and Climate Change Canada, 2019; Nagy-Reis et al., 2021; Rempel et al., 2021). In contrast, it is anticipated that habitat quality, and especially high quality habitat, will diminish over time, primarily due to current forest management practices (St-Laurent et al., 2022).

Quantifying habitat suitability is essential to evaluate boreal caribou recovery strategies (Leblond et al., 2014). A number of techniques are currently used for estimating caribou habitat quality, including the K-select analysis (Calenge et al., 2005), ecological niche factor analyses (Hirzel et al., 2002), envelope models (Phillips et al., 2004), habitat suitability models (HSMs) (Brooks, 1997; Leblond et al., 2014) and machine learning techniques (Kobler and Adamic, 2000). However, the most widely used approach is the Resource Selection Function (RSF) (Brown et al., 2007; St-Laurent et al., 2022). In this method, telemetry locations of caribou are compared to random points using a logistic regression, which leads to the relative probability of caribou occurrence (hereafter RPOC) (Boyce and McDonald, 1999; Boyce et al., 2002; Brown et al., 2007; Hornseth and Rempel, 2016; Manly et al., 2007; St-Laurent et al., 2022). Caribou avoid areas recently disturbed by harvesting (Gaudry, 2013; Nadeau Fortin et al., 2016), deciduous forests (Boisjoly et al., 2010; Mosnier et al., 2008; Nadeau Fortin et al., 2016), areas with large lakes (Gagné et al., 2016; Hins et al., 2009; Losier et al.,

2015), non-forested patches (Leclerc et al., 2014a), and roads (Leblond et al., 2011a; Leclerc et al., 2012, 2014a). Conversely, they thrive in old coniferous forests, marshes, and lichen woodlands (Mosnier et al., 2003; Ouellet et al., 1996; Stone et al., 2008).

While high suitability of habitat can increase longevity of animals and density of populations (Courtois et al., 2007; Leblond et al., 2013), there is no direct relationship between habitat quality and caribou populations (Losier et al., 2015; Mosnier et al., 2008; Van Horne, 1983). Even if habitat composition is favorable, if caribou are unable to move across habitats due to barriers such as roads or cut blocks, their ability to access food and find mates can be compromised (Dyer et al., 2002; Gaudry, 2013; Johnson et al., 2002; Mosnier et al., 2008; Whittington et al., 2011). While habitat loss is a catalyst, predation induced by extensive road networks and cut blocks is the primary cause of mortality (Boisjoly et al., 2010; Boudreau, 2017; Crête and Desrosiers, 1995; Festa-Bianchet et al., 2011; Gaudry, 2013; James and Stuart-Smith, 2000; Mosnier et al., 2008; St-Laurent et al., 2009; Whittington et al., 2011; Wittmer et al., 2005).

The prey-predator dynamics are even more acute for the caribou population of Atlantic-Gaspesie. Inside the range of caribou in Gaspesie, intensive forest management has changed the forest structure surrounding the Gaspesie National Park by favoring younger forests containing seedlings and saplings that provide browse for alternative prey species like moose (*Alces americanus*) and deer (*Odocoileus* spp.) (Bergqvist et al., 2018; Frenette et al., 2020; Stevenson et al., 2024). The increased density of these ungulates has attracted black bears (*Ursus americanus*) and coyotes (*Canis latrans*), which in turn increases predation pressure on caribou (Boudreau, 2017; Nadeau Fortin et al., 2016). These predators use the extensive road networks created for timber harvest to penetrate deep inside caribou habitat, leading to their predation, especially on the calves (Boudreau, 2017; Gaudry, 2013; Mosnier et al., 2008). As a result, the Gaspesie population faces a substantial threat from the loss of mature coniferous forests and associated functional loss of habitat due to predator incursions (Boudreau, 2017).

To keep the Atlantic-Gaspesie population of caribou viable, conservation strategies include the protection of large, contiguous blocks of mature forest and ensure adequate connectivity inside caribou ranges. It has also been suggested to modulate the silvicultural treatments along with dismantling of roads in order to maintain habitat attributes that support growth of arboreal lichen while reducing the prominence of early-seral vegetation that attract predators (BFEC, 2022; Caouette, 2024; Équipe de rétablissement du caribou de la Gaspésie, 2018; Gouvernement du Québec, 2024; MRN, 2013; MRNF, 2013, 2015, 2023b). Suitable conservation measures significantly effect wood supply by decreasing the forest area where harvesting is permitted (Yemshanov et al., 2022). It requires the relocation of timber extraction to more distant locations or increase return time of harvesting (Yemshanov et al., 2020). These restrictions inevitabily lead to increased costs of wood supply (Yemshanov et al., 2020).

Previous research evaluating the tradeoff between wildlife conservation objectives and timber harvesting is generally based on optimization models (De Jager et al., 2025; Gustafson et al., 2006; Johnson and Scheurman, 1977; McDill et al., 2016; McKenney et al., 1998; Öhman, 2000; Tóth and McDill, 2008). While these optimization approaches based on linear programming and heuristic models are efficient for scheduling harvests and setting up landscape level conservation zones, they usually depend on deterministic succession rules and aggregated stand level yield tables that can be ineffective to precisely capture natural forest dynamics and structural complexities (Fortin et al., 2022; Ruppert et al., 2016). Compared with these standard simulation frameworks, the ARTEMIS forest growth model is an individual tree-based model (ITBM) which dynamically simulates tree mortality, survivor growth, and recruitment over time (Fortin and Langevin, 2010). What makes ARTEMIS stand out from traditional optimization approaches is its stochastic harvest submodel, which estimates the probability of harvesting events at both individual tree and plot levels instead of employing theoretical, rule-based volume removals (Fortin et al., 2022). By assessing fine-scale forest characteristics and extending both model and sampling uncertainties

(Fortin et al., 2022), ARTEMIS can realistically simulate the structural outputs of complex, partial silvicultural treatments (like selection and irregular shelterwood cutting) that are critical for retaining mature forest characteristics caribou depend on (Fortin et al., 2022). Therefore, coupling ARTEMIS with a habitat model constitutes a complete framework which is efficient in simultaneously projecting sustainable timber yields and plot-level habitat quality indicators that conventional, aggregated landscape optimization models cannot resolve (Fortin et al., 2022).

This study aimed to evaluate the effect of caribou habitat protection strategies on timber harvest and caribou habitat quality. To achieve this, we modeled different management scenarios using ARTEMIS, ranging from changes in silvicultural practices to various road management decisions, to estimate timber supply and caribou habitat quality. We hypothesized that combining extensive silvicultural treatments with road decommissioning will significantly increase the RPOC. Extensive treatments conserve essential canopy cover and hinder the regeneration of early-seral vegetation which favors alternative prey, while road decommissioning restricts predator access into these habitats (Lochhead et al., 2022; Nadeau Fortin et al., 2016). We predict these collective strategies will significantly improve the RPOC within the caribou range, though at the cost of reduction in the regional wood supply.

2.3 METHODOLOGY

2.3.1 Study area

The study area (Figure 2) is composed of the three forest management units (FMU: 11161, 11262 and 11263) found in the Gaspesie region (47°52′34″N to 49°15′07″N; 64°08′31″W to 67°17′42″W) of Eastern Quebec, Canada (MRNF, 2023b). The area is covered by the Eastern balsam fir (*Abies balsamea* Mill.), yellow birch (*Betula alleghaniensis*) and the Eastern balsam fir-white birch (*Betula papyrifera*)

bioclimatic subdomains. Forests cover over 95% of the peninsula, with 80% of the area being public land (MRNF, 2015, 2022). Balsam fir, white spruce (*Picea glauca* Voss.), and black spruce (*Picea mariana* BSP.) are the major species in the forested landscape (MRNF, 2015). The climate is maritime with an average temperature ranging from -11.6 °C in January to 16.8 °C in July and has an average annual precipitation of 1,135 mm (Environnement et Changement climatique Canada, 2023). The most important natural disturbances are spruce budworm outbreaks, with wildfires being rare (MRNF, 2013; MRNF, 2022). The area's extensive road network and forest harvesting are the main human disturbances. The largest protected area in the region is Gaspesie National Park.

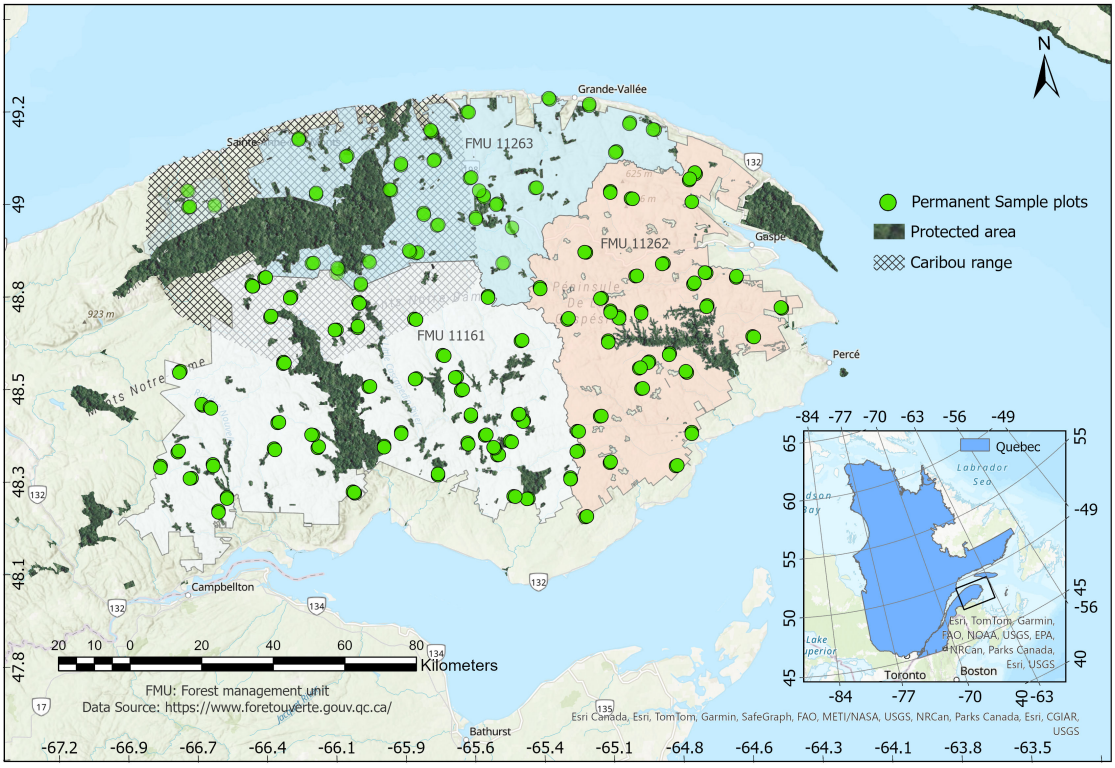


Figure 2. Location of the permanent sample plots and the three Forest Management Units (FMU: 11161, 11262, and 11263) in Gaspesie

2.3.2 Methods

2.3.2.1 Acquisition of forest inventory data

The Ministry of Natural Resources and Forests (MRNF) maintains a network of over 12,000 permanent sample plots (PSPs). The PSPs are clustered by groups of two on cruise lines, with a distance of 425 m between the plots (MRNF, 2019). The cruise lines were randomly placed across the province. The database is freely accessible online (MFFP, 2014, 2020; MRNF, 2025). All trees having a diameter at breast height (DBH, measured at 1.3 m above ground) greater than or equal to 9.1 cm within an 11.28 m radius of the plot center are numbered and their DBH is measured. Additionally, trees with a DBH greater than or equal to 31.1 cm within a 14.10 meter radius are also measured. Height is measured for a subset of these trees. Topographic and edaphic features such as drainage, slope, and soil texture are also recorded. Although there were 224 permanent plots in the study area (Table 1, Figure 2), we only used the 208 plots that were measured between 2017 and 2021.

Table 1. The number of permanent sample plots in each forest management unit (FMU) and the plots measured between 2017 and 2021 kept for modeling purposes

Forest management units	**Number of plots**	**Plots used**	**Area (km^2)**
FMU 11161	94	85	6469
FMU 11262	65	63	4060
FMU 11263	65	60	3644
Total	**224**	**208**	–

Tree species, status, quality class, slope class, ecological type, age class, altitude, and DBH were extracted from the PSPs data base. When slope class, age class, drainage

class and ecological type were missing, photo-interpreted information from Open Forest (*Forêt ouverte*) was used to fill in the missing values in the inventory data (MRNF, 2025). The R package elevatr was used to extract missing altitude values in inventory data by direct retrieving from a digital elevation model (Hollister, 2023). Additional missing ecological types were retrieved from the Ecological Classification of Quebec Territory database (MRNF, 2023a).

2.3.2.2 Classification of ecoforest map into landuse map categories

The ecoforest map data was obtained from the same source as the PSPs data (MRNF, 2025), and the protected areas from the Government of Canada (2025b). The protected areas and ecoforest map layers were then spatially merged. Following that, the merged polygons were classified as wood production, unproductive, inaccessible, and conservation land use categories in ArcGIS Pro (ESRI, 2023) using the classification criteria listed in Table 15. Each permanent plot in the study area was assigned to these land use categories. Unproductive areas are those where forest stands can not produce 50 m^3/ha gross merchantable volume in one rotation (Dhital et al., 2013; MRNF, 2023b). These include bodies of water, as well as dry and wet bare areas. Inaccessible areas cannot be easily accessed, such as areas with steep slopes (i.e. slope $> 40\%$), and islands of less than 250 hectares. Protected areas where harvesting is prohibited are included in the conservation category. These areas include wildlife habitats, national parks, and biodiversity reserves. Wood production land use types are defined as places other than conservation, inaccessible, and unproductive areas.

2.3.2.3 Growth simulation

ARTEMIS is a distance-independent individual tree-based model (ITBM) using a 10-year simulation step that is presently being used to support strategic forest

management planning. Trees are harvested using an enhanced harvest sub-model (Fortin, 2014b; Melo et al., 2017) based on statistical regression to predict the occurrence of harvesting events or declared dead by a mortality sub-model (Fortin et al., 2022). Diameter increment of the remaining trees is then predicted, followed by the recruitment of new trees over the 10-year simulation step. A height–diameter (HD) relationship (Fortin et al., 2009b), and two-entry volume equation (Fortin et al., 2007) are used to estimate tree volume.

The predictions are then aggregated to the plot level. Stochasticity is incorporated into the model at all levels using 1000 Monte Carlo realizations (Fortin et al., 2022). This includes producing random numbers to replicate errors in parameter estimates, random effects, and residual errors in all the sub-models. Sampling error is also included in ARTEMIS through the implementation of a full stochastic approach combined with parametric bootstrap point and variance estimators (Fortin et al., 2018).

We used a 50-year simulation horizon. The simulation from ARTEMIS yields large area estimates of wood supply while accounting for long-term forest changes using bootstrap estimators. Moreover, the model considers climate sensitivity through mean annual temperature and precipitation, which partly influences mortality, diameter growth, recruitment, and height-diameter relationships (Fortin and Langevin, 2012). In this study, we used Representative Concentration Pathways (RCPs) 2.6 as the climatic scenario, which accounts for average rise in temperature of 1.2 °C over the next century and a 5% increase in precipitation.

2.3.2.4 Linking growth simulation with caribou habitat model

The growth realizations were used as input for the resource selection function (RSF) in order to estimate realized habitat quality for caribou (Figure 3). Details for the RSF can be found in Annex I. Canopy cover was established using the basal area

of the species (Conifer dominated stands: basal area (BA) of conifer species > 75%; Broadleaf dominated stands: BA of broadleaved species > 75%; Mixed stands: the rest of the stands. The time since the last harvesting was obtained from the PSPs and the ecoforest map data and was then updated when a harvest was carried out during one of the simulation steps. Harvesting was divided into two categories (extensive or intensive) according to the list found in Table 2. Non-commercial silvicultural treatments and natural disturbances were set according to PSPs and ecoforest maps (Table 2) and not updated during the simulation runs, as these were not simulated in this study. Age class of the plot was extracted from the PSPs or ecoforest map, and the age was randomly set to a value within the age class for each Monte Carlo simulation (e.g. a plot with an age class of 50 was randomly set to a value between 41 and 60 years). The age was then tracked for each simulation step.

Then, by combining stand age, disturbance history, and canopy cover, 13 land cover types were produced as indicated in Table 3. We used the Near function in ArcGIS Pro (ESRI, 2023) to find the distance between each permanent plot to the nearest forest road using the available road network information of the year of the PSPs measurements (Gouvernement du Québec, 2025). Assuming that a road would be constructed during harvest, the distance to the nearest road was randomly reset to be between 5 and 200 meters when a harvest occurred during the simulation step, corresponding to the usual operational constraints in the area.

The simulation framework then produced the RSF score for each realization of each plot at 10-year intervals between 2017 and 2067. The RSF function is a logistic regression (see Annex I), with the linear logit transformed into the RPOC given by:

$$P(y|x) = \frac{e^{logit}}{1 + e^{logit}} \tag{10}$$

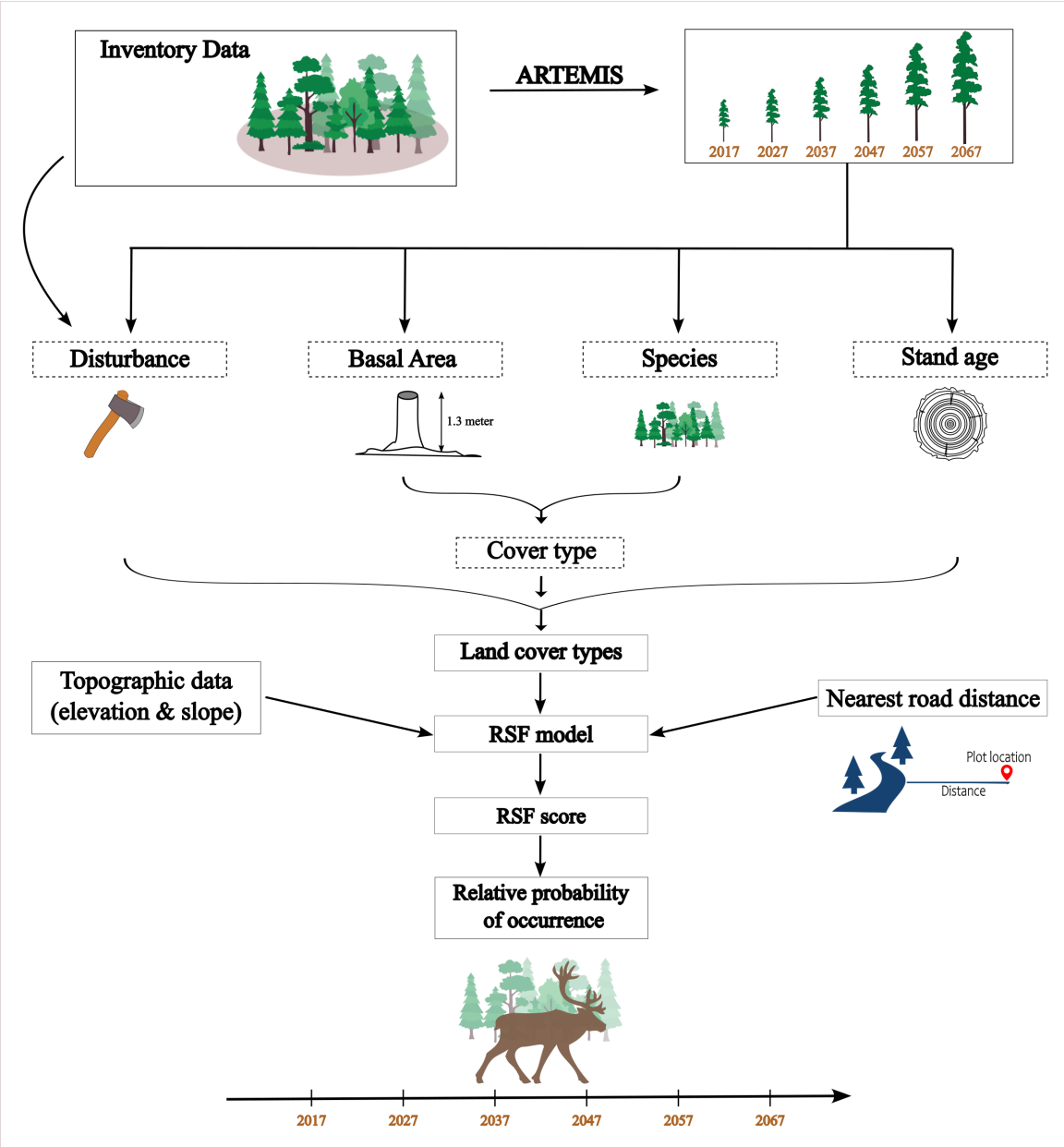


Figure 3. Schematic diagram of the integration framework linking ARTEMIS-2009 forest simulations with the resource selection function (RSF) model to generate relative probability of caribou occurrence values

Table 2. A functional grouping of forest disturbance and silvicultural intervention codes used in Quebec's public forest inventory system. Codes are categorized by management intensity (Intensive, Extensive), disturbance origin (Natural), and other intervention types

Disturbance type	**Code**	**Description**
Intensive forest management	CPRS	Clearcut with protection of regeneration and soils
	CT	Total cut / Clearcut
	P	Plantation
	CPRS_U	Uniform clearcut with protection of regeneration and soils
Extensive forest management	EC	Commercial thinning
	CP	Partial cut
	CPI	Irregular shelterwood cut
	CPR	Shelterwood cut
	CJMSCR	Selection cutting after 2004
	ECJ, CJ	Selection cut
Natural disturbance	BR	Burn / Wildfire
	ES	Severe insect epidemic
	EL	Lightening
Other intervention	EPC	Site preparation
	RR	Scarification and reforestation
	DEG	Cleaning / Weeding

Table 3. Land cover classes used in the resource selection function (RSF) model, defined by cover type, treatment history, and stand age

Final habitat class	**Age category**	**Actual age**	**Cover type**	**Disturbance type**
Landcover types				
Mature coniferous forests	Mature (> 50 yrs)	≥ 41 yrs	Conifer	–
Immature coniferous forests	Immature ($21 - 50$)	$21 - 40$ yrs	Conifer	–
Mature mixedwood forests	Mature (> 50 yrs)	≥ 41 yrs	Mixedwood	–
Immature mixedwood forests	Immature ($21 - 50$)	$21 - 40$ yrs	Mixedwood	–
Hardwood forests	Immature/Mature	≥ 21 yrs	Broadleaf	–
0–20 yrs cutblocks	Young ($0 - 20$ yrs)	$0 - 20$ yrs	–	Intensive harvest
0–20 yrs extensive treatments	Young ($0 - 20$ yrs)	$0 - 20$ yrs	–	Extensive harvest
0–20 yrs natural disturbances	Young ($0 - 20$ yrs)	$0 - 20$ yrs	–	Natural
Other Polygons	Default class for plots not meeting criteria above			

The RPOC is then scaled up to the study area level using the parametric bootstrap estimator (Fortin et al., 2018). The design-based Horvitz – Thompson estimator was used to generate an unbiased estimate of the mean (Horvitz and Thompson, 1952). We assumed that the population size is significantly larger than the sample size. Thus, the estimate of the population mean $\hat{\mu}_y$ is the mean of the realized estimates B:

$$\hat{\mu}_y = \frac{1}{B}\sum_{b=1}^{B}\hat{\mu}_{y,b} \tag{11}$$

The variance was calculated as presented by Fortin, Manso and Schneider (2018):

$$\hat{V}_{md,CORR}(\hat{\mu}_{BS} - \mu_y) = \hat{V}_m(\hat{\mu}_{y,b}) + 2\hat{V}_d(\hat{\bar{\mu}}_y) - \hat{E}_m[\hat{V}_d(\hat{\mu}_{y,b})] \tag{12}$$

Where $\hat{V}_{md,CORR}(\hat{\mu}_{BS} - \mu_y)$ is the hybrid estimator of the difference between the bootstrap mean estimator $\hat{\mu}_{BS}$ and the true mean population parameter μ_y for both model and sampling design uncertainty. $\hat{V}_m(\hat{\mu}_{y,b})$ is the model-based variance of the bootstrap replicate estimates, which measures variability of estimates due to the parametric bootstrap model. $\hat{V}_d(\hat{\bar{\mu}}_y)$ is the design-based variance estimator of the sample mean (or estimator) $\hat{\bar{\mu}}_y$, which quantifies sampling design variability. $\hat{E}_m[\hat{V}_d(\hat{\mu}_{y,b})]$ is the expected value under the bootstrap model of the design-based variance estimator for each bootstrap replicate, which estimates the average design variance estimate across bootstrap samples.

2.3.2.5 Business-as-usual and alternative scenarios

The business-as-usual management scenario was compared to multiple alternative scenarios which have been proposed for the protection of caribou (BFEC, 2022; Équipe de rétablissement du caribou de la Gaspésie, 2018; Gouvernement du Québec, 2024; MRN, 2013; MRNF, 2015, 2023b).

2.3.2.5.1 Business-as-usual scenarios

The business-as-usual scenario used 197 plots in the wood production zones, 3 plots in the conservation zones, and 8 plots in inaccessible zones using the categories described in Table 15 (Annex II). The area of each stratum is presented in Table 4. The initial estimate of annual allowed cut (AAC) was set to 1.76 m^3/ha/yr in the whole study area (Morin, 2014). Silvicultural treatments for the 9 potential vegetations found in the area was set to those presently used in the area, and are found in Table 5 (MRNF, 2023b). Clearcut with protection of regeneration and soils (CPRS), focuses on protecting the regeneration process and soil during the harvesting, and removes 97-99% of the merchantable volume (Poulin, 2013d). Shelterwood cutting is a regeneration process that involves gradual opening of the forest canopy through a series of partial cuts (Noualhaguet et al., 2025). Its main objective is to establish or develop natural regeneration under the protection of an existing forest cover that includes mature seed trees (Matthews, 1991; Raymond et al., 2013; Smith, 1998). In the Gaspesie region, shelterwood cutting removes 30% to 50% of the merchantable volume per intervention, depending on the transition strategy (Nadeau Fortin et al., 2016; MRN, 2013). If the time interval between the cuts is greater than 1/5 of the rotation, it can lead the stand to develop an irregular structure (CPI) (Poulin, 2013a), and if it is less than 1/5 of the rotation, it can lead the stand to develop a regular structure (CPR) (Poulin, 2013b). Selection systems (ECJ-CJ) are a family of regeneration processes consisting of periodic cuts in uneven-aged stands to harvest its production while keeping the forest's natural structure intact and helping it regenerate (MRNF, 2023c). Selection cutting also aims to maintain an optimal tree density, which accelerates tree growth and reduces mortality. In the Gaspesie region, selection cutting removes 25% to 35% of the merchantable volume (Nadeau Fortin et al., 2016; MRN, 2013). They are generally practiced to produce large-diameter, high-quality trees (Poulin, 2013c). Among these three silvicultural treatments, CPRS is the important harvesting pattern when compared to shelterwood and selection cutting (Table 6).

Table 4. Land use stratification: number of sample plots and area by strata

Land use	**Current (BAU)**		**Conservation (CONS)**		**Constraint 1**		**Constraint 2**	
	No. of plots	**Area (ha)**	**No. of plots**	**Area (ha)**	**No. of plots**	**Area (ha)**	**No. plots**	**Area (ha)**
Wood production	197	1182039.84	184	1113060.45	161	976563.53	152	935931.28
Conservation	3	68771.63	16	137751.02	16	137751.02	16	68771.63
Inaccessible	8	236537.91	8	236537.91	8	236537.91	8	236537.91
Sensitive wood production	0	0.00	0	0.00	23	236537.91	32	246108.57

Table 5. Potential vegetation types identified in the Gaspesie, associated silvicultural treatment methods, and their respective treatment return intervals

Code	**Potential vegetation**	**Wood production**		**Constraint 1**		**Constraint 2**	
		Treatment	**Return time**	**Treatment**	**Return time**	**Treatment**	**Return time**
MS1	Fir - Yellow birch	CPR	40 yrs	CPI	25 yrs	ECJ–CJ	25 yrs
MS2	Fir - White birch	CPRS	45 yrs	CPI	30 yrs	ECJ–CJ	25 yrs
MS6	Fir - Red maple	CPRS	45 yrs	CPI	30 yrs	ECJ–CJ	25 yrs
RC3	Fir - Cedar	CPI	40 yrs	CPI	40 yrs	ECJ–CJ	25 yrs
RE2	Black spruce - Moss	CPRS	70 yrs	NH	0	NH	0
RE3	Black spruce - Sphagnum	CPRS	70 yrs	NH	0	NH	0
RS1	Fir - Cedar	CPRS	50 yrs	CPI	40 yrs	ECJ–CJ	25 yrs
RS2	Fir - Black spruce	CPRS	50 yrs	CPI	40 yrs	ECJ–CJ	25 yrs
RS5	Fir - Red spruce	CPRS	50 yrs	CPI	40 yrs	ECJ–CJ	25 yrs
FE3	Sugar maple - Yellow birch	ECJ–CJ	25 yrs	CPI	25 yrs	ECJ–CJ	25 yrs

Table 6. Maximum annual area allocated by silvicultural treatment type (ha) across different scenarios, including treatment codes. The area for clearcutting with protection of regeneration and soils (CPRS) remained fixed in all scenarios. In contrast, the areas for shelterwood and selection cutting in the constrained 1 and 2 were variable and could exceed the baselines set in the current business-as-usual and conservation scenarios

Treatment	**Codes**	**Area (ha)**		
		Current/ Conservation	**Constraint1**	**Constraint2**
Clearcut with protection of regeneration and soils	CPRS	11,064	9,140.72	8,760.40
Shelterwood cutting	CPI, CPR	1,080	0	0
Selection cutting	ECJ–CJ, EC	670	0	0

2.3.2.5.2 Alternate scenarios

a. Identification of habitat restoration zones

The Quebec government has undertaken a comprehensive habitat restoration strategy within the caribou range (BFEC, 2022; Équipe de rétablissement du caribou de la Gaspésie, 2018; Gouvernement du Québec, 2024; MRNF, 2013, 2015, 2023b). The caribou range (Gouvernement du Canada, 2025a) was divided into three zones (Figure 4, BFEC, 2022): peripheral habitat zone (PHZ), predator management zone (PMZ), and critical habitat zone (CHZ). CHZ receives maximum protection, with all timber harvesting and construction of new roads prohibited to keep critical habitats undisturbed. The goal of PMZ is to reduce predator effectiveness by managing the forest to be less favorable for alternate prey like moose. Current forest management practice aims to keep the proportion of young forests (0–20 years), which are an important component for moose habitat, to a maximum of 16% in the PMZ. PHZ acts as a buffer. Forest harvesting is allowed but must follow guidelines to restore a forest structure

that benefits caribou in the long term, such as favoring conifer regeneration (MRNF, 2023b,c). All three zones, hereafter called the habitat restoration zone (HRZ = CHZ + PMZ + PHZ), are where alternate forest and road management scenarios are to be tested to favor caribou conservation. The areas of each zone are presented in Table 7 and Figure 4.

Table 7. Caribou habitat restoration zones in the caribou range, including zone codes and respective area in hectares, representing critical habitat, predator management, and peripheral habitat zones

Caribou management zones	**Codes**	**Area (ha)**
Critical habitat zone	CHZ	68,979
Predator management zone	PMZ	136,497
Peripheral habitat zone	PHZ	109,612

b. Alternate forest management scenarios

Following the guidelines of the Quebec government (MRNF, 2023c,b), no harvesting took place in the critical habitat zone. However, in the predator management and peripheral habitat zones, we modulated forest management practices including, shelterwood cutting and selection cutting, in order to maintain important elements for biodiversity while also allowing for timber production (MRNF, 2023c,b).

c. Road management scenarios

We proposed three road management scenarios: no dismantling of roads (DR0), dismantling 50% of the roads (DR50) and dismantling 100% of the roads (DR100). Thus, in the zone where roads are dismantled, either the distance to the nearest road is kept as described earlier (DR0) or set to the closest road outside the road management zone (DR100). In the case of DR50, the distance to the closest road is set to the closest road outside the road management zone, for half of the plots that are randomly selected

for each realization. We assumed that after dismantling the road, it would take 20 years for the road to be considered forest and no longer be preferred by predators. In our scenarios, the impact of road closure only becomes apparent from 2037 onwards, given that the simulation began in 2017. In addition, the plots that were harvested and the newly formed roads were dismantled, which would also take 20 years to be regenerated, only if they lie in a previously dismantled area of the road network.

d. Matrix of alternative scenarios

A matrix of alternative scenarios was created, from the combination of road and forest management alternatives in the various habitat zones. For all the alternate scenarios, CHZ was added to the conservation zone. In addition, DR0, DR50 and DR100 were tested within this extended conservation zone.

As described in Figure 4, the combination of road management strategy used in CHZ is called conservation strategy. Next, the combination of road management and forest management strategies used in the combined zones CHZ and PMZ was considered as protection strategy one (P1). P1 was composed of an adjustment in forest management practices, including shelterwood and selection cutting (constraint 1 in Table 6). Each forest management approach was examined using DR0, DR50 and DR100. Finally, the combination of road management and forest management strategies used in CHZ, PMZ, and PHZ was referred to as protection strategy two (P2). Similar forest management (constraint 2 in Table 6) and road management strategies as in P1 were applied in P2. Aside from conservation and protection strategies, business-as-usual scenarios were applied in the remainder of the study area i.e. outside of HRZ. The combination of all these forest and road management options led to 16 scenarios (Table 8, Figure 4), comprising business-as-usual and alternative forest and road management scenarios in various habitat zones [1 (current scenario) + 1 (conservation scenario) $\times$ 3 (road management scenarios) + 2 (protection scenarios) $\times$ 2 (forest management scenarios) $\times$ 3 (road management scenarios) = 16 scenarios].

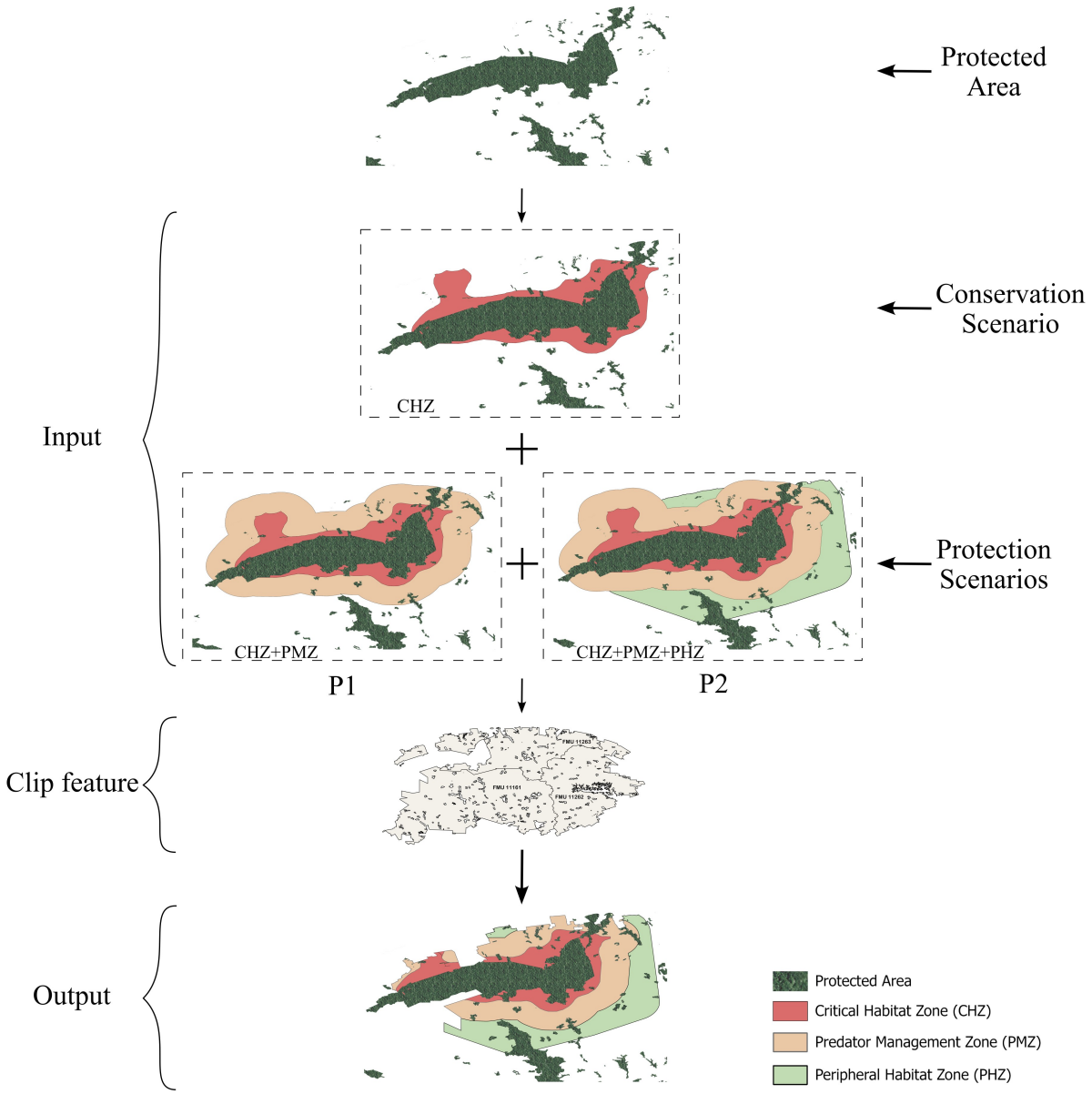


Figure 4. Schematic workflow illustrating the spatial integration of protected areas with conservation and protection scenarios, using sequential overlay and clipping of critical (CHZ), predator management (PMZ), and peripheral (PHZ) habitat zones by the study area

Table 8. Forest and road management decisions used to construct the different scenarios. Each combination of forest and road management possibilities are used, leading to 16 scenarios

Land use / Scenarios	**Conservation area**		**Caribou sensitive zone**		**Wood production**	
	Area	**Action**	**Area**	**Action**	**Area**	**Action**
Current scenario	Actual area	NH	None	None	Actual area	BAU
Alternative forest management scenarios	Actual area + CHZ	NH	None	None	Actual area − CHZ	BAU
			PMZ	SW	Actual area − (CHZ + PMZ)	
			PMZ + PHZ	SL	Actual area − (CHZ + PMZ + PHZ)	
Alternative road management scenarios	—	DR50	—	DR50	—	—
		DR100		DR100		
Example scenario	Actual area + CHZ	NH + DR50	PMZ + PHZ	SW	Actual area − (CHZ + PMZ + PHZ)	BAU

Note: BAU: Business-as-usual; CHZ: Critical habitat zone; DR50: Dismantling of 50% roads; DR100: Dismantling of 100% roads; NH: No harvest; PHZ: Peripheral habitat zone; PMZ: Predator management zone; SL: Selection cutting; SW: Shelterwood cutting.

2.3.2.6 Data analysis

In order to estimate the RPOC for the study area, the simulation framework was employed (section 2.3.2.4). The RPOC was calculated for each scenario (section 2.3.2.5) at ten-year intervals from 2017 to 2067. The distribution of the RPOC was then analyzed using the fitdistr package in R (Delignette-Muller and Dutang, 2015). To get a complete landscape-level view, the mean RSF score and its standard deviation of each sample plot were interpolated using Empirical Bayesian Kriging (EBK) (Gribov and Krivoruchko, 2020). This method is a flexible, robust, and computationally efficient geostatistical method for data interpolation that leverages Bayesian principles, data subdivision, and adaptive modeling to provide accurate predictions and uncertainty estimates, particularly for complex and nonstationary spatial data (Gribov and Krivoruchko, 2020). From growth simulations using ARTEMIS, we also estimated the actual annual harvested volumes for the same period, which is always less than the specified annual allowable cut (AAC). AAC is the maximum amount of wood that can be harvested annually on a specific area without affecting the ability of forest environment to produce, in order to fulfill all of the forest management goals (BFEC, 2021; MRNF, 2023b). We conducted a trade-off analysis by plotting the values of 50 years average of the actual timber harvested (proxy of wood supply) against the 50 years average of RPOC (proxy of habitat quality) for each scenario. A trade-off existed if scenarios with a high timber harvest tended to have a low RPOC. A synergy was observed if high timber harvest was associated with a high RPOC. No relation was identified if the two outcomes were independent.

2.4 RESULTS

2.4.1 RPOC under BAU

For all landcover types, the average RPOC was below 0.25, except for recent extensive forest treatment (Figure 5a). Of the types with an average below 0.25, mature forests had the highest RPOC and recent intensive cut blocks the lowest. The RPOC of caribou was lowest in close proximity to the roads (Figure 5b). This RPOC values increases gradually as distance from the road network increases and remains relatively stable beyond 500 m.

The simulation of BAU scenario showed a steady decline in the RPOC over the 50 year simulation period. The RPOC decreased from 0.1502 ± 0.009 in 2017 to 0.1157 ± 0.0066 in 2067. This drop is statistically related to the expansion of 0–20 years old cutblocks, which exhibited a strong negative influence on habitat selection (β = -3.044 in Annex I). Further, the RPOC (Figure 6) was characterized by a high density of low suitability of habitat and a long tail extending toward higher probabilities.

2.4.2 Effects of alternative management strategies on RPOC

2.4.2.1 RPOC across the landscape

The implementation of caribou-oriented scenarios demonstrated that road dismantling is the most important factor for habitat restoration, significantly overshadowing the modulation of silvicultural treatments (Figure 7). In the absence of road removal, a consistent decline in habitat quality is observed across all management scales from 2017 to 2067. The conservation scenario showed a 3% increase in RPOC to BAU (0.1187 ± 0.0067). The application of extensive forest management strategies such as SW_P1, SW_P2, SL_P1 and SL_P2 resulted in the RPOC between 5% and

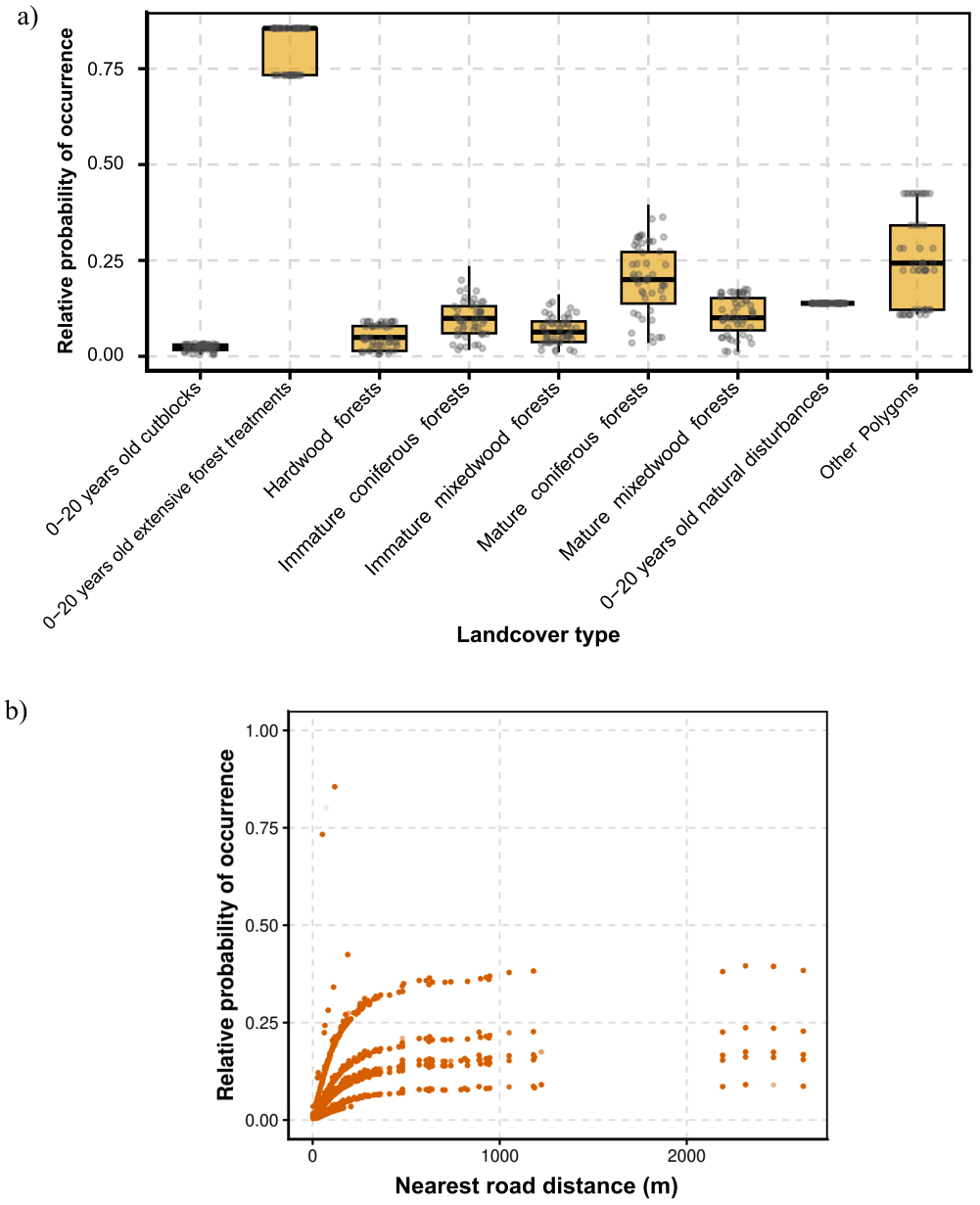


Figure 5. Results of application of resource selection function (RSF) on ARTEMIS forest growth simulator. Results are computed using 1,000 Monte Carlo simulations of 208 permanent sample plots for 50 simulation years. (a) Relative probability of caribou occurrence across landcover types; boxes depict the interquartile range (IQR), the central horizontal line represents the median, and whiskers scale to the 95% confidence interval, with individual simulation realizations shown as randomly selected 50 jittered points. (b) Response to nearest road distance (m)

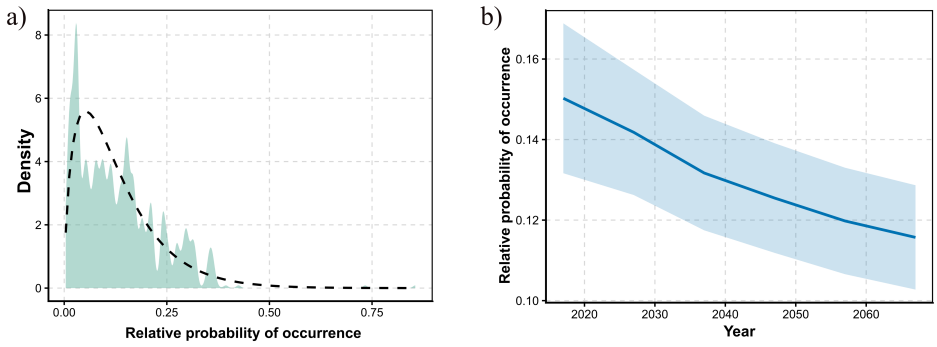


Figure 6. Distribution and projection of relative probability of caribou occurrence in Gaspesie. (a) Density plot showing the gamma distribution of the relative probability of caribou occurrence, (b) Projected forecast of the mean relative probability of caribou occurrence from 2017 to 2067 with the 95% confidence interval across the simulation period

6%. In contrast, the implementation of road removal acts as a primary catalyst for habitat recovery. While 50% road removal generally stabilizes the downward trend, the 100% removal scenario results in sharp increase in the RPOC, typically peaking around the year 2037 before reaching a stable plateau. In the 50% road removal scenarios, the conservation scenario showed 9% increase in the RPOC (0.1257 $\pm$ 0.0069). In comparison, shelterwood cutting and selection cutting within the predator management zone enhanced the RPOC by 17% (0.1356 $\pm$ 0.0069) and 20% (0.1386 $\pm$ 0.0070), respectively. It is worth noting that at the 50% road decommissioning level, treatments localized within the predator management zone maintained a slight improvement over those extended into peripheral habitat zones. The contribution of alternative management scenarios was even more noticeable under 100% road removal. While the conservation scenario realized an increase of 12% (0.1290 $\pm$ 0.0069) in comparison to BAU, the application of silvicultural treatments in both management zones (P1 and P2) enhanced the RPOC to a greater extent. Precisely, the selection cut scenario in both zones (SL_P2) confirmed the increase in RPOC, with a 35% increase (0.1564 $\pm$ 0.0071). The results indicated that while selection cutting applied in the

predator management zone is effective under partial road removal (50%), extensive silvicultural treatment across both predator and peripheral zones integrated with total road decommissioning (100%) provides the most favourable pathway for caribou habitat restoration over the 50-year simulation period.

2.4.2.2 RPOC across the caribou range

In scenarios lacking road removal, extending the conservation area only approach increased the RPOC by 10% (0.102 ± 0.0065). Under the same conditions, alternative forest management scenarios through selection cutting applied in both predator and peripheral zones (SL_P2) increased the RPOC by 33% (0.1244 ± 0.0086). The impacts of these treatments scaled substantially with road restoration intensity. The moderate restoration intensity (50% road removal) nearly doubled the RPOC. The SL_P2 strategy was identified as the most impactful, leading to a 107% increase (0.1931 ± 0.014). Total decommissioning acted as an accelerator for alternative caribou-oriented management. Under this scenario, SL_P2 nearly tripled the RPOC, (i.e. increase of 215%, 0.2936 ± 0.0128), while shelterwood treatments in the same zones (SW_P2) increased the RPOC by 172% (0.2534 ± 0.014).

2.4.2.3 RPOC across conservation strata

Within designated and proposed conservation strata, the combined effect of road removal and silvicultural treatments was evident. When no roads are decommissioned, effect of extensive forest management and conservation only approach yielded nearly identical RPOC. With partial road decommissioning, both shelterwood and selection cutting resulted in slightly lower RPOC than the conservation only approach, yet they continued to be higher than the business-as-usual scenario in the caribou range. Under 100% road removal, all silvicultural treatments brought about an increase beyond

220% (0.2728 ± 0.0223), suggesting effect of silvicultural treatments in sensitive zones are only evident at complete road dismantling in the conservation strata.

2.4.2.4 RPOC across caribou sensitive and wood production strata

In caribou sensitive zones, the effect of extensive forest management on the RPOC was relatively stable in the absence of road decommissioning. However, the contribution of silvicultural treatments became evident under partial and total road decommissioning. Particularly, under total road removal, SL_P2 strategy increased the RPOC by 186%, attaining the highest RPOC at 0.3188 ± 0.0147. Conversely, caribou-oriented forest management interventions did not produce significant gains in wood production strata. Both the conservation and extensive forest management scenarios caused a negligible or marginally negative shifts in the RPOC, with declines persistently restrained below 2%. These results suggested that forest management strategies are highly effective when confined to sensitive strata and when coupled with road removal but have marginal effect in the wood production strata.

2.4.3 Mapping RPOC

Figure 8 illustrates the spatial pattern of the RPOC of optimal alternative forest management strategies across all road removal simulations from 2017 to 2067. The interpolation of the RPOC highlights that road decommissioning was a dominant factor driving the increase in RPOC. Under no road removal scenario, the RPOC in SL_P1 forest strategy stays persistently low throughout the entire projection period (2017-2067). Contrarily, the 50% road removal under SL_P1 led to steady rise in the RPOC starting in 2037. The RPOC showed a moderate rise within the caribou range. The most notable increases were recorded under 100% road removal scenario under SL_P2. By 2037, large contiguous patch of CHZ switch to deep green, reflecting the

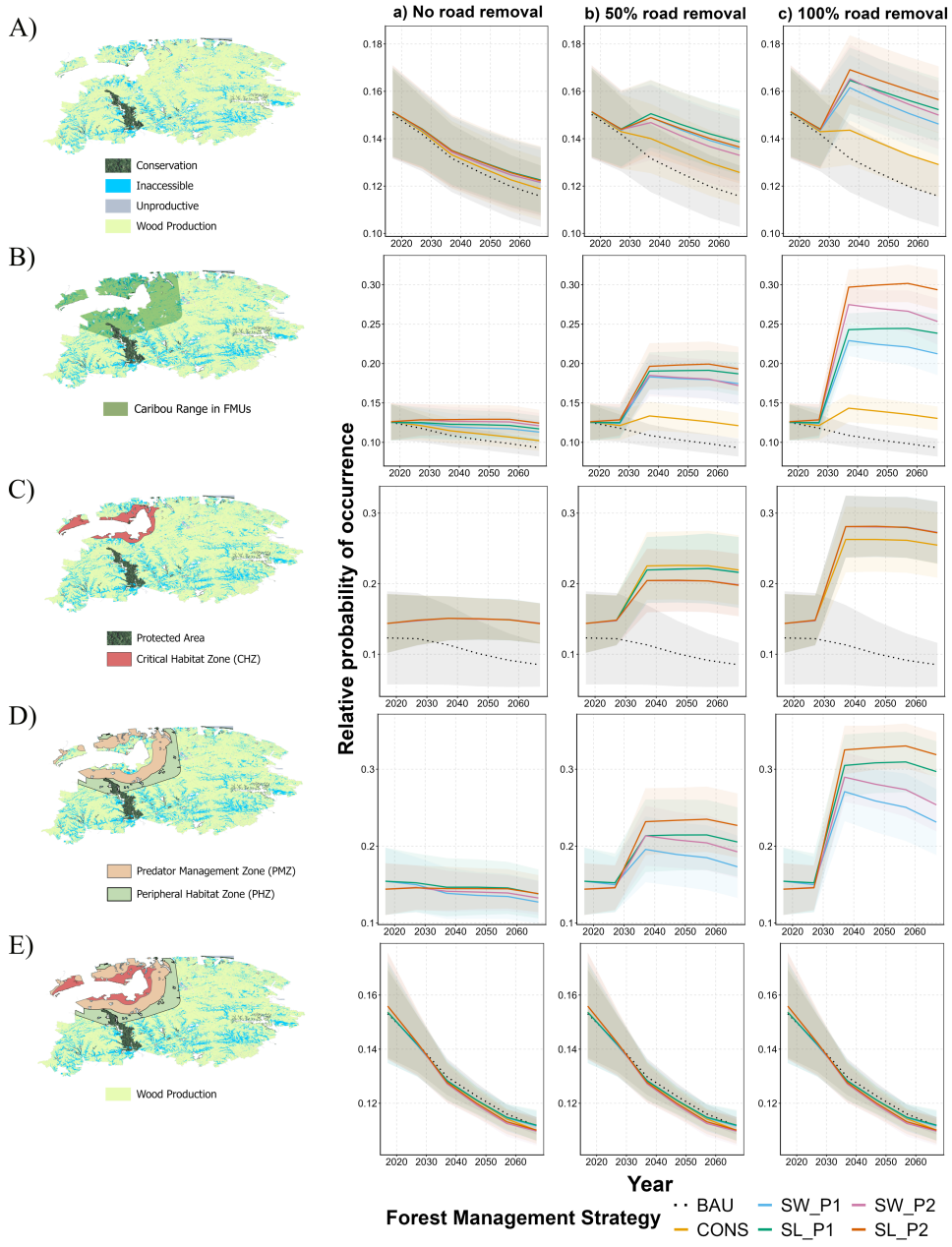


Figure 7. Scenario-based projections of the relative probability of caribou occurrence (2017-2027) under multiple forest management and road decommissioning strategies. Left panel maps symbolize the extent of management across five spatial scales: (A) the entire study area, (B) caribou range, (C) conservation strata (protected area + critical habitat zone), (D) sensitive wood production strata (predator management zone + peripheral habitat zone), and (E) general wood production strata. The multi-figure layout displays the forecasted mean relative probability of occurrence across three road management decisions: (a) No road removal, (b) 50% road removal, and (c) 100% road removal

peak RPOC at 0.378. This high RPOC core is maintained through 2067, providing evidence that total road removal may generate a stable long-term refuge for caribou. Degree of response to road removal showed variation between management zones; the CHZ and PMZ were most sensitive, evolving from low RPOC in 2017 to peak value of 0.378 by 2037 under SL_P2 strategy. While the PHZ experienced less dramatic changes, it still showed positive effects from complete road removal. The southern portion of the Gaspesie region constantly retained lower RPOC irrespective of treatment intensity.

2.4.4 Effect of forest management scenarios on wood supply

2.4.4.1 Harvest volume

In the first harvesting period (2017-2027), the BAU strategy resulted in the maximum timber harvest, approaching 1.75 million m^3/yr (Figure 9). In contrast, the conservation strategy (CONS) commenced at a prominently lower level of roughly 1.65 million m^3/yr. The extensive forest management strategy (SW_P1, SW_P2, SL_P1, SL_P2) showed almost identical harvest levels, situated between the BAU and CONS harvest levels. Table 9 summarizes these shifts in comparison to the BAU 2017-2027 baseline. Initially (2017-2027), the CONS reflected the greatest reduction in harvested volumes (-6.0% or -105,834 m^3/ha), while the extensive forest management strategies presented modest decreases ranging from -5.3% to -5.6%. Most alternative scenarios had reductions in harvest volumes over the middle of the simulation horizon (2027-2057), and by the 2037-2047 interval, SL_P1, SW_P2, and SL_P2 remained steady at a -2.5% deviation from the baseline, suggesting a partial stabilization in harvest over time. In the final decade (2057-2067), all scenarios show a decline. The BAU decreases by -3.4% below its initial value, and CONS fell to its minimum of -9.4%. Notably, SL_P2 came forth as the most resilient alternative, reaching only -3.1% of the initial BAU.

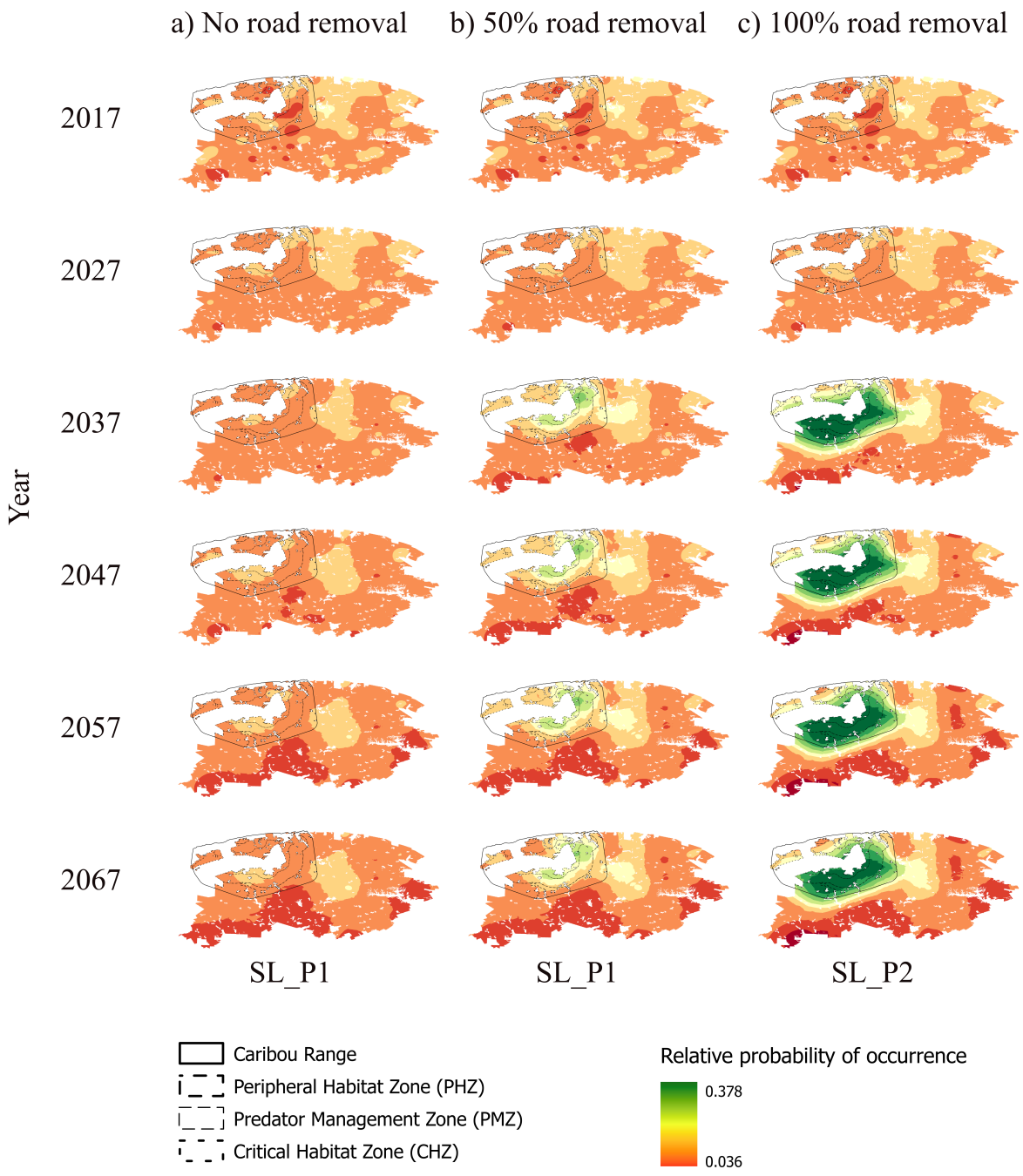


Figure 8. Spatiotemporal pattern of mean relative probability of caribou occurrence of optimal forest management strategies under each road decommissioning scenarios (2017-2067). The maps portray the empirical Bayesian kriging based spatial interpolation of mean relative probability of caribou occurrence for: (a) SL_P1 under no road removal, (b) SL_P2 under 50% road removal, and (c) SL_P2 under 100% road removal

2.4.4.2 Standing volume

At the beginning of the simulation period in 2017, the standing volume for CONS and all forest management strategies was uniform, at approximately 150 m^3/ha. However, from 2027 and thereafter, a clear and steady decreasing pattern was visible across all strategies. The BAU strategies persistently marked the highest standing volume throughout the 50-year period, though it lowered to approximately 118 m^3/ha by 2067. The CONS and extensive forest management strategies indicated a uniform decline, with the SL_P2 and SW_P2 strategies with the lowest values, reaching close to 112 m^3/ha in 2067. The error bars across all scenarios remained consistent, implying a uniform degree of uncertainty across the different management scenarios. Overall, while the total harvest volume stays relatively constant over time for all strategies, there is a notable and gradual reduction in standing volume per hectare. BAU arose as the strategy that optimizes both annual harvest yield and the remaining forest stock, whereas strategies like SL_P2 decreases in the standing volumes towards the end of the projection period.

Comparative analysis of caribou-oriented management scenarios (combining a matrix of forest and road management strategies) indicated that the RPOC under BAU differed significantly from all extensive forest management strategies (SW_P1, SW_P2, SL_P1, and SL_P2) when accompanied by road removal (section 2.4.2, Figure 7A). Remarkably, the associated loss in harvest volume (wood supply) for the Gaspesie region were marginal across these scenarios as evident by overlapping error bars (Figure 9a). When quantifying differences in the mean RPOC against mean harvest volumes over 50-year periods (Figure 9c), the SL_P2 strategy with 100% road removal turned out to be the optimal scenario for habitat restoration. Under 100% removal intensity, SW_P2 was confirmed as the next-most impactful possibility for restoration, despite marginal greater loss in wood supply compared to SL_P2. In scenarios where road decommissioning was restricted to 50%, SL_P2 remained the better alternative.

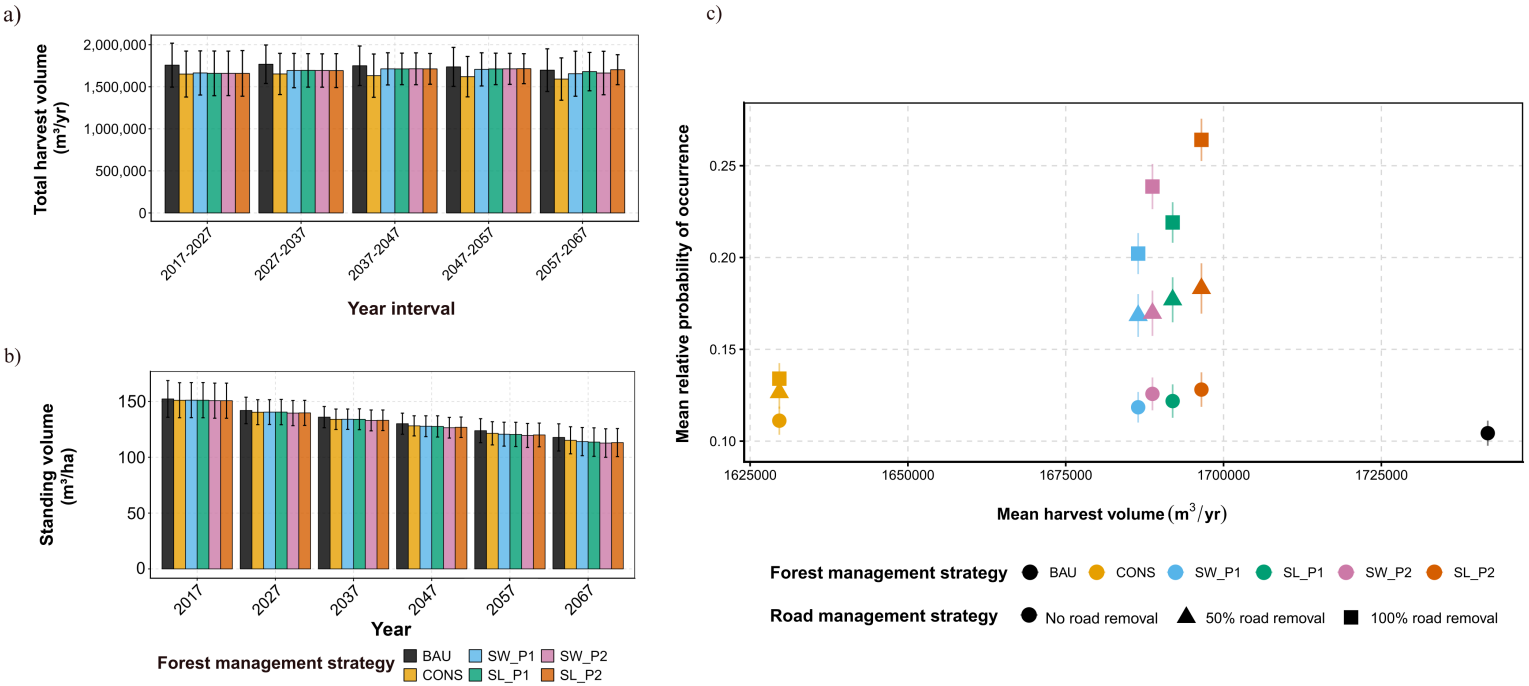


Figure 9. Projected impacts of forest management strategies on timber harvest and standing volume (2017-2067). (a) Total annual harvest volume (m^3/ha) is sum of timber harvest aggregated in 10-year intervals. (b) Forecast of standing volume (m^3/ha). (c) Trade-off analysis between caribou habitat quality and wood supply across 16 management scenarios. The scatterplots demonstrate the 50-year average relative probability of occurrence (habitat quality) against the 50-year average timber harvest (m^3/yr; wood supply). Error bars capture the standard error with 95% confidence intervals estimated from the 1000 Monte Carlo realizations. Color bars depicts specific forest management strategies: BAU (business-as-usual), CONS (conservation), SW (shelterwood), and SL (selection). Management intensity is denoted by intervention area: P1 denotes the predator management zone, and P2 comprises both the predator management and peripheral habitat zones making SW_P1: shelterwood cutting in P1, SW_P2: shelterwood cutting in P2, SL_P1: selection cutting in P1, SL_P2: selection cutting in P2. The CONS scenario is baseline alternative management. The BAU scenario is current forest management strategy

Table 9. Temporal patterns in timber harvest volume (m^3/yr) in reference to the 2017-2027 business-as-usual (BAU) harvest volume. Values indicate the absolute change in harvest volume and the corresponding percentage shift (in parentheses) for six forest management strategies across five 10-year intervals from 2017-2027 to 2057-2067. Positive values represent increase and negative value represent decrease in harvest volume compared to the initial BAU. Strategies include: BAU (business-as-usual), CONS (conservation), SW (shelterwood), and SL (selection). Management intensity is denoted by intervention area: P1 denotes the predator management zone, and P2 comprises both the predator management and peripheral habitat zones making SW_P1: shelterwood cutting in P1, SW_P2: shelterwood cutting in P2, SL_P1: selection cutting in P1, SL_P2: selection cutting in P2. The CONS scenario is baseline alternative management. The BAU scenario is current forest management strategy

Year interval	**BAU**	**CONS**	**SW_P1**	**SL_P1**	**SW_P2**	**SL_P2**
2017–2027	+0 (+0.0%)	−105,834	−92,724	−97,471	−97,597	−97,957
		(−6.0%)	(−5.3%)	(−5.5%)	(−5.6%)	(−5.6%)
2027–2037	+10,926	−104,500	−64,359	−62,245	−63,745	−65,013
	(+0.6%)	(−5.9%)	(−3.7%)	(−3.5%)	(−3.6%)	(−3.7%)
2037–2047	−7,161	−125,010	−43,989	−44,665	−43,203	−44,061
	(−0.4%)	(−7.1%)	(−2.5%)	(−2.5%)	(−2.5%)	(−2.5%)
2047–2057	−20,551	−136,686	−50,231	−44,766	−43,797	−42,011
	(−1.2%)	(−7.8%)	(−2.9%)	(−2.5%)	(−2.5%)	(−2.4%)
2057–2067	−59,415	−165,314	−101,818	−76,657	−93,469	−53,961
	(−3.4%)	(−9.4%)	(−5.8%)	(−4.4%)	(−5.3%)	(−3.1%)

2.5 DISCUSSION

The findings reveal that linking outputs from ARTEMIS to a RSF model efficiently represents the functional, instead just physical impact of anthropogenic disturbances. By introducing a stochastic road-reset mechanism at each harvest event, the simulation captures the immediate road penalty that comes with even the most responsive silvicultural treatments. This methodological framework presents why silvicultural modulation solely is inadequate: the model logic assures that new harvesting events activates a nearest road distance effect that statistically cancels the gains from maintaining canopy cover. A major advantage of utilizing an individual-tree model like ARTEMIS is its capability to forecast uneven-aged stand structures that are unobservable with conventional stand-level yield tables. When paired with the RSF, the method permits us to convert these fine-scale structural changes into landscape level RPOC. Moreover, this multi-scale integration facilitates the identification of sensitive zones and where forest and road management can be adjusted for both wood supply and RPOC.

2.5.1 Modulation of silvicultural treatments

No significant deviations in the RPOC were observed across forest management strategies with no road removal scenarios. These results are due to the small differences in coefficients values of the RSF function (Annex I). In ARTEMIS, the harvest sub-model activates a stochastic event informed by basal area, stem density, species composition, return time and annual allowable cut (AAC). Under business-as-usual scenarios, the model mostly selects CPRS, which harvests nearly all the trees and reassigns the plot as 0-20 years intensive cutblocks, which classes the plot as young intensive cut-block with the lowest coefficient of all land-cover types in the RSF (β = -3.044, Annex I). Conversely, in the P1 and P2 sensitive zones, the model selects

selection or shelterwood cutting systems which classifies the plot as 0-20 years old extensive treatments that as the highest landcover coefficient (β = 2.444, Annex I). The increase in RPOC under extensive silvicultural scenarios follows what is known about the preferences of caribou, where mature forest attributes are essential. Clear-cutting resets stand succession and fosters early seral vegetation preferred by apparent competitors (moose) and predators (bears, coyotes), whereas selection and shelterwood cutting preserve partial canopy cover which is preferred by caribou (Caouette, 2024; Équipe de rétablissement du caribou de la Gaspésie, 2018; Gagné et al., 2016; Nadeau Fortin et al., 2016; Tremblay et al., 2018).

2.5.2 Inclusion of dynamic road component in the simulation

The results indicate that changes in management strategies alone do not change the average RPOC without the simultaneous reclamation of roads. When a plot receives an extensive silvicultural treatment (such as selection or shelterwood cutting) to conserve forest structure, it simultaneously faces a high road effect penalty due to its new proximity to the road. Because the distance to roads is a dominant variable in the RSF model with a high positive decay coefficient (β = 2.8982, Annex I), the reduction in the RPOC driven by road proximity often dominates the smaller increase due to extensive treatments. Consequently, the RPOC stays limited in recently harvested plots until the road removal is assumed after a 20-year restoration lag. The sharp increase in RPOC followed by stabilizing trend in the 50% and 100% road removal scenarios is governed by this road reclamation dynamics based on the hypothesis that it takes 20 years for the effect of a road effect to disappear.

While the physical footprint of road induces direct habitat loss, the functional loss is larger (Anderson et al., 2002; Yemshanov et al., 2020). In previous studies, higher road densities correlated with lower caribou density. One study reported that road densities higher than 0.6 to 0.9 km/km^2 led to caribou density reductions of

86% (Nellemann and Cameron, 1998). Furthermore, females that efficiently reared calves showed stronger deterrence from high road density in comparison with females that lost their calves to predation (Leclerc et al., 2014). A study on the southern mountain caribou population revealed that roads in the areas neighboring core caribou ranges had more negative influences on caribou abundance when compared to roads within the core range itself (Lochhead et al., 2022): a 1% expansion of road density (buffered by 50 m) in the neighboring areas of the ranges was linked to 42% reduction in caribou abundance. Roads allow predator mobility into caribou ranges and augment the encounter rates with caribou (Dickie et al., 2017; Lesmerises et al., 2012; Mumma et al., 2019; Whittington et al., 2011), efficiently negating the advantages of high-quality forest habitat by diminishing its functional utility linked to predation risk (St-Pierre et al., 2022; Whittington et al., 2011). The combined impact of integrating extensive harvest under road removal supports the idea that habitat quality is an outcome of both stand-level structure and landscape-level connectivity.

2.5.3 RPOC in caribou range and management strata

The RPOC was significantly higher within the caribou range than across the whole study area. This distinction is mainly due to the fact that alternative caribou-oriented scenarios were applied cumulatively within specific sensitive zones. The conservation (CONS) scenario started with the suspension of harvesting in the critical habitat zone (CHZ). In addition, protection scenarios add the application of shelterwood and selection cutting in the predator management (P1) and peripheral habitat (P2) zones. Because most of these zones are nested within the caribou range, management interventions led to retain mature forests, resulting in higher RPOC. Conversely, areas beyond these sensitive strata continued to be managed under business-as-usual (BAU) scenario. This scenario is dominated by clearcutting, which creates a high number of 0–20 year-old cutblocks which are negatively penalized by the RSF. When averaged at

the regional scale, these low RPOC areas negate the gains attained within the caribou range, resulting in a lower overall landscape RPOC. Spatial mapping showed that gains were most visible in the CHZ and PMZ, with the PHZ with limited improvement. This difference is likely due to the existing road infrastructure near to the PHZ outside the caribou range, which lowers the RPOC in contrast to the more interior zones. Furthermore, the northern portion of the caribou range demonstrated lower RPOC than the southern section, a result of proximal existing road networks.

2.5.4 Effect on total harvest volume

BAU scenario has the highest harvesting volumes, as the area for carrying harvesting is the largest, enabling the harvesting sub-model to fulfill close to the user-defined AAC by means of CPRS. In comparison, the CONS scenario showed a drop in wood supply because the critical habitat zone (CHZ) is treated as a conservation area (i.e. no harvesting), reducing the total available area for wood production. Moving to protection strategy 1 (P1) and protection strategy 2 (P2) increases timber harvest relative to CONS because these scenarios allow timber extraction through shelterwood and selection systems in sensitive zones, which may not be used in the CONS scenario. Precisely, SL_P2 produces marginally higher wood production than SL_P1 because it extends the wood production into the peripheral habitat zone (PHZ), providing the ARTEMIS model with a larger wood production stratum to meet the AAC targets. The same is true for SW_P2, which harvests more timber than SW_P1. Despite the slight decrease in harvested volumes, the study shows that harvest levels vary marginally. While intensive wood production was gradually isolated from caribou ranges with the increase in intensity of caribou-oriented management, active management was still conducted across a reduced number of plots outside the caribou range to meet sustainable forest management goals. In all cases, ARTEMIS tried to reach harvest volumes close to the AAC.

On the other hand, the initial standing volumes in the study were higher than the estimates made by the chief forester's office (BFEC, 2021). These differences may be attributed to the fact that a four-year interval exists between the input data utilized in this study and that used to calculate the AAC. Additionally, it may stem from using a 50-year simulation horizon rather than the 150-year horizon used for the estimates made by the chief forester's office. There is a possibility of systematic avoidance of cutting marked trees in PSPs by practitioners during the harvesting operations (Phillips et al., 1998). Moreover, if these plots were harvested less often than the average across the region, the standing volume would be greater than what is observed over the whole region (Phillips et al., 1998). The results also reveal a decreasing trend in standing volume over time. This pattern can be attributed to the harvesting of mature stands without constraints due to availability of abundant initial standing volume.

Empirical study assessing ecosystem-based management (EBM) strategies in eastern Canadian boreal forests showed that simulation of natural disturbance dynamics to promote biodiversity can lower periodic timber supply by 3% to 11% (Dhital et al., 2013), which is comparable to outcomes of current study where reductions varied from 2 to 9%. Other studies forecast that conserving 65% of caribou ranges would decrease softwood timber supply within the range of 7.5% and 14.9% (Yemshanov et al., 2025). Analysis of past trends in northwestern Ontario similarly estimated that caribou habitat retention constraints could decrease the sustainable conifer harvest by nearly 23% across the first rotation due to the deferral of stands past their optimal operable range (Armstrong, 1998). Moreover, analysis of forest management units in the Gaspesie region have shown that adopting caribou recovery plans yields in an immediate 10% decline in AAC (Morin, 2014). On the other hand, optimization model employing graph theory support the idea of the current study that zoning approach can sometimes maintain high levels of caribou habitat (up to 84% of potential) without notably reducing harvesting (Ruppert et al., 2016).

2.5.5 Implementation of an optimal scenario

Our results highlight that the SL_P2 strategy with restoration of all the roads is the most effective approach for balancing RPOC with timber harvesting. Selection cutting is generally applied to stands with an uneven-aged or irregular structure to maintain permanent cover (MRNF, 2013). However, selection cutting may not be necessarily suitable for all stands where partial harvesting is applied. It goes without saying that selection cutting is an accepted silviculture practice in shade-tolerant hardwood stands and its implementation is increasingly being adapted to stands dominated by softwoods or mixed species (MRNF, 2013, 2023b). In stands where the structure is not yet favorable for selection cutting, shelterwood systems may be employed as a transitional strategy (Ligot et al., 2020; Saunders and Arseneault, 2013). Irregular shelterwood is recommended over regular shelterwood to preserve the habitat complexity for caribou. In this study, irregular shelterwood system applied in sensitive wood production zones produced less harvested volume than the selection system, with very little difference in the RPOC in softwood or mixed stands where long-lived species (Spruce, Cedar, Pine, Yellow Birch) are dominant. Irregular systems can be applied to irregular or even-aged stands that have the capacity to be converted into irregular structure (MRNF, 2013, 2023b). Even though extensive silvicultural treatments are better than clearcuts for caribou, they do not quite mirror the characteristics of mature forests (Nadeau Fortin et al., 2016). Therefore, high value caribou habitat should be preserved which is beyond the capacity of the modeling framework used here. In the current study, we tried to mimic this situation by restricting harvest in black spruce–moss (RE2) and black spruce–sphagnum (RE3) potential vegetations. RE2 and RE3 play a part in retaining a forest matrix primarily composed of mature conifers to reduce the predator-prey encounters (MRNF, 2023b).

2.5.6 Limitations and scope

Despite the increase in the RPOC, particularly inside specific management zones, the overall quality of habitat remains poor considering RPOC always remains below 0.5. In a region such as Gaspesie where forest harvesting and road networks are major disturbances (St-Laurent et al., 2022), even small positive shifts in RPOC may carry considerable biological implications for caribou persistence. The relevance of these insights is further made evident by the geographic positioning of the study area, which encloses the periphery of Gaspesie National Park rather than its undisturbed core. Moreover, the results from ARTEMIS coupled with a RSF come with limitations. The current approach is subject to the accuracy of the input forest inventory data used by simulator. While we embedded climate change via the optimistic RCP 2.6 scenarios in the growth models, we did not consider pest outbreaks such as the spruce budworm or extreme climate-related disturbances such as fire, drought and windstorms (Barber et al., 2018; Fortin et al., 2022; Valeria, 2014). Leaving out these disturbances appear to overestimate forest growth and under the uncertainty intrinsic to long-term predictions (Melo et al., 2019). This is why we used a 50-year simulation horizon, which limits the influence of long-term changes in forest structure and their potential impacts on the RPOC. Pertaining to restoration, this study presumed that decommissioned roads would return to forest cover within 20 years. However, this may not signify actual site conditions, as even after two decades, such recovering areas may remain suboptimal in the caribou range. Additionally, the exceptionally high effect recorded for extensive forest management relative to other land cover categories demands careful consideration. While this may present a maternal preference for these sites in the time of calving, the small sample size (n = 2 plots) of 0-20 years old extensive forest treatments in ARTEMIS simulations needs a cautious interpretation of the outcomes.

Future research should explore three key areas. First, spatially explicit economic analysis is required to estimate the cost effectiveness of targeted road removal strategies

relative to the ecological benefits quantified here. Second, while the current study uses a RSF to forecast the RPOC, there is no established connection between habitat quality and actual caribou numbers. Future research is necessary to estimate if the improved habitat quality forecasted by the models actually translates into caribou viability, such as more calves (recruitment) and lessened mortality (survival). Third, characterizing the relationship between climate-induced vegetation shifts and silvicultural treatments will be critical to verify that the forest types simulated by extensive treatments stay resilient under future climate scenarios.

2.6 CONCLUSION

This study reveals that active habitat restoration, particularly combining selection cutting with full road decommissioning in caribou range, is the most efficient strategy for recovering the endangered Atlantic-Gaspesie caribou. While this strategy reduces harvest outputs by 2% to 9%, it can almost triple the RPOC in sensitive zones, stressing the requirement for a paradigm shift in forest management. Applying a functional zoning approach is encouraged to spatially isolate intensive wood production from restoration zones while promoting silvicultural systems that prevent degradation of mature forest features.

The functional zoning approach such as TRIAD zoning devides the forest landscape into three specific areas to jointly achieve distinct economic and conservation objectives. Intensive management zones target maximizing timber yields through intensive forest management practices, which reduces the harvest footprint and offsets for wood supply reductions elsewhere. Conversely, ecological reserves are preserved, and designed to conserve biodiversity, protect ecological processes, and retain landscape connectivity. Between these extremes, extensive management zones serve as a multi-use landscape that manages moderate timber extraction with the conservation of

non-timber values by using ecologically friendly silvicultural practices. Future studies must address the cost-effectiveness of these road dismantling strategies and the caribou population viability to these simulated habitat improvements.

GENERAL CONCLUSION

The findings of this study facilitate a quantitative comparison of caribou-oriented forest management relative to existing forest management scenarios for a critical paradigm shift in the Gaspesie region, shifting from passive conservation to active habitat restoration to assure the habitat recovery of the endangered Atlantic-Gaspesie caribou. By embedding combination of dynamic road metrics and forest growth simulations into resource selection function model, this research highlights that the long-term stability of caribou habitat depends on a dual course of action focusing on both stand-level forest structure and landscape-level connectivity. This study improves a noteworthy limitation in existing literature by modeling road distance effect as a dynamic component rather than static one (St-Laurent et al., 2022). By changing the distance to the closest road after harvesting, this research updated distance of cut blocks from nearest roads and generates a more realistic assessment of impacts of roads on relative probability of caribou occurrence (RPOC) than previous models.

The results present that current business-as-usual (BAU) forest management scenario characterized by intensive clear-cutting is ecologically unsustainable for caribou habitat recovery, causing a gradual decline in the RPOC over a 50-year horizon. Specifically, this study emphasize that road decommissioning is the key force of habitat improvement, presenting an increased significant impact than silvicultural modulations alone. The study distinguishes a clear trade-off : attaining high-quality habitat demands a quantifiable harvest volume loss ranging from 2% to 9% relative to harvest level at BAU scenario. While the modeling shows that regional annual wood supply can exhibit minimal variation if sufficient standing volume exists, there is a gradual decrease in standing volume across all scenarios.

Even under the most effective scenarios, the overall RPOC remains below 0.5, signifying that the landscape remains a challenging environment for caribou persistence.

Despite the simulation outputs recognize the SL_P2 scenario (selection cutting in predator and peripheral zones) at 100% road removal as the optimal alternative scenario for both RPOC and wood supply closely followed by SW_P2. SL_P2 remains the best option even at a 50% removal level. These findings validate the hypothesis that extensive forest management results higher RPOC than even-aged management (BAU) by preserving mature forest structures favorable for caribou.

The relevance of this study for forest management in the Gaspesie region is twofold. First, the efficient ecological conservation of the Atlantic-Gaspesie caribou probably needs a functional zoning approach, aligns with the TRIAD model, where intensive production is spatially separated from the conservation zones (Burton, 1995; Nitschke and Innes, 2005; Seymour and Hunter, 1992). By spatially partitioning intensive wood production from conservation and sensitive zones, managers can target interventions where they are most effective. Second, road removal must be incorporated into caribou recovery plans as an essential operational necessity instead of an auxiliary measure. Although this offers fluctuating net harvest constraints, such a paradigm shift is an ecologically essential requirement for the long-term habitat recovery of this endangered population.

For forest management to have the least impact possible, we recommend combining road removal as main component of operational planning instead of a secondary measure. Complete road decommissioning would be ideal, if not so a range of 50% to 100% road removal is strongly recommended inside caribou ranges to help caribou to survive in Gaspesie region. It is also recommended to employ a functional zoning approach (e.g., TRIAD model) to prioritize caribou-oriented management within sensitive predator and peripheral zones. Besides zoning approach, selection and irregular shelterwood systems should be prioritized in the caribou range. Ultimately, identified declines in timber wood supply must be accepted to increase habitat quality.

Future research should consider these primary areas to optimize the implementation of these strategies. Since the current study did not consider the effect of caribou-oriented management on the cost of timber harvest, economic analysis is needed to estimate the cost-effectiveness of proposed road removal strategies as compared to the ecological gains estimated in this study. We assumed that roads would be restored in 20 years but the effect of this action on caribou response is uncertain. Consequently, empirical verification of restoration studies should evaluate the delayed impacts of disturbance of restoration. While the current study uses a resource selection function (RSF) to forecast the RPOC, there is no established connection between habitat quality and actual caribou numbers. Future research is necessary to estimate if the improved habitat quality forecasted by the models actually translates into caribou viability, such as more calves (recruitment) and lessened caribou mortality (survival). A critical concern is whether extensive treatments (like selection or irregular shelterwood cutting) can retain the particular forest features caribou need as the climate shifts (Girona et al., 2023a). It is also vital that future research explains the linkage between climate-induced shift in forest structure and various silvicultural treatments to verify that extensive treatments are resilient to future climate scenarios. ARTEMIS does not predict extreme climate events such as fires, droughts, and windstorms, but includes an occurrence of spruce budworm outbreak (Melo et al., 2019). Because of this assumption, excluding these large-scale disturbances in long-term simulations using ARTEMIS may result in overestimating forest growth and underestimating the uncertainty coupled with the predictions (Melo et al., 2019). Therefore, subsequent research should also explore the integration of the events like fires, insect outbreaks, and their combined effects with forest managements in simulation framework to understand its impact on caribou habitat quality.

ANNEX I

CARIBOU HABITAT QUALITY INDEX

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We used the relative probability of occurrence of caribou as a proxy of habitat quality, based on Hansen et al. (2001), who studied changes in habitat quality for a caribou population in British Columbia, and on St-Laurent et al. (2022) who studied the impacts of climate change and logging scenarios on caribou habitat in boreal forests of eastern Canada. To do so, we built a use-availability resource selection function (Boyce et al., 2002; Manly et al., 2002) and used the coefficients of the best-supported model to map habitat quality in our study area (see below). The RSF was built with the telemetry GPS locations obtained from adult caribou of the Atlantic-Gaspesie population and collected between 2013 and 2016.

We built our RSF models using GPS locations collected from 43 adult caribou (17 M, 26 F; corresponding to $\sim$ 52% of the population in 2013) proportionally distributed amongst the three groups (i.e., McGerrigle: n = 28, Albert: n = 6, Logan: n = 9). Caribou were captured using a net-gun fired from a helicopter (following Potvin and Breton (1988)), fitted with GPS-Argos telemetry collars (model TGW-4680, Telonics Inc. Mesa, Arizona) and followed for a maximum of 2.5 years. To limit potential negative impacts of disturbances from helicopter activity and associated collaring, animal captures occurred during two sessions of 22 and 21 animals in mid February

2013 and in early March 2014, respectively. Telemetry collars were programmed to acquire locations every 2 or 3 hours depending on the year of capture and collaring. No chemical immobilization was used, and manipulations were carried out using only physical contention. Our capture and manipulation protocols were approved by the Animal Welfare Committee (following the Canadian Council on Animal Care guideline) of the Université du Québec à Rimouski (certificate # CPA-52-13-112) and of the Québec government (Ministère des Forêts, de la Faune et des Parcs, hereafter MFFP; certificate # CPA FAUNE 13-08]. The first 5 days of GPS locations following an animal capture were removed to limit the influence of capture and collaring activities and helicopter flights on caribou behaviour.

A resource selection function (hereafter RSF) is a mixed-effect logistic regression that contrasts used (GPS locations) and available (random points) locations according to the different covariates. Then, the characteristics observed at caribou locations were compared to those of an equal number of random points distributed within the annual home range boundaries or each individual caribou. These home ranges were delineated using a 100% minimum convex polygon (MCP; Mohr, 1947) to increase the contrast between use and availability (Leclerc et al., 2012).

Variables included in the RSF models belong to three groups, i.e. landcover types, topography and linear features (see Table 10). For each caribou and random location, we extracted the landcover type, elevation, slope and Euclidian distance to the nearest road. We used 1:20,000 digital ecoforest maps published by the MFFP and updated every year to account for the disturbances that occurred in the study area. These digital maps have a minimum mapping unit size of 4 ha for forested polygons and of 2 ha for non-forested areas, although the resolution is finer for disturbed areas (0.1 ha). We classified the map polygons into 12 landcover types based on the disturbance type, forest cover type, age or time since disturbance (see Table 10). We used a 1:20,000 digital elevation model (25 $\times$ 25-m cell) to calculate elevation (in km) and slope (in degrees).

Finally, we used the digital forest road maps published by the MFFP to calculate the Euclidian distance to the nearest road (either paved roads used by motorized vehicles and gravel roads destined to forestry activities and used by trucks and ATV vehicles in summer, and by snowmobiles during winter). As we suspected a non-linear behavioural response of caribou to roads, thus, we used a decay function [exp(-α/distance)] to transform the distance measure. We tested a range of α values (50, 100, 250, 500, 1000, 2000) (Carpenter et al., 2010) and compared these transformed variables with the untransformed Euclidian distance using a Bayesian Information Criterion (BIC) model selection approach using only land cover types and the distance to road variable. We then used a α value of 50. Such a transformation is widely used in RSF studies (e.g. Lesmerises et al. 2018; St-Laurent et al. 2022) and allowed us to account for the non-linear response of caribou to road proximity by eroding the effect of roads beyond $\sim$ 500 m and making it almost null $>$ 965 m (for a α value of 50).

We built 8 candidate models representing different combinations of landcover types, slope, elevation and decay distance to roads; in all models, individual ID was considered as a random term to control for inter-individual variability in selection (Duchesne et al., 2010) as well as the non-independence of locations and the unbalanced number of observations per individual (Gillies et al., 2006). Water bodies (and the "other polygons", i.e. all the polygons that do not fall into the landcover categories presented in Table 10) were used as the reference category for all RSF models with a use-availability ratio of 0.95 (i.e. close to the neutral selection threshold). We used the variance inflation factor (VIF) to assess potential multicollinearity problems in our dataset, and found potential problems in models including landcover types and elevation simultaneously (i.e. VIF $>$ 10; Graham, 2003). As the different landcover types are known to be distributed along the elevation gradient in the Gaspé peninsula (Boudreau, 1981), and considering that our modeling framework and research question were based on changes in forest stand composition and structure, we decided to remove elevation from all candidate models, ending with 4 models having all the landcover types with

varying combinations of slope and decay distance to roads (Table 10). We found no multicollinearity problems in these 4 candidate models (VIF < 5.00).

We used BIC to identify the most parsimonious candidate model (Table 10; Burnham and Anderson, 2004) and a k-fold cross-validation (Boyce et al., 2002) to assess its predictive accuracy. We used the location data from 75% of the individuals to generate the RSF model and the remaining 25% for validation. We conducted 30 replicates of the k-fold process and then used a Spearman rank statistic to test for a significant correlation and reported the mean r_s value and its standard deviation. We conducted spatial analyses in ArcGIS 10 (ESRI, 2019) and statistical analyses in R v. 4.1.2 (R Core Team, 2021; glmer package for RSF).

The most parsimonious RSF model was the one including landcover types, slope and the decay distance to the nearest road (Table 10); the robustness of this model was high, with a r_s of 0.95 ($\pm$ 0.01) following the k-fold cross validation (Table 12). None of the other three candidate models performed in comparison with the most parsimonious model (ΔBIC > 2253.8; Table 10). According to this model, caribou were selecting the alpine tundra and bare areas, the 0-20 years old extensive forest treatments and the steeper slopes, while avoiding the mature and the immature coniferous forest stands, the mature and the immature mixedwood stands, the hardwood forests, the 0-20 years cutblocks and natural disturbances and the proximity of roads (Table 12).

Finally, we mapped the most parsimonious RSF model at the pixel (250×250-m cell) level and standardized the outputs so that a value of 0 meant that the relative probability of occurrence of a pixel was nil (i.e., a random location, referring to a very low habitat quality), while 1 referred to the maximal value of relative probability of occurrence (i.e., a caribou GPS location, referring to a very high habitat quality).

Table 10. Landcover types, topography variables and linear features considered in the different candidate models of resource selection functions used to evaluate habitat selection patterns of the 41 Atlantic-Gaspésie caribou monitored between 2013 and 2016

Variables	**Description**
Landcover types	
Alpine tundra and bare areas	Dry barren area covered by krumholtz and alpine vegetation, usually >700 m
Mature coniferous forests	Stands dominated by coniferous species of $\geq$ 50 years-old
Immature coniferous forests	Stands dominated by coniferous species of 20 to 50 years-old
Mature mixedwood forests	Stands co-dominated by coniferous and hardwood species of $\geq$ 50 year-old
Immature mixedwood forests	Stands co-dominated by coniferous and hardwood species of 20 to 50 years-old
Hardwood forests	Stands dominated by hardwood species of $\geq$ 20 year-old
0-20 years old cutblocks	Cutblocks originating from intensive silvicultural treatments of $\leq$ 20 years-old
0-20 years old extensive forest treatments	Cutblocks originating from extensive silvicultural treatments $\leq$ 20 years-old
0-20 years old natural disturbances	Stands impacted by natural disturbances of $\leq$ 20 years-old
Water bodies	Lakes and large rivers and streams
Other polygons	All the polygons that do not fall into the landcover categories presented above
Topography	
Elevation	Elevation (in km)
Slope	Slope (in degrees/10)
Linear features	
Roads (decay distance $\alpha = 50$)	Paved roads used by motorized vehicles and gravel roads destined to forestry activities and used by trucks and ATV vehicles (in summer) and by snowmobiles (during winter). Transformed as a decay distance (Carpenter et al. 2010).

Table 11. Candidate models considered in the model selection exercise aiming at characterizing habitat selection patterns of 41 Atlantic-Gaspésie caribou between 2013 and 2016 in Québec, Canada. Each group of variables is described in Table 10

Model #	**Groups of variables**	k	**Δ BIC**
1	Land cover types	9	7274.0
2*	Land cover types + Elevation	10	—
3	Land cover types + Slope	10	4747.2
4*	Land cover types + Elevation + Slope	11	—
5	Land cover types + Roads	10	2253.8
6*	Land cover types + Elevation + Roads	11	—
7	Land cover types + Slope + Roads	11	0.0
8*	Land cover types + Elevation + Slope + Roads	12	—

* Models marked with an asterisk and in shaded gray were experiencing multicollinearity issues and had to be removed from the list of candidate models.

Table 12. Coefficients (β) and 95% confidence interval (95% CI) [lower bound: upper bound] of the most parsimonious model describing habitat selection patterns of caribou based on the telemetry monitoring of 41 caribou between 2013 and 2016. Coefficients for which the 95% CI did not overlap zero are considered to have a significant influence on caribou behaviour. Results of the k-fold cross validation (Spearman correlation coefficient, $r_s \pm$ SD) are presented

Variables	$\boldsymbol{\beta}$	**95% CI**
Intercept	−2.572	[−2.758 : −2.386]
Landcover types[1]		
Alpine tundra and bare areas	2.489	[2.431 : 2.547]
Mature coniferous forests	−0.762	[−0.814 : −0.710]
Immature coniferous forests	−1.509	[−1.568 : −1.450]
Mature mixedwood forests	−1.889	[−1.949 : −1.829]
Immature mixedwood forests	−1.983	[−2.046 : −1.921]
Hardwood forests	−2.643	[−2.727 : −2.560]
0–20 years old cutblocks	−3.044	[−3.112 : −2.976]
0–20 years old extensive forest treatments	2.444	[2.269 : 2.619]
0–20 years old natural disturbances	−1.542	[−1.614 : −1.471]
Topography		
Slope (in degrees/10)	0.137	[0.131 : 0.143]
Linear structures		
Roads[2]	2.898	[2.800 : 2.996]
k-fold cross validation		
r_s ($\pm$ SD)		0.95 ($\pm$0.01)

[1] Water bodies and "other polygons" (composed of all polygons not in Table 10) were the reference category for all RSF models.

[2] Nearest-neighbour distance to a road was transformed using a decay function with $\alpha = 50$.

ANNEX II

LAND USE AND HABITAT CLASSIFICATION

Table 13. Rules for assigning cover types (Conifer, Mixed wood, Broadleaf) from simulated basal area by species group

Canopy cover types	**Description**
Conifer	Conifer constitutes $> 75\%$ of basal area of plot
Mixedwood	Conifer constitutes $\geq 25\%$ and $\leq 75\%$ of basal area of plot
Broadleaf	Conifer constitutes $< 25\%$ of basal area of plot

Table 14. Topography variables and linear features used in previously defined resource selection function

Variables	**Description**
Topography	
Elevation	Elevation (in m)
Slope	Slope (in degrees/10)
Linear features	
Roads (decay distance $\alpha = 50$)	Paved roads utilized by motorized vehicles and gravel roads destined to forestry activities and used by trucks and ATV vehicles (in summer) and by snowmobiles (during winter). Transformed as a decay distance (Carpenter et al., 2010).

Table 15. Land use category classification used in simulations, adapted from Ecoforest management maps

Layer	Description	Zone	Source
Ecoforest Map	Water bodies (major lakes, rivers and reservoirs) Alder forest Environment heavily disturbed by human activity (non-wooded) Flooded site, unregenerated flooded site Road and highway (right-of-way) Bare and semi-stripped humid area Bare and semi-stripped dry area Gravel pits Transmission line Forest camp Environment little disturbed by human activity (wooded) Unharvestable inclusion within a silvicultural treatment	Unproductive	https://www.foretouverte.gouv.qc.ca/
Ecoforest Map	Photo-interpreted Island < 250 ha Slope $> 40\%$ Slope $> 60\%$	Inaccessible	https://www.foretouverte.gouv.qc.ca
Protected area	Exceptional forest ecosystem Wildlife habitat Biological refuge Ecological reserve Reserved territory Biodiversity reserve Reserve territory for protected area purposes Quebec National Park Natural environment of voluntary conservation Recognized nature reserve	Conservation	https://open.canada.ca/data/en/dataset/f0250998-eac1-46a8-8e0c-d7278ae85506
Ecoforest Map	Area of Ecoforest Map that does not fall into Unproductive, Conservation and Inaccessible	—	Wood Production

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