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CLIMATE CHANGE, CARIBOU PROTECTION AND CANADA'S TIMBER SUPPLY

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ABSTRACT

Managed forests are a significant contributor to Canada's economic wealth. However, forestry activities increase landscape fragmentation and impact wildlife species, such as Canada's woodland caribou, that depend on large areas of undisturbed habitat. Proposed conservation policies for caribou in Canada aim to retain 65% or more of caribou ranges as undisturbed landscapes which would help achieve a 60% likelihood of self-sufficiency of caribou populations. This level of habitat protection may require moving some forest areas out of industrial forestry use and into habitat protection. We have assessed the extent to which this level of range protection would affect timber supply to forest mills in Canada at present-day harvest levels. For the six largest Canadian provinces (British Columbia, Alberta, Saskatchewan, Manitoba, Ontario and Quebec), we solved an optimization problem that allocated harvest sites across the industrial forestry zone to forest mills at present-day harvest levels with and without caribou conservation and under present and future climate conditions. Retaining 65% of each caribou range area under protection generated moderate timber supply reductions in Quebec and Alberta, with smaller reductions in British Columbia. Sensitivity analyses revealed modest timber supply shortages in Ontario, Saskatchewan and Manitoba at range retention levels as high as 75-80%. The estimated timber supply shortages from implementing caribou conservation measures were similar to, or smaller than, those resulting from climate change.

Keywords: Canada; Climate change; Forest mill timber supply; Habitat connectivity model; Harvest scheduling model I; Linear programming; Timber supply; Woodland caribou.

INTRODUCTION

Managed forests are a critical source of fibre and a significant contributor to Canada's economic wealth, providing 1.25% of Canada's GDP (NRCan, 2023) as well as a suite of ecosystem services (Taye et al. 2021). Legislative measures, such as Species-At-Risk Act (SARA, 2002), provincial forest management guidelines (OMNR, 2009; MFFP, 2022; GoA, 2023) and biodiversity stewardship programs (OMECP, 2023) aim to protect key services that forest ecosystems provide in regions with industrial forestry activities. Sustaining fibre supply while achieving ecosystem conservation objectives is a complex trade-off (Carpenter et al., 2017; Strengbom et al., 2017; Yemshanov et al., 2020; Eggers et al., 2022) because industrial forestry activities may overlap with critical habitat requirements for forest dwelling species, especially those associated with old-growth forests (Cadieux et al., 2023; Martin et al., 2023). A quantitative understanding of the trade-offs between the implementation of broad-scale biological conservation measures and the continued capacity of forests to provide timber supply is fundamental to the sustainable management of forest resources. The assessment of how climate change and conservation policies may impact the national timber supply is critical for an understanding of Canada's capacity to remain a major global exporter of wood products to international markets.

Maintaining large intact forest landscapes is critical for attaining biological conservation goals, such as protecting critical habitat or protecting wildlife movement corridors (FSC, 2020; Venier et al., 2018; 2022). This can be achieved by excluding human activities in areas large enough to maintain viable populations of all native biological diversity in a given region (Potapov et al., 2008, 2017). In particular, the boreal population of the woodland caribou (*Rangifer tarandus caribou*) is one of the most demanding boreal species in terms of the minimum area of undisturbed forest required to support viable populations, with existing ranges often exceeding 10000 km^2 (EC, 2011; 2012). As such, the undisturbed forest landscape requirement for caribou is considered an important umbrella conservation target for other species in boreal forests (Bichet et al., 2016; NRCan, 2018; Micheletti et al., 2023; Labadie et al., 2024).

In Canada, forestry and resource extraction activities have been shown to negatively impact woodland caribou populations. Industrial forestry activities create a pattern of harvested sites and access roads that increases forest fragmentation (EC 2012; ECCC 2017; 2020). Harvested landscapes, which often feature abundant early successional plant growth, attract deer and moose, which in turn attract predators. The resulting increase in predation pressure on caribou, coupled with their low reproductive rate, ultimately leads to local caribou decline (Whittington et al., 2011; McKenzie et al., 2012; Dickie et al., 2017). Since 2003, woodland caribou is considered a threatened species in Canada (SARA, 2002) and its declining numbers present a serious conservation management issue (Hebblewhite and Fortin, 2017).

Research has shown that a caribou population has a 60% likelihood of being self-sustaining in a range that contains at least 65% of its area that has not been affected by stand-replacing human disturbances (such as clearcuts and seismic line or road construction), and associated non-habitat elements, such as bogs and rock outcrops (EC, 2012). This 65% habitat protection rule has been considered in many guidelines designed to maintain the viability of caribou populations (EC, 2012; ERO, 2022; GoA, 2017). Areas managed for caribou protection are expected to experience only natural disturbances such as wildfires or native insect outbreaks. Ongoing climate change is expected to increase the area burned and alter pest outbreak regimes (Boulanger et al., 2013; Price et al., 2013; Venier et al., 2014), and therefore effective conservation planning must also account for the pace of changes in the occurrence and severity of such events, including increased efforts for their prevention and mitigation.

In Canada, known ranges of many woodland caribou populations overlap with industrial forestry activities (Fig. 1). There is therefore a trade-off between the maintenance of present-day harvesting levels and the achievement of range-level caribou conservation targets (Ruppert et al., 2016; Felton et al., 2017; Yemshanov et al., 2020). This trade-off can be examined with timber supply models, which identify a forest management strategy over a long-term planning horizon that maximizes timber harvest (or other economic objectives) while respecting sustainable forest management and biological conservation objectives (Bureau du Forestier en Chef, 2013). At regional scales, projections of timber supply have typically been made using linear programming models (Johnson and Scheurman, 1977; McDill et al., 2002; 2016) and have often incorporated conservation management objectives (Carvajal et al., 2013; St. John et al., 2016; Martin et al., 2017).

At broad scales, timber supply problems have generally been considered too complex to be solved using linear programming because the spatial constraints framing the harvest decisions forced the use of binary decision variables, which made the large-scale timber supply problem intractable. In a recent national-level assessment, McKenney et al. (2016) used a stochastic simulation model to assess the impacts of climate change, as represented by an increase in wildfire frequencies and changes in tree growth rates, on timber availability and mill gate prices across Canada. Their model predicted the occurrence of wildfires using a stochastic simulation model and applied heuristic, annual horizon harvesting decisions to meet the timber demands of forest mills. Other large-scale assessments included the analysis of timber supply vulnerability to changes in fire frequencies driven by climate changes in eastern Canada (Gauthier et al., 2015a,b; Bernier et al., 2016; St-Laurent et al., 2022), the assessment of timber supply and endangered species habitat for Alberta’s green zone (Hauer et al., 2010), a timber supply review for British Columbia (Fletcher, 2023), a non-spatial overview of timber supply in Canada (Runyon, 1990) and the assessment of future harvest rates in Quebec under climate change scenarios (Bureau du Forestier en Chef, 2021).

In this study we assess the potential impacts of the adoption of broad-scale caribou range protection measures on the capacity of Canadian forests to sustain the present-day levels of fibre supply to forest mills and wood processing facilities under present and future climate conditions. This was achieved by solving a linear programming (LP) harvest planning problem that apportions the harvested fibre over a long-term planning horizon to a set of forest mills located across the six largest Canadian provinces. We solved the LP problem with and without accounting for future changes in wildfire frequences and tree growth rates due to climate change and with and without the adoption of caribou protection measures which aim to protect 65% of each caribou range area from human disturbances and would require the removal of contiguous portions of the forest area from the harvestable land base. We further examined two higher levels of caribou range protection (75 and 80%), to explore the potential for higher conservation targets in certain provinces.

MATERIAL AND METHODS

Analytical framework

We formulated the harvest scheduling problem to find the supply of harvested timber to a set of forest mills located across a large forest landscape. For each planning period, each mill that received fibre from the harvested sites in the surrounding area was characterized by its demand level for softwood and hardwood timber. To ensure the sustainability of harvesting, we solved the harvest planning problem for a 100-year time horizon with forest management constraints to help maintain the minimum forest age, prevent overharvesting and ensure even flow of harvested fibre to forest mills over time. We established the baseline scenarios by solving the timber supply problem without considering the impact of caribou protection policies on forestry activities.

Many caribou ranges overlap with the industrial forestry zone (IFZ). For each province, the IFZ delineates the area where commercial forest management activities occur. For each caribou range that overlapped the IFZ by more than 35%, we have delineated the range area portions that would need protection to ensure that 65% of the range area remains undisturbed by humans. For example, if 50% of a caribou range overlaps the IFZ, achieving the 65% protection target would require the protection of an additional 15% of the range that overlaps the IFZ. Since the range-level protection target included all landcover classes in the range area, including the associated non-habitat landcover types (EC 2012), we estimated the protection target as 65% of the total range area.

To delineate the caribou range portion that would be removed from the IFZ to achieve the range-level protection target, we solved, for each caribou range, a reserve selection problem that delineates a connected forest area within the range with the lowest human footprint for habitat protection (Yemshanov et al., 2023). We then solved the timber supply problem in the caribou protection scenario using the resulting reduced IFZ area.

We compared the baseline scenario without caribou protection with the caribou protection scenario for two groups of climate pathways, one using the present-day climatic conditions, and one using the climate change scenario based on the CanESM2 GCM (Chyleck et al., 2011) with Representative Concentration Pathway (RCP) 8.5 emissions projections (Van Vuuren et al., 2011) over the next 100 years. The RCP 8.5 scenario represents the highest level of potential future climate changes, while the current climate conditions form the lowest level of this range. Together, they establish a wide range of possible climate pathways. Under the RCP 8.5 scenario, radiative forcing is assumed to reach 8.5 W-m^{-2} by 2100, with a 6-8°C increase in mean annual temperature and 10-25% increase in precipitation compared to year 2000 in Canada. Our climate change projections included the estimates of future changes in wildfire activity over the period between 2020 and 2100 based on Boulanger et al. (2014) with the corresponding impacts on harvestable forest area, and the adjustments of tree growth and yield estimates based on changes in net primary productivity (see Supplements S1, S2).

A harvest planning model

Our timber supply model was based on the harvest scheduling problem I (Johnson and Scheurman,1977; McDill et al., 2016; Martin et al.,2017) which is the simplest formulation of the harvest planning problem that has been adopted in forest management and forest policy analyses by federal, provincial and industry groups. The model finds the optimal harvesting plan for the landscape N of potentially harvestable patches n, $n \in N$ over a horizon of T planning periods, $t=1,\ldots,|T|$, where $|T|$ is a cardinality of set T. A forest stand could be harvested after it reached a minimum harvest age τ years or older. For each patch n, the model considers a set of possible management prescriptions in n, I, $i = 1,\ldots,|I|$ where each prescription depicts a sequence of silvicultural events over T periods including a no-harvest scenario. For each patch n, the model selects prescription i to maximize the objective, subject to the constraints in the forest management plan. To reduce the numeric problem complexity, we formulated the timber supply model as an LP problem without binary decision variables.

We only considered clear-cut harvest, which is the most impactful harvest activity for caribou populations and most common harvest type in Canada (NFD, 2019). To simplify the forest management problem, we assumed that forest stands in each patch n in planning period t were characterized by a single age and tree species composition. Patch n is characterized by forest area a_{nt} that includes recently harvested forest sites but excludes permanent disturbances and non-forested land. Since climate change could change the forest area available for harvest over time, we assumed that the effective forest area a_{nt} in patch n to decrease over time t due to more frequent fires driven by future climate change (Boulanger et al., 2014). A continuous decision variable x_{ni}, $x_{ni} \in [0;1]$ designates the portion of patch n to silvicultural prescription i over planning horizon T. Each patch n in prescription i in period t is characterized by the volume of harvested softwood and hardwood timber, V_{1nit} and V_{2nit}, forest stand age, E_{nit} and the net cash flows from delivering the harvested softwood (or hardwood) timber from site n to forest mill s, R_{1nits} and R_{2nits}. Here and below, subscripts 1 and 2 denote softwood and hardwood timber. The net cash flow accounts for the timber hauling cost differences based on the distance between the harvested patch n and mill s, i.e.:

$$R_{1nits} = a_{nt}V_{1nit}(c_{1\text{mill}} - \lambda_1 - c_{ns}) \quad \text{and} \quad R_{2nits} = a_{nt}V_{2nit}(c_{2\text{mill}} - \lambda_2 - c_{ns}) \qquad [1],$$

where λ_1 and λ_2 are the harvest unit costs and $c_{1\text{ mill}}$ and $c_{2\text{ mill}}$ are the mill gate prices for a unit of delivered softwood and hardwood timber, and c_{ns} is a distance-dependent timber hauling unit cost from patch n to mill s.

We assumed that timber harvested in period t is delivered to a large set S of forest mills s (local markets) located in landscape N and added to our harvesting problem the subproblem that apportions the timber harvested in patch n in period t to one or more mills s located in area N. We tracked the delivery of harvested timber at the level of softwood and hardwood species groups to two sets of mills in area N, S_1 and S_2 which receive softwood or hardwood timber. We used the geographical locations of mills s to calculate the distance-dependent timber hauling costs from patches n, c_{ns}.

Each mill s was characterized by the demand levels for softwood and hardwood timber per planning period t, D_{1s} and D_{2s}. Timber harvested in patch n in period t could be delivered to more than one mill. Continuous decision variables d_{1nits} and d_{2nits}, $d_{1nits}, d_{2nits} \in [0;1]$ tracked the proportions of timber harvested in patch n in prescription i in period t that was delivered to mill s. The delivery of softwood and hardwood timber in period t was tracked separately to processing mills S_1 and S_2.

For each mill s, we assumed a steady fibre demand over time and imposed a requirement to maintain even fibre flow over consecutive planning periods t and t+1 within the proportion $1 \pm \varepsilon$. To prevent overharvesting, we imposed the minimum limit on the average age of forest stands in area

N at the end of the planning horizon T, $E_{T\mathrm{min}}$, and precomputed the forest stand age in a patch n at the end of the planning horizon, E_{ni} for all possible prescriptions $i \in I$.

In some scenarios, the harvest across the landscape could not provide sufficient fibre supply to fulfill the demands of all mills, causing some mills to experience timber supply shortages. To keep the problem feasible in such a case, we assumed that the missing demand would be supplied from elsewhere at a cost that exceeds the highest local tree-to-millgate delivery cost. We introduced the non-negative penalty decision variables, P_{1st} and P_{2st}, that become positive when the total supply of softwood (or hardwood) timber to mill s in period t drops below the mill's demand level D_{1s} (or D_{2s}) thereby indicating the timber supply shortage at mill s in period t.

We have formulated the objective function [2] in our timber supply problem as maximizing the net discounted cash flow from harvesting timber in area N and delivering it to a set forest mills according to mill demands over $|T|$ planning periods. Since the objective function is maximized we have added the subtraction of timber supply shortage penalties P_{1st} and P_{2st} that creates negative feedback when timber supply shortages occur in the area in period t, i.e.:

$$\max \sum_{n\in N}\sum_{i\in I}\sum_{t\in T}\left(\sum_{s\in S_1} R_{1nits} d_{1nits} + \sum_{s\in S_1} R_{2nits} d_{2nits}\right) r - f\sum_{t\in T}\sum_{s\in S}(P_{1st}+P_{2st})r \qquad [2]$$

s.t.:

$$\sum_{i\in I} x_{ni} = 1 \quad \forall \quad n \in N \qquad [3]$$

$$\sum_{i\in I} x_{ni} \sum_{t\in T}(V_{1nit}+V_{2nit}) = 0 \quad \forall\, n \in N_{\mathrm{hab}} \qquad [4]$$

$$\sum_{n\in N}\left(\sum_{i\in I}\left[(E_{ni}-E_{|T|\mathrm{min}})a_{n|T|}x_{ni}\right]\right) \geq 0 \qquad [5]$$

$$(1-\varepsilon)\sum_{i\in I}\left(a_{nt}\sum_{t\in T}V_{1nit}d_{1nits}\right) \leq \sum_{i\in I}\left(a_{n(t+1)}\sum_{t\in T}V_{1ni(t+1)}d_{1ni(t+1)s}\right) \leq (1+\varepsilon)\sum_{i\in I}\left(a_{nt}\sum_{t\in T}V_{1nit}d_{1nits}\right) \forall\, s \in S_1, t \in [1,\ldots,|T|-1] \qquad [6]$$

$$(1-\varepsilon)\sum_{i\in I}\left(a_{nt}\sum_{t\in T}V_{2nit}d_{2nits}\right)\leq\sum_{i\in I}\left(a_{n(t+1)}\sum_{t\in T}V_{2ni(t+1)}d_{2ni(t+1)s}\right)\leq(1+\varepsilon)\sum_{i\in I}\left(a_{nt}\sum_{t\in T}V_{2nit}d_{2nits}\right)\ \forall\ s\in S_2, t\in[1,\ldots,|T|-1]$$

[7]

$$\sum_{s\in S_1}d_{1nits}=x_{ni}\quad\forall\quad n\in N, i\in I, t\in T\,|\,V_{1nit}>0$$ [8]

$$\sum_{s\in S_2}d_{2nits}=x_{ni}\quad\forall\quad n\in N, i\in I, t\in T\,|\,V_{2nit}>0$$ [9]

$$D_{1s}\leq\sum_{i\in I}\sum_{n\in N}\left(a_{nt}\sum_{t\in T}V_{1nit}d_{1nits}\right)+P_{1st}\leq D_{1s}(1+\varepsilon_{\text{mill}})\ \forall\ s\in S_1, t\in T$$ [10]

$$D_{2s}\leq\sum_{i\in I}\sum_{n\in N}\left(a_{nt}\sum_{t\in T}V_{2nit}d_{2nits}\right)+P_{2st}\leq D_{2s}(1+\varepsilon_{\text{mill}})\ \forall\ s\in S_2, t\in T$$ [11]

$$\sum_{n\in N}\sum_{i\in I}\zeta_{nit}x_{ni}\leq\zeta_{\max}\quad\forall\quad t\in T$$ [12].

The first term in the objective function equation [2] maximized the net discounted cash flow from harvesting area N and delivering fibre to forest mills over planning horizon $|T|$. Symbol r denoted the social discounting rate for planning period t. The second term of Eq. [2] denoted the sum of penalty decision variables P_{1st} and P_{2st} associated with timber supply shortages to hardwood and softwood mills S_1 and S_2 over $|T|$ periods. Symbol f denoted the importance factor for the penalty term. Table 1 lists the model symbolic notation.

Constraint [3] forced the sum of the area proportions with distinct harvest prescriptions i assigned to patch n is equal to one. Constraint [4] prevented harvesting of patches designated for habitat protection in caribou scenarios which are defined by the subset N_{hab}, $N_{\text{hab}}\in N$. Constraint [5] prevented overharvesting of the area N by forcing the average age of forest stands in area N at the end of the planning horizon $t=|T|$ to be equal or greater than the target forest age $E_{|T|\min}$. Constraints [6] and [7] ensured, for each forest mill s, a steady flow of delivered harvested softwood and hardwood timber over consecutive planning periods t and t+1 within the range $1\pm\varepsilon$. When the amount of harvested timber in area N was insufficient to satisfy the demands of all forest mills in period t, constraints [6] and [7] prevented the abrupt drops of timber supply to individual mills and forced the timber supply decline rate to 1-ε between periods t and t+1.

Constraints [8] and [9] linked the harvest prescription selection variable x_{ni} and the site-to-mill timber delivery variables d_{1nits} and d_{2nits} and ensured that the sum of proportions of softwood (or hardwood) timber harvested in patch n in prescription i in period t is equal to the sum of fibre proportions delivered from patch n to the forest mills s in the area (so all harvested timber must be delivered to mills). Equations [8] and [9] provided the link between the prescription selection variable x_{ni} from the harvest scheduling problem and the decision variables d_{1nits} and d_{2nits} that apportioned the harvested timber to softwood and hardwood mills S_1 and S_2 according to their demand levels D_{1s} and D_{2s}.

Constraints [10] and [11] enforced the full delivery of harvested timber to a set of hardwood and softwood mills S_1 and S_2. The first term with summations in equations [10] and [11] defined the total volume of softwood (or hardwood) timber harvested in area N in period t and delivered to mill s. The second term is the penalty decision variable (P_{1st} or P_{2st}) that indicates the shortage of timber delivery to mill s in period t. The total volume of delivered timber from the harvested patches, plus the shortage penalty must stay within the mill's demand range [D_{1s}; $D_{1s}+\varepsilon_{\mathrm{mill}}$] for softwoods and within [D_{2s}; $D_{2s}+\varepsilon_{\mathrm{mill}}$] for hardwoods, where $\varepsilon_{\mathrm{mill}}$ is a small rounding error (0.001). Because the penalty decision variables P_{1st} and P_{2st} were assigned the minus sign in the objective equation [2] (which is maximized), constraints [10] and [11], in conjunction with objective [2] forced the penalty values to become positive only if the supply of harvested timber was insufficient to satisfy the mill demand levels D_{1s} and D_{2s}.

Constraint [12] limited the maximum area of young stands ($\leq$40 years old) in period t by the target level $\zeta_{\max}$, which, together with constraint [5] prevented overharvesting the area and helped retain a sufficient area of mature forest over timespan $|T|$. The target value $\zeta_{\max}$ was set close to the current proportion of young stands in the area.

Protected habitat selection model

Protecting a portion of a caribou range that overlaps the IFZ requires the deferral of all activities which create human disturbances, so caribou can travel and avoid predators. In our timber supply problem [2-12], we defined the IFZ portion designated for protection by subset N_{hab}. The protected forest patches need to be connected to facilitate the unrestricted movement of animals. The remaining unprotected portion of the caribou range in the IFZ must also remain contiguous to ensure that all harvestable sites remain accessible.

For each range that overlapped the IFZ by more than 35%, we delineated the protected IFZ portions using the network flow habitat zoning model of Yemshanov et al. (2023). This model depicted a forest landscape as a connected network of landscape compartments j. Each compartment j can be designated for habitat protection and was characterized by the extent of anthropogenic disturbances – the human footprint value. We used an additive inverse of the human footprint value to characterize the suitability of compartment j to support caribou populations, B_j, so the compartments with the lowest human footprint received the highest B_j values. To ensure the spatial separation of caribou individuals from predators, the compartment size was set at 6000 ha, which is compatible with the distances covered by the animals in a day (Rettie and Messier, 2001; Rempel and Hornseth, 2018).

For each caribou range that overlapped the IFZ, we estimated the contiguous range portion that would need to be removed from the IFZ to achieve the 65% range protection target. We depicted all adjacent compartments j and k, between which caribou movements were possible, as connected by arcs ik and jk (Fig. 2a). To maintain the contiguity of the protected range area, each protected compartment needed to be connected to another adjacent protected compartment. The connectivity between the adjacent compartments was achieved by enforcing the flow through the arcs connecting the *protected* compartments (Fig.2a, bold red line). A flow is injected into one protected compartment, and every other protected compartment must receive the flow from one of the adjacent protected compartments, which guarantees that all protected compartments remain connected. Controlling the network flow between the protected compartments also helped prevent the selection of isolated protected compartments surrounded by harvestable area. Below we describe the habitat selection model based on the contiguous reserve approach of Jafari and Hearne (2013).

We controlled the flow between adjacent protected compartments k and j with two decision variables. A binary variable w_{kj} served as an indicator that flow can pass through arc kj between adjacent compartments k and j if both are selected for protection. For the same arc kj, a non-negative variable y_{kj} defined the amount of flow through arc kj. To inject the flow into the network of protected compartments, we added an auxiliary Node 0 that was the source of the flow to the set of connected compartments selected for protection, J_{hab} (Fig. 2a). Node 0 was connected to all compartments j in the habitat network by directional arcs $0j$ which could be used to inject flow from Node 0 to any compartment selected for protection. To allocate the protected compartments as a contiguous area, the flow injection from Node 0 to compartments j was limited to one arc $0j$ only. To track the number of compartments selected for protection, we added the constraint that each protected compartment can receive the flow from at most one other protected compartment (or from Node 0), so the number of incoming arcs kj connected to the protected compartments j was equal to the number of protected connected compartments (Fig. 2a).

Similarly, all compartments in the harvestable portion of the caribou range, J_{mgmt} must remain accessible from the locations with human infrastructure. This required maintaining the spatial connectivity of the harvestable area J_{mgmt}. We formulated the subproblem that enforces the connectivity of the harvestable portion of the range analogously to the habitat selection subproblem. The binary variable v_{kj} defined the connectivity between adjacent compartments k and j in the harvestable zone J_{mgmt} and the non-negative variable z_{kj} characterized the amount of flow through arc kj. The forest management and the protection zones did not overlap except at Node 0.

The delineation of the protected caribou range portions in the IFZ included two sets of network flow constraints to enforce the connectivity of both the protected and the management zones (Fig. 2b). Our habitat selection problem allocated the protection and forest management zones to maximize the protected area with the lowest human footprint (depicted as highest suitability B_j), subject to contiguity constraints in the protected and harvestable zones and the target range area portion δ designated for protection, i.e.:

$$\max \sum_{j \in J} \sum_{k \in Q_j} (w_{kj} B_j A_j) \qquad [13]$$

s.t.:

$$\sum_{k \in Q_j} y_{kj} - \sum_{k \in Q_j^+} y_{jk} = \sum_{k \in Q_j} w_{kj} \quad \text{and} \quad \sum_{k \in Q_j} z_{kj} - \sum_{k \in Q_j^+} z_{jk} = \sum_{k \in Q_j} v_{kj} \quad \forall \ j \in J \qquad [14]$$

$$y_{kj} \le M w_{kj} \quad \text{and} \quad z_{kj} \le M v_{kj} \quad \forall \ j \in J, k \in Q_j \qquad [15]$$

$$w_{kj} \le y_{kj} \quad \text{and} \quad v_{kj} \le z_{kj} \quad \forall \ j \in J, k \in Q_j \qquad [16]$$

$$\sum_{k \in Q_j} w_{kj} \le 1 \quad \text{and} \quad \sum_{k \in Q_j} v_{kj} \le 1 \quad \forall \ j \in J \qquad [17]$$

$$\sum_{j \in J} w_{0j} = 1 \quad \text{and} \quad \sum_{j \in J} v_{0j} = 1 \qquad [18]$$

$$\sum_{k \in Q_j} v_{kj} + \sum_{k \in Q_j} w_{kj} = 1 \quad \forall \ j \in J \qquad [19]$$

$$\sum_{k \in Q_j} v_{kj} \geq \Psi_j \quad \forall \quad j \in J \qquad [20]$$

$$\delta \sum_{j \in J} A_j \leq \sum_{j \in J} \sum_{k \in Q_j} (w_{kj} A_j) \leq \ (1+\varepsilon_{\text{hab}}) \delta \sum_{j \in J} A_j \qquad [21].$$

Objective [13] maximized the total amount of suitable habitat in the area selected for protection. Table 2 lists the symbolic notations. Equations in constraint [14] described the flow balance through compartment *j* in the selected harvestable and the protected zones. Set Q_j in Eq. [14] defined the compartments *k* (or auxiliary Node 0) that were adjacent to compartment *j* and connected by arcs *kj* and could transmit incoming flow from *k* to *j*, and set Q_j^+ defined adjacent compartments *k* that were connected to compartment *j* by arcs *jk* and could receive outgoing flow from *j*. The first equation in [14] enforced the amount of incoming flow to compartment *j* that was selected for protection to be equal to the amount of outgoing flow from *j* to other protected compartment, plus one unit of flow (which indicated the selection of compartment *j* for habitat protection). The second equation in [14] is an analogous flow balance constraint for a compartment *j* that remains in the harvestable zone.

Constraints [15] and [16] ensured the agreement between the amounts of flow through arc *kj* between adjacent compartments *k* and *j* in the harvestable and the protected zones and the corresponding arc selection binary decision variables w_{kj} and v_{kj}. Constraint [17] ensured that the flow to selected compartments *j* in the harvestable (or habitat protection) zones comes from at most one source which prevents cycles and enables tracking the size of the allocated zones by counting the number of connecting arcs with flow. Constraint [18] implies that the flow to the subnetworks of connected compartments *j* in the protected or harvestable zones comes from Node 0 through one arc only, which ensured that each zone remains a connected region. Constraint [19] specified that compartment *j* can only be a member of either the protected or the harvestable zone, but not of both. Constraint [20] ensured that the harvestable zone must include compartments *j* with human infrastructure (such as major roads and mills), which are delineated by the binary parameter Ψ_j=1. Constraint [21] defined the protected proportion of the caribou range area within the target level [δ; $\delta+\varepsilon_{\text{hab}}$], where A_j is the area of compartment j and ε_{hab} is a small rounding error (0.01).

Case study

The planning horizon T included 10×10-year planning periods t. We applied the model at the level of six Canadian provinces that are major timber producers and where both woodland caribou populations and industrial forestry activities overlap including British Columbia (BC), Alberta (AB), Saskatchewan (SK), Manitoba (MB), Ontario (ON) and Quebec (QC). Although cross-provincial and cross-border roundwood imports may change local harvesting decisions, we considered this aspect outside the scope of the current study. To keep the problem [2-12] size tractable, the forest patch size was set to 4 km^2.

We defined the harvestable zone using the Global Forest Watch Canada dataset (Lee et al., 2004), which delineates the timber harvest licence areas across Canada. We excluded parks and protected areas from the analysis. We assumed that the caribou range portions selected for protection would not experience harvest disturbances but will undergo the natural disturbance cycle typical for that ecozone. Due to the coarse scale of our assessment, we did not include all operational harvesting constraints which may be applied at the forest management unit scale and would require implementing the model at the resolution of individual cut blocks.

We used the map of woodland caribou ranges across Canada (EC, 2012) and the provincial delineation of caribou ranges for Quebec (Gouvernement du Québec, 2022) to select the caribou ranges that overlapped the industrial forestry zone. For each range whose area overlapped the IFZ by >35%, we solved the habitat connectivity model [13-21] at the level of 6000-ha hexagonal compartments. The compartment size defined the smallest cross-section for the selected protected areas. Since most of the protected areas in our coarse-scale study had the cross-sections wider than a single compartment, therefore the selection of the compartment size was not as critical as it would be in fine-scale, forest management unit-level analyses. For each province, we then aggregated the protected portions of the caribou ranges to the subsets of protected patches *n,* N_{hab} and removed these patches from the harvestable area N in our caribou scenarios (Fig. 3).

We used the Canadian Forest Service National Forest Inventory geospatial dataset (NFI) (Beaudoin et al. 2014; 2018) to select the starting values for forest age and tree species composition at the level of broad species groups. This dataset provides estimates of forest composition, age and other forest attributes on a rasterized grid of 250×250-m map cells across Canada's forests. We updated the NFI forest representation of Beaudoin et al. (2014; 2018) using recent Canada-wide 30-m geospatial data on clearcuts and burns (Guindon et al. (2014; 2024), as well as data on mountain pine beetle outbreaks that killed forest stands in BC and AB (Walton, 2014; NRCan, 2014). The Ontario dataset was updated using recent clearcut information from the provincial Forest Resource Inventory database (OMNRF, 2022).

We grouped tree species into seven broad species groups – coastal firs and spruces, coastal cedars and hemlocks, pine, spruce, fir, boreal hardwoods and temperate hardwoods (see Supplement S1 Table S1.1). For each patch *n*, we estimated the harvestable merchantable volumes for all plausible combinations of planning periods *t* and management prescriptions *i* using the species group abundances and stand age estimates in period t=1 from the NFI dataset and the corresponding normal yield equations for each species group (see Supplement S1). For each patch *n* in period *t* in prescription *i*, we aggregated the merchantable timber volumes to the level of softwood and hardwood groups, V_{1nit} and V_{2nit}. Our assessments did not incorporate future successional changes in tree composition, a simplifying assumption with a minimal effect on results since the majority of harvesting over the planning horizon T would be allocated to already growing stands. We also did not predict the future frequencies of forest pest outbreaks – this could be the focus of future research.

We used a combination of national climate-based merchantable timber yield equations (Ung et al. 2009) and provincial yield tables to estimate yield trajectories for each province and species group defined above (see Supplement S1). Briefly, we first defined a finite set of combinations (or bins) of mean annual temperature and annual precipitation across the study area. We then generated a normal yield table for each bin and species group using the climate-based yield equations from Ung et al. (2009). These yield estimates were then constrained to fall within provincial yield limits, providing us with provincially scaled yield estimates across our entire study area. However, although the Ung et al. (2009) equations were climate-based, they were not intended to be used for climate change projections, wherein tree populations are expected to experience novel climate conditions. Thus, to incorporate climate change, we used outputs from a process-based forest growth model StandLeap (Bernier et al., 2010) to modify the yield tables described above (see Supplement S2). The adjustment coefficients were estimated as the ratio of current to future net primary productivity (NPP) for each tree species group under the Representative Concentration Pathway (RCP) 8.5 emissions scenario (Van Vuuren et al., 2011) – and were summarized for decadal time steps at a 0.25×0.25-degree spatial resolution across the country. Thus, current year yield for a given patch was obtained by reading the yield value from the appropriate yield table, given patch age, species group, and temperature-precipitation bin, and multiplying this yield value by the appropriate NPP modifier under the climate change simulations.

We also adjusted the harvestable timber volumes to reflect expected losses due to wildfire under current and future climate. For each planning period t, we adjusted the forest area a_{nt} by the expected losses from recurring stand-replacing fire disturbances based on the annual burn area estimates predicted in Boulanger et al (2014) (Fig.S3.1 Supplement S3).

Hauling costs included the on-site harvest cost of $35m^{-3} for mountainous areas in BC and AB and $24 m^{-3} for other locations and hauling costs from patch n to mill s as a linear function of distance between harvest patch n and mill s using the unit cost $0.4km^{-1}m^{-3} for mountain areas in BC and AB and of $0.25km^{-1}m^{-3} for other locations. The rationale of tracking the timber hauling costs in the objective function equation [2] was to provide negative feedback from the hauling distance on local harvest and mill delivery decisions and factor in the timber supply limits imposed by the maximum hauling distance. While our hauling cost estimates did not include all costs that may be incurred by forest companies, the distance-dependent feedback was sufficient to depict the geographical variation of major timber supply patterns. Based on feedback from forest practitioners, we limited the maximum hauling distance to 450 km and set the substitution timber unit cost (scaling factor f) in timber supply shortage conditions to $250m^{-3}, which is significantly higher than the supply cost over the maximum hauling distance. The substitution timber cost was only needed to keep the timber supply problem [2-12] feasible when the total volume of harvested timber in the area was insufficient to satisfy the demands of all forest mills in period t.

For forest mill information, we adapted a dataset of mill locations and associated timber processing capacities used in a previous timber supply assessment (McKenney et al., 2016). We used data from the Forest Economics Advisor (FEA, 2021), Madison Lumber Directory (2011) and Krigstin et al. (2012) to determine approximate mill locations and timber demands (Fig. S3.2 Supplement S3). We only accounted for mills with capacity above 2500 m^{3}-year^{-1}. Notably, the sum of the wood processing capacities for all mills differed from the provincial volumes of harvest in recent years. Since our intent for using individual mill capacities was to depict the coarse-scale variation of local timber demands, we used the mill capacities as the coefficients to apportion the total volume of timber harvested in the province to a set of local markets (mills). In this context, we proportionally adjusted the provincial sums of mill demands D_{1s} and D_{2s} to match the total volume of softwood and hardwood timber harvested in the province in 2020. To reduce the size of the problem [2-12], we aggregated the multiple mills located within a ±5-km radius and their corresponding capacities into single local markets.

In British Columbia, coastal and interior forests are characterized by distinct historical harvest patterns. To keep the harvest levels in each ecoregion within the historical proportional limits, we added the constraint that limited the proportions of timber harvested in the BC coastal ecoregion vs. interior regions to the proportion from the historical harvest levels in each ecoregion over the last 10 years (BCER, 2018; NFD, 2023). This helped prevent overharvesting over the historical proportional limits in the coastal region when the model encountered timber shortages in interior BC.

Model scenarios

We solved the problem [2-12] with and without implementing the 65% range protection target (referred to as “no climate change” solutions hereafter). To find the solution with the habitat protection target, we solved the connectivity problem [13-21] separately for each range to ensure that every range meets the 65% protection area target. In order to protect the most intact portion of the range in the IFZ, we used the weighted average of the linear inverse of the human footprint values from the national dataset of Hirsh-Pearson et al. (2022a,b) and the distance to nearest mill, which prioritized the locations with lowest human footprint at farthest distances from the mills in our habitat protection problem [13-21](Fig. 3). We have delineated the area removed from the commercial forestry zone, N_{hab} as the union of the protected portions for all ranges across the province and then solved the timber supply model [2-12] with the N_{hab} area removed (the caribou scenario hereafter). The models were formulated in the General Algebraic Modeling System (GAMS, 2023) and solved with the GUROBI linear programming solver (GUROBI, 2023). The timber supply problem [2-12] included continuous decision variables only and was solved to optimality using the barrier method. The habitat selection problem [13-21] used fewer compartments and was solved separately for each caribou range within three hours or after reaching a 0.05% optimality gap.

The discounting factor in objective equation [2] was set to a 3% annual rate. The even flow constraint limit ε was set to ±15% per 10-year period. The use of 15% even flow threshold is common in forest management planning (see Yemshanov et al., 2023) and is close to the average change in provincial harvest volumes over the last ten years (NFD, 2023), which is estimated at 16.7% for 2011 vs. 2020 when weighted by the total harvested volume per province. We also evaluated solutions with a zero-discount rate that assigned equal importance to cash flows irrespective of the time period they occurred. These solutions helped evaluate long-term timber supply levels in situations where caribou protection or climate change could cause a reduction in the area of productive forest stands.

Notably, our depiction of the protected undisturbed area in caribou ranges may underestimate the actual disturbance rates because the selection of the caribou range portions with the lowest human footprint does not always track the levels of natural disturbances in the protected areas. Potentially, the natural disturbance rates in some caribou ranges could push the overall disturbance rates above 35%. To explore this situation, we evaluated several range-level protection targets above 65% – i.e., 75% and 80%. This aspect of the study functioned as a targeted sensitivity analysis to elucidate the conservation targets at which timber supply shortages emerge for several provinces in the study.

RESULTS

The implementation of the 65% habitat protection rule required some degree of habitat protection in the IFZ in 44 caribou ranges across the six provinces evaluated (BC, AB, SK, MB, ON and QC) (Table S3.1 Supplement S3). The average modelled reduction of the provincial IFZ area in the caribou scenarios was 11%. Manitoba and Saskatchewan showed the largest proportional IFZ area reductions, followed by Alberta and Québec (Table 3).

Decreasing the IFZ area did not always reduce the timber production capacity relative to the baseline scenario. The landscape's capacity to sustain the present-day supply demands is impacted by an interplay of several factors, such as current mill demand levels and how close all they are to the maximum timber production capacity defined by the annual allowable cut level, current forest age structure and history of past disturbances, and future changes in disturbance rates. Protecting a moderate portion of the IFZ caused significant timber supply shortages in our solutions only for Quebec and Alberta, and a minor shortage for British Columbia (Fig. 4). Notably, even without climate change and caribou protection, softwood timber production was projected to decline in Quebec and Alberta. No impacts of caribou habitat protection on the capacity to sustain present-day harvest levels were found in Saskatchewan, Manitoba or Ontario (Table 4).

Relative to the baseline scenario, the impacts of caribou protection policies on timber supply were equal to or smaller than that of climate change through the increased area burned. For example, in Quebec, the modeled decreases in timber supply due to caribou protection and climate change were between 7.5 and 14.9%, and between 37.9 and 41% respectively (Table 5). In Alberta, modeled decreases in timber supply due to caribou protection and climate change were between 7.9 and 13.3% and between 7.8% and 21.2% respectively. Also, Quebec, Alberta and British Columbia all showed moderate timber supply shortages in the climate change scenarios without caribou protection (Fig. 4), with the largest shortages estimated for softwood timber (Fig. 4, Table 4).

The use of a positive discount rate prioritized the near-term benefits over the long-term cash flows and tended to push timber supply shortages towards the end of the planning horizon *T* (Fig. 4). In the solutions with zero discount rate, where the cash flow priority does not depend on the timing of its occurrence, timber supply shortages led to near-term reductions in harvest volumes relative to present-day levels in British Columbia, Alberta and Quebec (Fig. 5). Since the even flow constraints [6,7] imposed a fixed limit on the rate of harvest change in period *t*, the harvested volume reductions in our solutions were gradual. The depiction of a gradual harvest level decline implied that the land management agencies and timber companies would continue assessing the forest landscape conditions and proactively readjust their forest management plans to keep the harvesting environmentally sustainable. While the use of 15% even harvest flow threshold was consistent with the recent harvest dynamics in Canada, we acknowledge that individual mills and local timber markets operate under diverse economic conditions and could respond differently to the supply shortages in changing market conditions. Addressing this aspect would require analyzing the mills' historical and current operational conditions and was deferred for future work.

The cost-driven apportionment of the harvested timber to a set of forest mills helped identify the local markets and mills which are likely to experience fibre supply reductions in the future. We have explored this situation by relaxing the even harvest flow constraint [Eqs. 6,7] from the individual mill level to the whole-landscape level. In this scenario, mills were allowed to respond abruptly to the changes in local timber cost and availability. The idea of relaxing mill-based even harvest flow constraints echoes the study of Mathey et al. (2009) which explored the profitability of sustained yield harvesting policies with and without even annual flow constraint. This scenario yielded a slightly more optimistic solution than our baseline solution to model [2-12] because it allowed the variation of timber deliveries to individual mills to exceed ±15%-period^{-1} (Fig. 6). In this scenario, almost all mills in Alberta and Quebec were estimated to experience partial timber supply shortages by the end of the planning horizon (Table 6). In British Columbia, partial timber supply shortages at the end of the planning horizon *T* were projected only under future climate change conditions. In Alberta and Quebec, 88% and 87% of the mills respectively were projected to incur partial shortages in the next 50 years under the climate change and caribou protection scenario. In Quebec, the mills in the eastern, wetter portion of the province (with fewer fires) tended to experience shortages under climate change with or without caribou conservation (Fig. 7, Figs. S4.1-S4.3 Supplement S4). In Alberta, the mill shortages were scattered across the entire province (Fig. 8, Figs. S4.4-S4.6 Supplement S4). In British Columbia, the bulk of timber supply shortages was projected to occur in the southern portion of interior BC. In Alberta and BC, the hotspots of local timber supply shortages did not correlate with the distance to areas with caribou presence. In Quebec, timber supply shortages north of the St. Lawrence river and in the northwestern regions tended to occur closer to the areas with caribou presence (Fig. 7, Figs. S4.1-S4.3 Supplement S4).

Protecting 65% of caribou ranges is expected to provide an approximately 60% probability that populations will be self-sustaining (EC, 2012). However, raising this protection target further increases the likelihood of conservation success and provides a buffer against the occurrence of stochastic natural disturbances. We have explored the potential impacts of stricter range protection levels at 75% and 80% (Fig. 9, Table 7). For the provinces of Ontario, Manitoba and Saskatchewan, which did not show the timber supply shortages under the 65% protection rule, these solutions have helped identify the protection levels at which timber supply could become impacted. Under the climate change scenario, Ontario was projected to start experiencing timber supply shortages when the range protection target approached 75%, while Manitoba and Saskatchewan exhibited timber shortages when the protection levels approached 80% (Fig. 9). Even at these elevated protection levels, the magnitude of the predicted timber shortages was relatively small (Table 7), indicating that higher range protection levels could be achieved in these provinces without causing major provincewide impacts on timber supply.

DISCUSSION

Broad-scale patterns of timber supply shortages

Our results indicate that the caribou range-level protection in areas that overlap the IFZ and the climate-driven increases in natural disturbance rates may generate moderate timber supply shortages in Quebec and Alberta, and to a lesser extent in British Columbia. Timber shortages in British Columbia appeared solely in the climate change scenarios, reflecting both the significant increase in area burned projected for this region and the limited number of boreal woodland caribou herds in the province. The shortages in interior BC may reflect large-scale pine mortality caused by the mountain pine beetle outbreak over the past two decades (Corbett et al., 2016), combined with the projected increase in future fire frequency for this region. In contrast, timber shortages in Alberta appeared under both climate change and caribou conservation scenarios, with similar levels of impact for these two drivers. In this case, dense caribou ranges in the northern portion of the province and sizeable impacts from climate change both applied downward pressure on the timber supply curves.

In Quebec, the magnitude of timber supply shortages caused by climate change was approximately twice higher than the level of timber shortages caused by the implementation of caribou conservation measures. The occurrence of timber shortages in mills near the US-Quebec border may indicate that these mills do not rely exclusively on local supply but also source timber from private lands in the US, a situation that was not considered in the current model. Overall, the timber supply reduction in Quebec is likely to be larger than our estimates following the recent devastating 2023 fire season, which is projected to reduce annual allowable cut by 0.850 million

m^3-year^{-1} for the period 2023-2028 (Bureau du Forestier en Chef, 2023a), with little impact on caribou habitats (Boulanger et al. 2024). This reflects the significant shifts in future fire frequencies projected for this region.

Our solutions may underestimate the future impacts of biological conservation needs on timber supply in Quebec. While our model has allocated the protected areas as the connected habitat areas in the IFZ, we did not enforce the north-south connectivity of caribou habitat corridors within each range. This aspect would require undertaking an in-depth analysis of caribou movement patterns in boreal landscapes and adding new model constraints to enforce the protection of likely movement corridors. Potentially, one could allocate a protected corridor that is wide enough to facilitate the north-south movement of animals in a similar fashion to the proposed corridor between the Lake Superior Coast range and the Pagwachuan ranges in Ontario (Yemshanov et al. 2022).

Our results indicate that the current level of anthropogenic alteration of caribou ranges is likely to influence the occurrence of timber supply shortages under climate change. The provinces with high levels of human disturbance of caribou habitat would have little flexibility to absorb the future impacts of climate change on timber supply (Gauthier et al., 2015b). Alternatively, the provinces with moderate levels of caribou range alterations (such as Ontario, Manitoba and Saskatchewan) would have more room to mitigate the future impacts of climate change because the harvest reductions in the caribou ranges could be compensated by increasing harvest levels in other parts of the IFZ. This was illustrated in our sensitivity analyses with the range protection targets raised to 75% and 80%, which showed that Ontario has sufficient room to increase the caribou range protection level to 75% and in Manitoba and Saskatchewan – up to 80% before experiencing provincewide timber supply shortages. However, these results need to be considered in relation to the differences between the present-day harvest levels and the total sustainable timber production capacity – as estimated by the annual allowable cut levels.

Timber supply and climate change

The reduction of harvest areas in regions currently with woodland caribou populations appears to be a realistic measure to maintain caribou habitat while facing climate-induced changes in boreal landscapes (St-Laurent et al., 2022). Such a strategy is expected to generate a smaller, but more stable timber supply in fire-prone regions (Raulier et al., 2014; Leduc et al., 2015), thus creating a buffer against increasing stand-replacing disturbances (Daniel et al., 2017, Brecka et al., 2020). Adopting this approach would also benefit communities that depend on timber, as they often prioritize having stable, predictable, and reliable access to wood resources (Charnley, 2006). For these same reasons, several studies have pointed out that the reduction of long-term harvesting targets may be unavoidable in some boreal forest areas in eastern Canada that face potential large increases in natural disturbance rates (Gauthier et al., 2015a; Brecka et al., 2020; Bureau du Forestier en Chef, 2021; St.-Laurent et al., 2022).

Future harvest adjustments have also been considered in Alberta, including changes in forest management to curb the impact of timber losses and the exploration of other silvicultural options to secure fibre supply (Pinno et al., 2021; GoA, 2020). Comparatively, the estimates of timber supply in Ontario, Manitoba and Saskatchewan have indicated more room to absorb the higher disturbance rate in future climate before major timber supply shortages would occur. This was due to a combination of lower recent harvest levels below annual allowable cut levels and ample amounts of standing timber supply available in the IFZ.

In Quebec, the timing of the first timber supply shortages in our solutions broadly agreed with the assessment of Gauthier et al. (2015a) (Figs. 4,5), suggesting that timber losses from climate-induced increases in wildfire frequencies and current levels of harvest could exceed the productive capacity of the forest in parts of this region before 2040 under the RCP 8.5 scenario. Previous assessments have also identified potential timber shortages in Quebec due to projected increases in fire frequency under climate change (Raulier et al., 2013; Leduc et al., 2015; Schab et al., 2021; Bureau du Forestier en Chef, 2021). As evidence of this situation, following Quebec's extreme fire season in 2023, the province's Chief Forester has recommended a reduction relative to current harvest levels (Bureau du Forestier en Chef, 2023b).

The magnitude of climate-induced decreases in our timber supply solutions is likely an underestimate because our analyses did not include the risks of forest regeneration failures through increased fire activity (Splawinski et al., 2019), as well as the increased costs of postfire regeneration silvicultural efforts, which may be needed to compensate for slower rates of forest regeneration (Cyr et al., 2022). Furthermore, an increase in climate-induced biological productivity in the northern boreal regions is unlikely to compensate for timber supply losses due to sharp increases in fire activity (Pau et al., 2023), while further decreases in productivity in the southern parts of the boreal biome may only exacerbate the estimated shortages (Brecka et al. 2020, Boulanger et al., 2023).

While our model accounted for the climate change-driven forest area reductions due to more frequent fires, we acknowledge that climate change, natural disturbances, harvesting, and caribou habitat quality are likely to interact in more complex ways. For example, our timber supply model did not track the climate-driven shifts in forest succession, which could favor deciduous pioneer species under increasing natural disturbance rates (Boulanger and Pascual, 2021). Such forest composition changes could degrade caribou habitat (Leblond et al., 2022; St-Laurent et al., 2022) and reduce timber supply quality, particularly for high-value conifers (Brecka et al., 2020). A combination of high harvesting rates and wildfires could exacerbate these impacts, triggering novel forest succession pathways (Brice et al., 2019; Boulanger and Pascual, 2021), regeneration failures (Cyr et al., 2022) and forest conversion to parklands in western provinces (Cadieux et al., 2020;

Stralberg et al., 2018). These interactions were evident during the 2023 fire season in Quebec, where extreme fire-weather conditions and record-breaking levels of area burned (Barnes et al., 2023) caused widespread regeneration failures in harvested landscapes (Boulanger et al., 2024; Forestier en chef, 2023b). Note that climate-induced stand conversions could also create negative feedback on wildfire activity by promoting less flammable hardwood stands, potentially mitigating the effects of increased fire weather severity (Boulanger et al., 2017; Chaste et al., 2019). Furthermore, shifts in the occurrence of forest pest outbreaks – either driven by climate change or by increased forest vulnerability (Safranyik et al., 2010; Régnière et al., 2012) – could cause cascading impacts on future timber supply and caribou habitat quality (Labadie et al. 2021), – these long-term interactions remain poorly understood and will require future research.

Methodological aspects

Our approach provides a linear programming solution to a large spatiotemporal problem that allocates the harvest across a large forest region and apportions it to a set of wood processing facilities in that region. In contrast to the previous timber supply assessments of Gauthier et al. (2015a) and St-Laurent et al. (2022), our approach incorporated key forest management constraints to prevent overharvesting, maintain mean forest age, and enforce a steady fibre supply to forest mills. Such constraints frequently appear in local forest management plans but rarely in broad-scale timber supply assessments. However, our approach did not incorporate certain fine-scale constraints, such as buffers and specific habitat set-asides, which are required in operational forest management plans. As such, our solutions likely depict an optimistic upper bound on the long-term timber supply in the area.

Our network flow model identified the potential areas for caribou protection in the IFZ with a combination of lowest human disturbance and farthest distances to the mills. One limitation of this approach is that, while human disturbance was minimized within the selected protected area, there were cases where patches with modest levels of disturbance were, by necessity, included in the protected habitat area. As such, these protected areas may not fully meet the criteria defined for caribou reserves in the EC (2011) report (e.g., areas with 65% of land having no human disturbance). This flexible interpretation of suitable habitat would further contribute to our findings being somewhat optimistic regarding caribou conservation and timber supply trade-offs.

Potentially, our timber supply and the protected habitat selection models could be combined into a single model that adjusts the protected habitat zone to maximize harvest benefits. However, the habitat selection problem included binary decision variables and indicator constraints, and its integration into an LP timber supply model (which does not use binary variables) would significantly increase the problem complexity and could render it intractable for province-wide datasets. Notably, the analogous model in a previous study (Yemshanov et al., 2023), which integrated both timber supply and caribou habitat protection constraints, allocated a significant proportion of forest patches in the habitat protection zone for the entire planning horizon. Such behaviour was caused by high timber hauling cost from the northernmost remote portions of the IFZ where caribou populations were present, and a delay between the harvest disturbance and the time when the forest stands mature and can support caribou populations. These findings support the use of a sequential approach that involves solving the timber supply problem after solving the protected area problem.

We have applied a simplified coarse-scale delineation of the habitat protection zone in the caribou ranges based on the national human footprint dataset and site-to-mill distance. Potentially, the protected areas could be delineated with more sophisticated and dynamic habitat suitability models that account for forest composition, human disturbance, and other spatial attributes (Elkie et al., 2008; Leblond et al., 2014; OMNRF, 2015). However, the nationwide application of such a fine-scale analysis could be challenging because many regions lack sophisticated caribou habitat suitability models and so results may become inconsistent across such vast areas.

Our timber harvest model followed a well-known harvest scheduling problem I, which makes it compatible with the current forest management planning LP applications conducted by forest industry and provincial land management agencies and forest industry. Optimization-based timber supply modelling has been routinely undertaken by provincial natural resource agencies to estimate the annual allowable cuts on Crown lands (Bureau du Forestier en Chef, 2013; 2021). Our approach could be adapted to explore other forest resource management policies, such as the protection of multiple species-at-risk or estimating the impacts of climate change on timber supply and forest carbon management. Since our approach can track the fibre supply to a large number of local markets, it could provide inputs for sectoral and global trade analysis models, such as computable general equilibrium (CGE) models (McMonagle et al., 2024) and so could be utilized to assess the impacts of climate change and conservation management initiatives on forest sector and trade.

Concluding comments

To our knowledge, this is the first study to consider both climate change and caribou conservation objectives in a national timber supply optimization context, a feature that has allowed us to tease apart the relative impact of these key drivers on future fibre supply. Our results indicate that the protection of caribou ranges and the projected climate-induced increase in wildfire frequencies may cause moderate timber supply reductions in Quebec and Alberta and minor shortages in British Columbia (mostly driven by climate change). Minor impacts on timber supply appear in Saskatchewan, Manitoba, and Ontario at habitat protection levels of 75% or more. The occurrence of timber supply shortages depends on the interplay between the fibre demands by industry, the amount of caribou habitat in the IFZ, expected forest losses to wildfires, and the amounts of standing timber in each region. Potentially, the impact of climate change-driven increasing disturbance rates could be partially mitigated by proactive measures, such as silvicultural fire prevention and mitigation efforts. Our results underscore the need for climate change adaptation by forest industry in response to increasing disturbance rates, especially given the perspectives of the nationwide adoption of broad-scale caribou conservation measures.

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Data generated during this study are available from the corresponding author upon reasonable request.

SUPPLEMENTARY MATERIAL:

SUPPLEMENT S1. DERIVING THE GROWTH AND YIELD CURVES FOR THE STUDY AREA.

SUPPLEMENT S2. CREATING TREE GROWTH MODIFIERS FOR THE CLIMATE CHANGE SCENARIO.

SUPPLEMENT S3. THE PREDICTED FIRE FREQUENCIES AND THE LOCATIONS OF FOREST MILLS.

SUPPLEMENT S4. MILL-BASED TIMBER SUPPLY SHORTAGES.

SUPPLEMENT S5. TIMBER DEMANDS DATA.

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Table 1. Harvest scheduling model variables and parameters.

Symbol	Parameter / variable name	Description
Sets:		
N	Forest patches n in a landscape – potential harvest locations	$n \in N$
N_{hab}	Forest patches n in the habitat protection zone – exempt from the harvest	$N_{hab} \in N$
S_1, S_2	Softwood and hardwood forest mills, s which can receive timber harvested in area N	$s \in S_1$, $s \in S_2$
T	Planning time periods, t	$t \in T$
I	Harvest prescriptions, i	$i \in I$
Decision variables:		
x_{ni}	Proportion of site n with harvest schedule i applied over horizon T	$x_{ni} \in [0;1]$
$d_{1\,nits}$, $d_{2\,nits}$	Proportions of softwood and hardwood timber harvested in site n in period t when prescription i is applied that is delivered to mill s	$d_{1nits}, d_{2nits} \in [0;1]$
$P_{1\,st}$, $P_{2\,st}{}^{*}$	Penalties when the total supply of softwood (or hardwood) timber to mill s in period t drops below the mill's demand $D_{1\,s}$ (or $D_{2\,s}$)	$P_{1\,st}, P_{2\,st} \geq 0$
Parameters		
$D_{1\,s}$, $D_{2\,s}$	Softwood and hardwood timber demands for mill s in period t (constant for all ts)	$D_{1\,s}, D_{2\,s} \geq 0$
a_{nt}	Forest area in a patch n in period t	$a_{nt} > 0$
$V_{1\,nit}$, $V_{2\,nit}$	Volumes of merchantable softwood and hardwood timber available for the harvest in patch n in period t when harvest prescription i is applied	$V_{1\,nit}$, $V_{2\,ni\,t} \geq 0$
$E_{\lvert T \rvert\,min}$	Average target age of forest stands in the managed area at the end of the planning horizon $\lvert T \rvert$	$E_{\lvert T \rvert\,min} > 0$
E_{ni}	Forest stand age in a patch n at the end of the planning horizon $t = \lvert T \rvert$ if prescription i is applied	0-300
ε	Allowable increase or decrease in harvest volume in consecutive planning periods t and $t+1$	0.15
$\varepsilon_{\text{mill}}$	Allowable deviation of the timber supply to mill s in period t (sets an upper bound of timber demand for mill s in period t above $D_{1\,s}$, $D_{2\,s}$)	0.001
$R_{1\,nits}$, $R_{2\,nits}$	Net cash flow of harvesting softwood (or hardwood) timber in patch n in period t in prescription i and delivering the harvest to mill s	$R_{1\,nits}, R_{2\,nits} \geq 0$
$c_{1\text{mill}}$, $c_{2\text{mill}}$	Mill gate prices for unit of delivered softwood and hardwood timber	$c_{1\text{mill}}, c_{2\text{mill}} > 0$
c_{ns}	Tree-to-mill harvest and hauling cost for timber that is harvested in patch n and delivered to mill s	$c_{ns} > 0$
c_{subst}	Substitution timber supply unit cost when the amount of harvested timber is insufficient to satisfy the demand of forest mills	$c_{subst} = \$250\text{-m}^{-3}$
λ_1, λ_2	Timber harvest unit cost for softwoods and hardwoods	$\lambda_1, \lambda_2 > 0$
r	Social discount rate for period t	0.03-year^{-1}
f	Scaling factor for the penalty values in the objective function equation	$f > 0$

[*] Subscripts $_1$ and $_2$ denote softwood and hardwood timber.

Table 2. Protected habitat area model variables and parameters.

Symbol	Parameter / variable name	Description
Sets:		
J	Forest compartments – members of habitat protection or management zones plus an auxiliary Node 0	$j \in J$
Q_j	Adjacent patches *k* (or Node 0) connected to *j*, which can transmit flow to *j*	$Q_j \in J$
Q_j^+	Adjacent patches *k* connected to *j*, which can receive flow from *j*	$Q_j^+ \in J$
Decision variables:		
w_{jk}	Binary indicator of the connection via an arc *jk* in the habitat protection zone	$w_{jk} \in \{0,1\}$
y_{jk}	Amount of flow between the adjacent patches *j* and *k* in the habitat protection zone	$y_{jk} \geq 0$
v_{kj}	Binary indicator of the connection via an arc *kj* in the management zone	$v_{kj} \in \{0,1\}$
z_{kj}	Amount of flow between the adjacent patches *k* and *j* in the management zone	$z_{kj} \geq 0$
Parameters:		
Ψ_j	Binary indicator of compartments *j* with large antropogenic disturbances	$\Psi_j \in \{0,1\}$
B_j	Amount of habitat in compartment *j*	$B_j \geq 0$
A_j	Area of compartment *j*	$\alpha'_j > 0$
ε_{hab}	Small error	$\varepsilon_{hab} = 0.01$
δ	Target proportion of the protected area	$\delta \in]0;1[$
M	Large positive (big-M) value	$M > 0$

Table 3. An overlap between the caribou ranges and the industrial forestry zone (IFZ) by province.

Province	Area of caribou ranges which overlap the IFZ by more than 35%, M ha	Caribou range area that needs protection in the IFZ to enforce the 65% protection rule, M ha	IFZ percentage that would need protection to enforce the 65% habitat protection rule
British Columbia	4.01	2.01	3.39%
Alberta	13.16	4.71	18.62%
Saskatchewan	26.67	3.54	31.96%
Manitoba	19.53	3.38	32.16%
Ontario	48.50	4.32	11.8%
Quebec	27.96	6.57	10.7%

Table 4. Timber supply shortages in the caribou and no-caribou scenarios.

Province	Climate change scenario[*]	Wood type	Total timber demand[**], M m^3-yr.$^{-1}$	Scenario / time horizon			
				No caribou protection		Caribou protection	
				2070 (t=5)	2120 (t=10)	2070 (t=5)	2120 (t=10)
Alberta	No	Softwoods	19.1	10.1%	60.1%	38.6%	72.8%
		Hardwoods	10.5	-[***]	27.7%	-	55.0%
	Yes	Softwoods	19.1	27.7%	67.9%	45.5%	75.8%
		Hardwoods	10.5	-	49.0%	15.0%	62.3%
British Columbia	No	Softwoods	54.1	-	-	-	-
		Hardwoods	2.7	-	-	-	-
	Yes	Softwoods	54.1	-	52.7%	-	54.4%
		Hardwoods	2.7	-	-	-	-
Quebec	No	Softwoods	20.3	-	39.6%	23.3%-	60.0%
		Hardwoods	5.9	-	9.0%	-	27.6%
	Yes	Softwoods	20.3	34.1%	70.8%	53.4%	75.1%
		Hardwoods	5.9	0.1%	53.8%	18.1%	57.3%
Manitoba	No	Softwoods	0.8	-	-	-	-
		Hardwoods	0.6	-	-	-	-
	Yes	Softwoods	0.8	-	-	-	-
		Hardwoods	0.6	-	-	-	-
Ontario	No	Softwoods	10.7	-	-	-	-
		Hardwoods	3.3	-	-	-	-
	Yes	Softwoods	10.7	-	-	-	-
		Hardwoods	3.3	-	-	-	-
Saskatchewan	No	Softwoods	2.2	-	-	-	-
		Hardwoods	2.5	-	-	-	-
	Yes	Softwoods	2.2	-	-	-	-
		Hardwoods	2.5	-	-	-	-

[*] RCP 8.5 scenario.

[**] Based on recent harvest levels.

[***] No timber shortages.

Table 5. Net impact of climate change and caribou protection policies on timber supply shortages[*].

Province	Wood type	Timber shortage difference, % of total supply		
		Caribou protection: No CC vs. CC[**]	No CC, no caribou protection vs. CC[**], caribou protection	CC: no caribou vs. CC[**], caribou protection
Alberta	Softwoods	7.8%	15.7%	7.9%
	Hardwoods	21.2%	34.5%	13.3%
British Columbia	Softwoods	52.8%	54.5%	1.7%
	Hardwoods	0	0	0
Quebec	Softwoods	37.9%	58.9%	14.9%
	Hardwoods	41.0%	53.1%	7.5%

[*] Net differences at the end of the planning horizon ($t = 10$), percentage from total timber demand at $t = 0$.

[**] Climate change RCP 8.5 scenario.

Table 6. Proportion of mills experiencing partial timber supply shortages in the caribou and no-caribou scenarios.

Province	Scenarios							
	No caribou protection				Caribou protection			
	No climate change		Climate change*		No climate change		Climate change*	
	2070	2120	2070	2120	2070	2120	2070	2120
Alberta	55%	100%**	88%	100%	88%	100%	100%	100%
British Columbia	0***	0	0	96%	0	0	0	96%
Quebec	0	99%	87%	100%	61%	100%	10%	100%
Ontario, Manitoba, Saskatchewan	0	0	0	0	0	0	0	0

* RCP 8.5 scenario.

** All mills experience at least partial timber shortages.

*** No mills experience any shortages.

Table 7. Timber supply shortages in the caribou scenarios at range protection levels above 75% and 85%.

Province	Climate change scenario[*]	Caribou range-level protect target / time horizon					
		65% (baseline)		75%		80%	
		2070 (t=5)	2120 (t=10)	2070 (t=5)	2120 (t=10)	2070 (t=5)	2120 (t=10)
British Columbia	Yes	-[**]	51.9%[***]	0.5%	52.2%	0.4%	54.0%
	No	-	-	-	-	-	-
Alberta	Yes	34.7%	71.0%	38.4%	72.7%	41.4%	74.0%
	No	24.9%	66.4%	28.4%	68.2%	32.1%	69.9%
Quebec	Yes	34.9%	71.1%	39.5%	73.2%	41.3%	74.0%
	No	7.6%	52.7%	16.1%	58.3%	19.8%	60.5%
Ontario	Yes	-	-	0.9%	15.6%	1.5%	23.1%
	No	-	-	-	-	-	-
Manitoba	Yes	-	-	0.6%	0.9%	1.1%	1.5%
	No	-	-	-	-	-	-
Saskatchewan	Yes	-	-	-	-	0.2%	0.5%
	No	-	-	-	-	-	-

[*] RCP 8.5 scenario;
[**] No timber shortages;
[***] Total shortages (hardwoods + softwoods).

Figure captions:

Fig.1. Industrial forestry zone (IFZ) and areas of woodland caribou distribution (caribou ranges) in Canada. Data sources: administrative boundaries – 2021 Statistics Canada Census of Population (https://www12.statcan.gc.ca/census-recensement/alternative_alternatif.cfm?l=eng&dispext=zip&teng=lpr_000b21a_e.zip&k=%20%20%20130596&loc=//www12.statcan.gc.ca/census-recensement/2021/geo/sip-pis/boundary-limites/files-fichiers/lpr_000b21a_e.zip); harvestable zone - Global Forest Watch Canada (Lee et al., 2004); caribou range boundaries – Environment and Climate Change Canada (EC, 2012) https://open.canada.ca/data/en/dataset/890a5d8d-3dbb-4608-b6ce-3b6d4c3b7dce and Gouvernement du Québec, (Gouvernement du Québec, 2022) https://www.donneesquebec.ca/recherche/dataset/aires-de-repartition-des-populations-de-caribous-forestier. Mapping software used – ESRI ArcMap 10.8.

Fig.2. a) The network flow model concept. Arrows show the set of arcs - potential connections between the neighboring patches in the habitat network. Dashed arrows show connections from Node 0 to patches *n* in the network, which are used to inject the flow into the network. Bold arrows in red show the flow injected from Node 0 through the selected connected patches. Patches outlined in red show the selected connected patches. b) The delineation of contiguous areas and an example of flow from Node 0 in the protected and forest management zones.

Fig.3. The solutions to the habitat delineation problem that allocated, in each caribou range, the contiguous area in the IFZ to ensure the protection of the 65% of the range area (plotted for all caribou ranges which overlap the IFZ by >35%). Yellow circles indicate the locations and demands

of softwood mills (local timber markets). See Figure 1 caption for spatial data sources and Supplement S5 for timber demands. Mapping software used – ESRI ArcMap 10.8.

Fig.4. Timber supply shortages in baseline scenarios over the planning horizon *T*. The projections for Manitoba, Saskatchewan and Ontario had no shortages in any scenario and were not shown. Y-axis shows the timber supply level, m^3-year^{-1}. The portions of the graphs in callout I show the historical harvest dynamics between 2010 and 2020. A straight line in the timber supply curve near the 2020 harvest level indicates no timber shortages. A 3% annual discount rate was used.

Fig.5. Timber supply shortages in the baseline scenario over the planning horizon *T* with zero discount rate. The projections for Manitoba, Saskatchewan and Ontario had no timber supply shortages and were not shown. Y-axis shows the total timber supply level, m^3-year^{-1}.

Fig.6. Timber supply shortages in the scenarios with even flow harvest constraint relaxed from individual mill level to the whole-landscape level. The projections for Manitoba, Saskatchewan and Ontario had no shortages in any scenario and were not shown. Y-axis shows the timber supply level, m^3-year^{-1}. The portions of the graphs in callout I show the historical harvest levels between 2010 and 2020. A straight line in the timber supply curve near the 2020 harvest level indicates no timber shortages. A 3% annual discount rate was used.

Fig. 7. Geographic distribution of softwood timber supply shortages in Quebec. The planning horizon 2120 ($t = 10$). See Figure 1 caption for spatial data sources and Supplement S5 for timber supply shortages. Mapping software used – ESRI ArcMap 10.8.

Fig. 8. Geographic distribution of softwood timber supply shortages in Alberta and British Columbia. The planning horizon 2120 ($t = 10$). See Figure 1 caption for spatial data sources and Supplement S5 for timber supply shortages. Mapping software used – ESRI ArcMap 10.8.

Fig. 9. Timber supply shortages in caribou scenarios with the range-level protection targets set to 65% (baseline), 75% and 80%. Y-axis shows the timber supply level, m^3-$year^{-1}$. A 3% annual discount rate was used. The only scenarios with timber supply shortages are shown.

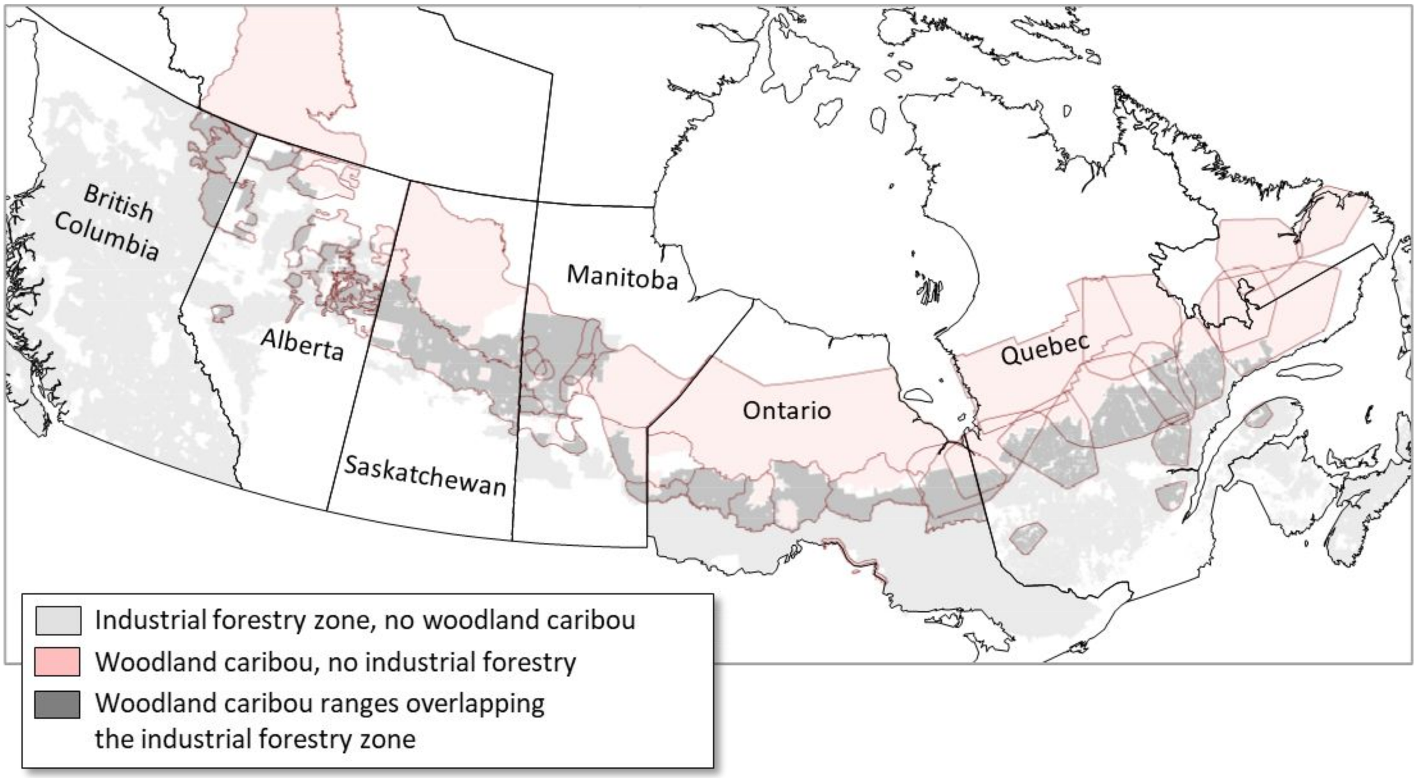

British Columbia
Alberta
Saskatchewan
Manitoba
Ontario
Quebec
Industrial forestry zone, no woodland caribou
Woodland caribou, no industrial forestry
Woodland caribou ranges overlapping the industrial forestry zone

Fig.1

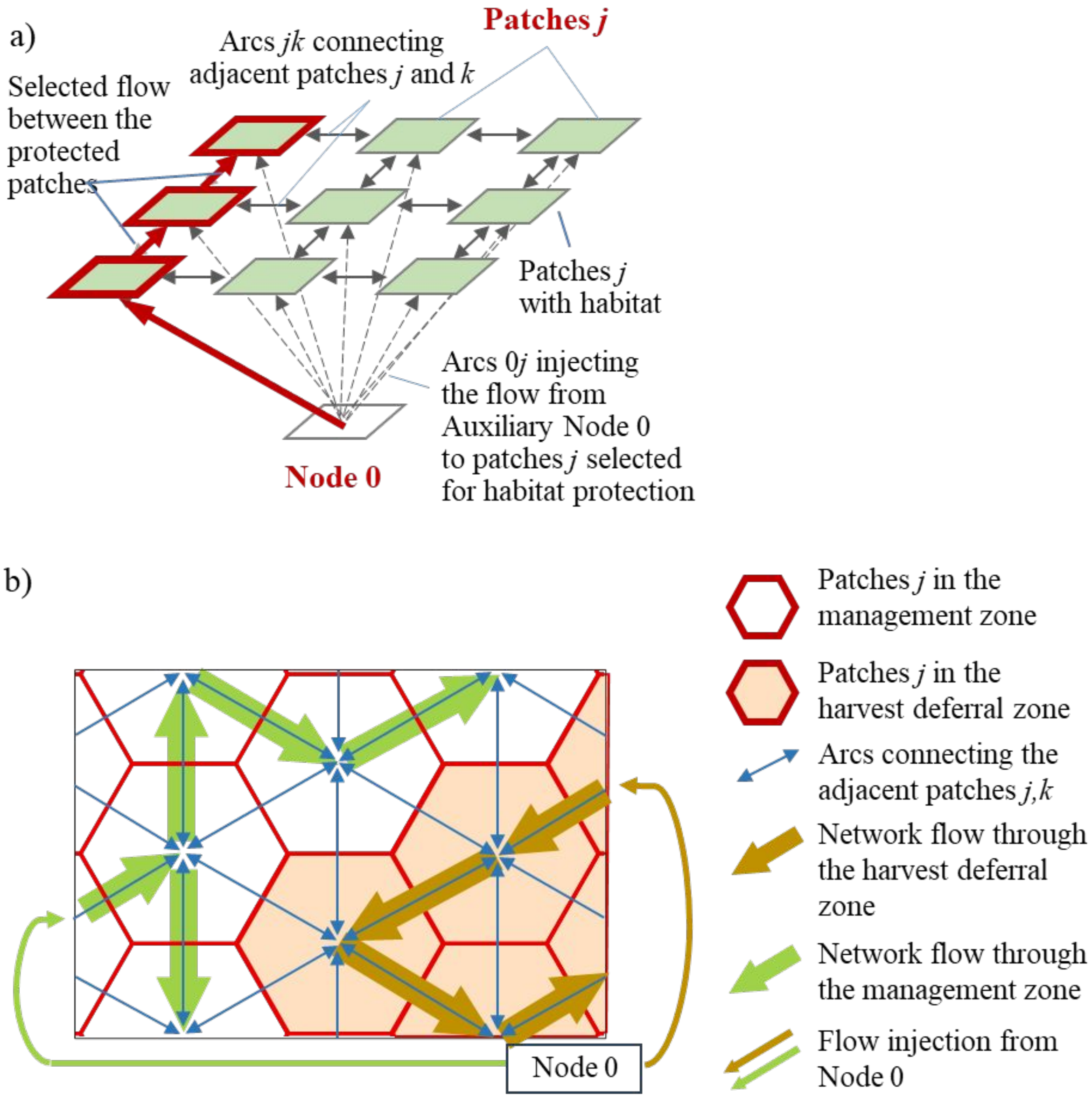

a)
Selected flow between the protected patches
Arcs *jk* connecting adjacent patches *j* and *k*
Patches *j*
Patches *j* with habitat
Arcs 0*j* injecting the flow from Auxiliary Node 0 to patches *j* selected for habitat protection
Node 0
b)
Node 0
Patches *j* in the management zone
Patches *j* in the harvest deferral zone
Arcs connecting the adjacent patches *j*,*k*
Network flow through the harvest deferral zone
Network flow through the management zone
Flow injection from Node 0

Fig.2.

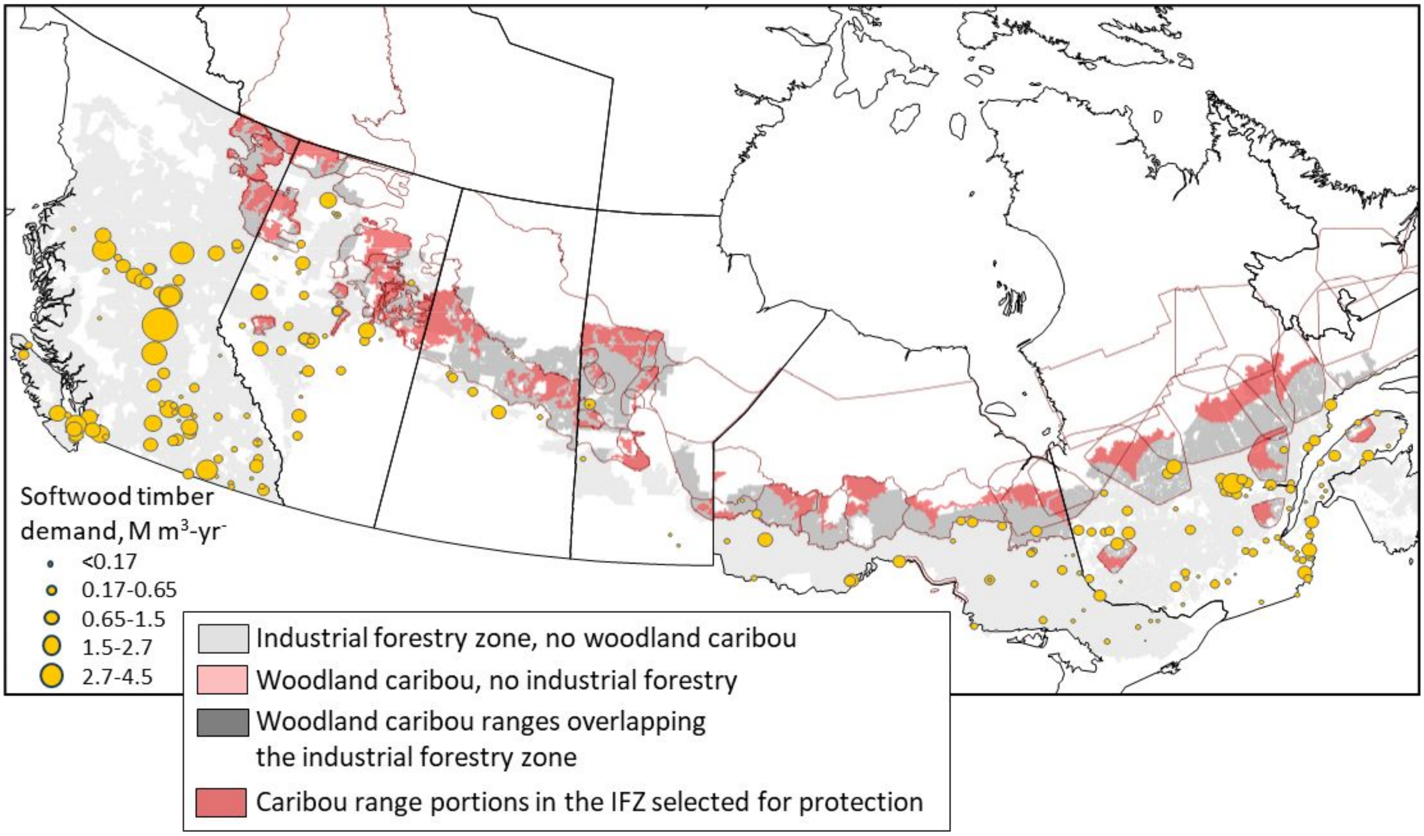
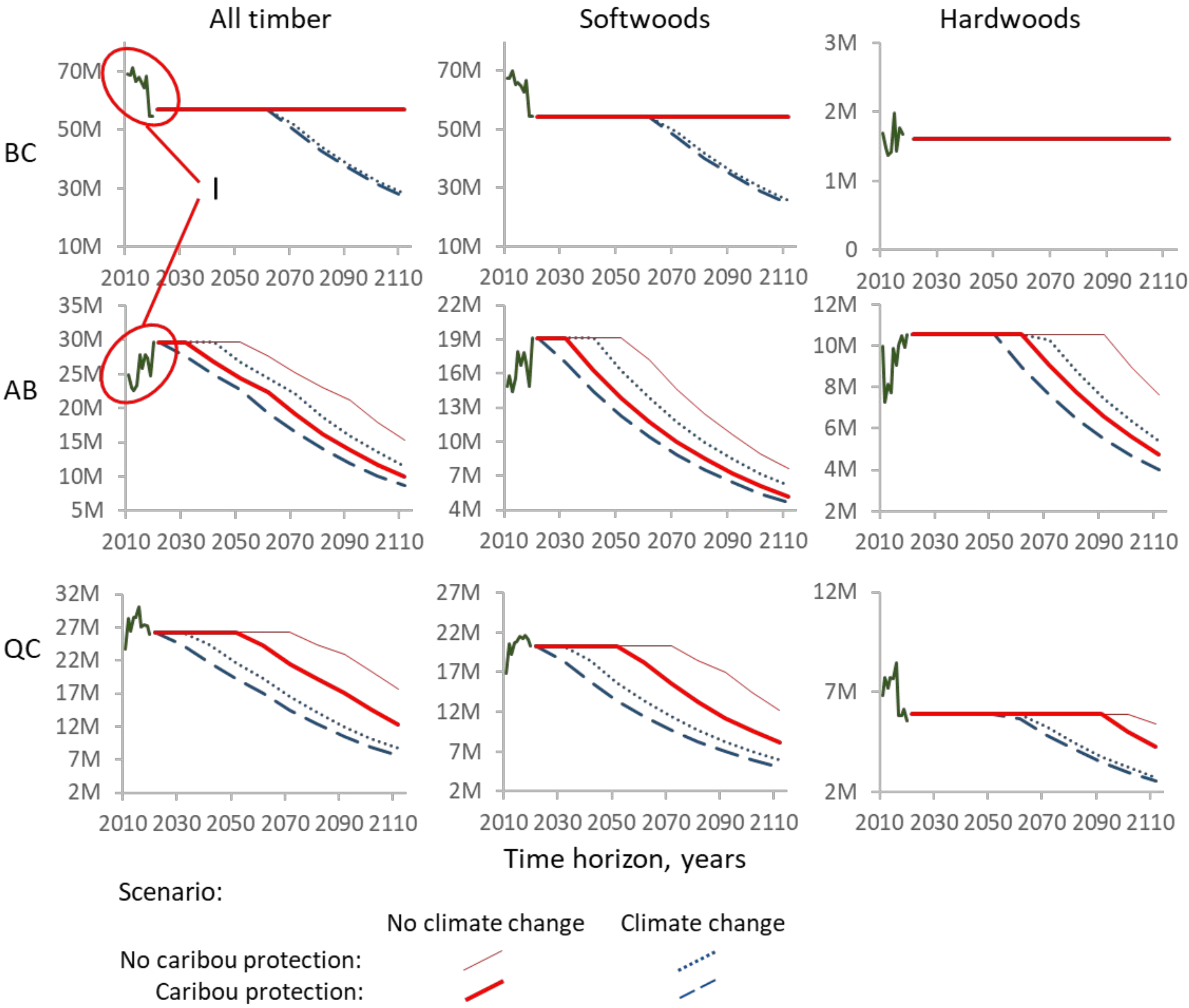

Softwood timber demand, M m³-yr⁻
<0.17
0.17-0.65
0.65-1.5
1.5-2.7
2.7-4.5
Industrial forestry zone, no woodland caribou
Woodland caribou, no industrial forestry
Woodland caribou ranges overlapping the industrial forestry zone
Caribou range portions in the IFZ selected for protection

Fig.3.


All timber
Softwoods
Hardwoods
BC
AB
QC
I
70M
50M
30M
10M
3M
2M
1M
0
35M
30M
25M
20M
15M
10M
5M
22M
19M
16M
13M
10M
7M
4M
12M
10M
8M
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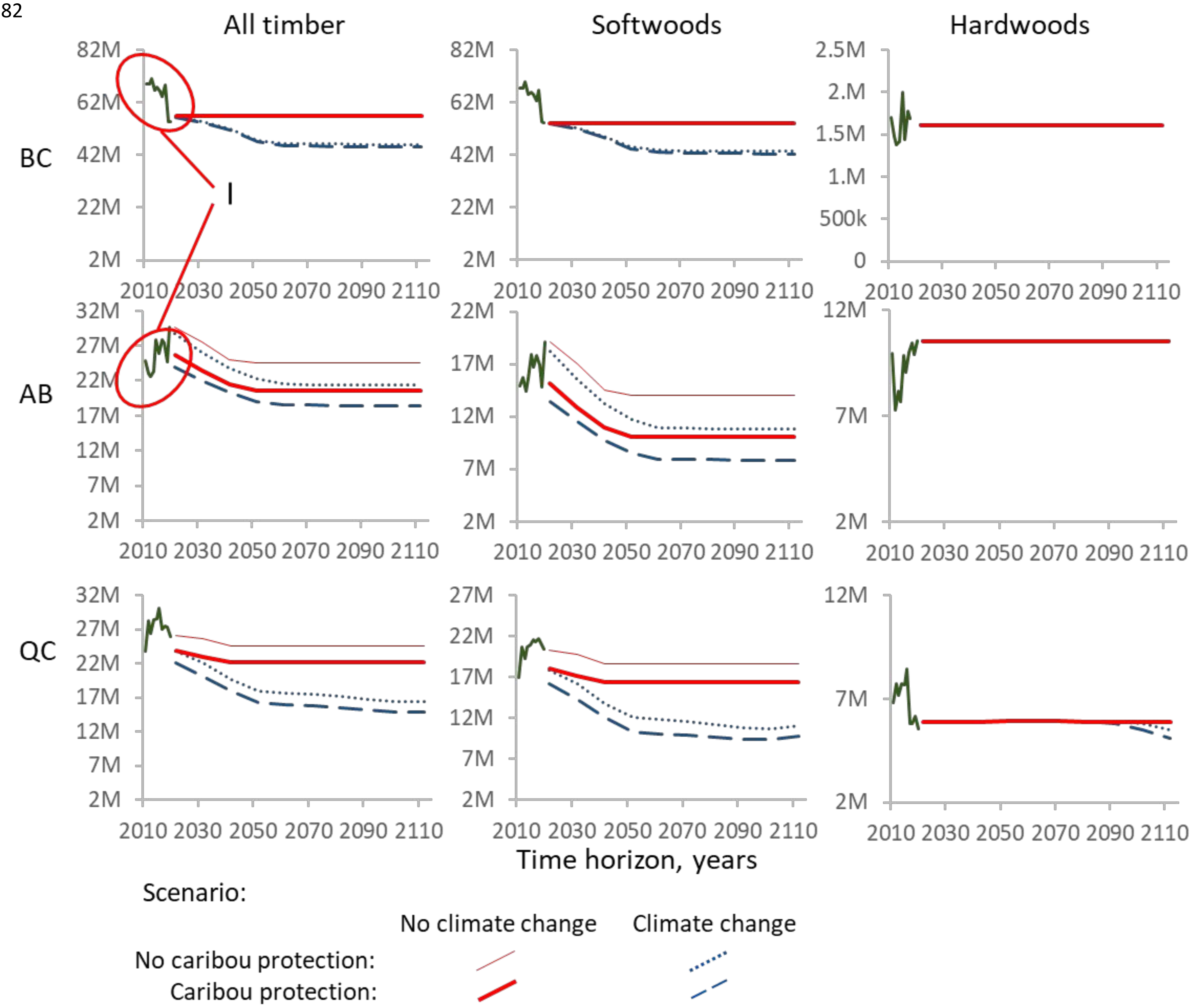
4M
2M
32M
27M
22M
17M
12M
7M
2M
27M
22M
17M
12M
7M
2M
12M
7M
2M
2010 2030 2050 2070 2090 2110
Time horizon, years
Scenario:
No climate change
Climate change
No caribou protection:
Caribou protection:

Fig.4.


All timber
Softwoods
Hardwoods
BC
AB
QC
I
82M
62M
42M
22M
2M
2.5M
2.M
1.5M
1.M
500k
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32M
27M
22M
17M
12M
7M
12M
2010 2030 2050 2070 2090 2110
Time horizon, years
Scenario:
No climate change
Climate change
No caribou protection:
Caribou protection:

Fig.5.

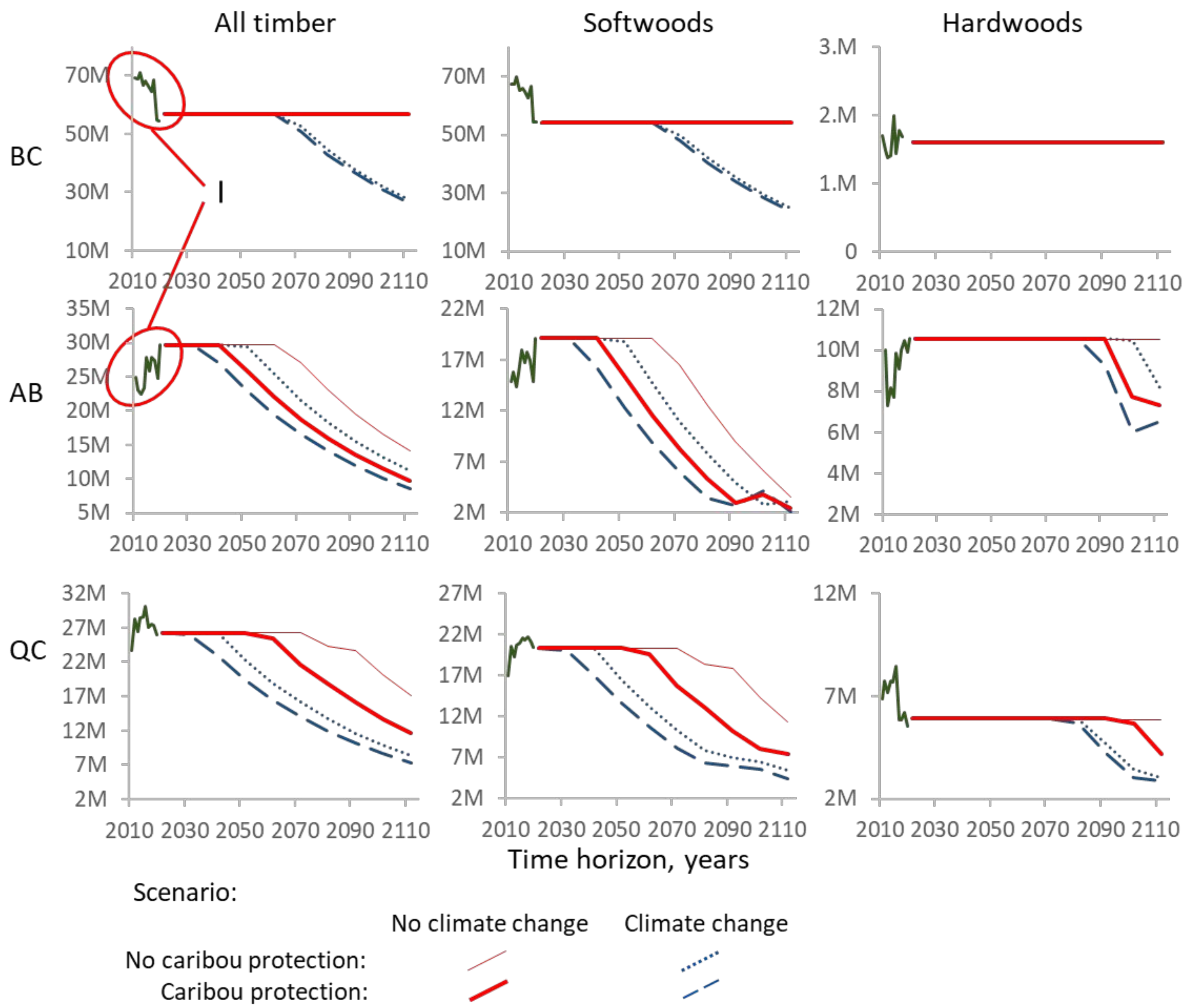
All timber
Softwoods
Hardwoods
BC
AB
QC
70M
50M
30M
10M
3.M
2.M
1.M
0
35M
30M
25M
20M
15M
10M
5M
22M
17M
12M
7M
2M
12M
10M
8M
6M
4M
32M
27M
22M
17M
12M
7M
2010 2030 2050 2070 2090 2110
I
Time horizon, years
Scenario:
No climate change
Climate change
No caribou protection:
Caribou protection:

Fig.6.

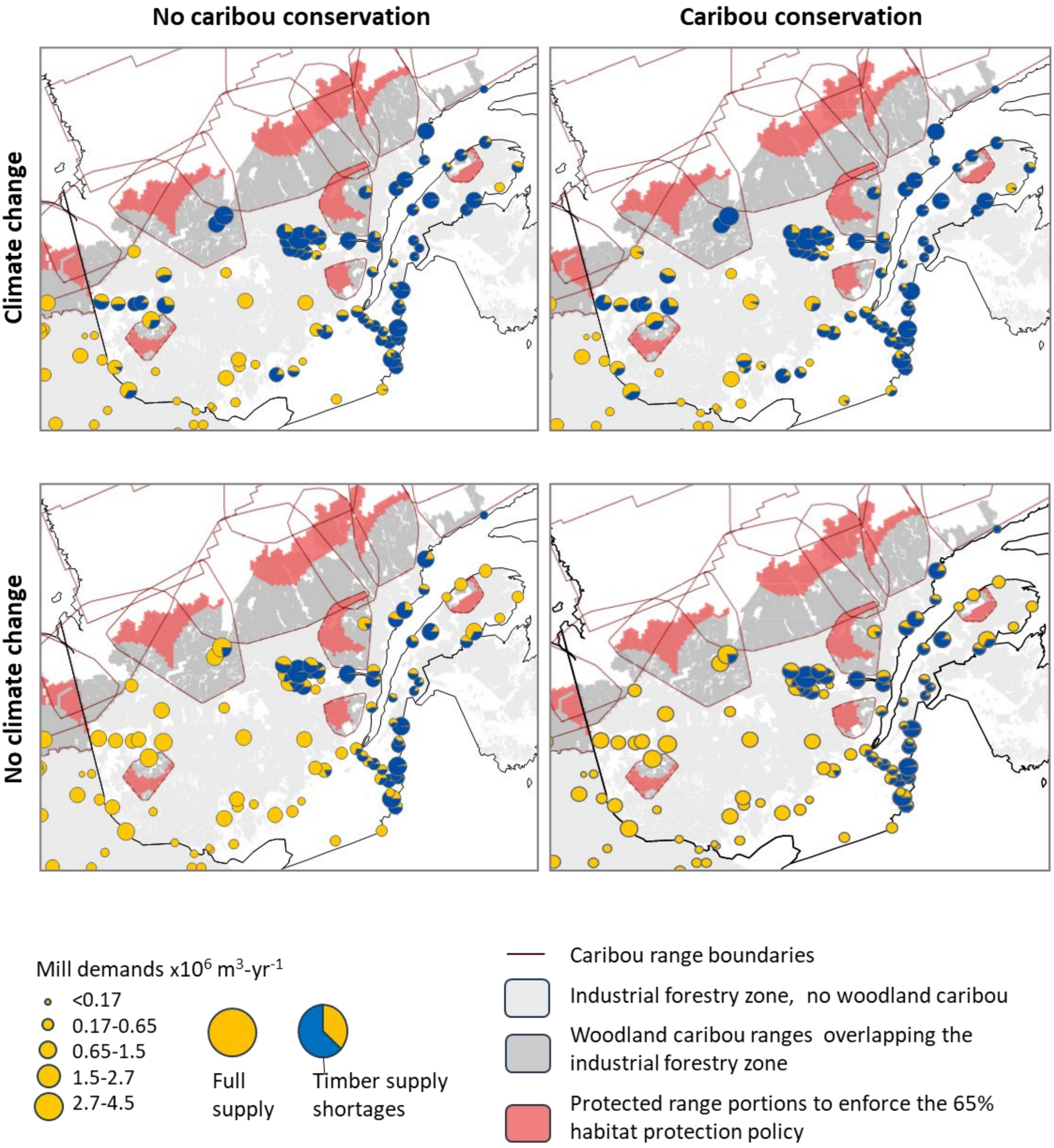
No caribou conservation
Caribou conservation
Climate change
No climate change
Mill demands x10^6 m^3-yr^{-1}
<0.17
0.17-0.65
0.65-1.5
1.5-2.7
2.7-4.5
Full supply
Timber supply shortages
Caribou range boundaries
Industrial forestry zone, no woodland caribou
Woodland caribou ranges overlapping the industrial forestry zone
Protected range portions to enforce the 65% habitat protection policy

Fig.7.

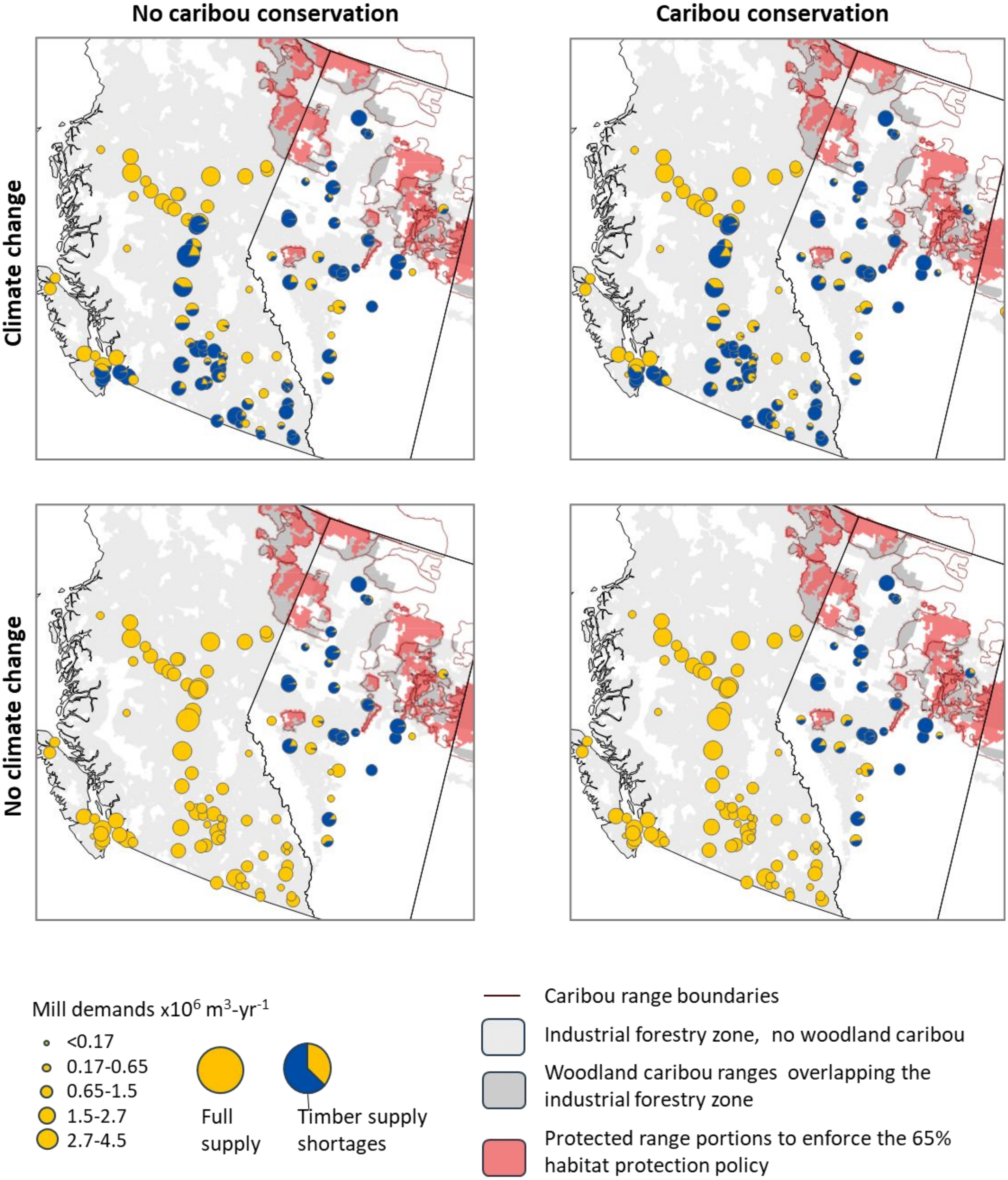
No caribou conservation
Caribou conservation
Climate change
No climate change
Mill demands x10⁶ m³-yr⁻¹
<0.17
0.17-0.65
0.65-1.5
1.5-2.7
2.7-4.5
Full supply
Timber supply shortages
Caribou range boundaries
Industrial forestry zone, no woodland caribou
Woodland caribou ranges overlapping the industrial forestry zone
Protected range portions to enforce the 65% habitat protection policy

Fig.8.


65% (Baseline protection)
75%
80%
BC
AB
QC
ON
MB
SK
82M
62M
42M
22M
2M
32M
27M
22M
17M
12M
7M
2M
17M
12M
7M
1.6M
1.4M
1.2M
1.M
5.M
4.5M
4.M
3.5M
3.M
2010 2030 2050 2070 2090 2110
Time horizon, years
(No shortages)
(No shortages)
(No shortages)
(No shortages)
Scenario:
No CC
Climate change
No caribou:
Caribou:

Fig.9.