

Comparing landscape partitioning approaches to protect wildlife habitat in managed forests

Denys Yemshanov^a, Triin Hart^b, Jeff Cameron^b, Ning Liu^a, Frank H. Koch^c, and Mathieu Leblond^d

^aNatural Resources Canada, Canadian Forest Service, Great Lakes Forestry Centre, Sault Ste. Marie ON, Canada; ^bNorthWinds Environmental Services, Thunder Bay ON, Canada; ^cUSDA Forest Service, Southern Research Station, Eastern Forest Environmental Threat Assessment Center, Research Triangle Park, NC, USA; ^dEnvironment and Climate Change Canada, National Wildlife Research Centre, Ottawa, ON, Canada

Corresponding author: Denys Yemshanov (email: denys.yemshanov@nrcan-rncan.gc.ca)

Abstract

Industrial forestry activities can increase landscape fragmentation, impacting wildlife populations, particularly Canada's woodland caribou, *Rangifer tarandus caribou*. To protect caribou in areas with forestry activities, the province of Ontario, Canada, implemented a Dynamic Caribou Harvest Schedule (DCHS). The DCHS spatially aggregates harvest disturbance into regions and distributes them across the landscape to maintain forest patch size–age distributions consistent with a natural variation range. However, the DCHS may negatively impact the cost of timber supply. We compared the DCHS with an alternative zoning approach that assigned the harvest deferral and operational management zones within a large forest area. We compared these approaches using an optimization model that combined harvest scheduling, access road construction, and caribou protection sub-problems. We formulated the protection of caribou habitat and road construction as network flow problems, while the harvesting problem incorporated the ecological constraints prescribed by the forest management plan. We compared the DCHS and zoning approaches in the Wabadowgang Noopming Forest of Ontario, a boreal area within the caribou distribution zone. For the same volume of sustainable harvest, the zoning approach protected less total area but more habitat and old-growth stands over the long term, and yielded lower timber costs by 1.2–2.2 \$·m⁻³ than the DCHS.

Key words: dynamic caribou habitat schedule, habitat connectivity, harvest scheduling model I, woodland caribou, road network management

1. Introduction

Industrial forestry activities in Canada have caused habitat loss and negatively affected the abundance of some wildlife species, particularly boreal populations of woodland caribou (*Rangifer tarandus caribou*) (Vors et al. 2007). Clear-cut harvesting creates early successional regrowth, which attracts deer and moose, followed by predators that also prey on caribou (Wittmer et al. 2007; Beauchesne et al. 2013; Fryxell et al. 2020). Recovery efforts for caribou aim to manage landscapes to restore age–size distributions of forest patches suitable as caribou habitat and to eliminate movement corridors for predators (EC 2011, 2012).

Long-term policies designed to protect caribou in areas of industrial forestry aim to maintain large patches of mature conifer forest while aggregating harvest areas, as caribou tend to avoid disturbed sites (Dyer et al. 2001). This strategy provides an opportunity for separation from predators (Racey et al. 1999; OMNR 2009). However, the need to protect habitat for extended periods can reduce the area of productive

forest available for harvesting or add scheduling constraints, leading to a trade-off between achieving forest management versus habitat protection goals in a forest landscape (Ruppert et al. 2016; Yemshanov et al. 2020).

In 2009, the Ontario Ministry of Natural Resources released the Caribou Conservation Plan (CCP) with directions to maintain naturally occurring low densities of alternate prey (moose and deer) and caribou predators (OMNR 2009). The CCP enhances the forest management planning process with a variety of tools and guidelines, such as the requirements for silviculture, harvest deferrals, decommissioning strategies for forest roads, and a dynamic caribou habitat schedule (DCHS) in the harvest plan. The DCHS is used primarily as a tool to encourage spatial separation of moose and deer from areas inhabited by caribou. Over several 20-year periods, the DCHS aggregates harvest disturbance into relatively few, compact regions distributed across entire forest management units, designed to be surrounded by areas with undisturbed habitat. The DCHS delineates harvest

regions over a long planning horizon and is updated every 10 years or sooner if there is a major disturbance (Martell et al. 1998; Baskent and Keles 2005).

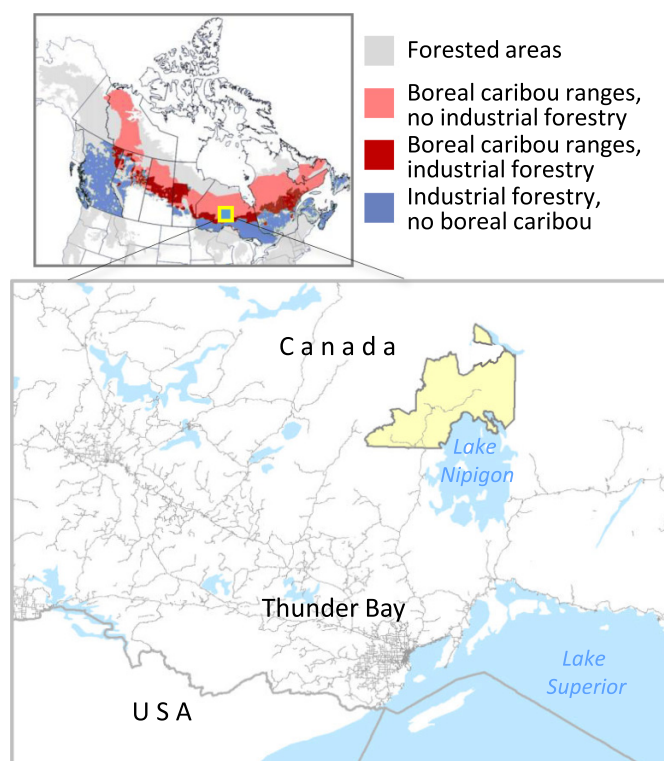
Aggregating harvest within DCHS regions aims to maintain connectivity between undisturbed habitat surrounding the harvested areas, though it offers timber companies some flexibility to reallocate harvest within the regions. Currently, the DCHS does not incorporate a dynamic adjustment of harvest in response to rapidly changing economic conditions. Even distribution of DCHS regions across the entire managed area necessitates the construction of access roads to remote harvest locations, which has implications on the cost of timber supply. Once built, forest roads are likely to remain used by the public, and their continued availability increases the hunting efficiency of predators by allowing them to move farther and faster into caribou habitat (Courbin et al. 2009; Houle et al. 2010; Dickie et al. 2017).

An alternative to DCHS is the zoning approach, which protects caribou habitat by partitioning the forest landscape into a harvest deferral zone and an operational management zone where timber harvesting is permitted. A variant of the zoning approach is currently under consideration in the province of Québec, Canada, where caribou habitat would be maintained in contiguous areas near the northern limit of commercial forests in the boreal caribou range (GoC 2020; MFFP 2022). This approach considers the current state of the habitat while adjusting forestry practices to meet targets for restoring caribou habitat. Compared to the DCHS, this approach strives to defer harvest in large forest regions containing the high-quality habitat that is most crucial for caribou, and to temporarily protect habitat connectivity corridors. The management zone includes the areas with the highest levels of human disturbance, which helps reduce the harvest footprint. Periodically, the harvest deferral and management zones can be reconfigured in response to changes in habitat quality and forest composition.

In this study, we compared the DCHS and zoning approaches in terms of their habitat protection capacity and the cost of timber supply, under constraints consistent with current forest management planning practices, using optimization (Ohman 2000; McDill et al. 2016). Optimization models are frequently used in forest planning, including in situations where planners are faced with competing or conflicting objectives, such as maintaining adequate harvest levels but also sufficient habitat protection. For example, some models have addressed the habitat protection objective by applying habitat adjacency restrictions to harvested sites (McDill et al. 2002; Snyder and ReVelle 1997) and maximizing the area of protected habitat by selecting among the plausible habitat clusters (Tóth et al. 2009). Other models have enforced the connectivity of protected habitat by selecting a contiguous set of landscape patches that cover a desired habitat amount (Onal and Briers 2006) or maximizing the desired properties of the habitat network (Cerdeira et al. 2005; Toth et al. 2011).

A common approach to managing habitat connectivity in a forest planning problem is to depict a landscape as a spatial network of habitat patches interconnected by arcs—indicating potential wildlife movement corridors—and

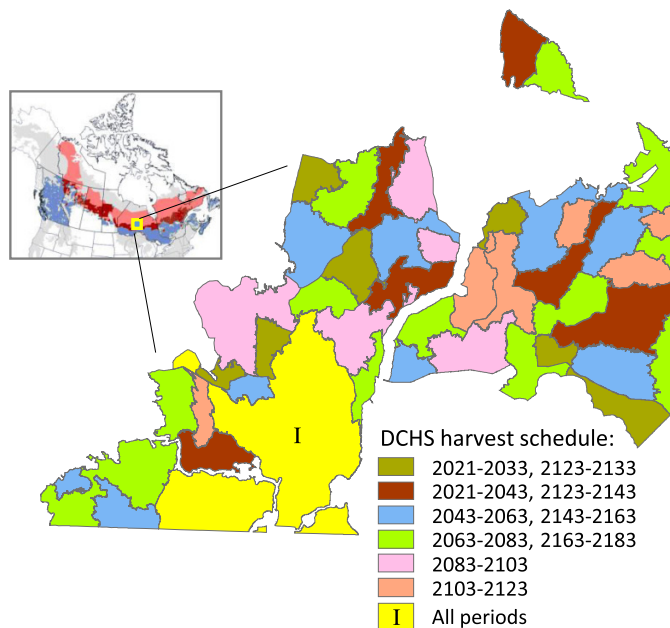
Fig. 1. Case study area—Wabadowgang Noopming Forest Management Unit, Ontario (shaded). The map was created using ESRI ArcMap version 10.3 and used Canvec base layers (NRCan 2019).



enforce connectivity between patches by solving a network flow model for the system (St. John et al. 2016; Yemshanov et al. 2020, 2021a, 2021b). This follows the approach outlined by Sessions (1992), which depicts the connected habitat as a Steiner network and finds a sub-graph of connected patches that maximizes a chosen conservation management metric under spatial and harvest planning constraints (St. John et al. 2016; Yemshanov et al. 2020, 2021a, 2021b). This network optimization approach also relates to the contiguous protected reserve problem of Jafari and Hearne (2013), as well as to the network flow models of Conrad et al. (2012) and Dilkina et al. (2016), which find minimum-cost corridors for a set of isolated habitats. Other studies solved a joint habitat protection and forest planning problem by applying a sequence of heuristic and optimization models (Ruppert et al. 2016; Martin et al. 2017). For each period, a heuristic model calculated the habitat priority map, followed by solving a harvest planning problem. At the next period, the harvest solution updated the forest composition and then the heuristic model was applied to calculate a new habitat map, followed by re-solving the harvest problem and so on.

We applied a network optimization approach to compare the DCHS and zoning approaches in the Wabadowgang Noopming Forest of Ontario, a boreal forest area with existing caribou habitat (Fig. 1). Our model formulation goes further than abovementioned examples and includes three sub-problems

Fig. 2. An example of Dynamic Caribou Harvest Schedule (DCHS) regions for Wabadowgang Noopming Forest Management Unit. Region I can be harvested in any period. The protected areas with no DCHS plan are not shown. The map was created using ESRI ArcMap version 10.3. Base map layer was provided by NorthWinds.



that represent practical considerations in the face of somewhat conflicting objectives (e.g., the need for roads for harvest versus wildlife habitat protection). We formulate a harvest planning problem with habitat connectivity requirements, a protected area target and a set of harvest sustainability constraints, as prescribed in the Wabadowgang Noopming Forest Management Plan (FMP) (OMNR 2014a, 2014b; NorthWinds 2021). The harvesting problem finds the maximum timber volume that can be harvested, subject to sustainability requirements prescribed by the FMP. This formulation gives timber companies maximum flexibility of operations within the limits approved by the FMP. The actual harvest levels may be lower than these limits, and we have tested a scenario with the harvest volume levels anticipated in present conditions.

2. Materials and methods

Protecting caribou habitat in areas of clear-cut harvesting requires creation of interconnected undisturbed corridors that allow caribou to travel and avoid predators (Saher and Schmiegelow 2005; Beauchesne et al. 2013). Under the DCHS approach, this is achieved through even placement of compact harvestable regions across the landscape while retaining a matrix of unharvested forest between these regions. The harvestable status of regions is changed every 20 years (Fig. 2). By comparison, the zoning approach delineates larger areas with deferred harvest based on their assessed quality as caribou habitat, and these areas may stay

undisturbed over longer periods. We conceptualize habitat protection in the zoning scenario as a connected pattern of protected forest habitat with the total protected area equal to a desired conservation threshold. We depict a forest landscape as a network of J forest patches (or nodes) over a timespan of U periods where any pair of adjacent patches containing habitat is connected by arcs. A patch j , $j \in J$, is characterized by the amount of suitable caribou habitat in period u , β'_{ju} , $u \in U$, which is the habitat suitability to support caribou populations times the patch area.

Individual patches j must be sufficiently large to ensure the separation of caribou from predators (Lesmerises et al. 2013), so the patch size was set compatible with the daily distances covered by the animals (i.e., 5000–10 000 ha) (Rettie and Messier 2001; Rempel and Hornseth 2018). The suitability of habitat to support animals in patch j depends on the composition and age of the forest in j in period u (Ferguson and Elkie 2004a, 2004b; OMNRF 2015). Clear-cut harvesting temporarily degrades the caribou habitat by increasing predation risk until forest cover matures in 40–60 years (Wittmer et al. 2005; Latham et al. 2011).

In each period u , the landscape J is divided into a harvest deferral zone J_{defer} with interconnected habitat and a management zone J_{mgmt} where harvest is allowed. Zoning decisions are reconsidered for every period u . All patches in the harvest deferral zone in period u need to be connected. We depict the connectivity between adjacent patches j and k as a bi-directional pair of arcs, jk and kj , and conceptualize the connectivity between the patches as a flow through a sub-network of *connected* patches j in period u . A binary variable w_{kju} indicates that flow can pass through an arc kj between patches k and j in period u in harvest deferral zone J_{defer} . A non-negative variable y_{kju} defines the amount of flow through arc kj . An auxiliary Node 0 is introduced to inject the flow into the sub-network of patches in zone J_{defer} to maintain their connectivity. It is connected to all patches j and could pass the flow to any selected patch (Figs. 3a and 3e).

Similarly, all patches in the management zone J_{mgmt} must be accessible from locations where permanent roads enter the area, which enforces the contiguity of set J_{mgmt} . A binary variable v_{kju} defines the connection between the patches k and j in the management zone J_{mgmt} , and a non-negative variable z_{kju} characterizes the flow amount through arc kj in period u . The management and harvest deferral zones do not overlap except at Node 0 (Fig. 3e).

The zoning problem allocates the connected harvest deferral and management zones to maximize the amount of habitat in the deferral zone, subject to the target area proportion designated for habitat protection, δ , $\delta \in [0;1]$, i.e.,

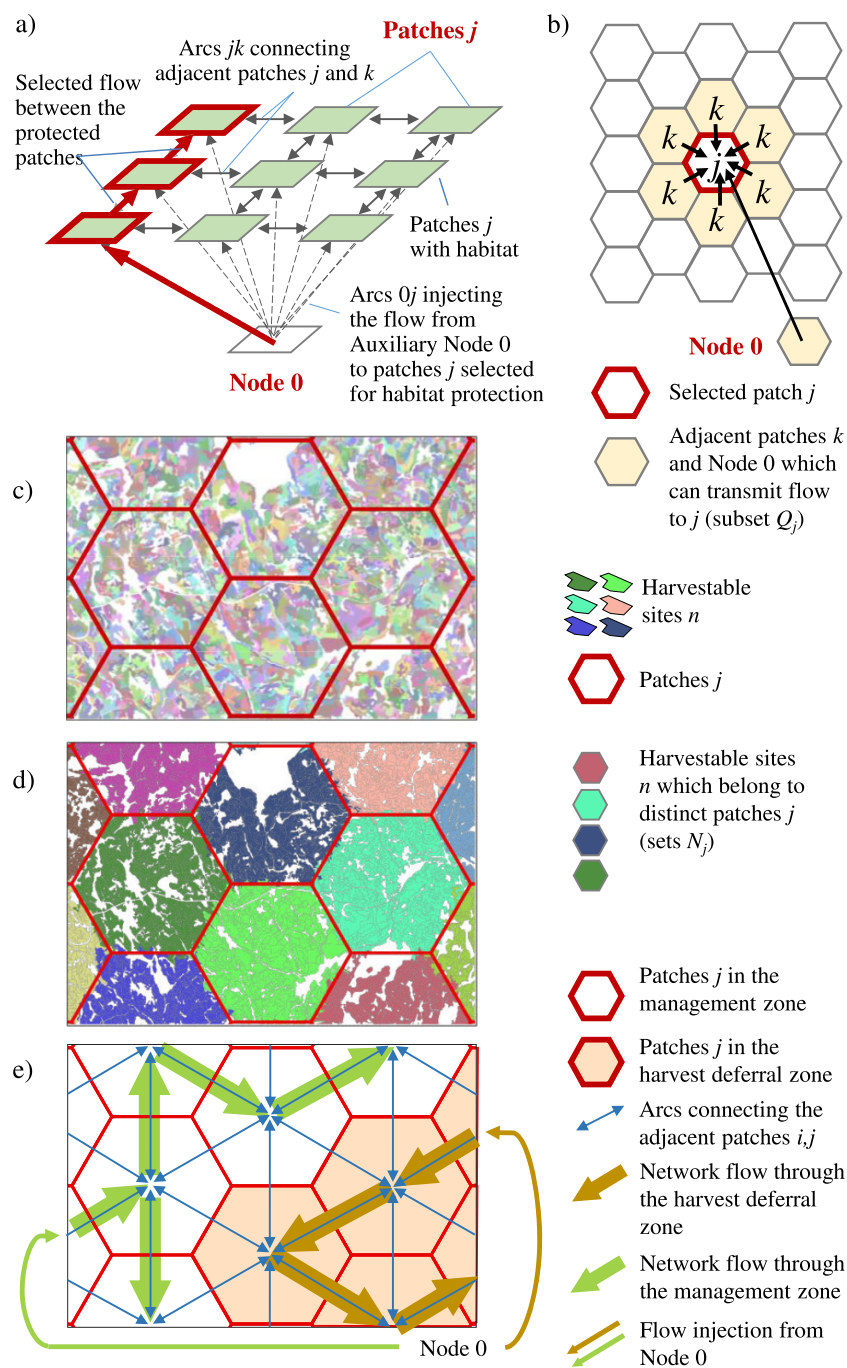
$$(1) \quad \max f_1 \sum_{u \in U} \sum_{j \in J} \sum_{k \in Q_j} (w_{kj} \beta'_{ju}) - \sum_{u \in U} f_2 (p_{1u} + p_{2u})$$

such that

$$(2) \quad J_{\text{defer}} \text{ is connected}$$

$$(3) \quad J_{\text{mgmt}} \text{ is connected}$$

Fig. 3. (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 concept of an adjacency set Q_j around a patch j ; (c) spatial alignment between harvestable sites n (forest inventory polygons) and habitat patches j ; (d) the subsets of harvestable sites n that are located in distinct habitat patches j . Set N_j includes harvestable sites n located in patch j . When patch j is in the harvest deferral zone, no harvest is allowed at any site n inside patch j ; (e) connectivity network between patches j and an example of network flow from Node 0 through the selected connected patches in the harvest deferral and the management zones. **Figs. 3c–3e** depict the same area.



$$(4) \quad p_{1u} \geq \sum_{j \in J} w_{0ju} - 1 \quad \forall u \in U$$

$$(5) \quad p_{2u} \geq \sum_{j \in J} v_{0ju} - \theta \quad \forall u \in U$$

$$(6) \quad \sum_{k \in Q_j} v_{kju} + \sum_{k \in Q_j} w_{kju} = 1 \quad \forall j \in J, u \in U$$

$$(7) \quad \sum_{k \in Q_j} v_{kju} \geq \Psi_j \quad \forall u \in U, j \in J$$

$$(8) \quad \sum_{j \in J} \Phi_j \sum_{k \in Q_j} v_{kju} \geq 1 \quad \forall u \in U$$

$$(9) \quad 0.95\delta \sum_{j \in J} \alpha'_j \leq \sum_{j \in J} \sum_{k \in Q_j} (w_{kju} \alpha'_j) \leq \delta \sum_{j \in J} \alpha'_j \quad \forall u \in U$$

Objective (1) maximizes the total amount of connected habitat in the area minus the penalties p_{1u} and p_{2u} (see Appendix A). Penalty p_{1u} denotes the number of connections to Node 0 above one in the deferral zone in period u . Penalty p_{2u} defines the number of connections to Node 0 in the management zone above θ nodes in period u , where θ is the total number of nodes with access points where roads enter the managed area. The coefficients f_1 and f_2 are scaling factors that adjust, respectively, the relative priorities for the objective term and the penalties (Appendix A). Table 1 lists the symbolic notations.

Equations 2 and 3 specify that the harvest deferral and management zones J_{defer} and J_{mgmt} must each be contiguous (see the formulation of eqs. 2 and 3 in eqs. A2.1–A2.4 and A3.1–A3.4 in Appendix A). Constraints (4, 5) define penalties p_{1u} and p_{2u} . Constraint (6) specifies that patch j can only be a member of the harvest deferral or management zone in period u but not both. Subset Q_j denotes patches k and an auxiliary Node 0 that are connected to patch j and can transmit flow to j (Fig. 3b). Constraint (7) ensures that the management zone includes patches j with permanent roads, as identified by the binary parameter $\Psi_j = 1$. Constraint (8) specifies that the management zone includes at least one patch in period u where roads enter the area. A binary parameter $\Phi_j = 1$ defines patches j with access points where permanent roads enter the area. Constraint (9) sets the target proportion of the harvest deferral area in period u to $[0.95\delta; \delta]$, where α'_j is the area of patch j .

2.1. Harvest planning model

Forest sites in the management zone can be harvested for timber. In boreal Canada, harvest planning is implemented at the scale of individual clear-cut blocks (NFD 2019). We depict the landscape as a set of N harvestable forest sites n covering the same area as the J patches in the zoning problem (eqs. 1–9) (Fig. 3c). The area of harvestable site n is smaller than the area of patch j (Fig. 3c); each patch j includes N_j sites n (Fig. 3d).

The harvest schedule covers a timespan of T periods, $t = 1, \dots, |T|$, where $|T|$ is a cardinality of set T . We only consider clear-cut harvest, which is the most common harvest type in Canada (NFD 2019), and assume binary harvest decisions in site n . For each site n , with a forested area a_n , we define a set

of harvest prescriptions I , $i = 1, \dots, |I|$, that represents all possible sequences of silvicultural events over a timespan T . A binary variable x_{ni} selects whether a prescription i is applied in site n over T periods.

For each site n , prescription i provides tree species composition, age, the volume of harvested softwood (γ_{1nit}) and hardwood (γ_{2nit}) timber in period t , and a cash flow φ_{ni} from harvesting n over T periods minus harvest, hauling, and regeneration costs, i.e.,

$$(10) \quad \phi_{ni} = \alpha_n \sum_{t \in T} (\gamma_{1nit}(\rho_1 - \sigma_{1n}) + \gamma_{2nit}(\rho_2 - \sigma_{2n}) - \eta_{nit})$$

Symbols ρ_1 and ρ_2 denote the mill gate timber unit prices for softwoods and hardwoods, σ_{1n} and σ_{2n} are the respective hauling unit costs from site n , and η_{nit} is the post-harvest regeneration cost. We estimate undiscounted cash flow φ_{ni} to avoid decisions prioritizing near-term profits and undervaluing long-term sustainability of harvest. The tree species composition and age define the amount of suitable caribou habitat in site n in period t , β_{nit} . We also used the site-based habitat amounts β_{nit} to calculate the amounts of habitat in patches j in periods u , β'_{ju} , in the zoning problem (eqs. 1–9).

We adapted the harvest scheduling Model I formulation (McDill et al. 2016) to find an optimal set of harvest prescriptions for area N over timespan T . Our harvesting problem maximizes net cash flow from managing the forest area N over T periods, i.e.,

$$(11) \quad \max \sum_{n \in N} \sum_{i \in I} \phi_{ni} x_{ni}$$

s.t.:

$$(12) \quad \sum_{i \in I} x_{ni} = 1 \quad \forall n \in N$$

$$(13) \quad 0.85m \leq \sum_{n \in N} \sum_{i \in I} (\gamma_{1nit} + \gamma_{2nit}) \alpha_n x_{ni} \leq m \quad \forall t \in T$$

$$(14) \quad \sum_{n \in N} \left(\sum_{i \in I} [(\varepsilon_{ni} - \varepsilon_{T \min}) \alpha_n x_{ni}] \right) \geq 0$$

Constraint (12) ensures that each forest site n is assigned one prescription only. A non-negative decision variable m defines the maximum volume of timber that can be harvested in any combination of the area and period t . Constraint (13) limits the allowable departure from the maximum harvest level m to 15%. We introduce a minimum average age of forest stands in area N at the end of planning horizon T , $\varepsilon_{T \min}$, and define ε_{ni} as the forest stand age in site n at the end of the planning horizon in prescription i , $t = |T|$. Constraint (14) ensures that the average age of forest stands in area N at the end of the horizon $t = |T|$ is greater than or equal to the target age $\varepsilon_{T \min}$.

Forest age composition in area N needs to be aligned with FMP requirements (NorthWinds 2021), which control the composition over planning horizon T at the level of forest type (Appendix B). We define a set of G forest types g , $g \in G$ ($|G|=4$ types in this case study, see Appendix B), and calculate the areas of mature and old-growth stands, χ_{gnit} and ξ_{gnit} , for

Table 1. Summary of the model variables and parameters.

Symbol	Parameter/variable name	Description
<i>Sets</i>		
J'	Forest patches—members of habitat protection or management zones plus an auxiliary Node 0	$j \in J'$
J	Forest patches—members of habitat protection or management zones (excluding Node 0)	$J \in J'$
J_{roads}	Forest patches with pre-existing roads	$J_{\text{roads}} \in J$
J_{defer}	Network of patches in the harvest deferral (habitat protection) zone	$J_{\text{defer}} \in J$
J_{mgmt}	Network of patches in the management zone	$J_{\text{mgmt}} \in J$
J_{access}	Network of patches in the road construction sub-problem	$J_{\text{access}} \in J$
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	$Q_j^+ \in J$
U	Habitat protection and management zone planning periods u	$u \in U, U = 5$
N	Forest sites n —potential candidates for harvesting	$n \in N$
G	Major forest types g	$g \in G, G = 4$
T	Harvest planning time periods t	$t \in T, T = 15$
I	Harvest prescriptions i	$i \in I$
<i>Decision variables</i>		
w_{jku}	Binary indicator of the connection via an arc jk in period u in the harvest deferral zone	$w_{jku} \in \{0,1\}$
y_{jku}	Amount of flow between the adjacent patches j and k in period u in the harvest deferral zone	$y_{jku} \geq 0$
x_{ni}	Binary selection of harvest schedule i in site n	$x_{ni} \in \{0,1\}$
v_{kju}	Binary indicator of the connection via an arc kj in the management zone in period u	$v_{kju} \in \{0,1\}$
z_{kju}	Amount of flow between the adjacent patches k and j in the management zone in period u	$z_{kju} \geq 0$
h_{kjt}	Binary indicator of the flow through arc kj (denotes road construction in j) in period t	$h_{kjt} \in \{0,1\}$
q_{kjt}	Amount of flow between patches k and j when a road is built from k to j in period t	$q_{kjt} \geq 0$
b_{jt}	Binary indicator of the occurrence of harvest in patch j in period t	$b_{jt} \in \{0,1\}$
m	Maximum volume of timber that can be harvested in any combination of area N and period t	$m \geq 0$
p_{1u}	Penalty on the number of connections to Node 0 above one in the harvest deferral zone in period u	$p_{1u} \geq 0$
p_{2u}	Penalty on the number of connections to Node 0 above θ in the management zone in period u	$p_{2u} \geq 0$
p_{3t}	Penalty on the number of patches with roads built above the defined maximum limit τ in period t	$p_{3t} \geq 0$
<i>Parameters: binary indicators</i>		
Φ_j	Binary indicator of patches j with access points where permanent roads enter the area	$\Phi_j \in \{0,1\}$
Ψ_j	Binary indicator of patches j with permanent roads	$\Psi_j \in \{0,1\}$
Γ_j	Binary indicator of patches j with permanent or temporary roads existing in period $t = 1$	$\Gamma_j \in \{0,1\}$
Λ_{nj}	Binary indicator that harvest site $n, n \in N$ is in patch $j, j \in J$	$\Lambda_{nj} \in \{0,1\}$
Ξ_{ut}	Binary time overlap between period u in the zoning problem and period t in harvest planning problem	$\Xi_{ut} \in \{0,1\}$
X_{nit}	Binary indicator that site n is harvested in period t in prescription i	$X_{nit} \in \{0,1\}$
Ω_{nt}	Binary indicator that site n is harvestable in period t according to the static Dynamic Caribou Harvest Schedule plan	$\Omega_{nt} \in \{0,1\}$
<i>Other parameters</i>		
β_{nit}	Amount of habitat in site n in prescription i in period t	$\beta_{nit} \geq 0$
β'_{ju}	Amount of habitat B_{ju} in patch j in period u (the habitat quality times the patch area)	$\beta'_{ju} \geq 0$
α_n	Forest area in harvest site n	$\alpha_n \geq 0$
α'_j	Area of patch j	$\alpha'_j > 0$
χ_{gnit}	Area of mature stands of forest type g in site n in prescription i in period t	$\chi_{gnit} > 0$
ξ_{gnit}	Area of old-growth stands of forest type g in site n in prescription i in period t	$\xi_{gnit} > 0$
ζ_{nit}	Area of young forest stands in site n in prescription i in period t	$\zeta_{nit} > 0$
γ_{1nit}	Volume of softwood timber available for the harvest at a patch n in period t in prescription i	$\gamma_{1nit} \geq 0$
γ_{2nit}	Volume of hardwood timber available for the harvest at a patch n in period t in prescription i	$\gamma_{2nit} \geq 0$
φ_{ni}	Net cash flow associated with harvesting a patch n according to prescription i	$\varphi_{ni} \geq 0$
ε_{ni}	Forest stand age in a site n at the end of the planning horizon if prescription i is applied	$\varepsilon_{ni} = [0;220]$
$\varepsilon_{T_{\min}}$	Average target age of forest stands in the managed area at the end of the planning horizon T	$\varepsilon_{T_{\min}} > 80$
δ	Target proportion of the harvest deferral area in any period u	$\delta \in [0;1]$
ρ_1	Unit price for softwood timber at the mill gate	$\rho_1 = \$70 \cdot \text{m}^{-3}$
ρ_2	Unit price for hardwood timber at the mill gate	$\rho_2 = \$50 \cdot \text{m}^{-3}$
η_{nit}	Post-harvest regeneration cost in site n in prescription i in period t	$\eta_{nit} \geq 0$
σ_{1n}, σ_{2n}	Hauling and harvest unit cost at site n for softwood and hardwood timber	$\sigma_{1n}, \sigma_{2n} > 0$

Table 1. (concluded).

Symbol	Parameter/variable name	Description
ψ_1, ψ_2	Fixed payments per unit of harvested softwood and hardwood timber to the species regeneration fund	$\psi_1, \psi_2 > 0$
π_j	Road maintenance cost in patch j in period t (only incurred if harvest occurs in j in period t)	$\pi_j > 0$
λ_j	Road construction cost in patch j	$\lambda_j > 0$
τ	Maximum number of patches with roads that can be built in period t	$\tau = 5$
θ	The number of patches with access points where roads enter the study area	$\theta = 2$
f_1 – f_3	Scaling factors	f_1 – $f_3 \in [0;1]$
M	Large positive (big-M) value	$M > 0$

each forest type g in site n in prescription i in period t . Constraints (15) and (16) set the minimum target areas $\chi_{g_{\min}}$ and $\xi_{g_{\min}}$ for mature and old-growth stands in forest type g in period t according to the FMP, i.e.,

$$(15) \quad \sum_{n \in N} \sum_{i \in I} \chi_{gnit} x_{ni} \geq \chi_{g_{\min}} \quad \forall t \in T, g \in G$$

$$(16) \quad \sum_{n \in N} \sum_{i \in I} \xi_{gnit} x_{ni} \geq \xi_{g_{\min}} \quad \forall t \in T, g \in G$$

The FMP also limits the maximum area of young stands in the area, $\zeta_{\max}$, i.e.,

$$(17) \quad \sum_{n \in N} \sum_{i \in I} \zeta_{nit} x_{ni} \leq \zeta_{\max} \quad \forall t \in T$$

where ζ_{nit} denotes the area of young stands in site n in prescription i in period t .

Conifer stands, which represent suitable habitat for caribou (Appendix B) but also high timber value, may not always regenerate after harvest (Harvey and Bergeron 1989; Carleton and MacLellan 1994). Replanting enhances regeneration of conifer stands but is costly. A common practice to cover replanting costs in Ontario is to set aside a portion of harvest revenue via fixed payments per unit of harvested timber to a special fund that pays for replanting. Thus, the replanting budget depends on the volume of timber harvested in period t and cannot exceed the sum of payments to the special fund from harvest revenue, i.e.,

$$(18) \quad \sum_{n \in N} \sum_{i \in I} \alpha_n \eta_{nit} x_{ni} \leq \sum_{n \in N} \sum_{i \in I} (\alpha_n x_{ni} (\gamma_{1nit} \psi_1 + \gamma_{2nit} \psi_2)) \quad \forall t \in T$$

where symbols ψ_1 and ψ_2 denote the fixed payments per unit of harvested softwood and hardwood timber, respectively, to the special fund. Note that the cash flow value φ_{ni} in objective (11) already accounts for the regeneration cost η_{nit} incurred in site n in prescription i in period t . Since we have two regeneration options, the prescriptions I include two subsets with natural regeneration and replanting of harvested sites for all sequences of silvicultural events in sites n (Appendix B).

2.2. Road construction

Harvesting remote areas requires building access roads. We adapted the model of Yemshanov et al. (2022) to track expansion of the forest road network over timespan T . To reduce combinatorial complexity, we implement the road construction

problem at the coarse scale of patches j used in the zoning problem (1–9). Since the area of patch j in network J is larger than the area of a harvest site n , we used a binary parameter Λ_{nj} to indicate whether site n is located in patch j ($\Lambda_{nj} = 1$ and $\Lambda_{nj} = 0$ otherwise) (Fig. 3d).

For each period t , we find a connected subgraph of roads that start from patches with roads either pre-existing or built in periods $1, \dots, t-1$ and end at patches with harvest in period t . Analogous to the zoning problem (1–9), an auxiliary Node 0 injects the flow into the network of patches with roads. Node 0 is connected to all patches with pre-existing roads where the construction of new roads could potentially start. The flow from Node 0 through all patches j with roads ensures the connectivity of the road network. Binary variable h_{kjt} indicates the selection of flow through arc kj between patches k and j , which denotes road construction from k to j in period t . A non-negative variable q_{kjt} defines the amount of flow between patches k and j when a road is built from k to j in period t (i.e., $q_{kjt} > 0$ when $h_{kjt} = 1$). Patches j with incoming flow from other patches or Node 0 compose the road access network J_{access} in period t , $J_{\text{access}} \in J$. The following constraints control the expansion of the road network over timespan T :

$$(19) \quad J_{\text{access}} \text{ is connected}$$

$$(20) \quad h_{0jt} \leq \Gamma_j \quad \forall j \in J$$

$$(21) \quad h_{0jt} \leq \Gamma_j + \sum_{t' \in [1; t-1]} \sum_{k \in Q_j} h_{kjd} \quad \forall t \in [2; |T|], t' \in T, j \in J$$

$$(22) \quad h_{kjt} \leq 2 - \Gamma_j - \Gamma_k \quad \forall j, k \in J_{\text{roads}}, t \in T$$

$$(23) \quad \sum_{t' \in [1; t]} \left[\sum_{k \in Q_j} h_{kjd} \right] \geq \frac{1}{M} \sum_{n \in N} \left(\Lambda_{nj} \sum_{i \in I} (x_{ni} x_{nit}) \right) \quad \forall t, t' \in T, j \in J, j \notin J_{\text{roads}}$$

$$(24) \quad p_{3t} \geq \sum_{j \in J} \sum_{k \in Q_j} (h_{kjt}) - \tau \quad \forall t \in T$$

$$(25) \quad \sum_{k \in Q_j} h_{kjt} \leq \sum_{u \in U} \left(\Xi_{ut} \left[1 - \sum_{k \in Q_j} w_{kju} \right] \right) \quad \forall j \in J, t \in T$$

$$(26) \quad 1 - \sum_{k \in Q_j} w_{kju} \geq \frac{1}{T} \sum_{t \in T} \left(\Xi_{ut} \sum_{k \in Q_j} h_{kjt} \right) \quad \forall j \in J, u \in U$$

$$(27) \quad b_{jt} \geq \frac{1}{M} \sum_{n \in N} \left(\Lambda_{nj} \sum_{i \in I} (x_{ni} X_{nit}) \right) \quad \forall j \in J, j \notin J_{\text{roads}}, t \in T$$

Equation 19 specifies that the patches j in road network J_{access} must be connected (see the formulation of eq. 19 in eqs. A19.1–A19.4 in Appendix A). Constraint (20) restricts the selection of arcs $0j$ connecting Node 0 to patches j with pre-existing roads in period $t = 1$. A binary parameter Γ_j defines patches with pre-existing roads ($\Gamma_j = 1$ and $\Gamma_j = 0$ otherwise). Constraint (21) restricts the flow from Node 0 in periods $t = 2, \dots, |T|$ to patches with roads either pre-existing or built in the previous periods $1, \dots, t - 1$. Subscript t' denotes time periods $t' = 1, \dots, t - 1, t' \in T$. Constraints (20) and (21) ensure that road construction between patches k and j in period t can only proceed from patches that had roads prior to period t . Constraint (22) prevents road construction between patches with pre-existing roads in period $t = 1$.

Constraint (23) implies that harvesting sites n in period t in patch j that did not have pre-existing roads (i.e., with $\Gamma_j = 0$) is only possible if the road network is extended to j during periods $1, \dots, t$. A binary parameter χ_{nit} indicates that site n is harvested in period t in prescription i (i.e., $\chi_{nit} = 1$ when $\gamma_{1nit} + \gamma_{2nit} > 0$). Subscript t' denotes time periods $1, \dots, t, t' \in T$.

Constraint (24) defines penalty p_{3t} for each period t as equal to the total number of patches with roads built above the maximum limit τ . The τ value is based on the historical extent of road construction activities in the area. Constraint (25) prevents road construction to a patch j if j is in the harvest deferral zone in period t . A binary parameter Ξ_{ut} indicates that harvest period t occurs within a planning period u in the zoning problem (1–9) ($\Xi_{ut} = 1$ and $\Xi_{ut} = 0$ otherwise). Constraint (26) ensures that patch j is assigned to the management zone in period u if roads are built in j during the period u . Constraint (27) defines a binary decision variable b_{jt} that indicates harvest in patch j in period t and is used to track the road maintenance cost in patch j if harvest occurs in j in period t . The site-level harvest planning model ultimately is reconciled with the coarser-scale habitat zoning and road construction at the patch level.

2.3. Full problem formulation

The full problem maximizes the weighted sum of the total amount of caribou habitat in area N and the net cash flow from harvest minus road construction and maintenance costs and penalties p_1 – p_3 , i.e.,

$$(28) \quad \max f_1 \sum_{n \in N} \sum_{i \in I} \sum_{t \in T} (\beta_{nit} x_{ni}) + \left(\sum_{n \in N} \sum_{i \in I} (\phi_{ni} x_{ni}) - \sum_{t \in T} \sum_{j \in J} \left[b_{jt} \pi_j + \lambda_j \sum_{k \in Q_j} h_{kjt} \right] - \sum_{u \in U} f_2 (p_{1u} + p_{2u}) - \sum_{t \in T} (f_3 p_{3t}) \right)$$

subject to constraints (2–9, 12–27) and

$$(29) \quad \frac{1}{M} \sum_{n \in N} \left(\Lambda_{nj} \sum_{i \in I} \left(x_{ni} \sum_{t \in T} (\Xi_{ut} X_{nit}) \right) \right) \leq 1 - \sum_{k \in Q_j} w_{kju} \quad \forall j \in J, u \in U$$

The first term in objective (28) estimates the total amount of habitat, the second term denotes harvest revenue minus the road construction and maintenance cost, and the last two terms depict the penalties. Symbol π_j denotes the road maintenance cost in patch j in period t . Since the habitat amount and harvest revenue have different units, we needed a scaling factor f_1 to balance the terms in the objective equation. The scaling factor f_1 is set to 0.1 to give harvest revenue a slight priority over habitat protection. The use of penalties p_{1u} , p_{2u} , and p_{3t} in the full problem (2–9, 12–28) is intended to keep the solution feasible in the presence of errors in the spatial data that otherwise would cause violations of hard constraints. In this context, the scaling factors f_2 and f_3 should be set sufficiently high to push the model towards a solution with zero penalties under normal circumstances. The penalties would be positive in the presence of complex patterns in the underlying spatial data (such as the presence of isolated harvestable regions or habitat refugia surrounded by the management zone). The penalty formulation of the constraints in the network flow sub-problems also helps reduce the time to find a feasible solution compared to a hard constraint formulation. Constraint (29) ensures no harvesting in patches j as assigned to the harvest deferral zone in period u .

We modified the zoning problem (2–9, 12–28) to follow the DCHS policy that restricts harvest in site n in period t to a fixed schedule outlined in the area's FMP (Fig. 2). For each harvest site n , a binary parameter Ω_{nt} defines whether a site n can be harvested in period t according to the DCHS plan ($\Omega_{nt} = 1$ and $\Omega_{nt} = 0$ otherwise). Constraint (30) restricts harvest in period t to regions prescribed by the DCHS plan, i.e.,

$$(30) \quad \sum_{i \in I} x_{ni} X_{nit} \leq \Omega_{nt} T \quad \forall t \in T, n \in N$$

The left side of eq. 30 defines the number of harvest events in site n over horizon T in prescription i .

The DCHS scenario maximizes the cash flow from timber harvest net of road construction and maintenance costs, i.e.,

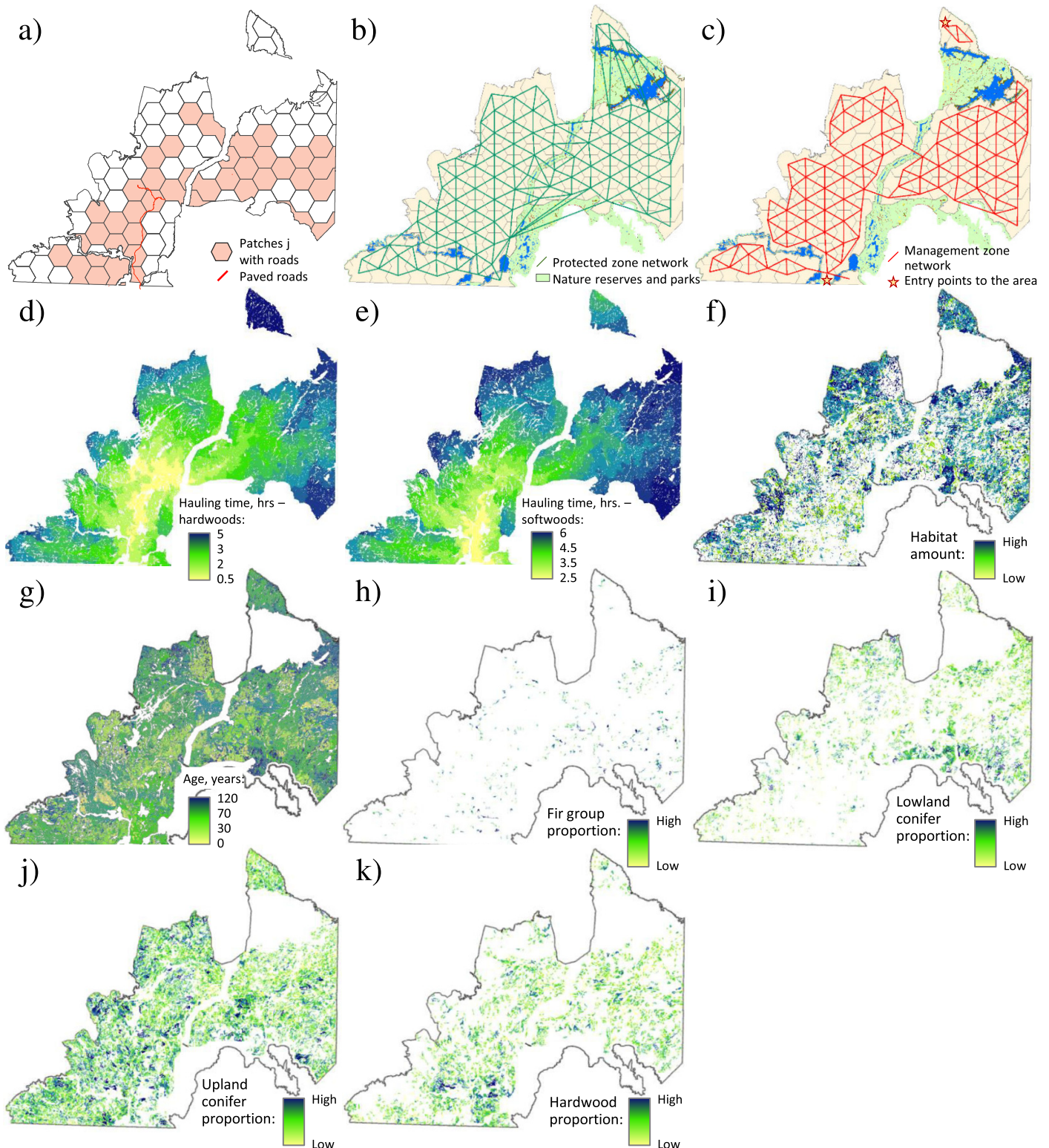
$$(31) \quad \max \sum_{n \in N} \sum_{i \in I} (\phi_{ni} x_{ni}) - \sum_{t \in T} \sum_{j \in J} \left[b_{jt} \pi_j + \lambda_j \sum_{k \in Q_j} h_{kjt} \right] - \sum_{t \in T} (f_3 p_{3t})$$

subject to constraints (12–24, 27, 30) and

$$(32) \quad \sum_{k \in Q_j} h_{kjt} \leq \sum_{n \in N} \left(\Lambda_{nj} \sum_{i \in I} (x_{ni} X_{nit}) \right) \quad \forall j \in J, t \in T$$

Constraint (32) allows road construction to patch j in period t only if there is one or more harvest events in patch j during that period. While the DCHS plan was applied to a set of defined DCHS regions (Fig. 2), road construction was tracked at the scale of patches j (Fig. 4a). Note that our DCHS scenario

Fig. 4. Model spatial inputs: (a) patches j with major roads at time $t = 0$; (b) habitat patch connectivity network in the harvest deferral zone; (c) site access network in the management zone; (d) hauling times for hardwood timber, hours; (e) hauling times for softwood timber, hours; (f) habitat amount β_{nit} at $t = 0$; (g) forest stand age at $t = 0$. General forest types (g: h) fir-dominated; (i) lowland conifer; (j) upland conifer; (k) hardwood. The maps were created using ESRI ArcMap version 10.3. Forest composition, age, and habitat layers were composed using the Ontario Forest Resources Inventory database (OMNRF 2020). Connectivity network and hexagon layers were composed using Python Geopandas package.



does not track habitat degradation by roads built through DCHS regions that were not harvested.

The DCHS problem is simpler than the full zoning problem, so we solved it first under the ecological constraints prescribed by the FMP. We then solved a series of zoning problems using the same set of ecological constraints and selected the solution with the harvested timber volume closest to the DCHS solution so that both scenarios harvested roughly the same volume of timber. We also evaluated a scenario with the anticipated present-day harvest level ($0.11\text{--}0.12\text{ M}\cdot\text{m}^3\cdot\text{ha}^{-1}$ of softwood species). This scenario used the same set of ecological constraints and helped estimate the timber supply cost at present-day harvest levels.

The full zoning model included 15.1 k continuous and 10.2 M binary variables before pre-solve. To reduce the solution time, we first solved the coarse-scale zoning model (1–9) for a desired deferral area target δ . Then, we solved the full problem with harvesting and road construction constraints and fixed decision variables from the previous zoning solution. This represented a suboptimal solution to the full problem because the previous zoning solution did not include feedback from the harvest decisions. However, it provided a sufficient basis from which to warm start the full problem. The model was composed in the General Algebraic Modeling System (GAMS 2022) and solved with the GUROBI linear programming solver (GUROBI 2022). We ran the full model on an HP Gen-10 workstation with dual Xeon Gold processors for 48 h or until reaching a 0.5% optimality gap (whichever came first).

2.4. Case study

We compared the DCHS and zoning policies in the Wabadowgang Noopming Forest Management Unit (FMU) in northwestern Ontario, Canada (Fig. 1). The area overlaps parts of the Nipigon and Brightsand caribou ranges (OMNR 2012) and is moderately fragmented by harvesting. The nearest timber markets include a sawmill and a pulp mill owned by Resolute Forest Products in Thunder Bay, Ontario, and a proposed wood pellet plant in Armstrong, Ontario (Neegan Burnside 2014; Bieler et al. 2019).

We estimated the starting values for age, timber volume, and land cover composition from Ontario's Forest Resource Inventory database (OMNRF 2020). The FMU area included 30 393 harvestable sites n . To estimate future timber volumes in harvest prescriptions, we applied yield curves for northwestern Ontario described in the Wabadowgang Noopming FMP (NorthWinds 2021). We adjusted the timber volume by the projected annual losses of forested area due to wildfires using fire regime zones from Boulanger et al. (2014). Future forest composition was adjusted by forest succession rules based on descriptions in the FMP (Appendix B).

Previous assessments of caribou movement patterns in Ontario suggested that individuals move regularly over relatively broad regions (Hornseth and Rempel 2015). Therefore, we depicted patches J as a network of 986 000 ha hexagons (Figs. 4a–4c). We used the CanVec database (NRCan 2019) and data provided by NorthWinds Environmental Services to

estimate the locations of major roads (Fig. 4a). We chose a relatively coarse resolution of the road network to reduce the combinatorial complexity of the problem. The road expansion problem tracked the average per-unit road construction and maintenance cost in patch j . Based on estimates provided by Resolute Forest Products (M. Kaiser, pers. comm.), the average road construction cost in patch j was set to $\$29\,000\text{ km}^{-1}$ (all costs are in Canadian dollars). Road maintenance costs for patch j were estimated at $\$3500\text{ km}^{-1}$ for each period when harvest occurred in j . The road cost value in patch j was based on an estimated median road length of 29 km patch^{-1} .

Hauling costs included an on-site harvest cost of $\$24.75\text{ m}^{-3}$ and costs for delivery of hardwood timber to a proposed pellet plant in Armstrong, Ontario, and softwood timber to mills in Thunder Bay, Ontario (Figs. 4d and 4e). The hauling costs assumed an hourly rate of $\$125\text{ h}^{-1}$, a load capacity of 41 tonne, and 30 min of time each to load, check, and unload harvested timber (M. Kaiser, pers. comm.) (Table 2).

The planning horizon T included 15×10 -year planning periods. The planning period u in the zoning problem (1–15) was set to 30 years, each of which included three harvest planning periods t , for a total of five periods u over a 150-year timespan. We used Ontario's Forest Resource Inventory (FRI) database (OMNRF 2020) to calculate the amount of suitable habitat for caribou in current conditions (Fig. 4f). Each forest site in the FRI was classified as one of 13 "forest units" that depict forest landscape composition classes (OMNR 2014a) (see Appendix B). Using forest composition and age, we estimated the amount of suitable caribou habitat in site n in period t in prescription i , b_{nit} , using a caribou habitat model for Ontario's Northwest Region (Elkie et al. 2018) (Appendix B).

Areas of mature and old-growth forest were tracked at the level of four general forest types g (Figs. 4h–4k): stands dominated by balsam fir; the lowland conifer group (black spruce and other conifer-dominated stands in poorly drained sites); the upland conifer group (conifer-dominated stands in other topographical positions); and the hardwood group dominated by deciduous species. For each site n , we estimated the areas of each forest group g reaching mature and old-growth status in prescription i in period t , χ_{gnit} and ξ_{gnit} , and the proportion of young stands ≤ 40 years old, ζ_{nit} , from age and forest composition data generated for prescriptions i (Table 3).

3. Results

The DCHS and zoning solutions harvested roughly the same volume of timber (Table 4) but applied different spatial approaches to allocate broad harvest regions (Fig. 5). The DCHS solution distributed the harvestable regions across the entire FMU area according to a pre-defined plan (Fig. 2) to ensure that each region was harvested at least once over a 100-year timespan. The zoning solution allocated the harvest deferral zone in areas with the largest amounts of suitable habitat, and frequently over a longer term. While the deferral zone was reconfigured every 30 years (Fig. 6a), 40.2% of the FMU area was kept unharvested for

Table 2. Summary of scenario inputs.

Assumption	Description
Harvest sites n	Ontario Ministry of Natural Resources and Forestry (OMNRF)'s Forest Resource Inventory spatial polygons (potential harvest blocks)—0.1–150 ha (OMNRF 2020)
Temporal resolution t	10-year periods
Planning horizon T	150 years
Initial forest composition and age	OMNRF's Forest Resource Inventory (OMNRF 2020)
Caribou habitat suitability	Elkie et al. (2018)—based on forest stand age and forest composition: a score of 1.0 is assigned for the presence of each habitat type (i.e., useable, preferred, or refuge); the habitat value is the sum of scores for all habitat types for a given forest composition/age
Habitat patches j	6000 ha hexagons
Minimum forest age when site n achieves a suitable habitat status	≥ 40 years after harvest
Timber hauling costs	Based on CanVec road network data (NRcan 2019), \$125 h ⁻¹ hauling rate, 41 tonne truckload, and 30 min loading, checking, and unloading times
On-site timber harvest cost	\$24.75 m ⁻³
Projected yield assumptions	Forest Management Plan approved by the Province of Ontario (NorthWinds 2021)
Future forest area loss due to fire	Fire return intervals from Boulanger et al. (2014)
Even harvest flow range between planning periods t and $t + 1$	15%

Table 3. Major forest types and target proportions of mature and old-growth stands.

Forest types, g	Forest units (as per forest management plan)	Retention area target in period t , $\times 1000$ ha	
		Mature, $\chi_{g_{\min}}$	Old-growth, $\xi_{g_{\min}}$
Fir	Balsam fir-dominant conifer stands	0	2.57
Lowland conifers	Black spruce lowland, other conifer lowland	14.76	61.86
Upland conifers	Black spruce, black spruce conifer-dominant mix, conifer mix, jack pine-dominant, jack pine mix, red and white pine mix	23.76	117.71
Hardwoods	Birch-dominant, hardwood-dominant, hardwood mix, poplar-dominant	9.04	17.13

120 years or longer (Table 5). Changes in the configuration of the deferral zone were driven by changes in habitat suitability patterns and local timber availability through time (Fig. 6b).

In general, the DCHS plan aims to keep 40% of the area as a no-harvest zone with average forest age above 60 years, which translates to an 80–100-year timespan without harvest over a 150-year horizon (Table 5, Fig. 7a). In the DCHS scenario, 19% of the area was exempt from DCHS and eligible to be harvested at any time (Fig. 2, callout I). A similar harvest regime was allocated to 39.4% of the area in the zoning scenario (Fig. 7b). The maximum timespan without harvesting in the DCHS scenario was 100 years, whereas the zoning scenario was able to keep 39.3% of the FMU area without harvest for the entire horizon (150 years). These areas were located near parks and nature reserves and included the highest-quality habitat for caribou. In each planning period, the deferral zone remained connected (Figs. 6b and 7b). Note that our habitat connectivity network J allowed habitat to be connected through the protected reserves and provincial parks adjacent to the harvestable areas (Fig. 4b). This led to the creation of two deferral regions, one along the northern FMU border and a smaller region in the southeastern part of

the FMU that is adjacent to nature reserves along the northern shores of Lake Nipigon (Fig. 7b). The management zone included the fragmented areas with existing roads and previous history of harvest in the southern and central parts of the area (Figs. 6a and 7b).

The maximum level of sustainable harvest in the DCHS and zoning scenarios was 0.25 M·m³·year⁻¹, including 0.15 M·m³·year⁻¹ of softwoods (Table 4). At this level, the zoning scenario maintained the habitat in the harvest deferral zone over approximately 46% of the area in any period t . The bulk of the harvest was allocated close to the network of logging roads in the southern and central portions of the FMU (Fig. 5b). By design, the harvestable regions in the DCHS scenario were distributed across the entire FMU area (Fig. 5a), which necessitated building a larger network of forest roads than in the zoning scenario (Table 4, Fig. 8a). The road construction provided access to a larger footprint than in the zoning scenario (Figs. 7c and 7d). The peak period of road construction activities lasted longer in the DCHS scenario, and these activities cost more than that in the zoning scenario (Table 4, Fig. 8a).

The zoning scenario had 19% less area designated for habitat protection in any period t , yet the area accounted for

Table 4. Harvest summary for DCHS and zoning scenarios.

Scenario	Harvest area, M·ha	Net cash flow, \$M	Road cost, \$M		Mean harvest volume, M·m ³ ·year ⁻¹		Mill gate timber unit cost, \$·m ⁻³ harvested timber		Suitable habitat in period <i>t</i>		Replanting cost			
			Construction	Maintenance	Total	Softwoods	Without road construction	With road construc- tion	Road cost	Habitat amount	Protected area proportion	\$M·year ⁻¹ budget	% of replant. budget	
Maximum sustainable harvest volume target (baseline)														
DCHS	0.221	1103.6	92.3	58.7	0.248	0.151	40.03	42.51	2.48	12.06	0.65*	0.758	83%	
Zoning	0.188	1114.3	55.6	37.96	0.249	0.151	39.78	41.27	1.49	12.22	0.46	0.895	98%	
Limiting the harvest volume of softwoods to 0.12 m ³ ·year ⁻¹														
DCHS	0.146	611.0	65.4	35.1	0.160	0.111	43.39	46.12	2.73	13.14	0.65*	0.673	100%	
Zoning	0.122	661.8	52.8	37.7	0.163	0.112	41.74	43.90	2.16	13.13	0.46†	0.667	99%	

*Not accounting for disturbances due to negative impact of roads built through Dynamic Caribou Harvest Schedule regions without harvest.

†The zoning solution used a configuration of the harvest deferral and management zone from the maximum sustainable harvest solution.

roughly the same amount of habitat β_{nit} (which is the habitat quality times patch area) (Table 4, Fig. 8a). This is because the zoning scenario protected the highest-quality habitat in the deferral zone while concentrating the harvest in a 15% smaller footprint than in the DCHS scenario.

The timber supply unit cost in the zoning scenario was \$1.24 m⁻³ cheaper than in the DCHS scenario (Table 4). This difference, while small, approaches the royalties that timber companies pay to the province for harvesting Grade 2 timber according to Ontario Crown Timber Charges (OMNRF 2022). The cost difference was mainly due to higher road construction costs and a less flexible harvest schedule in the DCHS scenario, which does not permit full utilization of the available timber supply in the area.

The replanting budgets were close in both scenarios and characterized by similar dynamics (Fig. 8b). The zoning scenario utilized the entire replanting budget (97.9%), whereas the DCHS scenario utilized a lower percentage of the budget (82.8%) (Table 4). Replanting is more cost-effective in the zoning scenario because the harvest occurred over a smaller area than in the DCHS scenario.

The behavior of the solutions with present-day harvest levels resembled the solutions with maximum sustainable harvest levels (Table 4). These solutions harvested 0.11 M·m³·year⁻¹ of softwoods and 0.05 M·m³·year⁻¹ of hardwood species and fully utilized the replanting budget. The timber supply unit cost in the zoning solution was \$2.22 m⁻³ lower than in the DCHS solution. Both solutions protected the same amount of habitat (Table 4).

The DCHS and zoning scenarios used the same set of ecological constraints, which explains the relatively minor differences in forest age structure between scenarios (Fig. 8c). Over the long term, the zoning scenario protected a larger area of old-growth forests but created more young forest stands in the FMU. This is because the harvest was concentrated in a smaller area, while a significant portion of the FMU in the deferral zone was left unharvested over a long period.

We did not find significant differences in the composition of broad forest types *g* over time between the DCHS and zoning scenarios (Fig. 9a). Over the long term, the zoning scenario protected a larger area of old-growth and mature upland conifer stands (Fig. 9b) and a larger area of old-growth hardwood-dominated stands (Fig. 9c). This is a result of long harvest deferral periods across more than 39% of the FMU under the zoning approach. Since high-quality habitat for caribou is often represented by mature and old conifer-dominated stands, setting aside a larger area of these for habitat protection also helps attain the old-growth conservation objective.

4. Discussion

Increasingly, Canadian provinces and territories aim to reduce the negative impacts of forestry activities on boreal caribou populations by developing dynamic forest plans that account for habitat connectivity and suitability. Our study evaluated two distinct but practical management policies that strive to protect caribou populations in areas of forestry

Fig. 5. Optimal harvest selection and habitat connectivity patterns in the Dynamic Caribou Harvest Schedule (DCHS) and zoning scenarios: (a) DCHS scenario and (b) zoning scenario. Regions shaded in green indicate no-harvest regions in period t ; hexagons outlined in bold indicate road construction in period t ; red polygons indicate harvest in sites n in period t . The maps were composed using Python Geopandas package.

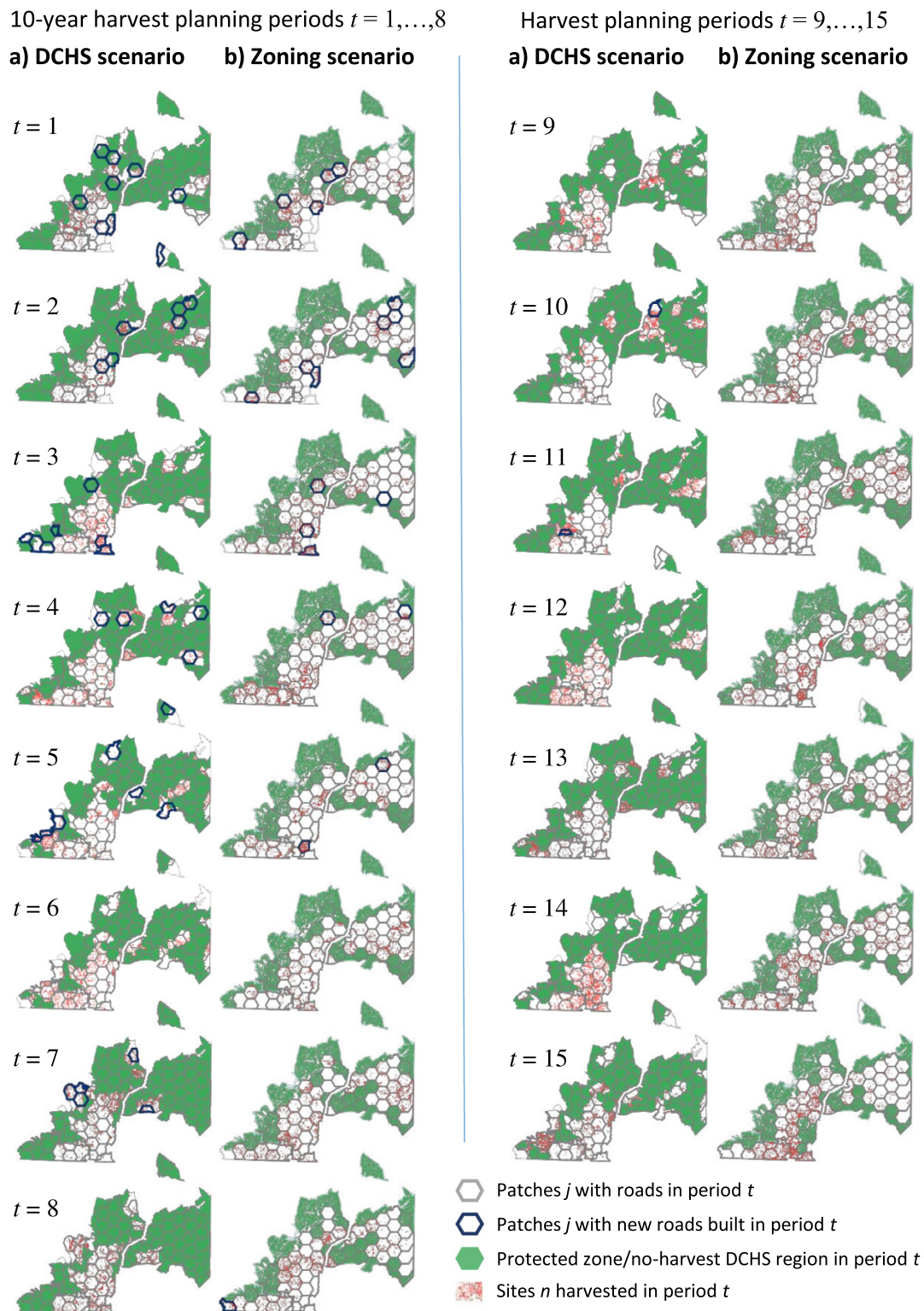


Fig. 6. Optimal configuration of the harvest deferral and management zones in the zoning scenario: (a) landscape zoning in period u (a 30-year timespan). Green hexagons indicate the harvest deferral zone and white hexagons indicate the management zone and (b) habitat amounts in patches j in period u . The maps were composed using Python Geopandas package.

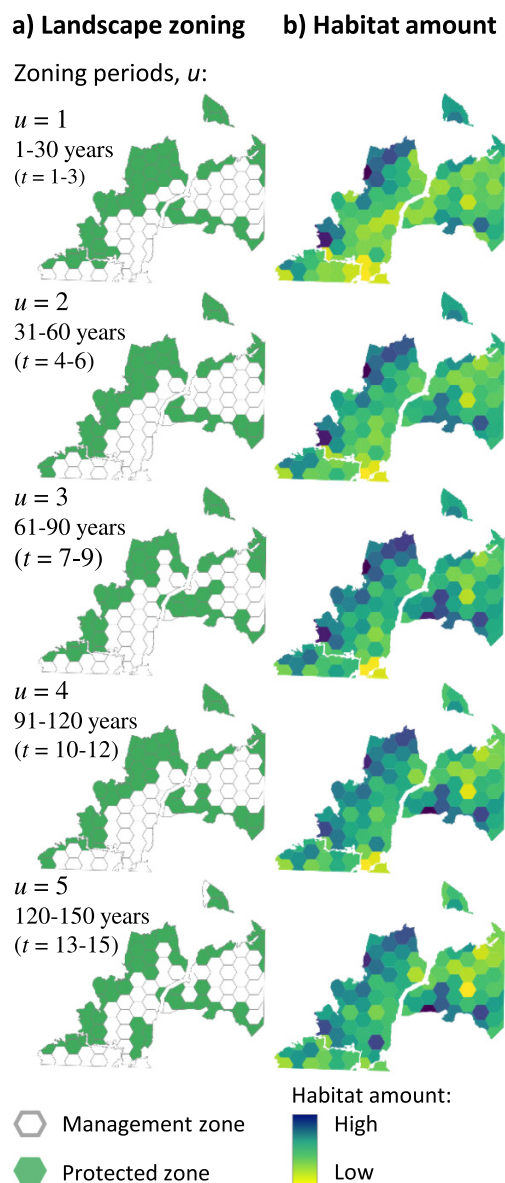


Table 5. Proportion of the Forest Management Unit area by the continuous protection timespan (years) in Dynamic Caribou Harvest Schedule (DCHS) and zoning scenarios.

Continuous harvest deferral period over horizon T , years	Zoning scenario	DCHS scenario
0	39.4%	19.0%
30	12.8%	
60 (60–80)	2.5%	12.7%
90 (80–100)	5.2%	68.3%
120	0.9%	
150	39.3%	

activities. Our intent was not to emphasize the advantages of either approach but instead offer a methodological framework to compare these (and potentially other) landscape management policies. The use of the same set of ecological constraints aligned with the FMP enabled a fair comparison between the two scenarios.

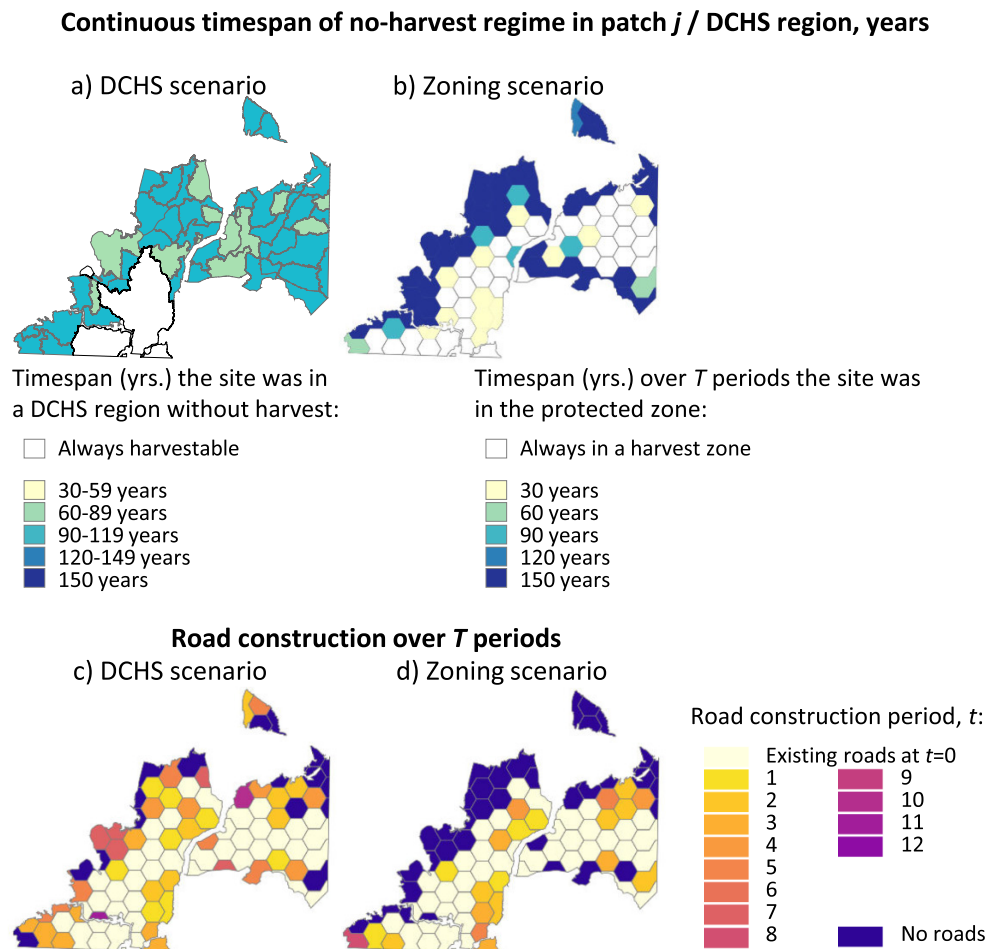
The DCHS approach concentrates harvest in compact regions distributed across the entire FMU but establishes undisturbed caribou habitat around these harvested areas. With the primary goal of protecting caribou populations, the DCHS may overlook several economic aspects that impact the cost of timber supply. Since the DCHS harvest regions are distributed across the entire FMU area, this requires building and maintaining a network of access roads, which increases the cost of timber supply. Furthermore, the DCHS, while trying to protect a desired proportion of the unharvested forest area, has limited flexibility to adjust the timing and harvest locations in response to rapid changes in forest composition or market-driven timber demand. As shown in a previous study (Yemshanov et al. 2021a), finding the optimal timing of harvest in DCHS regions helps reduce the timber supply cost but poses a hard combinatorial problem that requires further work to make the approach practical. The DCHS scenario was able to maintain a larger unharvested area than the zoning scenario. However, the network of access roads created in the DCHS scenario is likely to promote both human and predator access to undisturbed areas and, in turn, place further pressure on caribou populations (Dickie et al. 2017).

An alternative zoning approach divides the landscape into management and harvest deferral zones without enforcing the allocation of harvest regions across the FMU. Within the management zone, timber companies have flexibility to reallocate harvest in response to rapid changes in timber markets. Our results indicate that the zoning approach yields a lower timber cost than the DCHS scenario. The difference was relatively small in our case study because the DCHS scenario excluded the south-central portion of the FMU from the DCHS rules (Fig. 2, callout I). This region occupies 19% of the FMU area and has a fully flexible harvest regime. The impact of the DCHS rules on timber cost would be more significant if the entire FMU area was subject to these rules.

In our zoning scenario, the configuration of the road network and the distribution of high-quality caribou habitat translated to a relatively stable designation of the harvest deferral and management zones over time. Semi-permanent allocation of the zones over time helps facilitate long-term protection of high-quality caribou habitat. Although the zoning scenario protected less total area than the DCHS scenario in any period t , it protected virtually all areas with high concentrations of highly suitable habitat.

Our simulations did not account for all possible factors that might come into play for boreal caribou management. First, compared to the DCHS, the zoning approach protects less undisturbed habitat as defined in the recovery strategy for boreal caribou (EC 2012) that prescribes a 65% undisturbed habitat threshold. Note that this threshold applies to entire caribou ranges (which is a broader scale than the extent of

Fig. 7. Continuous timespan without harvesting, years: (a) Dynamic Caribou Harvest Schedule (DCHS) scenario and (b) zoning scenario. The timing of access road construction in the harvestable area: (c) DCHS scenario and (d) zoning scenario. Color shades indicate period t when new roads were built in patch j . The maps were composed using Python Geopandas package.



our study). Other areas outside of the FMU (such as parks and protected reserves) may contribute to achieving this conservation management threshold. Nevertheless, there exists a risk that a zoning approach may eventually exclude caribou from intensive management zones and push animals to harvest deferral zones, further reducing their distribution range (Schaefer 2003; EC 2012). The DCHS allows for a better interspersed management and conservation zones at the landscape scale, potentially supporting the co-occurrence of caribou and timber management over long temporal scales. However, DCHS promotes more road construction and maintains forests at a younger age, on average, than the zoning approach, meaning that alternate prey and predator species may be favored to the detriment of caribou (Wittmer et al. 2007). These trade-offs will need to be further evaluated in the context of caribou conservation. Furthermore, increasing the forest age in the harvest deferral zone is likely to increase the fire risk as the fuel accumulation period gets longer. The zoning approach would likely fail if economic and political pressures triggered the harvesting in the protection zones

before the end of the harvest plan (here, 150 years). This risk is always present, as timber industries may struggle to adapt to external pressures of changes in timber markets and climate change (Brecka et al. 2020).

Our model formulation followed the ecological sustainability prescriptions as defined in the FMP but used simpler forest succession rules at the level of major forest types than the succession rules in the plan. In addition, the model tracked the road construction cost at a coarse spatial resolution of habitat patches j , which might misrepresent local road costs in some areas. The coarse resolution helped reduce the computational complexity of the road construction problem, which is known to be combinatorically hard. Potentially, the problem could be formulated at a higher spatial resolution than patches j , but this would require introducing another network set and further increase the problem complexity. Since we aimed to track the general road construction feedback at a scale compatible with the size of DCHS regions, the use of a coarse resolution felt justified.

Fig. 8. The dynamics of road construction and replanting costs, habitat amounts, and the proportions of major forest age groups over time t : (a) habitat amount and road construction and maintenance cost; (b) the replanting budget and actual cost; and (c) FMU area proportion occupied by mature, old-growth, and young forest stands.

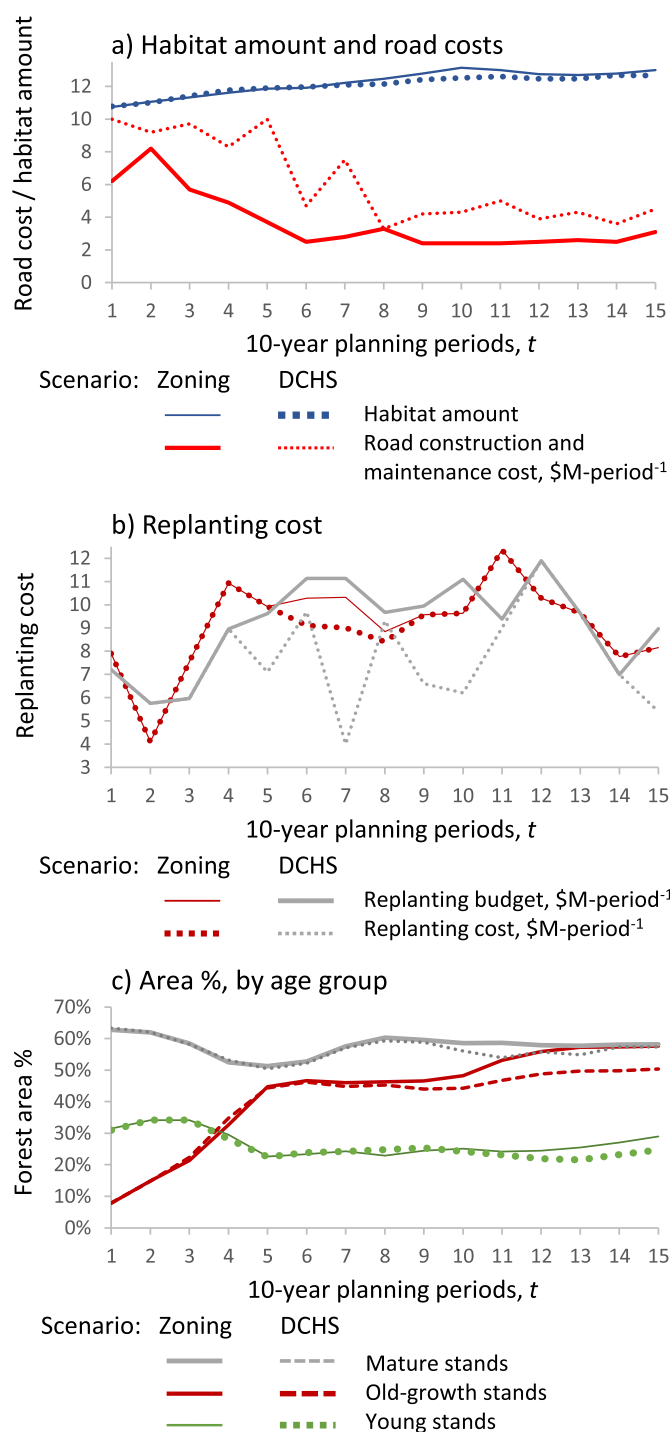
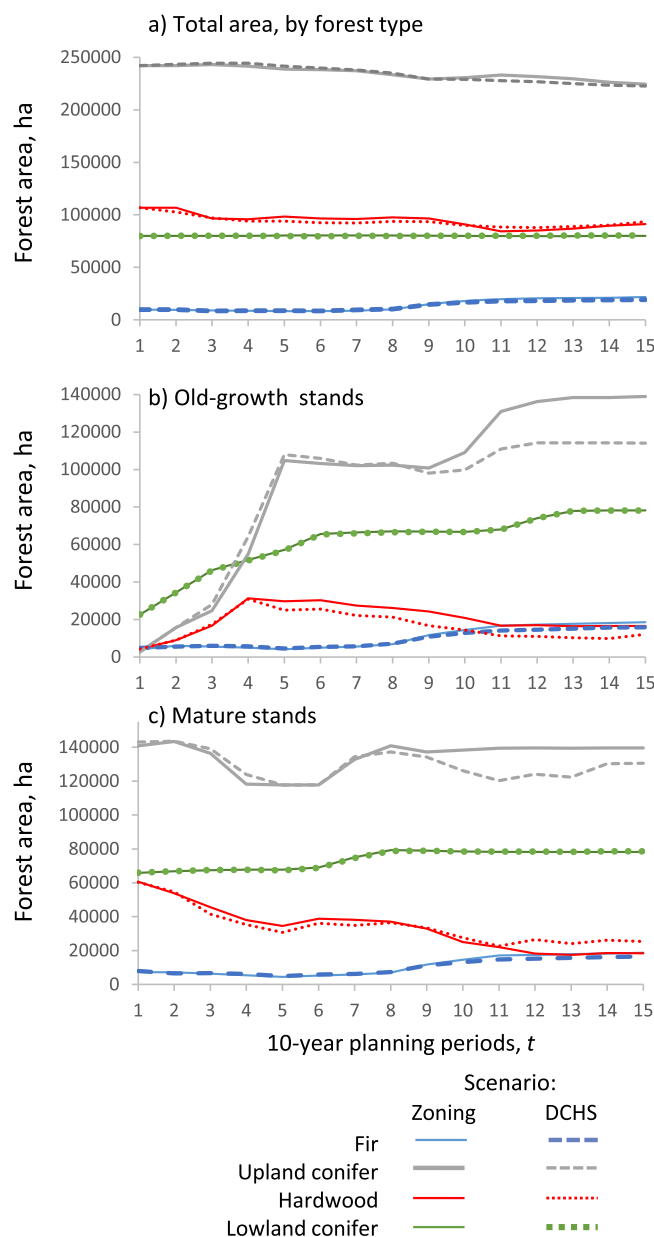


Fig. 9. Area of major forest types in planning periods t : (a) total area, by forest type g , ha; (b) the area of old-growth stands, by forest type g , ha; and (c) the area of mature stands, by forest type g , ha. General forest types: fir-dominated (in blue), upland conifer (in gray), lowland conifer (in green), and hardwood (in red).



We would like to thank Whitesand First Nation for the community input, Ontario Ministry of Northern Development, Mines, Natural Resources and Forestry Thunder Bay District for sharing forest management planning information, and Resolute Forest Products for providing operational estimates on road and wood transport costs. Special thanks to Tom Nudds (University of Guelph) and Mike Briennesse (Ontario Ministry of Natural Resources and Forestry) for helpful comments on an earlier version of the manuscript.

Acknowledgements

Funding for this work was provided by Natural Resource Canada's Cumulative Effects Program.

Article information

History dates

Received: 24 October 2022

Accepted: 10 July 2023

Accepted manuscript online: 13 July 2023

Version of record online: 23 August 2023

Copyright

© 2023 The Author(s). Permission for reuse (free in most cases) can be obtained from [creativecommons.org](https://creativecommons.org/licenses/by/4.0/).

Data availability

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

Author information

Author ORCIDs

Denys Yemshanov <https://orcid.org/0000-0002-6992-9614>

Author contributions

Conceptualization: DY, TH, JC, FHK

Data curation: JC, NL

Formal analysis: DY, TH, NL

Funding acquisition: DY

Investigation: DY, TH, JC, ML

Methodology: DY, FHK, ML

Project administration: DY

Software: DY

Supervision: DY

Validation: TH, JC

Visualization: NL

Writing – original draft: DY

Writing – review & editing: DY, TH, JC, FHK, ML

Competing interests

The authors declare there are no competing interests.

References

- Baskett, E.Z., and Kees, S. 2005. Spatial forest planning: a review. *Ecol. Modell.* **188**(2–4): 145–173. doi:[10.1016/j.ecolmodel.2005.01.059](https://doi.org/10.1016/j.ecolmodel.2005.01.059).
- Beauchesne, D., Jaeger, J.A., and St-Laurent, M.-H. 2013. Disentangling woodland caribou movements in response to clearcuts and roads across temporal scales. *PLoS ONE*, **8**(11): e77514. doi:[10.1371/journal.pone.0077514](https://doi.org/10.1371/journal.pone.0077514). PMID: 24223713.
- Bieler, A., Trush, M., and Jakob, J.B. 2019. Whitesand's BioEnergy Project. Ontario Centre for Workforce Innovation. Available from <https://ocwi-coie.ca/wp-content/uploads/2019/02/01-017-01-Whitesand-First-Nation-Final-Report-1.pdf> [accessed 15 March 2021].
- Boulanger, Y., Gauthier, S., and Burton, P.J. 2014. A refinement of models projecting future Canadian fire regimes using homogeneous fire regime zones. *Can. J. For. Res.* **44**: 365–376. doi:[10.1139/cjfr-2013-0372](https://doi.org/10.1139/cjfr-2013-0372).
- Brecka, A.F.J., Boulanger, Y., Searle, E.B., Taylor, A.R., Price, D.T., Zhu, Y., et al. 2020. Sustainability of Canada's forestry sector may be compromised by impending climate change. *For. Ecol. Manage.* **474**: 118352. doi:[10.1016/j.foreco.2020.118352](https://doi.org/10.1016/j.foreco.2020.118352).
- Carleton, T.J., and MacLellan, P. 1994. Woody vegetation responses to fire versus clear-cutting logging: a comparative survey in the central Canadian boreal forest. *Ecoscience*, **1**: 141–152.
- Cordeira, J., Gaston, K., and Pinto, L. 2005. Connectivity in priority area selection for conservation. *Environ. Model. Assess.* **10**(3): 183–192.
- Conrad, J., Gomes, C.P., van Hoes, W.-J., Sabharwal, A., and Suter, J. 2012. Wildlife corridors as a connected subgraph problem. *J. Environ. Econ. Manage.* **63**(1): 1–18. doi:[10.1016/j.jeem.2011.08.001](https://doi.org/10.1016/j.jeem.2011.08.001).
- Courbin, N., Fortin, D., Dussault, C., and Courtois, R. 2009. Landscape management for woodland caribou: the protection of forest blocks influences wolf-caribou co-occurrence. *Landscape Ecol.* **24**: 1375–1388. doi:[10.1007/s10980-009-9389-x](https://doi.org/10.1007/s10980-009-9389-x).
- Dickie, M., Serrouya, R., McNay, R.S., and Boutin, S. 2017. Faster and farther: wolf movement on linear features and implications for hunting behaviour. *J. Appl. Ecol.* **54**: 253–263. doi:[10.1111/1365-2664.12732](https://doi.org/10.1111/1365-2664.12732).
- Dilkina, B., Houtman, R., Gomes, C., Montgomery, C., McKelvey, K., Kendall, K., et al. 2016. Trade-offs and efficiencies in optimal budget-constrained multispecies corridor networks. *Conserv. Biol.* **31**: 192–202. doi:[10.1111/cobi.12814](https://doi.org/10.1111/cobi.12814).
- Dyer, S.J., O'Neill, J.P., Wasel, S.M., and Boutin, S. 2001. Avoidance of industrial development by woodland caribou. *J. Wildl. Manage.* **65**(3): 531–542. doi:[10.2307/3803106](https://doi.org/10.2307/3803106).
- Elkie, P., Green, K., Racey, G., Gluck, M., Elliott, J., Hooper, G., et al. 2018. Science and information in support of policies that address the conservation of woodland caribou in Ontario: occupancy, habitat and disturbance models, estimates of natural variation and range level summaries. Electronic Document. Version 2018. Ontario Ministry of Natural Resources, Forests Branch.
- Environment Canada (EC). 2011. Scientific assessment to support the identification of critical habitat for woodland caribou (*Rangifer tarandus caribou*), boreal population, in Canada. Ottawa, ON. 115p.
- Environment Canada (EC). 2012. Recovery strategy for the woodland caribou (*Rangifer tarandus caribou*), boreal population, in Canada. Species at Risk Act Recovery Strategy Series. Environment Canada, Ottawa, ON. Available from http://www.registrelep-sararegistry.gc.ca/virtual_sara/files/plans/rs%5Fcaribou%5Fboreal%5Fcaribou%5F0912%5F01%2Epdf [accessed 10 March 2020].
- Ferguson, S.H., and Elkie, P.C. 2004a. Habitat requirements of boreal forest caribou during the travel seasons. *Basic Appl. Ecol.* **5**: 465–474. doi:[10.1016/j.baec.2004.04.011](https://doi.org/10.1016/j.baec.2004.04.011).
- Ferguson, S.H., and Elkie, P.C. 2004b. Seasonal movement patterns of woodland caribou (*Rangifer tarandus caribou*). *J. Zool.* **262**: 125–134. doi:[10.1017/S0952836903004552](https://doi.org/10.1017/S0952836903004552).
- Fryxell, J.M., Avgar, T., Liu, B., Baker, J.A., Rodgers, A.R., Shuter, J., et al. 2020. Anthropogenic disturbance and population viability of woodland caribou in Ontario. *J. Wildl. Manage.* **84**: 636–650. doi:[10.1002/jwmg.21829](https://doi.org/10.1002/jwmg.21829).
- GAMS (GAMS Development Corporation). 2022. General algebraic modeling system (GAMS). Washington, DC, USA. Available from <http://www.gams.com> [accessed July 2022].
- Government of Canada (GoC). 2020. Summary of the cost-sharing understanding for the protection and recovery of boreal caribou and its habitat in Quebec. Available from <https://www.canada.ca/en/environment-climate-change/services/species-risk-public-registry/conservation-agreements/summary-cost-sharing-boreal-caribou-quebec-2020.html> [accessed 6 February 2022].
- GUROBI (Gurobi Optimization Inc.). 2022. GUROBI optimizer reference manual. Version 9.5. Available from <http://www.gurobi.com> [accessed May 2022].
- Harvey, B.D., and Bergeron, Y. 1989. Site patterns of natural regeneration following clear-cutting in northwestern Québec. *Can. J. For. Res.* **19**: 1458–1469. doi:[10.1139/x89-222](https://doi.org/10.1139/x89-222).
- Hornseth, M.L., and Rempel, R.S. 2015. Seasonal resource selection of woodland caribou (*Rangifer tarandus caribou*) across a gradient of anthropogenic disturbance. *Can. J. Zool.* **94**: 79–93. doi:[10.1139/cjz-2015-0101](https://doi.org/10.1139/cjz-2015-0101).
- Houle, M., Fortin, D., Dussault, C., Courtois, R., and Ouellet, J.P. 2010. Cumulative effects of forestry on habitat use by gray wolf (*Canis lupus*) in the boreal forest. *Landscape Ecol.* **25**(3): 419–433. doi:[10.1007/s10980-009-9420-2](https://doi.org/10.1007/s10980-009-9420-2).
- Jafari, N., and Hearne, J. 2013. A new method to solve the fully connected reserve network design problem. *Eur. J. Oper. Res.* **231**(1): 202–209. doi:[10.1016/j.ejor.2013.05.015](https://doi.org/10.1016/j.ejor.2013.05.015).

- Latham, A.D.M., Latham, C., McCutchen, N.A., and Boutin, S. 2011. Invading white-tailed deer change wolf-caribou dynamics in northeastern Alberta. *J. Wildl. Manage.* **75**(1): 204–212. doi:10.1002/jwmg.28.
- Lesmerises, R., Ouellet, J.-P., Dussault, C., and St-Laurent, M.-H. 2013. The influence of landscape matrix on isolated patch use by wide-ranging animals: conservation lessons for woodland caribou. *Ecol. Evol.* **3**(9): 2880–2891. doi:10.1002/ece3.695.
- Martell, D.L., Gunn, E.A., and Weintraub, A. 1998. Forest management challenges for operational researchers. *Eur. J. Oper. Res.* **104**(1): 1–17. doi:10.1016/S0377-2217(97)00329-9.
- Martin, A.B., Ruppert, J.L.W., Gunn, E.A., and Martell, D.L. 2017. A re-planning approach for maximizing woodland caribou habitat alongside timber production. *Can. J. For. Res.* **47**: 901–909. doi:10.1139/cjfr-2016-0254.
- McDill, M., Rebain, S., and Braze, J. 2002. Harvest scheduling with area-based adjacency constraints. *For. Sci.* **48**(4): 631–642.
- McDill, M.E., Tóth, S.F., John, R.T., Braze, J., and Rebain, S.A. 2016. Comparing model I and model II formulations of spatially explicit harvest scheduling models with maximum area restrictions. *For. Sci.* **62**(1): 28–37. doi:10.5849/forsci.14-179.
- Ministère des Forêts, de la Faune et des Parcs (MFFP). 2022. La stratégie pour les caribous forestiers et montagnards. Available from <https://mffp.gouv.qc.ca/la-faune/especes/caribou-quebec/amenagement-habitat-caribou-forestier/> [accessed 5 March 2022].
- National Forestry Database (NFD). 2019. Harvest. 5.2 area harvested by jurisdiction, tenure, management and harvesting method. Available from <http://nfdp.ccfm.org/en/data/harvest.php> [accessed 20 January 2021].
- Natural Resources Canada (NRCan). 2019. Topographic Data of Canada - CanVec Series. <https://open.canada.ca/data/en/dataset/8ba2aa2a-7bb9-4448-b4d7-f164409fe056> [accessed 10 May 2020].
- Neegan Burnside Ltd. 2014. Whitesand First Nation Cogeneration and Pellet Mill Project Design and Operations Report. Prepared by Neegan Burnside Ltd. for Sagatay Cogeneration LP, with its General Partner, Sagatay Cogeneration Ltd., and Whitesand First Nation as agent. October 2014. Available from https://www.whitesandfirstnation.com/assets/files/REA/final/030895_8_Design_and_Operations_Report.pdf [accessed 3 June 2021].
- NorthWinds Environmental Services (NorthWinds). 2021. 2023–2033 Wabadowgang Noopming Forest Management Plan. (WN 2023-2033 FMP) Prepared by NorthWinds Environmental Services. Available from https://nrip.mnr.gov.on.ca/s/fmp-online?language=en_US [accessed 5 June 2022].
- Öhman, K. 2000. Creating continuous areas of old forest in long term forest planning. *Can. J. For. Res.* **30**: 1817–1823. doi:10.1139/x00-103.
- Önal, H., and Briers, R.A. 2006. Optimal selection of a connected reserve network. *Oper. Res.* **54**(2): 379–388. doi:10.1287/opre.1060.0272.
- Ontario Ministry of Natural Resources (OMNR). 2009. Ontario's Woodland Caribou Conservation Plan. Queen's Printer for Ontario, Toronto, ON.
- Ontario Ministry of Natural Resources (OMNR). 2012. Ontario's Woodland Caribou Conservation Plan progress report winter 2012. Ontario Ministry of Natural Resources, Toronto, ON. Queen's Printer for Ontario. Available from <https://www.porcupineprospectors.com/wp-content/uploads/Woodland-Caribou.pdf> [accessed 4 March 2021].
- Ontario Ministry of Natural Resources (OMNR). 2014a. Forest management guide for boreal landscapes. Queen's Printer for Ontario, Toronto, ON.
- Ontario Ministry of Natural Resources (OMNR). 2014b. Range management policy in support of woodland caribou conservation and recovery. Queen's Printer for Ontario, Toronto, ON.
- Ontario Ministry of Natural Resources and Forestry (OMNRF). 2015. General habitat description for the forest-dwelling woodland caribou (*Rangifer tarandus caribou*). Available from <http://govdocs.ourontario.ca/node/29324> [accessed 10 January 2022].
- Ontario Ministry of Natural Resources and Forestry (OMNRF). 2020. Forest resources inventory (FIM v 2.2D) packaged product. Available from <https://geohub.lio.gov.on.ca/datasets/forest-resources-inventory-fim-v2-2d-packaged-product> [accessed 10 June 2021].
- Ontario Ministry of Natural Resources and Forestry (OMNRF). 2022. Crown timber charges for forestry companies. Available from <https://data.ontario.ca/dataset/crown-timber-charges-for-forestry-companies> [accessed 10 April 2022].
- Racey, G., Harris, A., Gerrish, L., Armstrong, E., McNicol, J., and Baker, J. 1999. Forest management guidelines for the conservation of woodland caribou: a landscape approach. Ontario Ministry of Natural Resources, Thunder Bay, ON. Available from <https://docs.ontario.ca/documents/2813/guide-woodland-caribou.pdf> [accessed 10 March 2020].
- Rempel, R.S., and Hornseth, M.L. 2018. Range-specific seasonal resource selection probability functions for 13 caribou ranges in Northern Ontario. Ontario Ministry of Natural Resources and Forestry, Science and Research Branch, Peterborough, ON. Science and Research Internal File Report IFR-01.
- Rettie, W.J., and Messier, F. 2001. Range use and movement rates of woodland caribou in Saskatchewan. *Can. J. Zool.* **79**: 1933–1940. doi:10.1139/z01-156.
- Ruppert, J.L.W., Fortin, M.-J., Gunn, E.A., and Martell, D.L. 2016. Conserving woodland caribou habitat while maintaining timber yield: a graph theory approach. *Can. J. For. Res.* **46**: 914–923. doi:10.1139/cjfr-2015-0431.
- Saher, D.J., and Schmiegelow, F.K.A. 2005. Movement pathways and habitat selection by woodland caribou during spring migration. *Special Issue. Rangifer*, **16**: 143–154.
- Schaefer, J.A. 2003. Long-term range recession and the persistence of caribou in the taiga. *Conserv. Biol.* **17**: 1435–1439. doi:10.1046/j.1523-1739.2003.02288.x.
- Sessions, J. 1992. Solving for habitat connections as a Steiner network problem. *For. Sci.* **38**(1): 203–207.
- Snyder, S., and ReVelle, C. 1997. Dynamic selection of harvests with adjacency restrictions: the SHAR model. *For. Sci.* **43**(2): 213–222.
- St. John, R., Öhman, K., Tóth, S.F., Sandström, P., Korosuo, A., and Eriksson, L.O. 2016. Combining spatiotemporal corridor design for reindeer migration with harvest scheduling in northern Sweden. *Scand. J. For. Res.* **37**(1): 655–663. doi:10.1080/02827581.2016.1195441.
- Tóth, S.F., Haight, R.G., Snyder, S., George, S., Miller, J., Gregory, M., and Skibbe, A. 2009. Reserve selection with minimum contiguous area restrictions: an application to open space protection planning in suburban Chicago. *Biol. Conserv.* **142**(8): 1617–1627. doi:10.1016/j.biocon.2009.02.037.
- Tóth, S.F., Haight, R.G., and Rogers, L.W. 2011. Dynamic reserve selection: optimal land retention with land-price feedbacks. *Oper. Res.* **59**(5): 1059–1078. doi:10.1287/opre.1110.0961.
- Vors, L.S., Schaefer, J.A., Pond, B.A., Rodgers, A.R., and Patterson, B.R. 2007. Woodland caribou extirpation and anthropogenic landscape disturbance in Ontario. *J. Wildl. Manage.* **71**: 1249–1256. doi:10.2193/2006-263.
- Wittmer, H.U., Sinclair, A.R.E., and McLellan, B.N. 2005. The role of predation in the decline and extirpation of woodland caribou. *Oecologia*, **144**: 257–267. doi:10.1007/s00442-005-0055-y.
- Wittmer, H.U., McLellan, B.N., Serrouya, R., and Apps, C.D. 2007. Changes in landscape composition influence the decline of a threatened woodland caribou population. *J. Anim. Ecol.* **76**: 568–579. doi:10.1111/j.1365-2656.2007.01220.x.
- Yemshanov, D., Haight, R.G., Liu, N., Parisien, M.-A., Barber, Q., Koch, F.H., et al. 2020. Assessing the trade-offs between timber supply and wildlife protection goals in boreal landscapes. *Can. J. For. Res.* **50**: 243–258.
- Yemshanov, D., Haight, R.G., Rempel, R., Liu, N., and Koch, F.H. 2021a. Protecting wildlife habitat in managed forest landscape—how can network connectivity models help? *Nat. Resour. Model.* **34**: e12286. doi:10.1111/nrm.12286.
- Yemshanov, D., Haight, R.G., Liu, N., Rempel, R., Koch, F.H., and Rodgers, A. 2021b. Balancing large-scale wildlife protection and forest management goals with a game theoretic approach. *Forests*, **12**: 809. doi:10.3390/f12060809.
- Yemshanov, D., Haight, R.G., Liu, N., Rempel, R., Koch, F.H., and Rodgers, A. 2022. Exploring the tradeoffs among forest planning, roads and wildlife corridors: a new approach. *Optim. Lett.* **16**: 747–788. doi:10.1007/s11590-021-01745-w.

APPENDIX A. The habitat connectivity and road construction models

1. Habitat connectivity and site access model

Protecting caribou habitat in areas of clear-cut harvesting requires creation of interconnected, undisturbed corridors that allow caribou to travel and avoid predators. The zoning approach divides the landscape into (i) areas with deferred harvest based on their assessed quality as caribou habitat and which may stay undisturbed over longer periods and (ii) a management zone where harvesting is allowed. We conceptualize the protected habitat area in the zoning scenario as a connected pattern of protected forest with a total area equal to a desired conservation management threshold. We depict a forest landscape as a network of J forest patches (nodes) over a timespan of U periods where any pair of adjacent patches containing habitat is connected by arcs. A patch $j, j \in J$, is characterized by the amount of suitable caribou habitat in period $u, \beta'_{ju}, u \in U$, which is the habitat suitability (i.e., to support caribou populations) times the patch area. The suitability of habitat to support caribou in patch j depends on the composition and age of the forest in j in period u . Clear-cut harvesting temporarily degrades the caribou habitat by increasing predation risk until forest cover matures in 40–60 years.

In each period u , the landscape J is divided into a harvest deferral zone with interconnected habitat and a management zone where harvest is allowed. Zoning decisions are reconsidered every period u . All habitat patches in the harvest deferral zone in period u need to be connected. We depict the connectivity between adjacent patches j and k as a bi-directional pair of arcs, jk and kj , and conceptualize the ability of caribou to move between the protected patches as a flow through a sub-network of *connected* patches j in period u . A binary variable w_{kju} indicates that flow can pass through an arc kj connecting adjacent patches k and j in period u . A non-negative variable y_{kju} defines the amount of flow through arc kj . Connectivity between the patches is maintained by injecting the flow into one protected patch and ensuring that all other protected patches receive flow from that patch (Fig. 3a in the main text). An auxiliary Node 0 injects flow into the sub-network of patches in the harvest deferral zone to maintain their connectivity. Node 0 is connected to all patches j and can pass the flow to any selected patch (Fig. 3a in the main text). A patch j is a member of the harvest deferral zone if it receives incoming flow from any connected protected patch k or Node 0.

Similarly, all patches in the management zone need to be accessible from patches with roads, which requires enforcing connectivity between patches in the management zone. A binary variable v_{kju} defines the connection between the adjacent patches k and j in the management zone and a non-negative variable z_{kju} characterizes the amount of flow through arc kj in period u . The subnetworks of the management and harvest deferral zones pull from a shared set of candidate patches (nodes) J , but the selected patches can only be associated with either the deferral or management zone, except auxiliary Node 0 that is used to inject flow into the selected networks (Fig. 3e in the main text).

The zoning problem selects the connected subnetworks in the harvest deferral and management zones to maximize the amount of connected habitat in the deferral zone, subject to the target area proportion designated for harvest deferral, δ , $\delta \in [0;1]$, i.e.,

$$(A1) \quad \max f_1 \sum_{u \in U} \sum_{j \in J} \sum_{k \in Q_j} (w_{kj} \beta'_{ju}) - \sum_{u \in U} f_2 (p_{1u} + p_{2u})$$

s.t.:

$$(A2.1) \quad \sum_{k \in Q_j} y_{kju} - \sum_{k \in Q_j^+} y_{jku} = \sum_{k \in Q_j} w_{kju} \quad \forall \quad j \in J, u \in U$$

$$(A2.2) \quad y_{kju} \leq M w_{kju} \quad \forall \quad j \in J, k \in Q_j, u \in U$$

$$(A2.3) \quad w_{kju} \leq y_{kju} \quad \forall \quad j \in J, k \in Q_j, u \in U$$

$$(A2.4) \quad \sum_{k \in Q_j} w_{kju} \leq 1 \quad \forall \quad j \in J, u \in U$$

$$(A3.1) \quad \sum_{k \in Q_j} z_{kju} - \sum_{k \in Q_j^+} z_{jku} = \sum_{k \in Q_j} v_{kju} \quad \forall \quad j \in J, u \in U$$

$$(A3.2) \quad z_{kju} \leq M v_{kju} \quad \forall \quad j \in J, k \in Q_j, u \in U$$

$$(A3.3) \quad v_{kju} \leq z_{kju} \quad \forall \quad j \in J, k \in Q_j, u \in U$$

$$(A3.4) \quad \sum_{k \in Q_j} v_{kju} \leq 1 \quad \forall \quad j \in J, u \in U$$

$$(A4) \quad p_{1u} \geq \sum_{j \in J} w_{0ju} - 1 \quad \forall \quad u \in U$$

$$(A5) \quad p_{2u} \geq \sum_{j \in J} v_{0ju} - \theta \quad \forall \quad u \in U$$

$$(A6) \quad \sum_{k \in Q_j} v_{kju} + \sum_{k \in Q_j} w_{kju} = 1 \quad \forall \quad j \in J, u \in U$$

$$(A7) \quad \sum_{k \in Q_j} v_{kju} \geq \Psi_j \quad \forall \quad u \in U, j \in J$$

$$(A8) \quad \sum_{j \in J} \Phi_j \sum_{k \in Q_j} v_{kju} \geq 1 \quad \forall \quad u \in U$$

$$(A9) \quad 0.95\delta \sum_{j \in J} \alpha'_j \leq \sum_{j \in J} \sum_{k \in Q_j} (w_{kju} \alpha'_j) \leq \delta \sum_{j \in J} \alpha'_j \quad \forall \quad u \in U$$

Objective (A1) maximizes the total amount of connected habitat in the area minus the penalties p_{1u} and p_{2u} . Penalty p_{1u} denotes the number of connections to Node 0 above one in the deferral zone in period u , which defines the maximum number of separate connected subnetworks. Penalty p_{2u} defines the number of connections to Node 0 in the management zone above θ in period u , where θ defines the number of patches with access points where roads enter the target area. This penalty limits the maximum number of disjoint clusters of connected nodes in the management zone. Coefficients f_1 and f_2 adjust the relative weights of the objective and penalties and are set high to force the penalty equations to work under normal circumstances as hard constraints. The penalty formulation keeps the problem feasible when a complex landscape configuration does not allow delineating

either the management or the harvest deferral zone as a single contiguous area.

Constraints (A2.1 and A3.1) describe the flow balance through patch j in the subnetworks comprising the management and harvest deferral zones, respectively, in period u . Set Q_j denotes adjacent patches k and an auxiliary Node 0 that are connected to patch j and can transmit flow to j , and set Q_j^+ denotes adjacent patches k that are connected to patch j and can receive flow from j . Constraints (A2.2 and A2.3) and (A3.2 and A3.3) ensure agreement between the amounts of flow through arc kj in the subnetworks in the management and deferral zones and the corresponding arc selection variables w_{kju} and v_{kju} in period u . Constraints (A2.4 and A3.4) aim to track the flow between the connected patches j and ensure that the flow to a patch j in the management or deferral zone comes from at most one source.

Constraints (A4 and A5) define penalties p_{1u} and p_{2u} . Constraint (A6) specifies that patch j can only be in the harvest deferral or management zone in period u but not in both. Constraint (A7) ensures that the management zone always includes patches with permanent roads. A binary parameter Ψ_j defines patches j with permanent roads ($\Psi_j = 1$ and $\Psi_j = 0$ otherwise). Constraint (A8) specifies that the management zone includes at least one patch in period u where roads enter the area. This ensures the accessibility of the management zone in period u . A binary parameter Φ_j defines patches with access points to the area ($\Phi_j = 1$ and $\Phi_j = 0$ otherwise). Constraint (A9) sets the target proportion of the area with deferred harvest in period u to $[0.95\delta; \delta]$, where α'_j is the area of patch j .

2. Forest access roads construction model

Harvesting remote areas requires building access roads. We track expansion of the forest road network over timespan T with a network flow model that finds a growing subgraph of roads connected to the harvested sites for planning periods $t = 1, \dots, |T|$, where $|T|$ is a cardinality of set T . To reduce combinatorial complexity, we applied the road construction problem at the coarse scale of the network of patches j we used in the zoning problem (A1–A9). The forest area includes a set of harvestable sites n and is also divided into a set of coarse-scale patches j . The area of patch j in network J is larger than the area of a harvest site n , so we needed a binary parameter Λ_{nj} to indicate whether site n is located in patch j ($\Lambda_{nj} = 1$ and $\Lambda_{nj} = 0$ otherwise) (see Figs. 3c and 3d in the main text).

For each planning period t , we find a connected subgraph of roads that starts from patches j with roads built in previous periods $1, \dots, t-1$ and ends in patches with harvest in period t . Analogous to the habitat connectivity problem (A1–A9), an auxiliary Node 0 injects the flow into the network of patches with roads. Node 0 is connected to all patches with roads where the construction of new roads could potentially start. The flow from Node 0 through patches with roads ensures the connectivity of the road network. A binary variable h_{kjt} indicates the selection of flow through arc kj between patches k and j , which denotes road construction from k to j in period t . A non-negative variable q_{kjt} defines the amount of flow

between patches k and j when a road is built from k to j in period t (i.e., $q_{kjt} > 0$ when $h_{kjt} = 1$ and $q_{kjt} = 0$ when $h_{kjt} = 0$). Patches j with incoming flow from other patches or Node 0 form the road network in period t . The following constraints control the expansion of the road network over timespan T :

$$(A19.1) \quad \sum_{k \in Q_j} q_{kjt} - \sum_{k \in Q_j^+} q_{jkt} = \sum_{k \in Q_j} h_{kjt} \quad \forall \quad j \in J, t \in T$$

$$(A19.2) \quad q_{kjt} \leq Mh_{kjt} \quad \forall \quad j \in J, k \in Q_j, t \in T$$

$$(A19.3) \quad h_{kjt} \leq q_{kjt} \quad \forall \quad j \in J, k \in Q_j, t \in T$$

$$(A19.4) \quad \sum_{k \in \Theta_j} h_{kjt} \leq 1 \quad \forall \quad j \in J, t \in T$$

$$(A20) \quad h_{0j1} \leq \Gamma_j \quad \forall \quad j \in J$$

$$(A21) \quad h_{0jt} \leq \Gamma_j + \sum_{t' \in [1; t-1]} \sum_{k \in Q_j} h_{kjt'} \quad \forall \quad t \in [2; |T|], t' \in T, j \in J$$

$$(A22) \quad h_{kjt} \leq 2 - \Gamma_j - \Gamma_k \quad \forall \quad j, k \in J_{\text{roads}}, t \in T$$

$$(A23) \quad \sum_{t' \in [1; t]} \left[\sum_{k \in Q_j} h_{kjd} \right] \geq \frac{1}{M} \sum_{n \in N} \left(\Lambda_{nj} \sum_{i \in I} (x_{ni} x_{nit}) \right) \quad \forall \quad t, t' \in T, j \in J, j \notin J_{\text{roads}}$$

$$(A24) \quad p_{3t} \geq \sum_{j \in J} \sum_{k \in Q_j} (h_{kjt}) - \tau \quad \forall \quad t \in T$$

$$(A25) \quad \sum_{k \in Q_j} h_{kjt} \leq \sum_{u \in U} \left(\Xi_{ut} \left[1 - \sum_{k \in Q_j} w_{kju} \right] \right) \quad \forall \quad j \in J, t \in T$$

$$(A26) \quad 1 - \sum_{k \in Q_j} w_{kju} \geq \frac{1}{T} \sum_{t \in T} \left(\Xi_{ut} \sum_{k \in Q_j} h_{kjt} \right) \quad \forall \quad j \in J, u \in U$$

$$(A27) \quad b_{jt} \geq \frac{1}{M} \sum_{n \in N} \left(\Lambda_{nj} \sum_{i \in I} (x_{ni} x_{nit}) \right) \quad \forall \quad j \in J, j \notin J_{\text{roads}}, t \in T$$

For convenience, the numbering of equations follows the numbering in the main text. Constraints (A19.1–A19.4) enforce the connectivity of the road network and work analogously to constraints (A2.1–A2.4) in the habitat connectivity problem. Constraint (A20) restricts the selection of arcs $0j$ connecting Node 0 to patches j with pre-existing roads in period $t = 1$. A binary parameter Γ_j defines patches with pre-existing roads ($\Gamma_j = 1$ and $\Gamma_j = 0$ otherwise). Constraint (A21) restricts the flow from Node 0 in periods $t = 2, \dots, |T|$ to patches with roads either pre-existing or built in the previous periods $1, \dots, t-1$. Subscript t denotes time periods $t = 1, \dots, t-1, t' \in T$. Constraints (A20 and A21) ensure that

Table A1. Forest units (common tree species assemblages) and their basic attributes.

Forest unit*	Proportion of hardwood species	Post-harvest regeneration cost, \$·ha ⁻¹		Age when stands reach old-growth status	Transition age from early-successional to late-successional forest type
		Natural regeneration (mandatory)	Replanting (optional)		
BfMx1	0.216	118	1028	105	–
BwDom	0.801	95	99	115	105
ConMx	0.334	118	1090	105	115
HrDom	0.748	95	99	105	105
HrdMw	0.552	95	99	105	105
OcLow	0.022	95	99	105	105
PjDom	0.081	110	920	105	105
PjMx1	0.13	110	920	105	105
PoDom	0.879	95	99	105	105
PrwMx	0.279	95	99	105	105
SbDom	0.063	110	950	125	105
SbLow	0.032	95	250	165	125
SbMx1	0.136	110	950	115	165

*Forest units: BfMx1, balsam fir dominant conifer; BwDom, birch dominant; ConMx, conifer mix; HrDom, hardwood dominant; HrdMw, hardwood mix; OcLow, other conifer lowland; PjDom, jack pine dominant; PjMx1, jack pine mix; PoDom, poplar dominant; PrwMx, red and white pine mix; SbDom, black spruce; SbLow, black spruce lowland; SbMx1, black spruce conifer dominant mix.

Table A2. Transitions to late-successional forest types after forest stands reach a threshold age.

Forest unit*	BfMx1	BwDom	ConMx	HrDom	HrdMw	OcLow	PjDom	PjMx1	PoDom	PrwMx	SbDom	SbLow	SbMx1
BfMx1	1	0	0	0	0	0	0	0	0	0	0	0	0
BwDom	0.39	0	0	0	0.61	0	0	0	0	0	0	0	0
ConMx	0.17	0	0.13	0	0	0	0	0.19	0	0	0.51	0	0
HrDom	0.09	0	0.91	0	0	0	0	0	0	0	0	0	0
HrdMw	0.41	0	0.45	0	0	0	0	0	0	0	0.14	0	0
OcLow	0	0	0	0	0	0.93	0	0	0	0	0	0.07	0
PjDom	0	0	0	0	0	0	0	0.79	0	0	0	0	0.21
PjMx1	0.06	0	0	0	0	0	0	0	0	0	0.65	0	0.29
PoDom	0	0	0.11	0	0.89	0	0	0	0	0	0	0	0
PrwMx	0	0	0	0	0	0	0	0	0	1	0	0	0
SbDom	0.02	0	0	0	0	0	0	0	0	0	0.98	0	0
SbLow	0	0	0	0	0	0	0	0	0	0	0	1	0
SbMx1	0.1	0	0	0	0	0	0	0	0	0	0.9	0	0

*Forest units (as defined in the provincial forest management plan): BfMx1, balsam fir dominant conifer; BwDom, birch dominant; ConMx, conifer mix; HrDom, hardwood dominant; HrdMw, hardwood mix; OcLow, other conifer lowland; PjDom, jack pine dominant; PjMx1, jack pine mix; PoDom, poplar dominant; PrwMx, red and white pine mix; SbDom, black spruce; SbLow, black spruce lowland; SbMx1, black spruce conifer dominant mix. Rows: pre-transition forest type, columns: post-transition forest type.

road construction between patches k and j in period t can only proceed from patches that had roads prior to period t . Constraint (A22) prevents road construction between patches that are already connected by pre-existing roads in period $t = 1$.

Constraint (A23) implies that harvesting sites n in period t in patch j that is outside of the pre-existing road network (i.e., with $\Gamma_j = 0$) is only possible if the road network is extended to j during periods $1, \dots, t$. A binary parameter χ_{nit} indicates that site n is harvested in period t in prescription i (i.e., $\chi_{nit} = 1$ when $\gamma_{1nit} + \gamma_{2nit} > 0$ and $\chi_{nit} = 0$ when $\gamma_{1nit} + \gamma_{2nit} = 0$). Subscript t denotes time periods $1, \dots, t, t \in T$.

Constraint (A24) defines penalty p_{3t} for each period t as equal to the total number of patches j with roads built

above the maximum limit τ . The τ value is based on the historical extent of road construction activities in the area. Constraint (A25) prevents road construction to a patch j if j is in the harvest deferral zone in period t . Note that a single period u includes several harvest planning periods t . A binary parameter Ξ_{ut} indicates that harvest period t occurs within a planning period u in the zoning problem (A1–A9) ($\Xi_{ut} = 1$ and $\Xi_{ut} = 0$ otherwise). Constraint (A26) ensures that patch j is assigned to the management zone in period u if roads are built in j during the period u . Constraint (A27) defines a binary decision variable b_{jt} that indicates harvest in patch j in period t and is used to track the road maintenance cost in patch j if harvest occurs in j in period t .

Table A3. Post-harvest forest cover transitions—natural regeneration.

Forest unit*	BfMx1	BwDom	ConMx	HrDom	HrdMw	OcLow	PjDom	PjMx1	PoDom	PrwMx	SbDom	SbLow	SbMx1
BfMx1	0.25	0	0.17	0.14	0.27	0	0	0	0	0	0.17	0	0
BwDom	0	0.58	0	0.12	0.3	0	0	0	0	0	0	0	0
ConMx	0.04	0	0.47	0.14	0.27	0	0	0.05	0.01	0	0	0	0.02
HrDom	0	0	0	0.5	0.1	0	0	0	0.4	0	0	0	0
HrdMw	0.03	0.08	0.09	0.09	0.45	0	0	0	0.26	0	0	0	0
OcLow	0	0	0	0	0	1	0	0	0	0	0	0	0
PjDom	0	0	0.26	0	0.1	0	0.34	0.3	0	0	0	0	0
PjMx1	0	0	0.25	0	0.25	0	0.25	0.25	0	0	0	0	0
PoDom	0	0	0	0	0	0	0	0	1	0	0	0	0
PrwMx	0	0.01	0.09	0.03	0.18	0	0	0	0.65	0.04	0	0	0
SbDom	0	0	0.37	0	0.08	0	0.12	0	0	0	0.25	0.06	0.12
SbLow	0	0	0	0	0	0.1	0	0	0	0	0	0.9	0
SbMx1	0	0	0.5	0	0.25	0	0	0	0	0	0.25	0	0

* Forest units (as defined in the provincial forest management plan): BfMx1, balsam fir dominant conifer; BwDom, birch dominant; ConMx, conifer mix; HrDom, hardwood dominant; HrdMw, hardwood mix; OcLow, other conifer lowland; PjDom, jack pine dominant; PjMx1, jack pine mix; PoDom, poplar dominant; PrwMx, red and white pine mix; SbDom, black spruce; SbLow, black spruce lowland; SbMx1, black spruce conifer dominant mix. Rows: pre-harvest forest type, columns: post-harvest forest type.

Table A4. Post-harvest forest cover transitions—replanting after harvest.

Forest unit*	BfMx1	BwDom	ConMx	HrDom	HrdMw	OcLow	PjDom	PjMx1	PoDom	PrwMx	SbDom	SbLow	SbMx1
BfMx1	0.12	0	0.32	0	0	0	0.18	0	0	0	0.38	0	0
BwDom	0	0	0.25	0.03	0.2	0	0.07	0.08	0	0	0.27	0	0.1
ConMx	0.03	0	0.24	0	0	0	0	0.18	0	0	0.42	0	0.13
HrDom	0	0	0	1	0	0	0	0	0	0	0	0	0
HrdMw	0	0	0.35	0.03	0.27	0	0.14	0.06	0.05	0	0.05	0	0.05
OcLow	0	0	0	0	0	0	0	0	0	0	0	1	0
PjDom	0	0	0.12	0	0	0	0.59	0.24	0	0	0	0	0.05
PjMx1	0	0	0.12	0	0	0	0.75	0.13	0	0	0	0	0
PoDom	0	0	0	0	0	0	0	0	1	0	0	0	0
PrwMx	0	0	0.19	0.05	0.12	0	0.03	0.01	0.07	0.52	0.01	0	0
SbDom	0	0	0.13	0	0	0	0.23	0	0	0	0.51	0	0.13
SbLow	0	0	0	0	0	0.1	0	0	0	0	0	0.9	0
SbMx1	0	0	0.19	0	0	0	0	0.19	0	0	0.56	0	0.06

* Forest units (as defined in the provincial forest management plan): BfMx1, balsam fir dominant conifer; BwDom, birch dominant; ConMx, conifer mix; HrDom, hardwood dominant; HrdMw, hardwood mix; OcLow, other conifer lowland; PjDom, jack pine dominant; PjMx1, jack pine mix; PoDom, poplar dominant; PrwMx, red and white pine mix; SbDom, black spruce; SbLow, black spruce lowland; SbMx1, black spruce conifer dominant mix. Rows: pre-harvest forest type, columns: post-harvest forest type.

APPENDIX B. Generating a set of harvest prescriptions I

The harvest scheduling model required generating a set of prescriptions I , where each prescription defines a possible sequence of harvest events in site n over a planning horizon of T periods, including a scenario without harvest. We enumerated all possible management prescriptions that can be assigned to forest site n by a set of binary vectors of length T , $\{(1,0,\dots,0),(0,1,\dots,0),\dots\}$. The elements of each vector denote the harvest or other management actions undertaken in planning period t , $t = 1, \dots, T$. For each prescription i , $i \in I$, we calculated the vectors of harvest volumes V_{nit} , the volumes for softwood and hardwood species, V_{1nit} and V_{2nit} , the post-harvest regeneration costs e_{nit} , the amounts of caribou habitat b_{nit} , and a binary parameter W_{nit} indicating that site n is harvested in period t in prescription i . To simplify the formu-

lation of harvest sustainability constraints, we calculated the areas of mature and old-growth stands for each forest type g , χ_{gnit} and ξ_{gnit} , and the areas of young stands, ζ_{nit} , in site n in prescription i in period t . For each site n and prescription i , we also estimated the forest stand age at the end of the planning horizon T , E_{ni} , and the net cash flow from harvest minus harvest, hauling and post-harvest regeneration costs, R_{ni} .

We used Ontario's Forest Resource Inventory (FRI) database (OMNRF 2020) to depict the spatial locations of sites n representing potential candidates for harvest. The FRI provided initial tree species composition and stand age at $t = 1$. Each forest polygon in the FRI database provides tree species information at the level of "forest units", i.e., common tree species assemblages that are delineated from aerial photographs for practical forest management (Table A1). For each forest unit, the forest management plan (FMP) for our target area, Wabadowgang Noopming Forest (NorthWinds 2021), provided a

Table A5. Caribou habitat presence in major forest types and age classes (based on boreal caribou habitat model for Ontario's Northwest Region [Elkie et al. 2018](#)).

Forest unit	Habitat type		
	Useable	Preferred	Refuge
BfMx1			61
BwDom			
ConMx	51		71
HrDom			
HrdMw			
OcLow	51		Permanent
PjDom	41	61	Permanent
PjMx1	41	61	41
PoDom			
PrwMx			
SbDom	61		41
SbLow	41	101	Permanent
SbMx1	61		41

normal yield curve, which we used to estimate the volumes of harvested timber in site n as a function of stand age in period t . When calculating the harvested timber volume in prescriptions i , we adjusted the forest area in site n by the projected annual forest area losses due to fire disturbances using wildfire regime zones from [Boulanger et al. \(2014\)](#).

To estimate the future forest composition and harvest volumes in prescriptions i , we tracked two general types of forest succession over time. Aging succession depicted temporal changes in tree species composition without stand-replacing disturbances as forest stands change from early-successional to late-successional types. Based on the FMP and consultations with NorthWinds staff, we set, for each forest unit, the threshold age when forest composition in site n changes to a late-successional forest type ([Table A1](#)). A matrix of transition rates to late-successional forest types ([Table A2](#)) is applied when forest stands reach a threshold age.

The second type of forest succession depicted forest composition changes after clear cut harvest. Based on the FMP ([NorthWinds 2021](#)), two sets of succession rules were applied to track post-harvest forest changes in naturally regenerated stands and after replanting ([Tables A3 and A4](#)).

Using these succession rules, we generated two sets of prescriptions with natural regeneration and replanting after harvest for the same set of harvest schedules. Each set of prescriptions used a unique post-harvest succession matrix and a corresponding set of post-harvest regeneration costs ([Table A1](#)) and normal yield curves. Since natural regeneration and replanting options are characterized by different

cost and timber yields, these prescription sets also have different net cash flow values R_{ni} and vectors of harvested volumes V_{nit} , V_{1nit} , and V_{2nit} .

Our optimization model did not use individual forest units but instead tracked the forest age structure at the level of four general forest types (set G , see [Table 3](#) in the main text). The Fir group included conifer stands dominated by balsam fir; the Lowland conifer group included black spruce and other conifer-dominated stands in poorly drained sites; the Upland conifer group included stands dominated by conifer species in other topographic positions; and the Hardwood group included stands dominated by deciduous species. For each site n , we generated the areas occupied by each forest group g that reached mature and old-growth age in prescription i in period t , χ_{gnit} and ξ_{gnit} . For each forest unit, [Table A1](#) shows the forest age when forest stands reach old-growth status.

We estimated the amount of caribou habitat in site n in period t in prescription i using a boreal caribou habitat model for Ontario's Northwest Region ([Elkie et al. 2018](#)) ([Table A5](#)). A score of 1.0 was assigned for each habitat type (such as winter useable, winter preferred, and refuge habitat) if present in site n in period t . A forest site can, depending on its cover category and age class, have a score between 0 and 3 (i.e., 1 for refuge, +1 for useable, +1 for preferred habitat). The total habitat amount b_{nit} was calculated as the sum of these scores multiplied by the site area. When forest patches included a mix of different forest types, the total habitat value was estimated as a weighted average of scores for individual cover types and their corresponding areas. We assumed that forest stands regain suitable habitat status in 40 years after harvest. The total habitat amount in patch j , B_{ju} , was calculated as the sum of habitat amounts b_{nit} in sites n located in patch j , $n \in N_j$, over periods t within a timespan u , $t \in u$.

References

- Boulanger, Y., Gauthier, S., and Burton, P.J. 2014. A refinement of models projecting future Canadian fire regimes using homogeneous fire regime zones. *Can. J. For. Res.* **44**: 365–376. doi:10.1139/cjfr-2013-0372.
- Elkie, P., Green, K., Racey, G., Gluck, M., Elliott, J., Hooper, G., et al. 2018. Science and information in support of policies that address the conservation of woodland caribou in Ontario: occupancy, habitat and disturbance models, estimates of natural variation and range level summaries. Electronic Document. Version 2018. Ontario Ministry of Natural Resources, Forests Branch.
- NorthWinds Environmental Services (NorthWinds). 2021. 2023–2033 Wabadowgang Noopming Forest Management Plan. (WN 2023–2033 FMP) Prepared by NorthWinds Environmental Services. Available from https://nrp.mnr.gov.on.ca/s/fmp-online?language=en_US [accessed July 2022].
- Ontario Ministry of Natural Resources and Forestry (OMNRF). 2020. Forest resources inventory (FIM v 2.2D) packaged product. Available from <https://geohub.lio.gov.on.ca/datasets/forest-resources-inventory-fim-v2-2d-packaged-product> [accessed July 2022].