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Exploring the tradeoffs among forest planning, roads and wildlife corridors: a new approach

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Abstract

Protecting wildlife corridors is a common management problem in regions of industrial forestry. In boreal Canada, human disturbances have negatively affected woodland caribou populations (*Rangifer tarandus* caribou), which prefer to function in large undisturbed areas. We present a linear programming model that allocates a fixed-width corridor between isolated caribou ranges and estimates its impact on harvest activities. Our corridor placement problem minimizes total resistance for caribou passing through the corridor, which is protected by a prohibition on all economic activities. We link this corridor placement problem with a harvest planning problem that maximizes the net revenues from harvest minus the cost of building and maintaining forest access roads. We depict gradual expansion of the forest road network over time as a multi-temporal network flow problem. We applied our approach to explore corridor options for connecting caribou populations in the Lake Superior Coast Range, with the Nipigon and Pagwachuan Ranges in the Kenogami-Pic Forest, in northern Ontario, Canada. Our results revealed two locations where corridor placement is cost-effective. Optimal corridor placement depends on the perception of the severity of the impact of roads on caribou populations and decision-making objectives. When the negative impact of roads is perceived to be high and/or maximizing harvest revenues is important, the optimal corridor location is in the eastern part of the study area. However, it is optimal to place the corridor in the western part of the area when the negative impact of roads is perceived to be small or the shortest corridor is desired.

Keywords Network flow model · Mixed integer programming · Wildlife corridor · Road construction · Harvest scheduling model I · Woodland caribou · Habitat connectivity

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1 Introduction

The establishment of wildlife corridors connecting core areas of habitat is a common management goal in regions disturbed by human activity [1–7]. Corridors help maintain migration between isolated wildlife refugia and mitigate negative impacts of isolation on wildlife species populations [8–10]. For forest-based wildlife species, protection of corridors may be particularly important when harvesting creates networks of early successional habitat as well as access roads. For example, human activities and landscape fragmentation in boreal Canada have negatively affected woodland caribou populations (*Rangifer tarandus* caribou), which prefer large areas of undisturbed old-growth forest [11]. The network of clear-cuts and roads created by harvesting is dominated by early successional vegetation, which attracts deer and moose populations followed by predators of caribou [12–14]. This poses a notable conservation problem for woodland caribou [15–17], which is currently listed as a threatened species in Canada [18].

Various recovery efforts have been proposed for protecting caribou populations, including the creation of large regions with undisturbed, old-growth forest habitat and movement corridors between isolated caribou ranges [19–23]. Corridors are especially critical when caribou ranges are separated by fragmented landscapes, such as in north-central boreal Ontario, Canada, where the Lake Superior Coast Range on the lake's northern shores is separated from the Pagwachuan and Nipigon Ranges by a 100 + km swath of periodically harvested forest (Fig. 1).

The creation of corridors for caribou aims to establish networks of suitable habitat that are sufficiently large to protect the viability of the species' remaining populations [24]. For such corridors to work, they must be wide enough to facilitate the movement of caribou herds. Ideally, these corridors would have minimal impacts on forestry activities, but inevitably they reduce the area of productive forest available for harvesting and force the relocation of harvest to other sites that are farther away. Additional roads must be built and maintained to access these more remote sites, which increases the timber supply cost, sometimes substantially. To plan effectively, decision-makers need to assess the impacts of wildlife corridors on timber supply and find the best possible balance between competing economic and conservation objectives that are both considered critically important. Here, we present an optimization-based approach that provides a feasible way to achieve this balance.

1.1 Optimal placement of wildlife corridors

A frequently used approach for identifying wildlife corridors is to estimate landscape resistance, which characterizes the relative resistance of a wildlife population to movement through a particular location in a landscape of interest [25–28]. The resistance concept assumes that animals are likely to follow a corridor with comparatively low resistance and higher abundance of suitable habitat [29–32]. Resistance can be depicted as a function of environmental, spatial or biological attributes, such as the availability of habitat, exposure to predators or geographical distance to

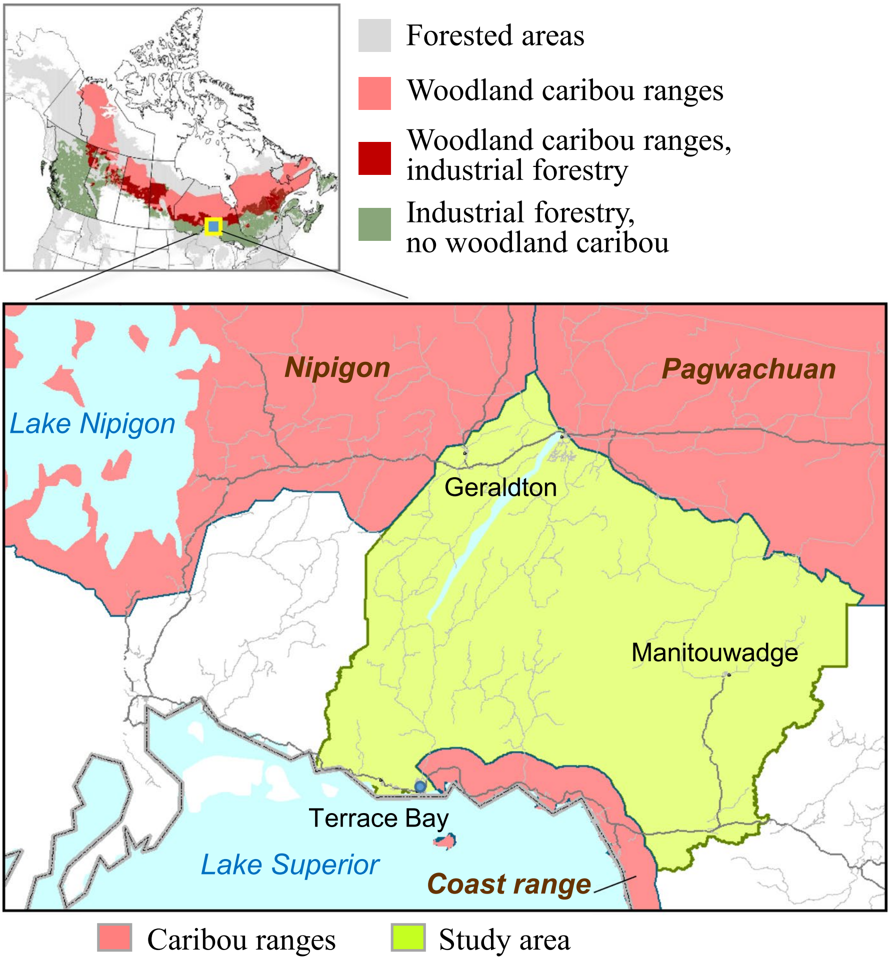


Fig. 1 Study area in the Pic River and Kenogami Forest Management Units, northwestern Ontario, Canada

the closest population [33, 34]. Applications of a resistance metric include designing migration corridors, delineating least-cost paths [27, 35], analyzing wildlife movement networks [36] and simulating movements of wildlife populations [37]. The concept has also been used for identifying conservation priorities in heterogeneous landscapes [3, 38], prioritizing the protection of corridors via land acquisition [5, 39] and excluding forest harvest from a wildlife corridor to enable migration [40].

To be practical, corridor planning should consider the costs associated with setting aside habitat and prohibiting human activities in corridor areas. This type of accounting for trade-offs between conservation and various economic activities has been the focus of much research [37, 41–43], including work dealing specifically with wildlife corridor design [3, 5, 40]. Several optimization-based models have been proposed to design corridors for wildlife conservation. For example, formulations proposed in [44] and [45] minimized the number of sites comprising a corridor system but ensured that the system still protected a target suite of species. Many formulations have used a network flow approach to maximize the amount of suitable habitat across connected areas [3, 4, 46]. Williams [47] proposed an integer programming model with decision variables connecting adjacent patches in a corridor system while maintaining flow conservation constraints. Dilkina et al. [5] proposed a formulation that minimized resistance in corridors between core habitat areas under a given conservation budget. Least-cost corridor planning problems have been formulated as a Steiner network problem [48, 49] and recently as an instance of the minimum delay generalized Steiner network problem [1]. Other habitat conservation models have used distance-dependent connectivity criteria [50, 51], maximized compactness of the reserved habitat area while minimizing its perimeter [52, 53], and enforced habitat connectivity to build a fully contiguous reserve design [54, 55].

There have also been efforts to solve the habitat connectivity problem in the context of broader forest planning, commonly through the application of graph-theoretic approaches [40, 56, 57]. Öhman and Lämås [58] used a spatial structure metric, the shape index, and Öhman and Wikström [59] minimized the perimeter of selected patches to optimize the protection of old-growth habitats from harvest (but with no guarantee of connectivity). Yoshimoto and Asante [60] and Yoshimoto [61] proposed a network flow formulation to solve a similar connectivity problem of aggregating land clusters for forest management. Martin [62] used a spanning tree formulation for controlling connectivity and later proposed using block variables to control connectivity between habitats. St. John et al. [63] proposed a formulation to control the minimum width of corridors, ensuring that the connected patches comprising a corridor are large enough to facilitate animal movement. However, none of the proposed algorithms could guarantee both connectivity between isolated habitats and the desired width of the established corridors.

In this paper, we consider the problem of designing a protected corridor for caribou in an area with active forest harvesting. We adapt concepts pioneered in [40] and [5] and formulate a corridor placement problem that minimizes total resistance for caribou passing through the corridor. Caribou individuals require sufficiently wide corridors and large habitat patches for unimpeded movement [64, 65]. Therefore, we specify a minimum fixed width for the corridor where all economic activities (such as harvesting and road construction) are prohibited. We then link the corridor placement problem with a harvest planning problem that maximizes the net revenues of harvesting a target volume of timber minus the cost of building and maintaining a network of access roads to the harvest sites. We propose a multi-temporal network flow formulation that depicts a gradual expansion of the road network over time and finds an exact road network solution (see [66]). We use the proposed model to assess corridor placement options between the isolated Lake Superior Coast Range and caribou populations in the Pagwachuan and Nipigon Ranges in the northern portion of the Kenogami-Pic Forest in Ontario, Canada (Fig. 1).

2 Material and methods

We depict a landscape as a network of forest patches (nodes hereafter) that can support caribou. When moving through the landscape, caribou tend to avoid open spaces and areas disturbed by humans where they may be exposed to predation [12, 14]. To protect the movement of animals between isolated ranges, one management option is to create a corridor in which all economic activities are suspended. Creating a corridor will reduce the area where forest could be harvested for timber, thereby reducing revenue and increasing the cost of harvesting if that must occur elsewhere.

Harvesting in remote forested areas requires construction of access roads. We formulate a network flow sub-problem to account for the costs of building and maintaining the roads to harvested sites. We link the corridor placement and road construction sub-problems with a harvest planning problem that schedules timber harvests in the area over a horizon T. We assume that caribou can move between neighboring nodes m and n in landscape N via the nodes' common boundaries. We depict connectivity between nodes m and n as a bi-directional pair of arcs, mn and nm, and conceptualize the movement of caribou across landscape N as a flow through a corridor of interconnected nodes.

To define the corridor, we must find a path between two geographically separated caribou ranges and ensure its connectivity. The borders between the study area and these ranges represent possible locations for the beginning and end of the corridor (Fig. 1). We introduce an auxiliary start node 1 in the habitat connectivity network, $n = 1$, which serves as a source of the flow through the connected path (Fig. 2a). Node 1 is connected to landscape nodes n—possible locations of the corridor's beginning—via arcs $1n$. We also introduce an auxiliary end node, $m = N$, as a recipient of the flow from node 1 through the connected path. Node N can receive the flow from landscape nodes m', where the connected path could end, via arcs mN.

Our second network flow sub-problem finds optimal road construction patterns to harvest sites without current road access. For each planning period t within the horizon T, we find a distinct road network to the harvest sites, starting from sites with pre-existing roads or roads that were built in the previous planning period 1, …, t-1. To ensure the connectivity of the road network, we introduce an auxiliary node 0 as the source of the flow that is injected into the road network built in period t (Fig. 2b). Node 0 is connected to all nodes (forest patches) from which the road network could potentially originate in period t via arcs $0n_t$.

The corridor placement sub-problem allocates a single wildlife corridor over the entire planning horizon T and the road construction sub-problem allocates the road networks for each planning period t, for a total of T interconnected networks. Our global node set is a union of the node sets in the corridor and road construction sub-problems. As described above, the corridor sub-problem utilizes auxiliary start and end nodes 1 and N and landscape nodes 2, …, N-1 (i.e., potential forest patches in the corridor). The road construction sub-problem utilizes auxiliary node 0 and landscape nodes 2, …, N-1, in this case representing locations

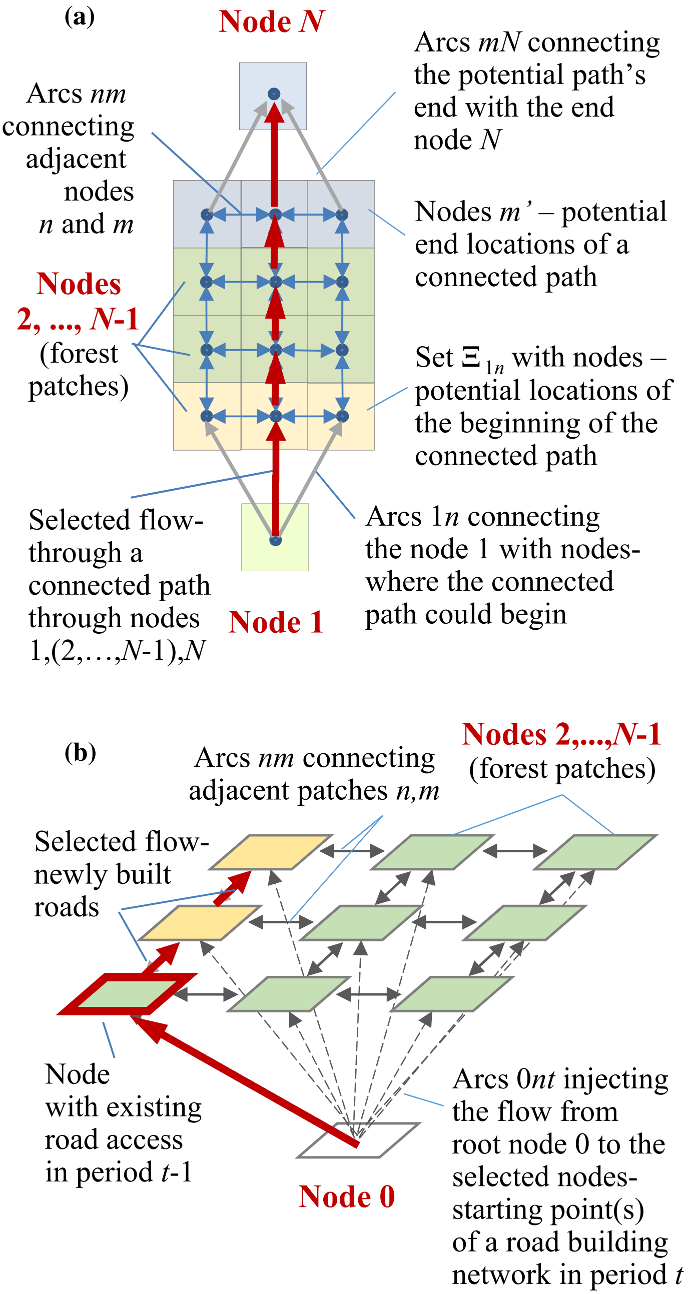


Fig. 2 **a** Corridor connectivity sub-network (nodes 1, …, N); **b** road construction sub-network (nodes 0, 2, …, N-1)

where road construction could occur. The harvest allocation problem ignores the auxiliary nodes from the two sub-problems and utilizes nodes 2, …, N-1 only.

2.1 Corridor placement sub-problem

Our corridor placement sub-problem considers two things: the delineation of a connected path between the two geographically separated caribou ranges, and the selection of a corridor space of fixed width μ from both sides of the connected path (Figs. 2a,

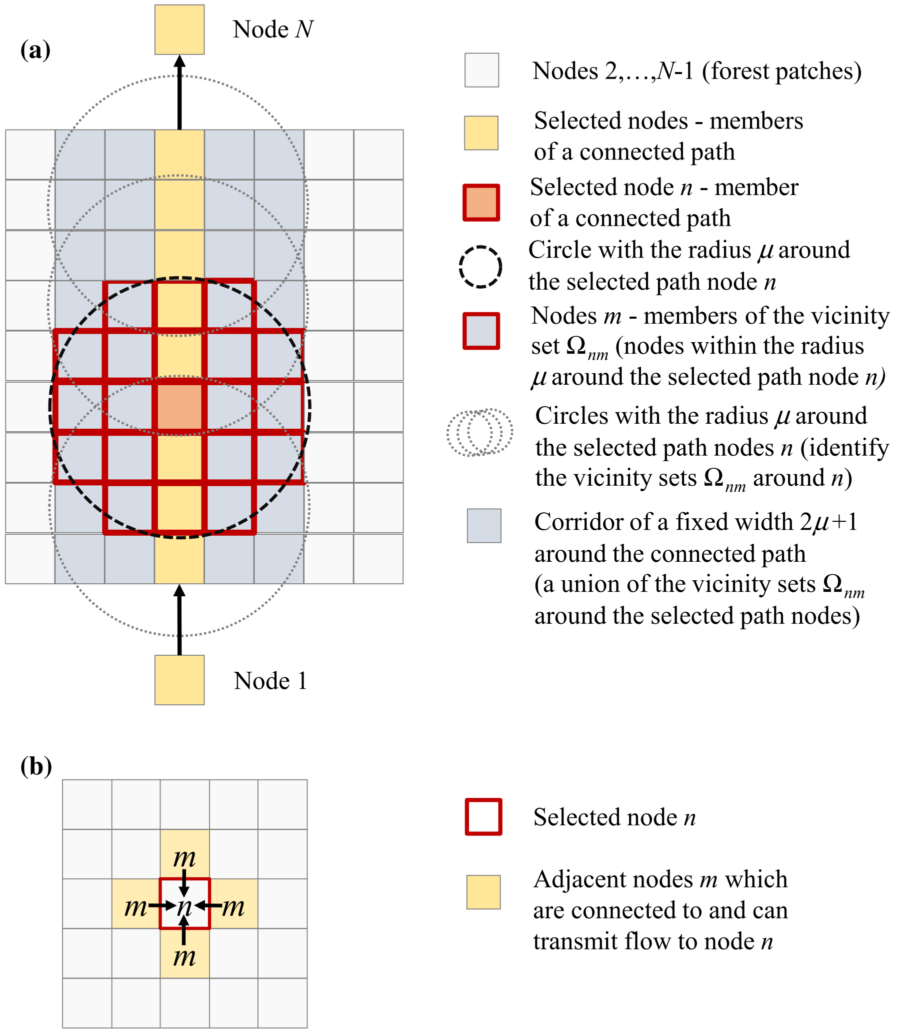


Fig. 3 **a** The connected path concept: a vicinity set, Ω_{nm}, of nodes m around the selected path node n and a fixed-width corridor connecting two isolated areas (nodes 1 and N); **b** Subset of neighboring nodes, $m = \{0), 2, \ldots, (N\text{-}1)_n$, which are connected to node n and can transmit flow to n

3a). The following formulation ensures the selection of this fixed-width corridor space bounding the path.

For each node n (i.e., a potential location in the connected path), we define a vicinity subset, Ω_{nm}, of surrounding nodes m; the nodes in Ω_{nm} comprise a circle with radius μ around n (Fig. 3a). For the complete path of connected nodes n, the union of the corresponding vicinity subsets Ω_{nm} around each individual node defines a corridor space with total width $2\mu+1$ (i.e., the selected path node plus μ nodes from each site, Fig. 3a). A binary variable, q_n, defines the selection of node n in a path connecting start node 1 and end node N through nodes 2, …, N-1 ($q_n=1$ and $q_n=0$ otherwise). Another binary variable, z_{nm}, specifies flow through arc nm between adjacent nodes n and m along the path ($z_{nm}=1$ and $z_{nm}=0$ otherwise). A third binary variable, w_m, selects the nodes m that comprise vicinity subset Ω_{nm} surrounding each selected path node n ($w_m=1$ and $w_m=0$ otherwise). Together, the selected nodes with $w_m=1$ define the fixed-width corridor.

Each node n in a landscape N is characterized by a flow resistance parameter, b_n, that describes how likely individuals are to move through that node. The resistance is tracked for all nodes in the selected corridor (i.e., with $w_n=1$). We assume that caribou prefer to move through undisturbed patches with large amounts of suitable habitat and assign those patches the lowest resistance. Conversely, caribou tend to avoid roads and other open spaces to minimize their exposure to predation, so we assign the highest resistance to recently harvested patches and sites with roads.

We formulate the optimal corridor placement problem as minimizing the total resistance for caribou passing through the selected corridor space, i.e.:

$$\min \sum_{n=2}^{N-1} \left(w_n b_n\right) \tag{1}$$

s.t.:

$$\sum_{n=1}^{N-1} z_{nk} = \sum_{m=2}^{N} z_{km} \,\forall\, k = 2, ..., N-1 \tag{2}$$

$$q_n \le \Delta_n \,\forall\, n = 1, ..., N, \Delta_n \in \{0, 1\} \tag{3}$$

$$w_m \ge q_n \,\forall\, n = 2, ..., N-1 \mid \Omega_{nm} = 1 \tag{4}$$

$$w_m \le \sum_{\substack{n=2,\\ \Omega_{nm}=1}}^{N-1} q_n \,\forall\, m = 2, ..., N-1 \tag{5}$$

$$q_m = \sum_{n=1}^{N-1} z_{nm} \,\forall\, m = 2, ..., N \tag{6}$$

$$\sum_{n=2}^{N} z_{1n} = 1 \, \forall \, \Xi_{1n} = 1 \tag{7}$$

$$\sum_{m=1}^{N-1} z_{mN} = 1 \, \forall \, \Xi_{mN} = 1 \tag{8}$$

Minimizing the total resistance of a fixed-width corridor tends to minimize its length, which is a desirable feature for caribou protection since a shorter corridor translates to less travel time and potential exposure to predators. Note that minimizing the average resistance (i.e., the total resistance of a fixed-length corridor divided by its area) does not similarly lead to a minimized length, so total resistance was used in the problem formulation.

Constraint (2) ensures the connectivity of the selected path (i.e., nodes with $q_n = 1$) and implies that the amount of flow coming to node k is equal to the amount of outgoing flow from k. Constraint (3) stipulates that the path can be allocated through a node n only if n belongs to a designated area. The designated area is defined by the binary parameter Δ_n (Δ_n =1 and Δ_n =0 otherwise). The connected path should be located at least a distance μ from the left and right borders of the landscape to guarantee the inclusion of the full corridor width. This is enforced by excluding the sites at a distance less than μ from the left and right border in the designated area. Constraints (4) and (5) ensure the selection of the corridor space around nodes n in the connected path. Constraint (4) implies that all nodes m surrounding a given node n at a distance μ (i.e., all members of the vicinity subset Ω_{nm} around n, as shown in Fig. 3a) must be included in the corridor space if n is in the connected path (i.e., $q_n = 1$). Constraint (5) guarantees that a node m will not be selected for the corridor if no potential path nodes n that have m in their vicinity subsets Ω_{nm} are actually included in the connected path. Constraint (6) enforces agreement between the selection of node m in the connected path and the selection of flow to m along the connected path. Constraints (7) and (8) specify the designated locations for possible path's beginning and end. Constraint (7) ensures that the flow from auxiliary start node 1 can only go to nodes as plausible candidates for the beginning of the path and ensures that the flow only goes through one arc (which guarantees a single connected path). Set Ξ_{1n} denotes the arcs $1n$ connecting node 1 with the plausible beginning nodes n (Fig. 2b). Similarly, constraint (8) ensures that the flow from a node m'—a plausible candidate for the path's end—comes to node N (the recipient of the flow) through a single arc. Set Ξ_{mN} denotes the arcs mN connecting the plausible end nodes m' to node N.

For narrow corridors, the model would need a constraint that sets an upper bound on resistance for a given cross-section of the corridor. The constraint would set a maximum total resistance for the vicinity subset Ω_{nm} around each selected path node n in the corridor. This would prevent the selection of bottleneck path locations with insufficient suitable habitat in surrounding nodes (i.e., the nodes in Ω_{nm}). This constraint was not required in our problem because the caribou corridor was wide enough (20 km) to guarantee sufficient suitable habitat along its entire length.

2.2 Harvest planning with a road construction sub-problem

Forest patches in the landscape network can be harvested for timber if they are not part of the wildlife corridor. The harvest allocation model maximizes the total revenue from harvesting timber minus the cost of harvesting, hauling and constructing roads to harvested sites and maintaining them over the remainder of the planning horizon T, subject to a target volume of harvested timber in each period t and an environmental sustainability constraint that maintains the minimum average forest age in the area at the end of the planning horizon. We assume that no human activities are allowed in the corridor area.

We adopt a Model I formulation [67–69] for the harvest scheduling problem. The model considers a landscape of N forest patches (nodes) over a horizon of T planning periods (each spanning 10 years in this case). For a given node n, a set of possible harvest prescriptions i, $i\in I$, defines the sequences of all harvest actions over T periods, including a no-harvest scenario. We enumerate all possible prescriptions that can be assigned to node n by a set of prescription binary vectors of length T, $\theta_{ni}=\{(1,0,\ldots,0),(0,1,\ldots0),\ldots\}$. The elements of each vector denote the harvest (or no harvest) conditions in periods t, $t=1, \ldots, T$. We define a binary decision variable x_{ni}, $x_{ni}\in\{0,1\}$, to select whether a forest patch n follows prescription i with a vector of harvest times θ_{ni}. Only one prescription i can be selected for a patch. We only consider clear-cut harvest, which is the most common harvest type in boreal Canada [70]. A forest stand can be harvested after it reaches a minimum harvest age or older. Each node n is characterized with a forested area, a_n, that could be harvested for timber, and a volume of merchantable timber per area unit, V_{nit}, that is available when trees are harvested in period t in prescription i. We define $Q_{t\,\min}$ and $Q_{t\,\max}$ as lower and upper bounds on the volume of timber harvested in period t and R_{ni} as the undiscounted net revenue flow associated with harvesting patch n according to prescription i. The revenue value is calculated as the difference between the mill gate price for delivered timber (customarily set by large mills in the region) and the actual cost of harvesting and delivering timber to the mill. Thus, maximizing timber revenues maximizes the difference between the mill gate price and the actual timber cost, so for a fixed mill gate price the mill gate cost of timber supply is minimized. We also add a minimum bound for the average age of forest stands in the managed area at the end of the planning horizon T, $E_{T\min}$, and define E_{ni} as the forest stand age in a patch n at the end of the planning horizon if prescription i is applied.

Clear-cut harvesting temporarily degrades caribou habitat as it reduces the amount of local foraging resources and exposes animals to predation until trees mature for 35–60 years [13, 14, 71, 72]. Thus, the quality of habitat depends on the age since harvest [73–76]. For each prescription i, we define the amount of suitable habitat β_{nit} that could potentially support caribou in node n in period t, $t\in T$. We then estimate the pass-through resistance b_{nit} as an inverse of the habitat suitability, $b_{nit}=\beta_{\max}-\beta_{nit}$, where $\beta_{\max}$ is the highest habitat suitability value in the area. Sites with roads and recent harvest receive the highest resistance and sites with large amounts of suitable habitat receive the lowest resistance.

Harvesting in remote areas requires building and maintaining forest roads. Road construction starts from locations with existing roads. For each planning period t, we find a subgraph of forest roads built to harvest sites from sites with existing roads in period t-1. In turn, nodes with roads built in period t can be used as starting points for building roads in period $t+1$ and so on. We introduce an auxiliary root node 0 that is connected to all other nodes 2, …, N-1 in the landscape from which the access roads could potentially originate. Node 0 serves as a source of the flow when building the road network. Binary variable v_{nmt}, $v_{nmt} \in \{0,1\}$, defines the flow through arc nm which denotes road construction between nodes n and m in period t. A non-negative variable y_{nmt}, $y_{nmt} \geq 0$, defines the amount of flow between nodes n and m when a road is built from n to m in period t (i.e., $y_{mnt} > 0$ when $v_{mnt} = 1$ and $y_{nmt} = 0$ otherwise). For each period t, we find a connected road network that starts from nodes with roads built in periods 1, …, t-1 and ends at the nodes harvested in period t.

To avoid loops, we stipulate that extending the road network to a node can only proceed in one direction (incoming arc). This implies that the flow can only come to a node from one source. A node n with incoming positive flow becomes a part of the road network in period t when:

$$\sum_{\substack{m=2,\{0\}\\ m\in\Theta_n}}^{(N-1)_n^-} v_{mnt} = 1 \tag{9}$$

Term $(N-1)_n^-$ defines a subset Θ_n of neighboring nodes m (including node 0) which are connected to node n and can transmit flow to n. In our case of a rectangular gridded network, at most four adjacent nodes m can transmit flow to n (Fig. 3b).

We assume that all roads will need maintenance from the time they are built until the end of the planning horizon T. Let c_{mn} be the cost of building a road mn between nodes m and n and j_{mn} the cost of maintaining road mn over period t. The construction and maintenance cost for a road mn built in period t is $c_{mn}+j_{mn}(T\text{-}t)$ and the total road construction and maintenance cost over a horizon T is $\sum_{n=2}^{N-1}\sum_{t=1}^{T}\sum_{\substack{m=2\\ m\in\Theta_n}}^{N-1}(v_{mnt}[c_{mn}+j_{nm}(T-t)])$.

We then define the harvest planning problem as maximizing the net revenue flow associated with harvesting the forest over T periods minus the road construction and maintenance costs, i.e.:

$$\max \sum_{n=2}^{N-1}\left[\sum_{i=1}^{I}(R_{ni}x_{ni}) - \sum_{t=1}^{T}\sum_{\substack{m=2\\ m\in\Theta_n}}^{N-1}(v_{mnt}[c_{mn}+j_{mn}(T-t)]) - f_1\sum_{t=1}^{T}P_{1_{nt}}\right] - f_2\sum_{t=1}^{T}P_{2_t} \tag{10}$$

s.t.:

$$\sum_{i=1}^{I}x_{ni} = 1\,\forall n \in 2,\ldots,N-1 \tag{11}$$

$$Q_{t\,\mathrm{min}} \leq \sum_{n=2}^{N=1} \sum_{i}^{I} a_n V_{nit} x_{ni} \leq Q_{t\,\mathrm{max}} \,\forall\, t \in T \tag{12}$$

$$\sum_{n=2}^{N-1} \left(\sum_{i=1}^{I} \left[(E_{ni} - E_{T\,\mathrm{min}}) a_n x_{ni} \right] \right) \geq 0 \tag{13}$$

$$y_{1nt} = 0 \,\forall\, t \in T,\ n = 0, 2, ..., N-1 \tag{14}$$

$$y_{nNt} = 0 \,\forall\, t \in T, n = 0, 2, ..., N-1 \tag{15}$$

$$\sum_{\substack{m=2,\{0\} \\ m \in \Theta_n}}^{(N-1)_n^-} y_{mnt} - \sum_{m=2}^{(N-1)_n^+} y_{nmt} = \sum_{\substack{m=2,\{0\} \\ m \in \Theta_n}}^{(N-1)_n^-} v_{mnt} \,\forall\, t \in T, n, m = \{0\}, 2, ..., N-1 \tag{16}$$

$$y_{nmt} \leq U v_{nmt} \,\forall\, t \in T,\ n, m = \{0\}, 2, ..., N-1 \tag{17}$$

$$v_{nmt} \leq y_{nmt} \,\forall\, t \in T,\ n, m = \{0\}, 2, ..., N-1 \tag{18}$$

$$v_{0n1} \leq \Gamma_n \,\forall\, n = 2, ..., N-1,\ \Gamma_n \in \{0, 1\} \tag{19}$$

$$v_{0nt} \leq \Gamma_n + \sum_{u=1}^{t-1} \sum_{\substack{m=2,\{0\} \\ m \in \Theta_n}}^{N-1} v_{nmu} \,\forall\, t = 2, ..., T, u \in T, n = \{0\}, 2, ..., N-1,\ \Gamma_n \in \{0, 1\} \tag{20}$$

$$\sum_{u=1}^{t} \left[\sum_{\substack{m=2,\{0\} \\ m \in \Theta_n}}^{N-1} v_{mnu} \right] \geq \sum_{i=1}^{I} (x_{ni} W_{nit}) \,\forall\, u \in T, t \in T, n = 2, ..., N-1,\ W_{nit} \in \{0, 1\} | \Gamma_n = 0, \tag{21}$$

$$\sum_{t=1}^{T} v_{nmt} \leq 1 \,\forall\, n, m \in 2, ..., N-1 \tag{22}$$

$$\sum_{\substack{m=2,\{0\} \\ m \in \Theta_n}}^{(N-1)_n^-} v_{mnt} \leq 1 \,\forall\, t \in T,\ n = \{0\}, 2, ..., N-1 \tag{23}$$

$$v_{nmt} + v_{mnt} \leq 1 \,\forall\, n, m \in N \tag{24}$$

$$v_{nmt} \leq 2 - \Gamma_n - \Gamma_m \, \forall \, n, m = 2, \ldots, N-1, t \in T | \Gamma_n = 1 \wedge \Gamma_m = 1 \tag{25}$$

$$\sum_{i=1}^{I} \left(x_{ni} \sum_{t=1}^{T} V_{nit} \right) = 0 \, \forall \, n = 2, \ldots, N-1 | \xi_n = 0 \tag{26}$$

$$P_{1nt} \geq \sum_{\substack{m=2,\{0\} \\ m \in \Theta_n}}^{N-1} v_{mnt} - \sum_{k=2}^{N-1} v_{nkt} - \sum_{i=1}^{I} (x_{ni} W_{nit}) \, \forall \, t \in T, n = 2, \ldots, N-1 \tag{27}$$

$$P_{2t} \geq \sum_{m=2,\{0\}}^{N-1} \sum_{\substack{n=2,\{0\} \\ m \in \Theta_n}}^{N-1} (v_{mnt}) - B_t \, \forall \, t \in T \tag{28}$$

Objective function (10) includes the following terms: the net harvest revenues, the road construction and maintenance costs and penalties that control the extent of the road network. These penalties, P_{1nt} and P_{2t}, are captured as constraints (27) and (28), respectively.

Constraint (11) ensures that each node n is assigned one prescription i. The set of prescriptions I includes a prescription with no harvest and no impact on habitat. Constraint (12) ensures that the harvest volume for each period stays within a target range $[Q_{t\,\min}; Q_{t\,\max}]$. Constraint (13) sets the average age of forest stands at the end of the planning horizon T to be greater than or equal to the minimum age $E_{T\,\min}$. This prevents overharvesting and ensures that a portion of the old-growth forest stands is left unharvested. The revenue value R_{ni} is calculated as the undiscounted value of harvested timber (at the mill gate) net of harvest, hauling and optional post-harvest regeneration costs, e_n:

$$R_{ni} = \sum_{t=1}^{T} \left(a_n \phi_n V_{nit} - e_n \right) \tag{29}$$

where φ_n is the per unit harvest and hauling cost value, V_{nit} is the volume of harvested timber in site n in period t in prescription i and a_n is the area of harvestable forest in site n. Because the corridor placement problem (1–8) did not incorporate discounting, we used undiscounted cash flows from harvest. Since the harvest planning problem includes a fixed harvest target and even harvest flow constraint, the use of discounted cash flows in long-term harvest planning could skew the allocated harvest patterns towards harvesting the least expensive and most productive sites first, while deferring the harvest of less productive sites and as much road construction as possible to future periods when the discounted value of their associated costs depreciates. By using undiscounted cash flows, we are able to keep the harvest and road construction patterns more balanced and environmentally sustainable over the planning horizon.

The model also required constraints controlling the road construction network. Constraints (14) and (15) separate the road construction and corridor connectivity arc sets and ensure no flow from auxiliary node 1 or to auxiliary node N (which are only used in the corridor sub-problem) in the road construction sub-problem. Equation (16) is a flow conservation constraint and specifies that the amount of flow coming to node n from neighboring nodes m in period t is equal to the amount of outgoing flow from n plus the allocated capacity (one unit of flow) at n. Constraint (16) ensures the connectivity of the road network between the nodes with existing roads and sites harvested in period t. Subset $\{0\},2,\ldots,(N-1)_n^-$ in Eq. (16) denotes the nodes connected to node n (including the root node 0) that could transmit flow to n and subset $2,\ldots,(N-1)_n^+$ denotes the nodes connected to n that could receive flow from n. Constraints (17) and (18) ensure correspondence between the selection of arcs nm connecting nodes n and m in period t and the allocation of flow between n and m. Equation (17) specifies no flow between nodes n and m in period t if arc nm is not selected, and U is a large positive value. Equation (18) ensures no arc selection if no flow occurs between nodes n and m in period t. Constraint (19) restricts the selection of arcs $0n$ connecting node 0 with landscape nodes where road construction to other locations could start at the beginning of the planning horizon, $t=1$. A binary parameter Γ_n, $\Gamma_n \in \{0,1\}$, indicates eligible nodes, which were those nodes that had existing roads in period $t=1$ ($\Gamma_n=1$ and $\Gamma_n=0$ otherwise). Constraint (20) restricts the flow from node 0 in periods $t=2, \ldots, T$ to nodes that had roads (either pre-existing or newly built) as of the previous planning period 1, …, t-1. An auxiliary subscript u denotes time periods $u=1, \ldots, t$-1. Constraints (19) and (20) ensure that road construction (and the corresponding flow) between nodes n and m in period t can only proceed from nodes that had roads prior to period t. Equations (19) and (20) also ensure inter-temporal connectivity of the road network over consecutive periods t-1 and t.

Constraint (21) ensures agreement between the construction of roads and allocation of harvest. Equation (21) implies that harvesting a node n in period t outside of the previously existing road network (i.e., nodes with $\Gamma_n = 0$) is only possible if road is built to n during periods 1,…,t. Binary parameter W_{nit} is an indicator of harvest in node n in prescription i in period t (i.e., $W_{nit}=1$ when a positive timber volume, $V_{nit}>0$, is harvested in node n in period t in prescription i and $W_{nit}=0$ otherwise). Subscript u denotes time periods 1, …, t. The left portion of Eq. (21) defines the presence of road built to a node n in periods 1, …, t and the right portion defines harvest in n in period t.

Constraint (22) ensures that a road between nodes n and m can only be built once over the planning horizon T. Constraint (23) prevents building multiple roads to node n and implies that the flow to n can only come through a single arc (i.e., one road). Constraints (24) and (25) tighten the formulation: constraint (24) prevents bidirectional flow between neighboring nodes n and m, and constraint (25) implies no flow (and no road construction) between nodes which are already connected by roads at the beginning of the planning horizon. The masking constraint (26) ensures no harvest outside of the designated area, with a binary parameter, ξ_n, indicating that a node n is within this harvestable area ($\xi_n=1$ and $\xi_n=0$ otherwise).

Building the forest road network may create situations when a terminal road segment is built to node n (i.e., with no further roads built beyond n) in period t, but the node is not harvested in that period. In theory, this road segment could be used to harvest trees in n in future periods $t+1, \ldots, T$. However, given the 10-year time span of each planning period t, we assumed that cost considerations would limit road construction to nodes that are scheduled for harvest in that same period. The penalty P_{1nt} in the objective function Eq. (10), which is defined in constraint (27), decreases the objective value if a terminal road segment is built to node n in period t, but n is not harvested in that period. The penalty does not affect transit road segments built in period t, i.e., when a road is built to node n and continues through it to other harvested nodes, but no trees are harvested from n during period t.

The length of roads built in a particular period t may vary depending on the spatial configuration of harvest and availability of local timber supply over time. However, the maximum road length that can be built in period t is usually limited by cost and personnel availability. We introduce an upper bound, B_t, that sets a road construction limit in period t. The penalty P_{2t} in the objective function Eq. (10) decreases the objective value when the total road construction length in period t exceeds this limit. Constraint (28) defines P_{2t} for each period t as equal to the total length of roads built above the limit B_t. Alternatively, the penalties P_{1nt} and P_{2t} could be formulated as hard constraints, but the combinatorial complexity of the road construction sub-problem makes it difficult to find feasible solutions with hard constraints, so we used a penalty formulation.

We then combine the harvest planning problem with the road construction and corridor placement sub-problems in a single objective that maximizes the harvest revenues minus the road construction costs, the road construction penalties P_{1nt} and P_{2t} and the rescaled habitat resistance value of the connected wildlife corridor, i.e.:

$$\begin{aligned} \max \sum_{n=2}^{N-1} & \left[\sum_{i=1}^{I} (R_{ni} x_{ni}) - \sum_{t=1}^{T} \sum_{\substack{m=2 \\ m \in \Theta_n}}^{N-1} (v_{mnt}[c_{mn} + j_{mn}(T-t)]) - f_1 \sum_{t=1}^{T} P_{1_{nt}} \right] \\ & - f_2 \sum_{t=1}^{T} P_{2_t} - f_3 \sum_{n=2}^{N-1} \left[w_n \left(\sum_{t=1}^{T} b_{n1t} \right) \right] \end{aligned} \tag{30}$$

s.t.:

constraints (2–8),(11–28) and:

$$\sum_{i=1}^{I} \left(x_{ni} \sum_{t=1}^{T} W_{nit} \right) \le \lambda (1 - w_n) \, \forall n = 2, \ldots, N-1 \tag{31}$$

$$\sum_{t=1}^{T} \left(\sum_{\substack{n=2,\{0\} \\ m \in \Theta_n}}^{N-1} v_{mnt} \right) \le 1 - w_n \, \forall n = 2, \ldots, N-1 \tag{32}$$

$$z_{0n} = 0 \, \forall n \in N \tag{33}$$

Compared to the harvest planning problem without the corridor (10), the objective function (30) includes the term $\sum_{n=2}^{N-1} \left[w_n \left(\sum_{t=1}^{T} b_{n1t} \right) \right]$ which defines the total habitat resistance for the selected corridor area. Because harvest and road construction are not allowed in the corridor area, this term only needs to track the selection of one harvest prescription without harvest. In our prescription set I, the prescription without harvest was encoded as $i = 1$, hence the resistance values in the corridor in Eq. (30) were always calculated for prescription 1, i.e., b_{n1t}.

Constraints (31) and (32) ensure no harvest or road construction in the corridor area. The term λ in Eq. (31) defines the maximum number of harvests that may occur in a node n over the planning horizon T, $\lambda < T$. The left portion of Eq. (31) calculates the number of harvest events in n over horizon T. Harvesting is allowed if node n is located outside of the corridor area, i.e., when $w_n = 0$. Constraint (32) ensures that no roads are constructed to nodes inside the corridor area over horizon T. Constraint (33) ensures no flow from node 0 (which is only used in the road construction sub-problem) to other nodes n in the corridor placement sub-problem. Parameters f_1-f_3 define the scaling factors for the objective terms.

Harvest restrictions in the corridor area may change the harvest pattern and increase the cost of timber. We explored this trade-off by comparing the optimal solutions in the harvest planning problem without the corridor, as defined by objective (10) with constraints (11–28), to the optimal solutions for the full problem with corridor placement, as defined by objective (30) with constraints (2–8), (11–28) and (31–33). The trade-off between prioritizing wildlife corridor protection versus harvest objectives can be explored by varying the scaling factor f_3 in Eq. (30). Due to space limitations, we only present the most distinct scenarios that prioritize harvest revenues over corridor placement (with $f_3 = 0.001$), or conversely, that prioritize corridor connectivity (with $f_3 = 10$). Table 1 lists the model parameters and variables.

2.3 Case study

We applied the model to examine options to establish a corridor for caribou between the Lake Superior Coast Range and the Pagwachuan and Nipigon Ranges in the Pic River and Kenogami Forest Management Units (FMU) of northwestern Ontario, Canada (Fig. 1) [77, 78]. The area between the ranges has been moderately fragmented by logging, with timber delivered to mills in Terrace Bay, Ontario and a number of small mills across the region. Creating a wide corridor through this area would help facilitate seasonal movement of caribou between the ranges and is seen as a measure to prevent further decline of caribou populations in the region. Nevertheless, it must compete with ongoing forestry operations.

2.4 Data

We divided the study area landscape into 1.5 × 1.5 km patches (5754 nodes in total). We adopted this relatively coarse patch size because it is compatible with

Table 1 Summary of the model symbolic notation

Symbol	Parameter / variable name	Description
Sets:		
N	Nodes (forest patches) n,m in a landscape N	$n,m \in N$
Θ_n	Subset of neighboring nodes m connected to node n which could transmit flow to n	$\Theta_n \in N$
T	Planning time periods, t, u	$t,u \in T$
I	Harvest prescriptions, i	$i \in I$
Decision variables:		
q_n	Selection of node n as a member of a connected path from the start node 1 to end node N through nodes-forest patches 2,…,N-1 (defines the center of the corridor)	$q_n \in \{0,1\}$
z_{nm}	Flow through an arc nm between the selected adjacent nodes n and m along the connected path mn in the center of the corridor	$z_{nm} \geq 0$
w_m	Surrounding nodes m – members of the vicinity subset Ω_{nm} around each selected path node n within distance $\leq \mu$ from n	$w_m \in \{0,1\}$
x_{ni}	Binary selection of harvest prescription i in node n	$x_{ni} \in \{0,1\}$
v_{nmt}	Selection of flow through arc nm which depicts the construction of road between nodes n and m in period t	$v_{nmt} \in \{0,1\}$
y_{nmt}	Amount of flow between nodes n and m when the road is built from n to m in period t ($y_{mnt} > 0$ when $v_{mnt} = 1$ and $y_{nmt} = 0$ when $v_{mnt} = 0$)	$y_{nmt} \geq 0$
P_{1nt}	Penalty for building a road segment mn to node n in period t and not harvesting the forest in n in the same period	$P_{1nt} \geq 0$
P_{2t}	Penalty for exceeding the target road construction length B_t in period t	$P_{2t} \geq 0$
Parameters		
b_{nit}	Species movement resistance through node n in prescription i in period t	$b_{nit} \geq 0$
b_n	Species movement resistance through node n – describes how likely individuals are to move through n	$b_n \geq 0$
$Q_{t\,\min}, Q_{t\,\max}$	Lower and upper bounds on harvest volume over a period t	$Q_{t\,\min}, Q_{t\,\max} \geq 0$
a_{n}	Forest area in a node n	$a_n \geq 0$
V_{nit}	Volume of timber harvested in node n in period t in harvest prescription i	$V_{nit} \geq 0$
R_{ni}	Net revenue associated with harvesting a node n according to prescription i	$R_{ni} \geq 0$
$E_{T\,min}$	Average target age of forest stands in the managed area N at the end of the planning horizon T	80
E_{ni}	Forest stand age in node n at the end of the planning horizon if prescription i is applied	0–220

Table 1 (continued)

Symbol	Parameter / variable name	Description
e_n	Postharvest regeneration costs	$e_n > 0$
c_{nm}	Cost of building a road segment *mn* between nodes *m* and *n*	$c_{nm} > 0$
j_{nm}	Cost of maintaining a road segment *mn* between nodes *m* and *n* in one time period	$j_{nm} > 0$
μ	Distance between the connected path in the center of the corridor and the corridor boundary. The total corridor width is $2\mu + 1$ nodes	6 nodes
λ	Maximum number of harvests in node *n* that may occur over a planning horizon *T*	$\lambda < T$
B_t	Maximum road construction length target in period *t*	$B_t > 0$
W_{nit}	Binary indicator of harvest in node *n* in prescription *i* in period *t*, ($W_{nit} = 1$ for $V_{nit} > 0$ and $W_{nit} = 0$ for $V_{nit} = 0$)	$W_{nit} \in \{0,1\}$
Γ_n	Nodes with existing roads at time $t = 1$, ($\Gamma_n = 1$ and $\Gamma_n = 0$ otherwise)	$\Gamma_n \in \{0,1\}$
Δ_n	Nodes-eligible locations for the placement of a connected path between isolated wildlife rages, ($\Delta_n = 1$ and $\Delta_n = 0$ otherwise)	$\Delta_n \in \{0,1\}$
Ω_{nm}	Vicinity subset of nodes *m* surrounding the selected path node *n* within the chosen distance $\leq \mu$	$\Omega_{nm} \in \{0,1\}$
Ξ_{1m}	Nodes in the southern border of the area *N* where a connected path (the center of the corridor) may begin—identifies the nodes adjacent to the southern caribou range	$\Xi_{1m} \in \{0,1\}$
Ξ_{nN}	Nodes in the northern border of the area *N* where a connected path (the center of the corridor) may end – identifies nodes adjacent to the northern caribou range	$\Xi_{nN} \in \{0,1\}$
ξ_n	Binary parameter indicating that a node *n* belongs to a harvestable area ($\xi_n = 1$ and $\xi_n = 0$ otherwise)	$\xi_n \in \{0,1\}$
f_1, f_2, f_3	Scaling factors for objective terms and penalties in the objective function (30)	$f_1\text{-}f_3 \geq 0$
U	Large positive value	$U > 0$

the large blocks of clear cuts that characterize the primary harvest practice in boreal Canada [70], and because we deemed it suitable for capturing the large-scale harvest patterns that are pertinent to caribou habitat protection. Furthermore, keeping the patch size sufficiently large guides the road construction model to track major road segments only. Notably, the chosen resolution provides a reasonable balance between the size of the network and the length of the planning horizon and keeps the network problem tractable.

For each node, we estimated the model spatial parameters including the amount of suitable habitat, β_{nit} (Fig. 4a), forest age and timber volume (Fig. 4b,c), timber hauling cost (Fig. 4d), presence of existing roads (Fig. 4e), whether the node was on the border of one of the caribou ranges where corridor connection could be possible (Fig. 4f) and whether the node was in the eligible area for the connected corridor path (Fig. 4g). The resistance value for each harvest time and forest age combination was estimated as $b_{nit}=\beta_{\max}—\beta_{nit}$. The habitat suitability values were estimated using the boreal caribou habitat model for Ontario's Northwest and Northeast Regions [79]. For every 10-year forest age class, for each habitat type (such as useable, preferred and refuge habitats), a score of 1 was assigned, and the total habitat suitability value was estimated as the sum of these scores. The nodes dominated by preferred and refuge-quality habitat end up with the highest suitability score. When forest patches included a mix of different land cover types and habitat types, the total habitat suitability value was estimated as a weighted average of habitat scores for individual cover types in a node and their corresponding areas. The cover types included jack pine and black spruce-dominated stands, jack pine, black spruce and conifer mixedwoods, black spruce lowlands, other conifer stands and treed muskeg. We assumed that forest stands regain suitable habitat status 40 years after harvest.

We used geospatial road network data from the CanVec database [80] to estimate the timber hauling costs, assuming an on-site harvest cost of CAN\$15 m^{-3} and delivery of timber to Terrace Bay, Ontario (the largest mill in the area) (Fig. 4d). The hauling costs were based on typical estimates for northern Ontario conditions [81] and included the delivery cost with a hauling rate of \$90-h^{-1}, assuming a 40-m^{3} truckload, one-hour waiting time and an overhead cost of \$4 m^{-3}. We used a road construction cost estimate of \$200,000-km^{-1} and a maintenance cost estimate of \$7000-km^{-1}-yr^{-1}, which are within the range of the known costs for northern Ontario conditions [82]. The starting values for stand age, merchantable timber volume, land cover composition, human disturbances and the extent of harvestable area were estimated from Ontario's Forest Resource Inventory database [83]. To estimate future timber yields in the harvest prescriptions, we used a set of yield curves for northwestern Ontario from a recent timber supply study [84]. These yield values were adjusted by the expected annual losses of forested area due to fires using fire regime zones from [85]. The minimum forest age eligible for harvest was set to 70 years. The minimum average age for the forest stands in the area at the end of the planning horizon, $E_{T\min}$ was set to 80 years. We set the difference between harvest target limits $Q_{t\min}$ and $Q_{t\max}$ for each period t to 2% and the harvest planning horizon T to 100 years with ten 10-year time steps t.

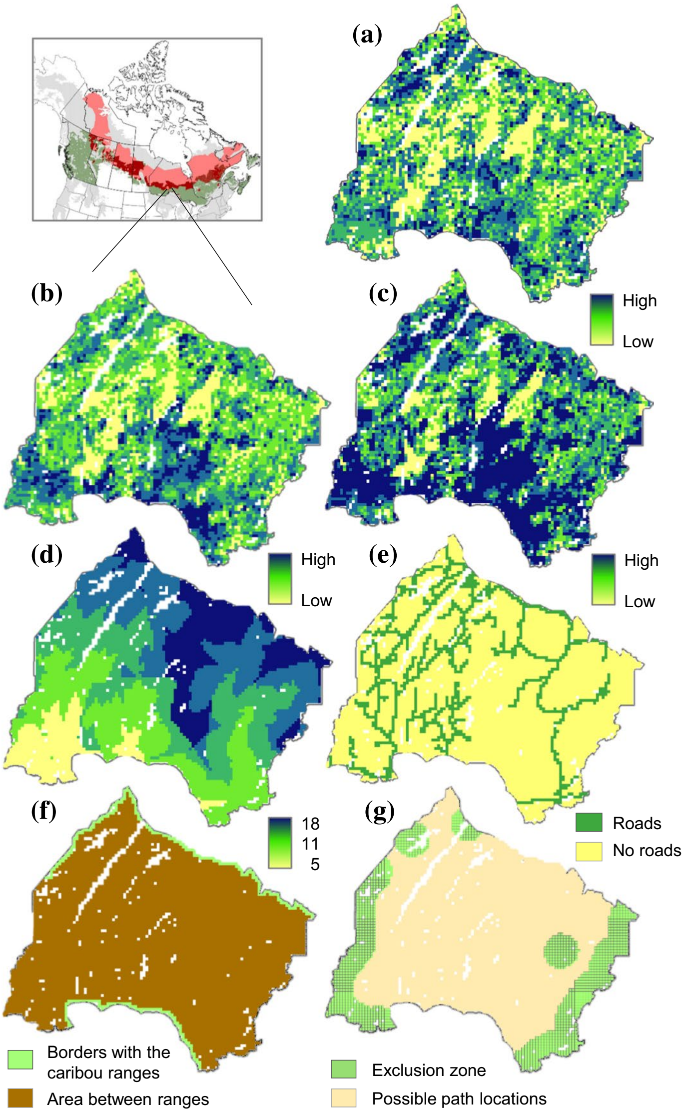


Fig. 4 Model spatial inputs: **a** Habitat capacity, β_{nit}, at $t=1$; **b** forest stand age, years, at $t=1$; **c** merchantable timber volume, m^3-ha^{-1}, at $t=1$; **d** timber hauling cost, \$-ha^{-1}; **e** existing roads at $t=1$; f) borders with the caribou ranges north and south of the study area; g) exclusion zones for the connecting path in the middle of the wildlife corridor, which ensures placement of the full corridor width in the study area

2.5 Corridor placement and forestry scenarios

We evaluated scenarios that assumed harvesting with and without corridor placement (Table 2), with a range of sustainable harvest levels between 0.3 and 0.85 M m^3-yr^{-1}. The upper bound of this range approaches the maximum sustainable

Table 2 Model scenarios

Scenario	Corridor placement	Management priority	f_3 scaling factor value
Harvest only	None	Harvest priority	–
Harvest + fixed corridor	The lowest-resistance fixed corridor position in the western part of the area	Harvest priority	–
"No roads" scenarios: Roads are ignored when calculating the habitat resistance			
Harvest + corridor, corridor priority	Optimal	Corridor priority	10
Harvest + corridor, harvest priority	Optimal	Harvest priority	0.001
"Roads" scenarios: Sites with roads are assigned the habitat resistance of recently harvested sites			
Harvest + corridor, corridor priority	Optimal	Corridor priority	10
Harvest + corridor, harvest priority	Optimal	Harvest priority	0.001

harvest limit in each problem formulation. Previous assessments of long-term caribou movement patterns in northern Ontario suggested that caribou tend to select habitat at broad scales (i.e., up to 10,000 ha) rather than finer scales [64, 65]. Discussions with caribou specialists from the Ontario Ministry of Natural Resources and Forestry indicated 20 km as a minimum corridor width to facilitate unrestricted movement of caribou.

Our "harvest only" scenario prioritized net harvest revenues minus road construction and maintenance costs without implementing a corridor, using objective (10). To assess the worst potential impact of a corridor on harvest, we also evaluated a scenario with a fixed corridor located in the western portion of the study area. We determined the placement of this fixed corridor based on a model solution without harvest; in this solution, the corridor had the shortest possible length and lowest possible resistance in the absence of harvest.

Next, we assessed optimal spatial positions for the corridor in two groups of scenarios that either did or did not account for the negative impact of roads on caribou habitat (Table 2). In the "no roads" scenarios, the resistance values b_{nit} were based on the amount of suitable habitat from the model of Elkie et al. [79], and the presence of roads was ignored. A second group of "road" scenarios assigned resistance values to nodes with roads that were equal to the resistance of recently harvested habitats.

For each of these groups, we compared two "corridor + harvest" scenarios (Table 2). Each of these scenarios used the full problem formulation with a corridor (30) and assumed there was no harvest or road construction in the corridor area. The "corridor priority" scenario prioritized minimizing the corridor resistance over harvest revenues and used a high scaling value, $f_3 = 10$, in the objective function (30). The "harvest priority" scenario prioritized harvest revenues over minimizing the corridor resistance and used $f_3 = 0.001$. All tested scenarios were set to meet the harvest target [$Q_{t\ \min}$; $Q_{t\ \max}$]. To reduce the solution time, we warm-started the full model using the initialization procedure described in Appendix 1.

We also explored the behavior of the road construction model. We first evaluated a short-sighted policy, where the construction of roads was optimized within a single planning horizon only (but harvest planning was optimized over the whole horizon *T*). This is the solution for a sequential initialization model in Appendix 1. A second evaluation implemented optimal road construction with corridor placement in the full problem formulation (30). A comparison of these solutions helps understand the impact of long-term strategic planning on road construction patterns.

3 Results

As expected, the harvest-only solutions without the corridor yielded the lowest optimality gap values, in the 0.002–0.06 range, after solving the model for 48 h. Solutions that included harvest and corridor placement were more combinatorically complex and had higher gap values, 0.09–0.21 and above, after 72 h. Due to a particular combinatorial nature of the network flow problem the spatial patterns of harvest and the corridor location stabilized at relatively high gap values after 48–60 h, with only minor incremental changes in harvest patterns afterwards. Solving the model for longer times did not change the general locations of the corridor and harvest patterns and the solution progress was mostly due to a reduction of the upper bound, hence a 72-h time limit was deemed sufficient.

3.1 Corridor placement and optimal harvest patterns

Both harvest-only and harvest + corridor solutions show the bulk of the harvest allocated in the southwestern portion of the study area, close to the nearest timber market (i.e., the mill in Terrace Bay, ON) as well as a major highway along the north shore of Lake Superior (Figs. 5, 6). The harvest + corridor solutions prioritized two distinct corridor locations in the western and eastern parts of the study area depending on the scenario assumptions. When the impact of roads on habitat was ignored and corridor placement was prioritized over harvest revenue, the corridor was located in the western part of the study area (Fig. 6b). With the corridor in place, a significant portion of the harvest was diverted to other locations in the surrounding area and increased the mill gate timber cost, on average, by \$3.6–5.4-m^3 compared to harvest-only solutions (Table 3).

When the negative impact of roads on caribou habitat use was considered or harvest revenue was prioritized, the corridor was nearly always located in the eastern part of the study area (Figs. 5b, c, 6c). The eastern part has a lower existing road density and, in most scenarios, saw less road construction and harvest activity than the western part. Although this may suggest the eastern part can better accommodate the corridor, it was consistently longer by 11–18 km than when located in the western part. At the same time, the impact on the mill gate timber cost was lower in

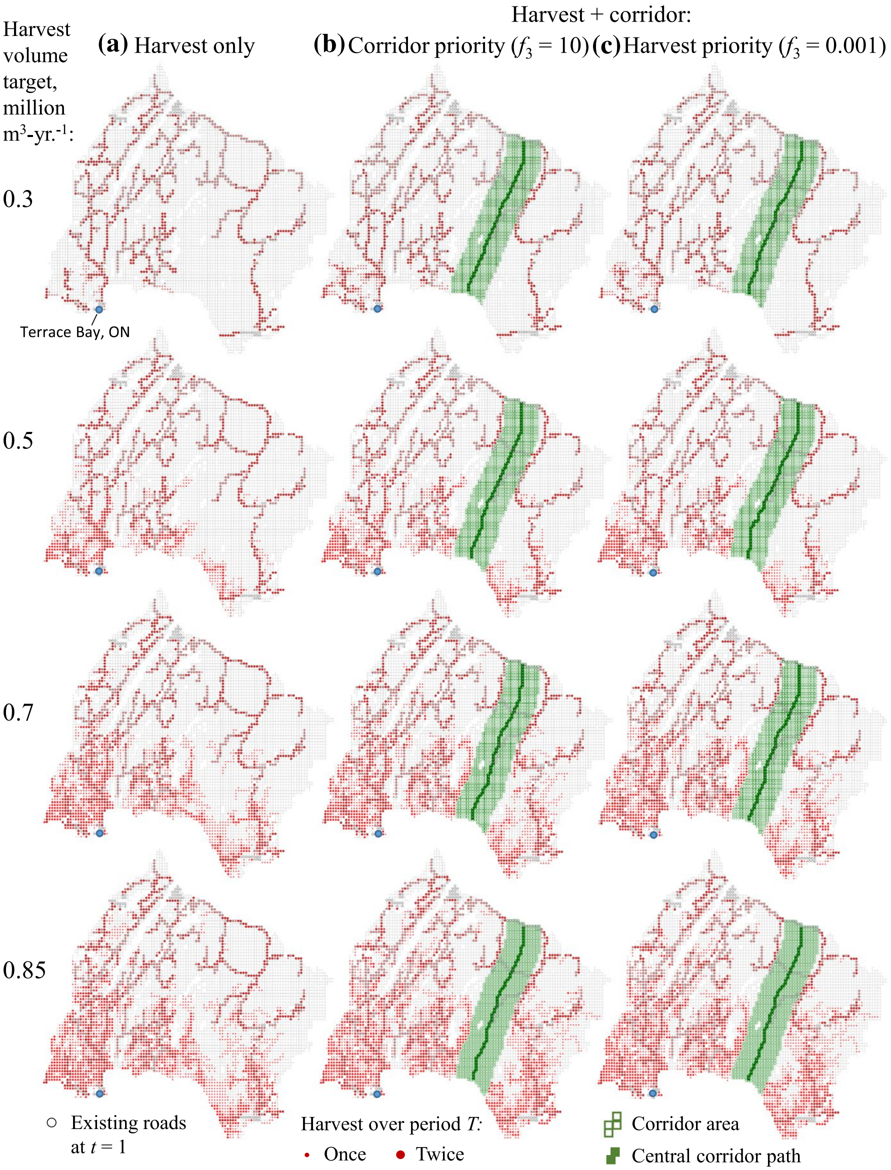


Fig. 5 Harvest and corridor placement patterns in optimal solutions for "roads" scenarios. Sites with roads are assigned habitat resistance values similar to the resistance of recently harvested sites. Optimal solutions: **a** harvest only, no corridor; **b** harvest + corridor, corridor priority; **c** harvest + corridor, harvest priority

these scenarios, ranging from \$1.1 to \$1.8-m^{-3} higher than the harvest-only solutions (Table 3).

When the impact of roads on habitat was ignored, the conservation manager's objective defined the optimal corridor location. Prioritizing the corridor (i.e.,

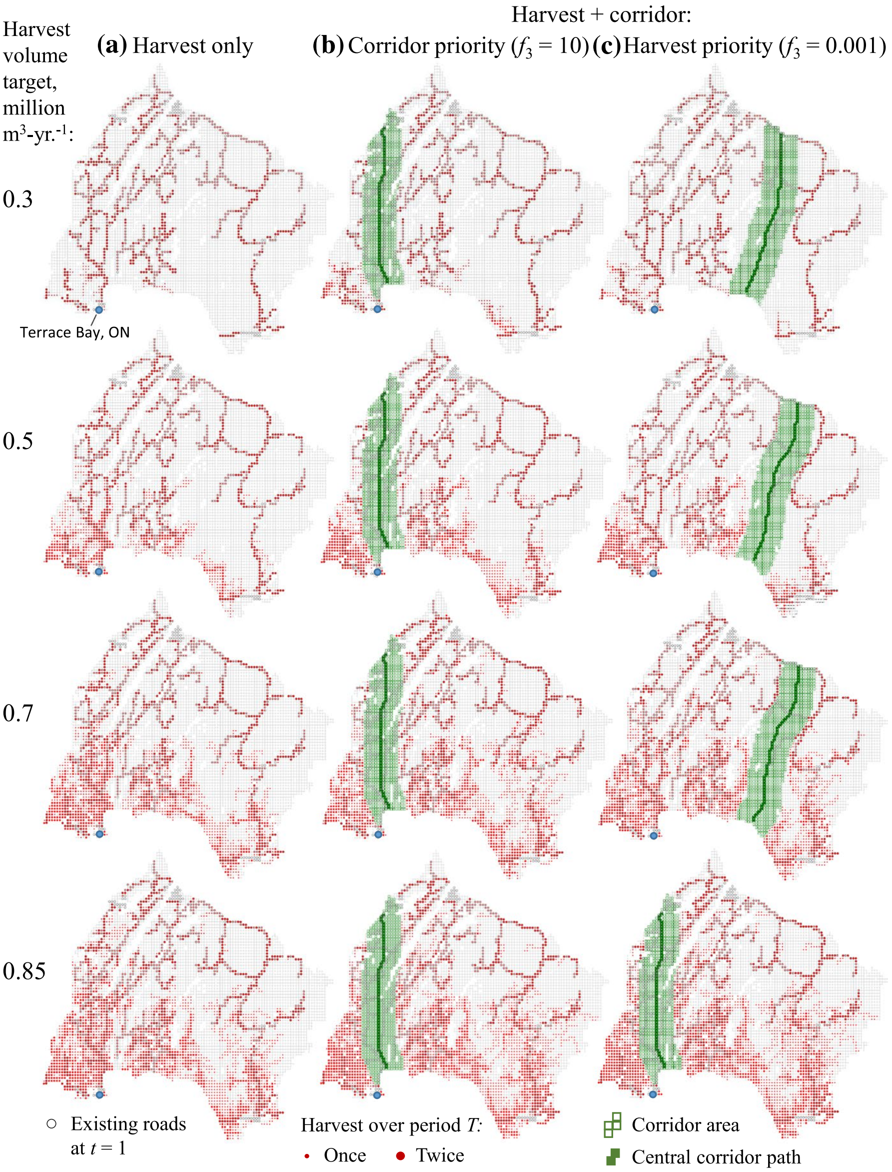


Fig. 6 Harvest and corridor placement patterns in optimal solutions for "no roads" scenarios. Roads are ignored when calculating the habitat resistance values. Optimal solutions: **a** harvest only, no corridor; **b** harvest + corridor, corridor priority; **c** harvest + corridor, harvest priority

minimizing habitat resistance within the corridor) over harvest revenue moved the corridor to the western portion of the study area, where the distance between the caribou ranges is shortest (Fig. 6b). Notably, this location overlaps an area of historically active harvesting that is close to the mill in Terrace Bay, ON. Consequently,

Table 3 Timber supply cost, net revenues and road construction summaries for harvest-only and harvest + corridor scenario solutions

Scenario	Harvest target, M m^3-yr.$^{-1}$	Corridor location in the area	Corridor length, km	Corridor resistance	Access roads built over *T* periods, km	Millgate unit price, \$-m^{-3}	% of road constr. and maint. cost from the total cost	Net revenue, \$M over *T* periods, net of the road cost	Road construction and maintenance cost, \$M over T periods		Area harvested over *T* periods, ha
									Construction	Maintenance	
	Harvest only (no corridor)										
Harvest priority	0.3	–	–	–	272	30.8	4%	1025	39	19	221,002
	0.5	–	–	–	5985	40.5	31%	1213	618	419	346,686
	0.85*	–	–	–	17,805	49.8	43%	1273	1782	1246	581,479
	Harvest + corridor: Solutions with a fixed, shortest-length corridor placement in the western part of the area										
Harvest priority	0.3	Western	93	10,257	1907	36.2	19%	856	204	133	215,894
	0.5	Western	93	10,257	8094	45.0	37%	987	817	567	341,522
	0.85	Western	93	10,257	19,914	53.4	45%	968	1991	1394	583,266
	Harvest + corridor, no roads: Roads are ignored when calculating the habitat resistance										
Corridor priority	0.3	Western	93	10,257	1907	36.2	19%	856	204	133	215,894
	0.5	Western	93	10,257	8094	45.0	37%	987	817	567	341,526
	0.85	Western	93	10,257	19,898	53.4	44%	970	1990	1393	583,429
Harvest priority	0.3	Eastern	104	10,577	968	32.1	11%	984	110	68	220,402
	0.5	Eastern	108	10,889	7001	42.0	34%	1140	711	490	348,720
	0.85	Western	93	10,257	19,926	53.4	45%	969	1993	1395	583,730
	Harvest + corridor, roads: Sites with roads are assigned the habitat resistance of recently harvested sites										
Corridor priority	0.3	Eastern	111	16,782	1140	32.5	13%	974	125	80	222,890
	0.5	Eastern	111	16,845	7002	41.8	34%	1146	708	490	345,443
	0.85	Eastern	110	17,010	19,218	51.4	45%	1142	1922	1345	593,266
Harvest priority	0.3	Eastern	111	16,854	884	31.9	11%	991	103	62	221,944
	0.5	Eastern	111	17,085	6971	41.9	34%	1147	709	488	347,678
	0.85	Eastern	111	17,994	19,034	51.1	44%	1162	1906	1332	592,597

* Harvest volume close to a maximum sustainable harvest level in a given problem formulation

when harvest revenue was prioritized the corridor shifted to the eastern part, so the area in the western part could be harvested at lower cost (Fig. 6c). Across all scenarios where the corridor was positioned in the eastern part, the corridor connected to the southern (coastal) caribou range boundary in roughly the same location. This is an area with no access roads and thus very limited harvest activity (Figs. 5b, c, 6c).

The manager's objective did not influence corridor placement in the "roads" scenarios; the corridor was always placed in the eastern portion of the study area (Fig. 5b, c). As just noted, this is because the eastern portion of the area has lower road densities and so resistance within the corridor is lower than when it is in the western part. Accounting for the impact of roads on habitat creates a negative feedback that increases resistance when the corridor is placed in the western portion of the study area with its high density of roads.

Increasing the harvest volume generally increased the mill gate timber cost (Fig. 7a, b), but the net cost difference between harvest-only and harvest + corridor solutions was relatively minor. This is because the changes in timber cost in the harvest + corridor solutions can be attributed mostly to the area of productive forest that is locked up under the corridor, which dictates that an equivalent volume of timber has to be harvested elsewhere. Within the study area, there were typically enough alternative locations for harvest that the cost increase was modest. The road construction and maintenance cost proportion increased with the harvested volume in a similar fashion (Fig. 7c, d). Nevertheless, there was a noticeable increase in the road construction maintenance cost and timber cost when the corridor was located in the eastern vs. the western part of the study area, as was consistently the case in the "no roads" scenarios that prioritized corridor placement (Fig. 7a–d). Across the corridor + harvest scenarios, the net harvest revenues tended to stabilize after the harvest volume reached 0.5 M m^3-yr.$^{-1}$ (Fig. 7e,f). Above this level, the road construction and maintenance cost started to offset the potential revenue gains from harvesting a larger area.

Changing the harvest volume target did not affect the corridor placement except in the "no roads" solutions when the harvest level was near the maximum sustainable limit (Fig. 6c). At this level, harvest encompasses most of the study area, such that either corridor placement option, eastern or western, necessitates a sizeable reallocation of harvest. However, a shorter corridor in the western part locks up a smaller harvestable area and imposes a smaller penalty on the objective value. Note that the evaluated maximum sustainable level is a theoretical limit and the true harvest levels in this region are close to the lower bound of the tested harvest volume range.

We also explored the trade-off between the net harvest benefits and the resistance of the corridor. Figure 8 plots the optimal solutions in dimensions of corridor resistance and mill gate timber cost. Rather than a gradual trade-off between minimizing corridor resistance versus minimizing timber cost, our results reveal a switching behavior that occurred under specific conditions. All optimal solutions placed the corridor in one of two distinct locations, i.e., in either the eastern or western portion of the study area (Figs. 5, 6). No gradual shifts in the corridor placement were observed when progressively changing the scenario assumptions. In general, when the priority was maximizing harvest revenues, the corridor resistance increased as the harvest volume target increased, whether roads were ignored (Fig. 8a) or included (Fig. 8b) in a scenario. But when roads were ignored and the harvest volume target was high, the corridor location switched from the eastern to the western portion. This switch had a much greater impact on the corridor resistance than changing the harvest target: it decreased the resistance dramatically compared to other harvest priority solutions and put it in line with the corridor priority solutions. Notably, the corridor priority solutions consistently placed a minimum-resistance corridor in the same location (the western region when roads were ignored, the eastern region when roads were included) regardless of the harvest target, so the corridor resistance was minimally affected. The observed switching behavior was a result of the particular configuration of forest cover, patterns of suitable habitat and the existing road network in our study area. If our approach was applied in other regions with different landscape composition, the solutions might reveal gradual shifts in the corridor position as the assumptions change.

3.2 Access road construction and corridor placement

Road construction and maintenance was a significant component of the timber supply cost and constituted up to 45% of the mill gate timber costs depending on the total volume harvested (Table 3). Furthermore, maintenance constituted a significant share of the total road cost (49–70%) and acted as a negative feedback that limited the length of roads built in a particular time period and guided the model to build roads in the same period the forest site was harvested. Nonetheless, a small portion of sites with built roads had harvest deferred to later periods (Fig. 9). This behavior was caused by the penalty P_{2t} on the maximum road length that could be built in a single period. This penalty helped distribute the road construction cost evenly over time (Fig. 10), which is consistent with actual road-building practices in northern Ontario, where the capacity is often limited by personnel and logistical constraints and requires long-term planning.

At low harvest levels, harvesting started from sites with existing road access and road construction ramps up only after the accessible wood supply near existing roads is depleted (Fig. 10). Larger harvest volume targets prescribed road construction to ramp up early and stay close to the maximum limit B_t until year 80. Road construction scaled down after year 80 because the parts of the study area with initial (or early) road access, where harvest was cost-effective in years 1–20, could be harvested again. Generally, road construction peaked at around years 60–70 (Fig. 10). The timing and duration of the road construction peak was shaped by the spatial configuration of forest age patterns in the study area, which, in turn, defined the local availability of timber and the need to access more remote sites in a particular time period.

3.3 Road construction cost and the planning strategy

The harvest planning strategy influenced the length and cost of built roads. For example, a short-sighted strategy, when road construction was optimized only

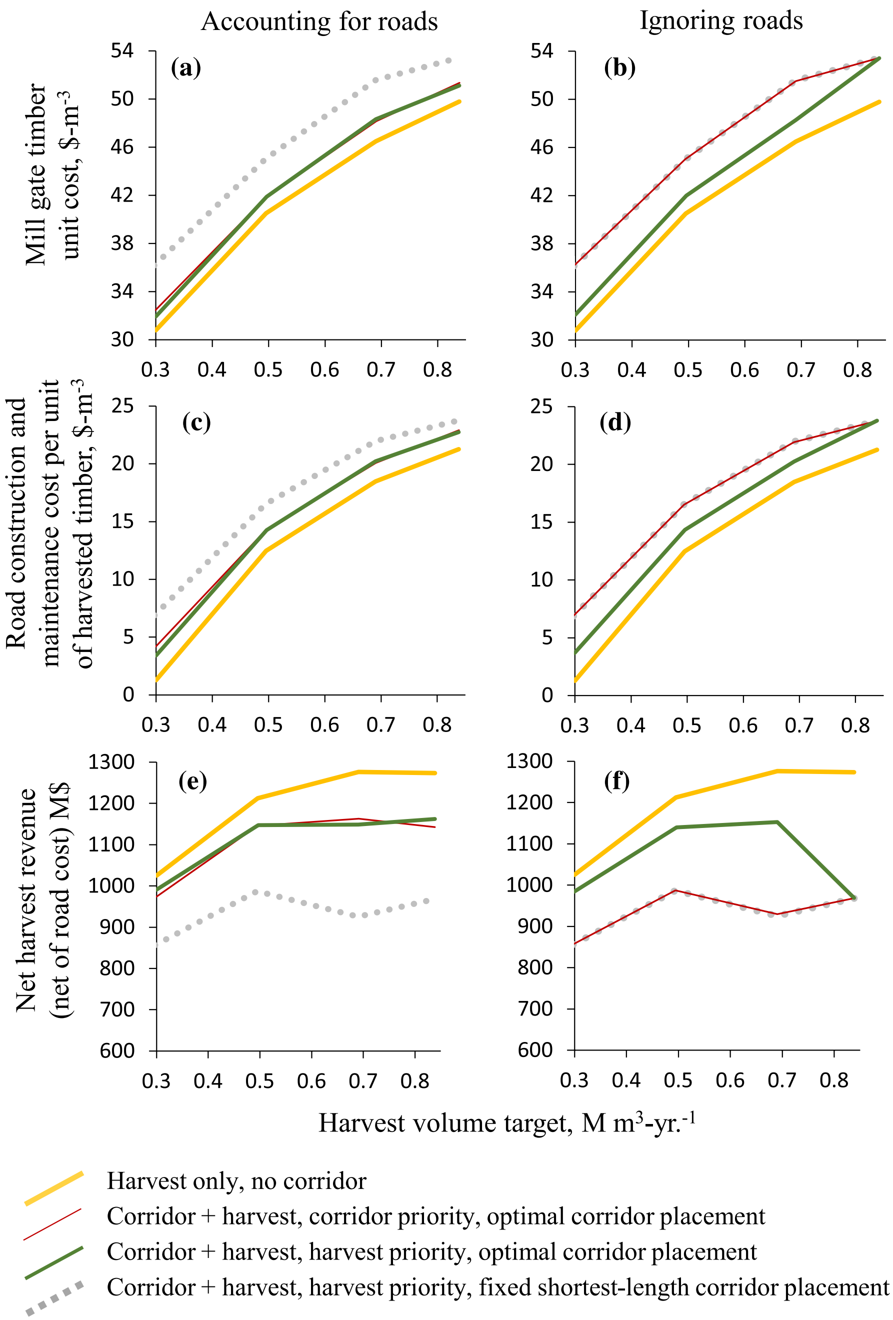


Fig. 7 Timber cost, road cost and net harvest revenue vs. harvested volume target $Q_{t\ \max}$, M m^3-yr.$^{-1}$. Mill gate timber unit price, \$-m^3: **a** solutions accounting for roads; **b** solutions ignoring roads. Road construction and maintenance cost, per unit of harvested timber, \$-m^{-3}: **c** solutions accounting for roads; **d** solutions ignoring roads. Net harvest revenue minus road costs over T periods, \$M; **e** solutions accounting for roads; **f** solutions ignoring roads

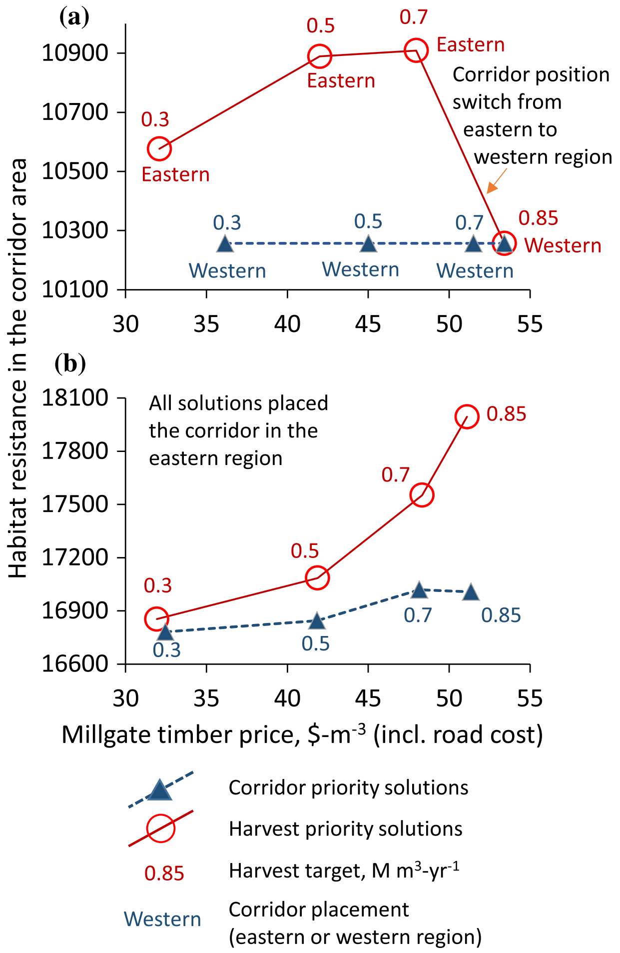


Fig. 8 Mill gate timber unit price vs. corridor resistance: **a** scenarios ignoring roads; **b** scenarios accounting for roads. Markers indicate optimal solutions. Values above the markers show the harvest volume target, M m^3-yr^{-1}. Corridor placement indicates location in either the eastern or western part of the study area (as shown in Figs. 5, 6)

within a single planning period (see Appendix 1), resulted in the construction of more roads than in the scenario that optimized road construction over the whole planning horizon (Fig. 10). In short, long-term strategic planning made it possible to harvest the same volume of timber via a smaller road network.

Adding the corridor did not significantly change the total harvested area but increased the length of access roads compared to harvest-only solutions (Table 3). Differences in road length were relatively small due to the high cost of road construction and maintenance, so both harvest-only and harvest + corridor solutions tended to minimize these costs where possible. In all solutions, the expansion of the road construction network followed the harvest hotspots in the south-central and southwestern sections of the study area, which, as noted previously, are close to the mill in Terrace Bay and accessible from the highway that runs along the north shoreline of Lake Superior.

4 Discussion

Our study demonstrates the potential utility of integrating optimal wildlife corridor placement into the forest planning process. By incorporating a corridor placement sub-problem within a broader harvest optimization problem, we were able to devise a set of long-term strategies to protect woodland caribou populations that must move between geographically separated refuges through a fragmented and actively harvested landscape. In general, optimal corridor placement depends on the perception of the impact of roads on caribou populations and decision-maker objectives. When the impact of roads on caribou is perceived to be analogous to harvesting and/or maximizing harvest revenue is a priority, the optimal corridor location is in the eastern region. Placing the corridor in the western region is optimal when the negative impact of roads is downplayed, or the shortest possible corridor is desired.

Our results also provided illustrative estimates of the potential impact of the corridor on timber supply cost in the study area. Notably, the upper bound of the potential timber cost premium (\$5.4-m^{-3}) exceeds the size of royalties paid by forest companies for harvesting timber on Crown lands in Ontario. An extra cost like this will reduce the profitability margins from harvesting timber and could be an important consideration when developing wildlife protection policies in regions of industrial harvesting. Moreover, Fig. 8a, b and Table 3 indicate that the corridor would have an appreciable impact on timber supply cost even at low harvest levels (0.3 M m^3-yr.$^{-1}$ and above). In our example, this is because sites with the most productive, mature coniferous stands represent both a desirable source of timber and are highly preferred habitat for caribou populations. Their protection within the corridor drives harvest toward more remote sites, which increases the timber cost.

A difficult aspect of our case study was dealing with the system of access roads. We proposed a network flow formulation to depict road construction and maintenance as a sub-problem within the harvest optimization problem. Compared to other implementations of road networks in harvest planning—such as the model in [66], which apportioned the harvested volume via the flow from harvested sites back through the road network to the road entry point—our formulation traces the flow in a forward direction, starting from an auxiliary node 0 and passing the flow via arcs $0nt$ directly to nodes where the construction starts in a particular period. Similar to other formulations based on a fixed charge network problem [86–89] and network flow designs [66, 90], our road network model required that decisions on the allocation of harvest blocks become binary. This entails high computational complexity, resulting in a problem that is characterized as NP-hard.

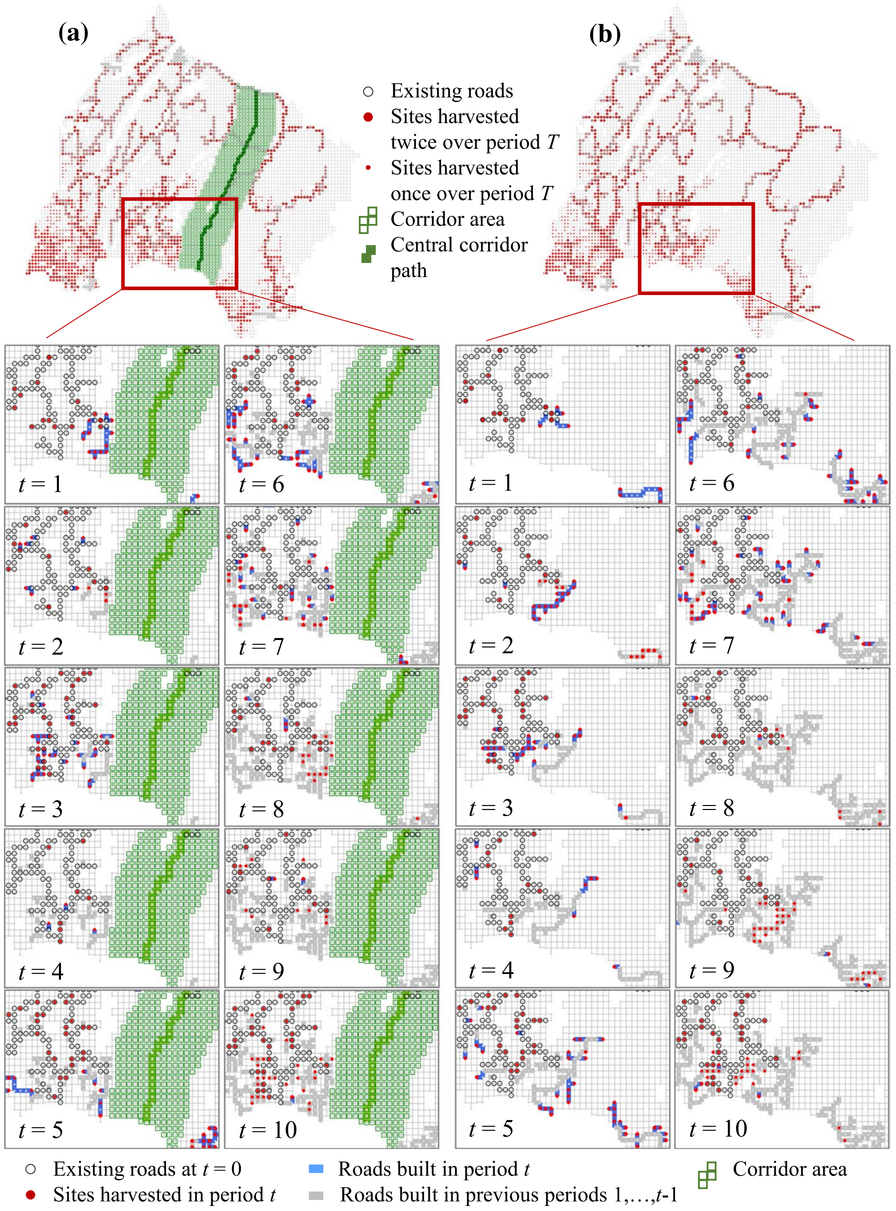
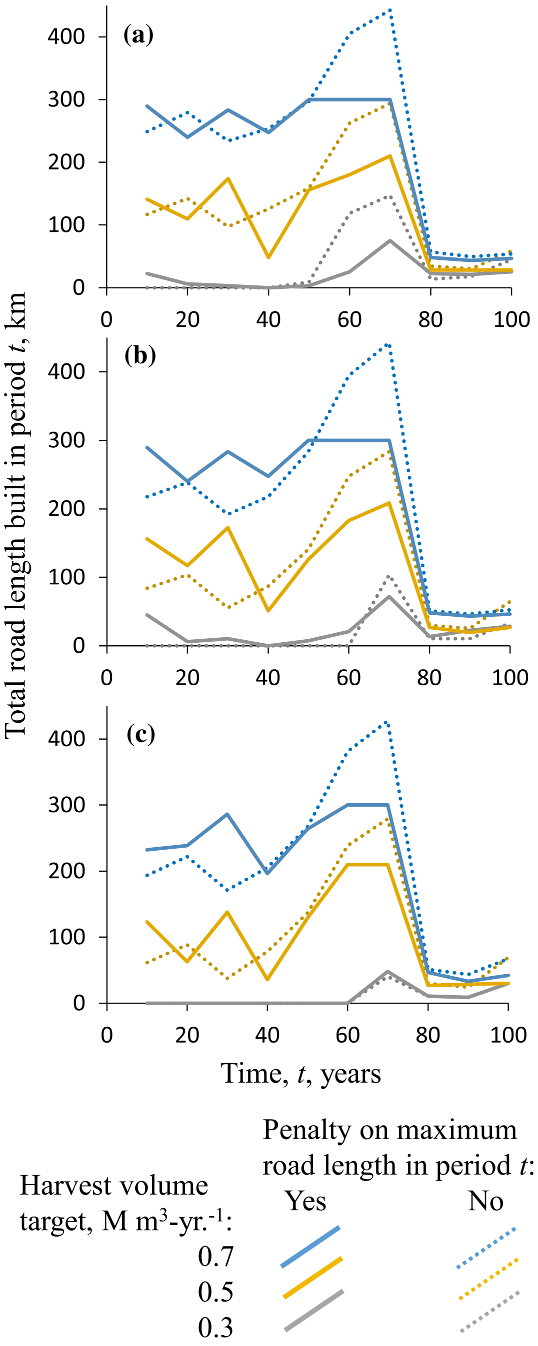


Fig. 9 Examples of road construction patterns over periods 1, …, T. The maps show the harvest-only and harvest + corridor "roads" scenarios for the harvest target 0.5 M m^3-yr.$^{-1}$ Optimal solutions: **a** harvest + corridor, corridor priority; **b** harvest-only

We adopted a relatively coarse resolution for our study, so the road construction sub-problem depicted the construction of major road segments only. Building roads in Ontario's boreal shield zone is costly, and once they are in place,

Fig. 10 Temporal road construction dynamics over time: **a** harvest + corridor scenario, harvest priority; **b** harvest + corridor scenario, corridor priority; **c** harvest-only scenario. Solid lines show the solutions with the penalty on the maximum road construction length in period *t*, and dotted lines show the short-sighted solutions based on the formulation in Appendix 1 without the penalty



forest roads are used regularly for many reasons other than harvesting. Moreover, forest companies may consider a return to previously harvested sites after forest stands regrow, providing further incentive to maintain existing roads. For these reasons, we made conservative assumptions regarding road construction and maintenance. While some road segments may be abandoned after 20–30 years of use, we did not have sufficient data to formulate the road abandonment conditions in the MIP model and so assumed roads would be maintained for the rest of the planning horizon. However, we calibrated the total maintenance costs to fit within a known general ratio between road maintenance and construction costs in boreal Ontario. This also provided sufficient negative feedback in the model to ensure that its behavior was consistent with current forest road construction practices in the region (Fig. 9), when new roads to undisturbed forest areas are only built when required to enable harvest.

Our road construction formulation included penalties on the maximum total road length and on terminal road segments built to sites that are not harvested in the same period. The reason for these limitations was the relatively long duration of our planning period t (10 years). This longer period made our problem more manageable computationally but is inconsistent with the typical practice of building access roads only to sites that are expected to be harvested within a short time frame. These penalties could be lifted if the planning period was shorter (e.g., 1–3 years). Potentially, an unrestricted (i.e., not penalized) formulation could be used to explore scenarios where, for instance, a large number of roads had to be built in advance to access remote areas for reasons other than harvest, such as settlements accessible only by winter roads or prospective mining areas (like the Ring of Fire region in Northern Ontario with large chromite deposits [91]). Such considerations could be formulated as additional objective terms or constraints that prioritized building of roads to destinations other than harvest sites. The road construction problem could also be reformulated as a joint project where the roads are partially subsidized from other projects aimed at improving access to human infrastructure in remote areas.

The corridor allocation problem considered the placement of a single, fixed-width corridor. To ensure that the caribou are separated adequately from predators, the corridor must be sufficiently wide (i.e., 20 km in our study). At this width, the corridor space occupies a significant portion of the study area landscape, so a single corridor is the only feasible option. Notably, eastern corridor placement coincided with the location of the proposed north–south Neys-Killala wildlife corridor that would connect the coastal caribou range and the area of continuous caribou distribution to the north [92]. For multiple corridors to fit in the landscape, they would have to be narrower and thus would not provide the required degree of separation. Given that only two isolated ranges needed connection, we felt justified in adopting a one-corridor formulation. Potentially, the problem could be modified to optimize a set of corridors between multiple isolated ranges using the formulation presented in [3–5].

Our problem was focused on depicting clear-cut harvest and road construction as the main factors negatively affecting the viability of caribou populations. Clear-cutting is the most common harvest type in boreal Canada [70] and is known to significantly increase the exposure of woodland caribou to predation. Road construction is another major factor that reduces the viability of caribou populations and, at the same time, imposes high costs for forest industry in boreal Canada. Potentially, the problem could be reformulated to include other forestry practices so it could be applied to other wildlife species in different regions. In this modification, one could explore the trade-offs between selecting alternative forestry practices in a particular geographic location versus their cost and impact on wildlife populations. Adding the option of multiple harvesting practices could also be an area of future work.

4.1 Potential model extensions

Our formulation depicts harvest planning and wildlife corridor placement as a nested network flow model that accounts for road maintenance costs. We assumed that newly built roads will require maintenance until the end of the planning horizon. This creates a negative cost feedback to build roads only when needed to access harvest sites. In reality, some roads could be maintained for a limited time and then abandoned. Although temporary roads may encourage more road construction in terms of the total length, they still may reduce the total maintenance cost since they can begin to be restored shortly after their associated sites are harvested. Depicting the abandonment and subsequent restoration of temporary roads is likely to increase the combinatorial complexity of the problem.

We used a simplified penalty formulation to control the dynamics of road construction over time. Potentially, more elaborate criteria could be used to control these dynamics. For instance, one could implement an inter-temporal constraint to enforce equal road-building costs for each planning period. This would ensure even flow of road expenditures over time, but we found that it would increase the computational burden significantly, so we opted to continue with the penalty formulation.

On a related note, the size and complexity of the corridor placement sub-problem depends on the width of the corridor. This is because the number of elements in the vicinity set Ω_{nm} around each selected node n in the connecting path as well as the number of constraints (4) and (5) defining the corridor space grow in quadratic proportion to the corridor width. The model size could be reduced by selecting special spatial shapes of the vicinity subset Ω_{nm} around node n, such as a star-like configuration instead of a full circle (as shown in Fig. 3a).

Appendix 1

Model initialization

Hard combinatorial complexity makes it difficult to find feasible solutions for the full problem with large datasets. We used the following initialization procedure to warm start the full problem in Eq. (30) in the main text. First, we solved the corridor placement problem without harvest planning, i.e.:

$$\min \sum_{n=2}^{N-1} \left(w_n \sum_{t=1}^{T} b_{n1t} \right) \tag{34}$$

subject to constraints (2–7) in the main text (see symbol definitions in Table 1 in the main text).

We then used the w_n values (which define optimal corridor placement in problem (34)) as a fixed parameter, w'_n, to solve the harvest planning problem with a fixed corridor.

To initialize the road construction model, we modified the problem formulation by introducing separate time sets for the harvest planning problem and the road construction sub-problem, $t \in T$ and $t' \in T'$, respectively. Harvest is always allocated over the full planning horizon T, but road construction may be planned over a shorter time span T', $T' \leq T$. All equations in the road construction sub-problem use the time set T' (a subset of the time set T), i.e.:

$$\max \sum_{n=2}^{N-1} \left[\sum_{i=1}^{I} (R_{ni} x_{ni}) - \sum_{t'=1}^{T'} \sum_{m=2}^{N-1} (v_{mnt'}[c_{mn} + j_{mn}(T-t)]) - f_1 \sum_{t'=1}^{T'} P_{1'_{nt}} \right] - f_2 \sum_{t'=1}^{T'} P_{2'_t} \tag{35}$$

s.t.: harvest planning constraints (11–13),(19) in the main text and:

$$y_{1nt'} = 0 \, \forall t' \in T', \, n = 0, 2, \ldots, N-1 \tag{36}$$

$$y_{nNt'} = 0 \, \forall t' \in T', n = 0, 2, \ldots, N-1 \tag{37}$$

$$\sum_{m=2,\{0\}}^{(N-1)_n^-} y_{mnt'} - \sum_{m=2}^{(N-1)_n^+} y_{nmt'} = \sum_{m=2,\{0\}}^{(N-1)_n^-} v_{mnt'} \, \forall t' \in T', n, m = \{0\}, 2, \ldots, N-1 \tag{38}$$

$$y_{nmt'} \leq U v_{nmt'} \, \forall t' \in T', \, n, m = \{0\}, 2, \ldots, N-1 \tag{39}$$

$$v_{nmt'} \leq y_{nmt'} \, \forall t' \in T', \, n, m = \{0\}, 2, \ldots, N-1 \tag{40}$$

$$v_{0nt'} \le \Gamma_n + \sum_{u'=1}^{t'-1} \sum_{m=2,\{0\}}^{N-1} v_{nmu} \, \forall \, t' = 2, ..., T', u' \in T', n = \{0\}, 2, ..., N-1, \, \Gamma_n \in \{0, 1\} \tag{41}$$

$$\sum_{u'=1}^{t'} \left[\sum_{m=2,\{0\}}^{N-1} v_{mnu'} \right] \ge \sum_{i=1}^{I} (x_{ni} W_{nit'}) \, \forall \, u' \in T', t' \in T', n = 2, ..., N-1, \, W_{nit'} \in \{0, 1\} | \Gamma_n = 0, \tag{42}$$

$$\sum_{t'=1}^{T'} v_{nmt'} \le 1 \, \forall \, n, m \in 2, ..., N-1 \tag{43}$$

$$\sum_{m=2,\{0\}}^{(N-1)_n^-} v_{mnt'} \le 1 \, \forall \, t' \in T', \, n = \{0\}, 2, ..., N-1 \tag{44}$$

$$v_{nmt'} + v_{mnt'} \le 1 \, \forall \, n, m \in N \tag{45}$$

$$v_{nmt'} \le 2 - \Gamma_n - \Gamma_m \, \forall \, n, m = 2, ..., N-1, t' \in T' | \Gamma_n = 1 \wedge \Gamma_m = 1 \tag{46}$$

$$\sum_{i=1}^{I} \left(x_{ni} \sum_{t'=1}^{T'} V_{nit'} \right) = 0 \, \forall \, n = 2, ..., N-1 | \xi_n = 0 \tag{47}$$

$$P_{1nt'} \ge \sum_{m=2,\{0\}}^{N-1} v_{mnt'} - \sum_{k=2}^{N-1} v_{nkt'} - \sum_{i=1}^{I} (x_{ni} W_{nit'}) \, \forall \, t' \in T', n = 2, ..., N-1 \tag{48}$$

$$P_{2t'} \ge \sum_{m=2,\{0\}}^{N-1} \sum_{n=2,\{0\}}^{N-1} (v_{mnt'}) - B_{t'} \, \forall \, t' \in T' \tag{49}$$

$$\sum_{i=1}^{I} \left(x_{ni} \sum_{t'=1}^{T'} W_{nit'} \right) \le \lambda (1 - w'_n) \, \forall \, n = 2, ..., N-1 \tag{50}$$

$$\sum_{t'=1}^{T'} \left(\sum_{n=2,\{0\}}^{N-1} v_{mnt'} \right) \le 1 - w'_n \, \forall \, n = 2, ..., N-1 \tag{51}$$

where w'_n is a binary parameter equal to the optimal w_n values from the corridor placement solution of the problem (34). The formulation in equations (34–53) above is similar to the harvest planning with road construction formulation in Eqs. (10–28) in the main text, except that a separate time domain *T*' is used in equations defining the road construction sub-problem. Using a shorter time domain for the road construction sub-problem, while solving the harvest allocation for the full planning horizon T with an account for road building cost over a time span T'), reduces the numeric complexity of the problem and makes it possible to find feasible solutions via a set of T consecutive optimizations with a stepwise increase of the time horizon T' from 1 to T, as described below.

The initialization was started by setting the road construction horizon T' to one period (i.e., the first period, $T'=1$), but solved the harvest allocation problem for the full horizon T. After finding the harvest solution for T periods and optimal road construction pattern for period 1, we set the time domain T' to two periods and solved the problem again using the decision variables x_{ni}, $v_{nmt'}$ and $y_{nmt'}$ from the solution with $T'=1$ as a warm start. After saving the optimal solution with $T'=2$, we increased the T' value to three periods and solved the model again using x_{ni}, $v_{nmt'}$ and $y_{nmt'}$ from the solution with $T'=2$ as a warm start, and so on until we solved the model for $T'=T$ periods. To speed up the solution we included, at each solution step starting from $T'=2$, two more constraints which fixed the road construction decision variables $v_{nmt'}$ and $y_{nmt'}$ to their initialized values for the planning periods $1,..,T'$-1 so that at each initialization step the model only needed to find the optimal road construction network for one period $t'=T'$, i.e.:

$$y_{nmt'} = y'_{nmt'}\ \forall\, t' = 1, ..., T' - 1,\ n, m = \{0\}, 2, ..., N - 1 \tag{52}$$

$$v_{nmt'} = v'_{nmt'}\ \forall\, t' = 1, ..., T' - 1,\ n, m = \{0\}, 2, ..., N - 1 \tag{53}$$

where $y'_{nmt'}$ and $v'_{nmt'}$ are fixed parameters equal to the optimal values of decision variables $y_{nmt'}$ and $v_{nmt'}$ in the solution in the previous step.

After solving the problem repeatedly for a sequence of 1 to T' horizons, the optimal solution depicted a short-sighted road planning policy where harvesting was optimized over the entire horizon T but the road construction network was optimized only within a single planning period t. We then used the set of decision variables from the last solution for $T'=T$ to warm start the full problem (30) in the main text. A similar procedure but without the corridor placement sub-problem (34) was used to solve the harvest-only problem with optimal road construction, In the harvest-only problem, the w'_n values were fixed to zeroes. We composed the model in the General Algebraic Modeling System (GAMS) [93] and solved it with the GUROBI linear programming solver [94].

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