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ASSESSING THE TRADE-OFFS BETWEEN TIMBER SUPPLY AND WILDLIFE PROTECTION GOALS IN BOREAL LANDSCAPES

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ABSTRACT

Protecting wildlife within areas of resource extraction often involves reducing habitat fragmentation. In Canada, protecting threatened woodland caribou populations (*Rangifer tarandus caribou*) requires preserving large areas of intact forest habitat, with some restrictions on industrial forestry activities. We present a linear programming model that assesses the trade-off between achieving a habitat protection objective for caribou populations while maintaining desired levels of harvest in forest landscapes. The habitat protection objective maximizes the amount of *connected* habitat that is accessible by caribou, and the forestry objective maximizes net revenues from timber harvest subject to even harvest flow, a harvest target, and environmental sustainability constraints. We applied the model to explore the habitat protection and harvesting scenarios in the Cold Lake Caribou Range, Alberta, Canada, a 6726-km^2 area of prime caribou habitat. We evaluated harvest scenarios ranging from 0.1M m^3-yr.$^{-1}$ to maximum sustainable harvest levels over 0.7M m^3-yr$^{.-1}$ and assessed the impact of habitat protection measures on timber supply costs. Protecting caribou habitat by deferring or reallocating harvest increases the timber unit cost by \$1.1-2.0 m^{-3}. However, this impact can be partially mediated by extending the harvest to areas of oil-and-gas extraction to offset forgone harvest in areas of prime caribou habitat.

Keywords: Caribou recovery; Network flow model; Mixed integer programming; Steiner network; Landscape connectivity; Harvest scheduling model I; Wildlife Habitat protection; Canada

INTRODUCTION

Woodland caribou (*Rangifer tarandus caribou*) is designated a threatened species under Canada's Species at Risk Act and Alberta's provincial Wildlife Act (COSEWIC 2002; EC 2012; SARA 2002) and poses a significant conservation problem in Canada (Festa-Bianchet et al. 2011; Hebblewhite 2017; Hebblewhite and Fortin 2017). Caribou populations have been declining throughout most caribou ranges, a phenomenon that is particularly pronounced in the province of Alberta (Vors and Boyce 2009; Hervieux et al. 2013). Increased disturbance and fragmentation of boreal forests in Canada has negatively affected the survival of caribou populations, which are adapted to use large, intact forest areas. Replacement of mature forest with early successional, harvested forests, along with the creation of large cuts and linear corridors, such as seismic lines, has led to increases in the number and efficiency of caribou predators in affected landscapes (James and Stuart-Smith 2000; Dickie et al. 2017; DeMars and Boutin 2018). In recent years, some caribou population declines have occurred in areas of industrial forestry operations within Canada's boreal forest region, where the area disturbed by clear-cuts can exceed the area disturbed by natural causes (Brandt et al. 2013; Venier, et al. 2014). Industrial harvesting creates a patchwork of large clear-cuts, which provide low-quality habitat for caribou until the regenerating forest stands mature and adequate vegetation cover is restored. Furthermore, industrial harvest increases the area of forest in early successional stages, which increases the abundance of deer and moose populations and subsequent predation by black bears and wolves, which, in turn, increases the predator pressure on woodland caribou (James et al. 2004; Wittmer et al. 2005; Latham et al. 2011).

Recovery efforts for caribou populations aim to create larger, contiguous habitat areas and eliminate deforested movement corridors for predators (GOA 2017). Protection of critical caribou habitat is a long-term policy that aims to limit the impact of the human activities that cause forest fragmentation (EC 2008; ECCC 2018). As a practical matter, caribou protection measures usually call for a reallocation, reduction or deferral of industrial forestry operations (FPAC 2018). When implemented over large areas, these measures may reduce the harvest area footprint, which, in turn, decreases the amount of available timber supply and increases its supply cost. Decision-makers seek a better understanding of the economic trade-offs between forest management goals and caribou protection measures so that caribou habitat restoration policies can be implemented with as little impact as possible on forestry activities in boreal forest regions (and vice versa; Festa-Bianchet et al. 2011; ECCC 2018; Hauer et al. 2018). The spatial interactions between industrial forestry operations and caribou populations occur over significant portions of the recognized caribou ranges in Canada (Fig.1), so the problem has a national scale.

Optimization approaches offer practical means to explore the trade-offs between industrial harvesting and habitat protection efforts. Previously, linear programming models have been applied to help balance trade-offs between competing economic and environmental objectives in forest planning (Johnson and Scheurman 1977; Weintraub et al. 1994; Ohman 2000; McDill et al. 2002, 2016). Forest management planning models have often included wildlife habitat management constraints, such as requirements to maintain habitat contiguity (Bettinger et al. 1997) or a minimum distance between species habitats (Bevers and Hof 1999). Gustafson et al. (2006) linked a harvest planning model with a simulation model that estimated the quality of wildlife habitat. Öhman et al. (2011) proposed a mixed-integer formulation of maximizing wildlife habitat alongside timber harvesting. Optimization-based approaches have also addressed the habitat protection problem specifically, for example by maximizing the number of adjacent pairs of habitats selected for protection (Williams et al. 2005), applying adjacency restrictions (Snyder and ReVelle 1997; McDill et al. 2002), maximizing the area of protected habitat by selecting among pre-defined contiguous habitat clusters (Tóth et al. 2009) and optimizing certain spatial properties of the habitat network (Cerdeira et al. 2005; Williams et al. 2004, 2005). Other approaches for optimizing the protection of connected habitat have adapted concepts from circuit theory (McRae and Beier 2007;

McRae et al. 2008; De Una et al. 2017) and least-cost analysis (Singleton et al. 2002; Beier et al. 2009).

Commonly, models that maximize habitat connectivity have utilized graph theory concepts, which depict a landscape as an interconnected network of habitat patches (or nodes) in a landscape connectivity graph. The connectivity corridors between adjacent suitable habitat patches (nodes) are defined as connecting arcs. Several formulations have been proposed to achieve optimal connectivity patterns in a landscape. Sessions (1992) was one of the first to propose the formulation of the connected habitat conservation problem as a Steiner network model. Williams (2002) identified the minimum-cost contiguous set of habitat patches with a required minimum area.

Typically, both spatial forest planning and habitat protection problems have been formulated using a mixed-integer programming (MIP) approach. Some MIP formulations have included habitat conservation and habitat adjacency constraints in harvest scheduling problems (Snyder and ReVelle 1996, 1997; McDill and Braze 2000; McDill et al. 2002; Crowe et al. 2003; Constantino et al. 2008). Önal and Briers (2006) described an MIP model to select the minimum-cost contiguous set of habitat patches that covered a desired set of sites with the species of interest. Meneghin et al. (1988) proposed a formulation of adjacency constraints in linear programming problems. Williams and Snyder (2005) outlined a shortest path formulation to solve a habitat restoration problem. Other MIP formulations have considered habitat restoration as a site selection problem (Snyder et al. 2004; Toth et al. 2011).

Some proposed MIP formulations control habitat contiguity and connectivity in a landscape by solving a network flow problem. Network flow problems (Ahuja et al. 1993) depict the area of interest as a set of nodes connected by a set of arcs and use flow preservation constraints to ensure connectivity between the nodes as elements of habitat corridors in a landscape. Jafari and Hearne (2013) and Jafari et al. (2017) adapted an MIP transshipment problem (i.e., a transportation network problem for which solutions may involve flow through intermediate nodes) to select arcs connecting adjacent habitat patches for the establishment of a contiguous nature reserve area. Conrad et al. (2012) and Dilkina et al. (2016) proposed a network flow model to determine minimum-cost corridors to connect a set of core areas with wildlife populations. Yemshanov et al. (2019) formulated an MIP network flow model to find a feasible flow that maximizes the amount of connected habitat in a fragmented network of suitable habitats.

Generally, prior work linking habitat connectivity models and optimization-based forest planning models has followed either of two approaches. A re-planning approach (e.g., Ruppert et al. 2016; Martin et al. 2017) uses a heuristic spatial model to prioritize sites for habitat protection in a particular time step and then applies a harvest planning model to reschedule future harvests over the planning horizon based on the habitat pattern calculated with the heuristic model. Calculation of a suitable habitat connectivity network is repeated at each time step, followed by re-planning of harvest schedules using a linear programming model. St. John et al. (2016) presented an alternative, more numerically demanding approach that combined a linear programming model for scheduling timber harvests with a network-flow-based habitat corridor model in a multi-temporal setting, where finding an optimal pass-through habitat corridor and optimal harvest schedule were solved jointly at each planning step. The model incorporated a transshipment-based formulation of a wildlife corridor problem following concepts similar to those described by Jafari and Hearne (2013). For each planning period, the model selected a fully connected corridor of habitats to ensure connectivity between the wildlife species entry and exit locations while also meeting the harvest targets.

Basic concepts

We utilize concepts from St. John et al. (2016) and Jafari and Hearne (2013) to formulate an MIP problem for protection of caribou habitat in areas with active forest management. We depict a forest landscape as a network of interconnected forest patches (nodes). Caribou move (flow) between adjacent patches (nodes) across a habitat network, and each node can be either a source or recipient of the species flow. For each node, we define a capacity measure that characterizes the amount of suitable habitat in a node and defines the extent of potential caribou movement between nodes. A set of binary decision variables determines the connection of nodes to the habitat network, while continuous decision variables control the species flow between adjacent nodes.

A patch (node) can also have productive forest that could be harvested for timber. Harvesting a forest stand in a node temporarily creates open space, which degrades the quality of caribou habitat and renders the patch unsuitable to support a caribou population until the forest stand matures. Increasing the area of harvest decreases the amount of suitable habitat in the area and increases fragmentation of the habitat network, so there is a trade-off between achieving harvesting objectives and maintaining a desired amount of connected caribou habitat in a landscape. We formulate a linear programming problem that helps address this trade-off. Our problem objective maximizes the weighted sum of two goals: (i) finding a subset of nodes and a feasible flow in the habitat network that maximizes the amount of habitat in *connected* nodes and (ii) maximizing the net revenues from harvesting a target volume of timber subject to cost and environmental sustainability constraints. We apply the model to the problem of woodland caribou protection in the Cold Lake Caribou Range (CLCR), a 6726-km^2 area of boreal forest in Alberta, Canada (Fig.1).

MATERIAL AND METHODS

Preliminaries

Consider a set of N forest patches that represent a forest landscape. Each patch may have suitable caribou habitat and some area of productive forest that could be harvested for timber. The target wildlife species, woodland caribou, moves from patch to patch through the landscape as a part of its natural behaviour. We depict this landscape as a spatial network of nodes (forest patches) where neighbouring nodes are connected by a universe of arcs. The movement of caribou individuals through the network of forest patches (nodes) can be modelled as a positive species flow y_{nm} through arcs nm, $nm \in \Theta$, connecting adjacent nodes n and m in a habitat network, $n, m \in N$. We set the node area smaller than average daily caribou travel distances (Rettie and Messier 2001; Johnson et al. 2002; Ferguson and Elkie 2004a,b; Avgar et al. 2013) to ensure that individuals would eventually move from a node n to other nodes regardless of the local amount of habitat available in n.

Caribou require suitable habitat to support their foraging and reproductive behaviour. Boreal caribou are associated with mature conifer stands and peatlands where terrestrial lichens are available for winter forage (Stuart-Smith et al. 1997; EC 2011). Caribou tend to avoid areas with high disturbance from human development (such as roads, seismic lines or recent forest cuts and burns less than 40 years old). The amount of suitable habitat in a node n depends on local land cover and tree species composition, proximity to human disturbances and linear features and forest age in a node.

Clear-cut harvesting temporarily degrades the quality of caribou habitat because it reduces the amount of local foraging resources and increases the access of predators to caribou populations through the creation of large open spaces (Hervieux et al. 2013). In the absence of harvest, caribou can pass from a node n to a neighboring node m without experiencing a higher risk of predation, which we depict as the species flow between n and m through an arc nm, y_{nm}. We assume that caribou avoid travelling through recently disturbed sites in order to reduce the risk of predation, and so the species flow between n and m is only possible through mature forest older than 40 years.

Because the amount of suitable habitat in a node is influenced by the age of the forest it contains, it also depends on when and how often that forest is harvested. To characterise the sequence of harvest operations and temporal availability of suitable caribou habitat that is associated with harvest, we define a set of possible harvest prescriptions for each node n i, $i = 1,\ldots,I$. For each node n, a harvest prescription i defines a sequence of harvest events, revenues associated with the harvests and the corresponding amounts of suitable habitat available at n in time steps t over the planning period T, including a scenario without harvest. A harvest prescription that can be assigned to a node n is defined by a set of binary vectors of length T, $p_{ni}=\{(1,0,\ldots,0),(0,1,\ldots 0),\ldots\}$, $p \in P$. The elements of each vector denote the harvest or no harvest binary indicators in periods $t = 1,\ldots,T$. Each prescription is also characterized by a vector of binary indicators λ_{nit}, which denote the presence of suitable habitat in n in prescription i in period t. We introduce a binary variable x_{ni}, $x_{ni} \in \{0,1\}$ to select whether a node n follows a harvest prescription i with a vector of harvest times p_{ni}. Only one harvest prescription can be selected for a given node (forest patch).

Defining the connected habitat

For each node $n,$ we define the amount of suitable habitat b_{nit} that could support caribou individuals in period t under harvest prescription i. We assume that a node n containing suitable habitat could be a *recipient* or *source* of the species flow from/to other nodes (i.e., animals moving from/to habitat in n). We also assume that the amount of suitable habitat available in a node n defines its capacity as a source or recipient of the species flow that the node could receive from or supply to other nodes (habitat capacity hereafter). Since the amount of suitable habitat in a node depends on forest age and sequence of harvest events, each prescription i is assigned a vector of habitat capacity values, $b_{nit},$ corresponding to time periods $t = 1,\ldots,T$. The habitat capacity of a node n under harvest prescription i in period t is estimated as $\sum_{i=1}^{I} b_{nit} x_{ni}$ and is controlled by a binary decision variable x_{ni} which selects the harvest prescription i for a node n.

We denote b_{nit} as the capacity of a node n if it is a source of the species flow and b'_{nit} as the capacity of a node n if is a recipient of the flow in period t, under prescription i. In our case, both source and recipient node capacities are defined by the same amount of suitable habitat in a node, so $b_{nit} = b'_{nit}$.

Potentially, the species flow in a habitat network can be established between any pair of neighbouring nodes *n* and *m* with suitable habitat. The selection of a node as either source or recipient of the flow in time period *t* depends on the spatial configuration of the habitat network, recent harvest patterns and the availability of habitat, and is controlled by binary decision variables w_{nt} and w'_{nt}, where $w_{nt}, w'_{nt} \in \{0,1\}$. The source and recipient capacities of a selected node *n* that is connected to other nodes can be written as:

$$\sum_{i=1}^{I} b_{nit} x_{ni} w_{nt} \quad \text{and} \quad \sum_{i=1}^{I} b'_{nit} x_{ni} w'_{nt} \qquad [1].$$

Equation [1] indicates that the amount of habitat that can be accessed in a node *n* depends on the selection of harvest prescription *i* (decision variables x_{nt} and x'_{nt}) and the establishment of the connection corridors to other nodes (variables w_{nt} and w'_{nt}). Equation [1] can be linearized by introducing binary decision variables z_{nit} and z'_{nit}, where $z'_{nit} \in \{0,1\}$, $z_{nit} = x_{ni}w_{nt}$ and $z'_{nit} = x'_{ni}w'_{nt}$, and a set of auxiliary constraints [3-8], as:

$$\sum_{i=1}^{I} b_{nit} z_{nit} \quad \text{and} \quad \sum_{i=1}^{I} b'_{nit} z'_{nit} \qquad [2]$$

and

$$z_{nit} \le x_{ni} \quad \forall \; i \in I, n \in N, t \in T \qquad [3]$$

$$z_{nit} \le w_{nt} \quad \forall \; i \in I, n \in N, t \in T \qquad [4]$$

$$z_{nit} \ge x_{ni} + w_{nt} - 1 \quad \forall \; i \in I, n \in N, t \in T \qquad [5]$$

$$z'_{nit} \le x_{ni} \quad \forall \; i \in I, n \in N, t \in T \qquad [6]$$

$$z'_{nit} \le w'_{nt} \quad \forall \; i \in I, n \in N, t \in T \qquad [7]$$

$$z'_{nit} \ge x_{ni} + w'_{nt} - 1 \quad \forall \; i \in I, n \in N, t \in T \qquad [8].$$

Linearizing the product of binary variables is a well-known technique, so from this point forward we only show the linearized problem formulation.

A node *n* may have more habitat than is necessary to satisfy the requirements of individuals moving to a node from other nodes, and a portion of habitat may remain unused. To account for partial utilization of the habitat in a selected node *n*, we introduce the non-negative decision variables v_{nt} and v'_{nt}, which define the node's unused source or recipient capacities after a connection corridor with a positive species flow is established through *n* from/to other nodes in period *t*. The unused capacity variables v_{nt} and v'_{nt} enable connection of nodes with source and recipient capacities that do not match.

Habitat connectivity problem

The habitat connectivity problem adopts the concepts presented in Yemshanov et al. (2019) and finds a habitat network configuration that maximizes the habitat capacity of the *connected* nodes over *T* planning periods in a landscape *N*, i.e.:

$$\max \frac{1}{T}\sum_{t=1}^{T}\sum_{n=1}^{N}\left(\sum_{i=1}^{I}(b_{nit}z_{nit})-v_{nt}+\sum_{i=1}^{I}(b'_{nit}z'_{nit})-v'_{nt}\right) \qquad [9]$$

s.t.:

$$\sum_{m=1}^{N_n^-} y_{mnt}-\sum_{m=1}^{N_n^+} y_{nmt}=[\sum_{i=1}^{I}(b'_{nit}\,z'_{nit})-v'_{nt}]-[\sum_{i=1}^{I}(b_{nit}z_{nit})-v_{nt}] \quad \forall \;\; n\in N, t\in T \qquad [10]$$

$$w_{nt}+w'_{nt}\le 1 \quad \forall\, n\in N, t\in T \qquad [11]$$

$$0\le v_{nt}\le \sum_{i=1}^{I} b_{nit}z_{nit}(1-\gamma) \quad \forall\, b_{nit}\ge 0, n\in N, t\in T \qquad [12]$$

$$0\le v_{1nt}\le \sum_{i=1}^{I} b'_{nit}\,z'_{nit}\,(1-\gamma) \quad \forall\, b'_{nit}\ge 0, n\in N, t\in T \qquad [13].$$

where γ is the minimum proportion of a node's habitat capacity that must be utilized when a node is selected as a connection corridor.

A flow conservation constraint [10] preserves the connectivity between the selected nodes and ensures that the amount of incoming flow to a node *n* is equal to the amount of outgoing flow from the node, plus its allocated source or recipient capacity at *n*. The terms N_n^- and N_n^+ denote the subset of nodes that supply flow to and receive flow from *n*. Constraint [11] specifies that a node can be designated as a source or recipient of the flow but not both. Constraints [12] and [13] prevent the conditions when a node *n* is selected as a connection corridor (so the node selection variables w_{nt} and w'_{nt} are set to one) but no habitat is used, such that the unused capacities v_{nt} and v'_{nt} are equal to their full capacities $b_{nit}z_{nit}$ and $b'_{nit}z'_{nit}$. These two constraints ensure that the selected nodes at least partially utilize the proportion of their respective capacities over the range [γ, 1].

We also need constraints to ensure agreement between the selection of nodes and the allocation of flow between the selected nodes. Constraint [14] limits the amount of flow y_{nmt} by an upper bound *U* and ensures that flow cannot occur to/from an unselected node, i.e.:

$$0 \le y_{nmt} \le U(w_{nt} + w'_{nt}) \quad \forall\, (n,m) \in \Theta, t \in T \qquad [14]$$

$$0 \le y_{nmt} \le U(w_{mt} + w'_{mt}) \quad \forall\, (n,m) \in \Theta, t \in T$$

Constraint [15] ensures that a source or recipient node cannot be selected if it has no incoming or outgoing flow, and constraint [16] tightens the formulation by ensuring that the node has to be selected if it has a positive incoming or outgoing flow, i.e.:

$$w_{nt} + w'_{nt} \le \left(\sum_{m=1}^{N_n^-} y_{mnt} + \sum_{m=1}^{N_n^+} y_{nmt} \right) M \quad \forall\ n \in N, t \in T \qquad [15]$$

$$(w_{nt} + w'_{nt})M \ge \sum_{m=1}^{N_n^-} y_{mnt} + \sum_{m=1}^{N_n^+} y_{nmt} \quad \forall\ n \in N, t \in T \qquad [16]$$

where *M* is a large positive value.

Harvest scheduling problem

Nodes with productive forest may be harvested for timber. We adopt a harvest scheduling problem that has been widely used in forest planning (see Johnson and Scheurman 1977; McDill and Braze 2000; McDill et al. 2016; Martin et al. 2016). The allocation of harvest maximizes the net revenue from timber harvest, subject to a harvested volume target, even harvest flow constraints, and a requirement to maintain a minimum average forest age in the area at the end of the planning horizon. The harvest scheduling problem – using what is commonly known as the model I formulation (see McDill et al. 2002) – denotes a set of N forest patches (nodes) and T time periods in the harvest planning horizon. As defined before, for each node n containing harvestable forest, we define a set of harvest prescriptions i, $i \in I$, which are complete sequences of all forest management actions in that node over a planning horizon T. A binary variable x_{ni} controls the selection of harvest prescription i at a node n. In this study, we only consider clear-cut harvest, which is the most common type of harvest in boreal forests in Canada (NFD 2019). We assume that a forest stand can be harvested after it reaches a minimum harvest age of k years or older (k is set to 70 years). Harvest prescriptions include the schedules with harvest ages equal to or above age k that could occur in a node over the planning horizon T and the scenario with no harvest over T.

For each node n we denote the forested area, a_n, and the volume of merchantable timber per unit area that is available for harvest in time period t in harvest prescription i, V_{nit}. Let Q_t be the volume of timber harvested in the area in period t, with lower and upper bounds $Q_{t\,\min}$ and $Q_{t\,\max}$, while d_n is the unit volume price of timber harvested from a node n net of harvest and hauling costs, and R_{ni} is the net revenue associated with harvesting from node n according to prescription i. To ensure the even flow of harvest over the planning periods, we set a maximum proportion, ε, that defines the allowable increase or decrease in harvest volume in consecutive planning periods, $1 + \varepsilon$

and $1-\varepsilon$. 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 set E_{ni} as the forest age in a node n at the end of the planning horizon if prescription i is applied. Then, we define the optimal harvest problem as maximizing the net timber revenues, R_{ni}, associated with managing the forest over T periods, i.e.:

$$\max \sum_{n}^{N}\sum_{i}^{I} R_{ni}x_{ni} \qquad [17]$$

s.t.:

$$\sum_{i=1}^{I} x_{ni} = 1 \quad \forall \quad n \in N \qquad [18]$$

$$Q_{t\min} \le \sum_{n=1}^{N}\sum_{i=1}^{I} a_n V_{nit} x_{ni} \le Q_{t\max} \quad \forall\, t \in T \qquad [19]$$

$$(1-\varepsilon)Q_t \le Q_{t+1} \le (1+\varepsilon)Q_t \quad \forall \quad t \le T-1 \qquad [20]$$

$$\sum_{n=1}^{N}\left(\sum_{i=1}^{I}\left[(E_{ni}-E_{T\min})a_n x_{ni}\right]\right) \ge 0 \qquad [21].$$

The net harvest revenue R_{ni} is calculated as the value of harvested timber (at the mill gate) net of harvest, hauling and optional postharvest regeneration costs, e_n:

$$R_{ni} = \sum_{t=1}^{T}\left(a_n d_n V_{nit} - e_n\right) \qquad [22].$$

Constraint [18] ensures that each node with forest is assigned one prescription. The full set of harvest prescriptions I also includes a possible no-harvest scenario with zero revenues. Constraint [19] ensures that the harvest volume for each time period stays within a target range [$Q_{t\,\min}$; $Q_{t\,\max}$]. Constraint [20] specifies that the harvest volumes in consecutive planning periods t and t+1 do not deviate beyond upper and lower bounds $1 \pm \varepsilon$. Constraint [21] ensures that the average age of all forest stands at the end of the planning horizon is greater than or equal to the minimum age target $E_{T\,\min}$. A minimum stand age constraint [21] follows environmental guidelines that prevent overharvesting by prescribing that a portion of old-growth forest is unharvested at the end of the planning horizon (GoA 2016). We also need a constraint [23] that ensures that connections can only be established between nodes with suitable habitat (as defined by a binary parameter λ_{nit}, i.e., $\lambda_{nit} = 1$ if a site n has suitable habitat in a selected harvest prescription i in time step t, and $\lambda_{nit} = 0$ otherwise):

$$w_{nt} + w'_{nt} \le \sum_{i=1}^{I} (x_{ni}\lambda_{nit}) \quad \forall \quad n \in N, t \in T \qquad [23].$$

In our case, we assume that connections can only be established between nodes with forest stands older than 40 years that can provide suitable habitat for caribou populations (i.e., $\lambda_{nit} = 1$), and $\lambda_{nit} = 0$ for nodes with younger forest (Sorensen et al. 2008).

Linking the harvest scheduling and habitat connectivity problems

In order to assess the trade-off between caribou habitat protection and forest management goals we combine the two objective terms [9] and [17] via scaling factors. Each objective is assigned the scaling factors F and $1 - F$, which represent the relative weights for the forest harvest and habitat protection objectives. An F value equal to 0 prioritizes harvest revenues and values close to 1 maximize the amount of connected habitat in the landscape. For convenience, we use a coefficient f to rescale the harvest objective [17] so both objectives vary within the same order of magnitude. The objective function maximizes the weighted sum of the amount of connected habitat in a landscape N and the net revenues from harvest over the planning horizon T, i.e.:

$$\max F \frac{1}{T} \sum_{t=1}^{T} \sum_{n=1}^{N} \left(\sum_{i=1}^{I} (b_{nit} z_{nit}) - v_{nt} + \sum_{i=1}^{I} (b'_{nit} z'_{nit}) - v'_{nt} \right) + (1 - F) \left[\sum_{n=1}^{N} \sum_{i=1}^{I} (R_{ni} x_{ni}) \right] f \qquad [24]$$

subject to constraints [3-8], [10-16] and [18-21 and 23].

The trade-off between maximizing the amount of connected habitat and maximizing harvest revenues can be assessed by solving the objective function equation [24] with different weights F to construct a trade-off curve. The *F* values vary within a fixed interval [0;1], but the objective terms in Eq. [24] (i.e., the net harvest revenues and the amount of connected habitat) do not have a fixed range and their absolute values depend on the parameter and scenario settings. This implies that setting an intermediate F value, for example 0.5, may not always produce a 50/50% apportionment between the objective terms. Furthermore, the presence of the target harvest volume constraint [19] in both habitat protection and harvest priority scenarios reduces the magnitude of this trade-off because the same harvest target has to be met in both scenarios. In our case, when the trade-off is severely constrained by Eq. [19], we report only the solutions for the end-points of this trade-off where the *F* value is equal to 0 or close to 1. These represent the most distinct solutions when prioritizing harvest revenues or habitat connectivity for the same harvest volume target and can be compared in terms of the cost of harvested wood, the protected habitat area and other parameters.

We composed the model in the General Algebraic Modeling System (GAMS 2018) and solved it with the GUROBI linear programming solver (GUROBI 2018). Table 1 lists the model parameters and variables. The full model that included both harvest scheduling and habitat connectivity objectives required a long time to arrive at a feasible solution hence we have solved the problem in stages. We first dropped the habitat connectivity term, which is equivalent to setting the factor *F* to 0, and solved the model to maximize the harvest revenues only. This is a harvest priority solution without considering the habitat connectivity. We then dropped the unused habitat capacity variables v_{nt} and v'_{nt} from the objective function in equation [24] and re-solved the model to maximize habitat connectivity by forcing the model to use the fixed harvest schedules x_{ni} from the previous solution. This formulation prioritized harvest revenues but ignored the unused habitat capacity at the connected sites when maximizing the habitat connectivity. We then used this solution as a warm start to solve a full-scale problem. We ran the model for 48 hours or until reaching a 0.5% optimality gap (whichever came first).

Case study

We applied the model to assess caribou recovery strategies in the Cold Lake Caribou Range (CLCR) in Alberta (Fig. 2). Caribou populations are commonly studied at the level of ranges (EC 2008, 2011; GOA 2017), which are geographic areas deemed large enough to support a healthy caribou population (McLoughlin et al. 2003; Saher and Schmiegelow 2005; DeMars and Boutin 2018). The CLCR includes extensive areas of mature forest and peatland habitat suitable for caribou (Stuart-Smith et al. 1997) but also covers major oil-and-gas deposits and areas of industrial forestry operations. Over the last four decades, forestry and resource extraction activities have fragmented the CLCR, which now is covered by a network of linear disturbances, well sites, and harvest blocks. The CLCR has the second highest proportion of anthropogenic disturbance at 72% (EC 2012) and the second highest rate of caribou population decline among the ranges in Alberta (Hervieux et al. 2013). Protection and restoration of sensitive habitat have been proposed as management tools to help prevent further decline of caribou populations (GOA 2017) but must compete with ongoing forestry and resource extraction activities.

We divided the CLCR into 1 × 1 km patches, and treated each patch as a node in a landscape network. A 1-km spatial resolution is consistent with restoration guidelines that follow from observed habitat preferences of caribou. Because caribou tend to avoid permanent anthropogenic disturbances, federal and provincial guidelines (GOA, 2017) call for minimum 500-m buffer between protected sites and human-caused disturbances to prevent negative impacts on caribou populations. This suggests that 1 km (a point with a 500-m buffer) is an appropriate spatial resolution at which to explore the habitat connectivity scenarios. While harvest planning is often performed at finer spatial resolutions, we used the 1-km grid in order to maintain tractability of the connectivity model solutions.

For each node, we estimated the amount of suitable caribou habitat, and thus the node's source and recipient capacities b_{nit} and b'_{nit}, for each harvest prescription and forest age using the methodology of Whitman et al. (2017) and Barber et al. (2018) (Fig. 2a; see Appendix S1 for additional details). The area may also have experienced other anthropogenic disturbances that are undesirable for caribou populations. We adjusted the capacities b_{nit} and b'_{nit} by a habitat intactness coefficient that accounts for natural and human-mediated disturbances in the area of interest (ABMI 2012; ALT 2009). Using the approach of the Athabasca Landscape Team (ALT 2009), we estimated intactness as the average of three criteria that negatively affect the habitat value: the density of linear disturbances (seismic lines, roads, pipelines and transmission lines); the areal proportion of post-disturbance forests younger than 30 years; and the areal proportion of non-linear anthropogenic disturbances (well sites, settlements, mines, and industrial sites) (Fig. 2b).

We set the intactness values in 500-m buffer zones around roads, pipelines, well sites, and other permanent human disturbances to zero. This adjustment creates an incentive to avoid protecting of habitats that are in close proximity to these kinds of disturbances. Additionally, we assumed that the protection measures would avoid areas of *in situ* oil-and-gas extraction because these areas are heavily fragmented by linear disturbances (Fig. 2c).

The harvest scheduling model also required estimates of the transport costs, the volumes of merchantable timber and the net revenues for a set of harvest prescriptions I. We used the spatial road network to estimate hauling costs, assuming an on-site harvest cost value of \$15 m^{-3} and calculating the hauling cost for each forest site based on the distance to the closest market (AlPac Inc. mill, Boyle, AB) (Fig. 2d). The study area is characterized by flat terrain with a dense network of legacy linear cuts (i.e., seismic lines) created over the last four decades by oil and gas exploration companies to move seismic testing equipment. It is relatively easy to convert these lines to access roads, so the issue of accessibility to more remote harvest sites is not as critical as in other parts of boreal Canada with complex terrain. Our simplified calculations of the hauling cost used the hourly trucking rate and total hauling distance with typical trucking speeds for a particular road type. We assumed a 40 m^3 truckload, waiting time 1 hour, an overhead cost of \$4 m^{-3} and used expert-based estimates of trucking speeds and a lower bound hourly trucking rate based on estimates for similar boreal forest conditions in Ontario (i.e., \$85-hr^{-1} (Maure 2013), inflation-adjusted to \$90-hr^{-1}).

The starting values for stand age and merchantable timber volume were estimated from a map developed by Beaudoin et al. (2014). This dataset resulted from the application of k^{th} nearest neighbour machine learning to estimate 127 forest attributes, measured at a network of survey plots, for all cells in a regular grid at 250-m resolution (Beaudoin et al. 2014). We used the forested area, stand age, and tree species composition attributes from this dataset. Notably, the dataset was updated to reflect recent changes in age structure by incorporating recent harvests and forest fires (see Guindon et al. 2014). We used the tree species composition and (updated) age data, in conjunction with provincial growth and yield curves, to estimate the volumes of merchantable timber available for harvest at a particular stand age. We used a set of yield curves for Alberta's boreal plains ecozone from Huang et al. (2009). We adjusted the yields by the expected area losses due to fire disturbances using fire regime zones from Boulanger et al. (2014). The minimum harvest age k was set to 70 years.

Long-term harvest planning is a common practice aimed at achieving sustainable harvest without depleting the future timber supply. We assumed that the area-wide mean forest age at the end of the planning horizon, $t = T$, should be equal to or greater than the mean forest age in the current conditions, $t = 1$. We set the even harvest flow bounds to ±2% and the harvest planning horizon T to 120 years with 10-year time planning steps.

Forest management and habitat protection scenarios

We evaluated the optimal solutions for land use policies with harvest levels between 0 and 0.7 M m^3-yr^{-1}; the latter value is close to the maximum sustainable harvest level under the given data assumptions and harvest scheduling constraints. "Harvest priority" scenarios maximize the net harvest revenues and achieve the required harvest target [$Q_{t\ \min}$; $Q_{t\ \max}$] without prioritizing caribou habitat connectivity, by setting the scaling factor F in the objective function equation to 0 (so the allocation of harvest is driven by revenue maximization only). Once the optimal harvest solution was found we fixed the harvest prescription variables x_{ni} and re-solved the connectivity problem by setting the scaling factor F to 1 to estimate the amount of connected habitat capacity and area connected in the harvest-priority scenario. Alternatively, a “habitat priority” policy scenario prescribed the same harvest target [$Q_{t\,\min}$; $Q_{t\,\max}$] but prioritized the protection of suitable habitat by maximizing the connected habitat capacity in the landscape and setting the scaling factor F in the objective function to 0.99, which gave low priority to harvest revenue maximization.

In Canada, the National Recovery Strategy for caribou established 65% of undisturbed habitat in a caribou range as a conservation threshold to provide a 60% probability of supporting a self-sustaining caribou population (EC 2012; ECCC 2017). We explored the combinations of harvest volume targets and habitat protection priorities that would maintain the connectivity of caribou habitat over 65% of the CLCR area. First, we solved the connectivity model without harvest scheduling, by solving problem objective [9]. These solutions estimated the maximum amount of habitat that could be connected in the CLCR. Then we solved the full problem objective [24] for scenarios with successively larger harvest volume targets $Q_{t\,\min}$ and $Q_{t\,\max}$ and examined the impact of increasing the harvest target on the area of connected habitat, area harvested and the unit price of harvested timber. The harvest priority scenarios reached the 0.5% gap values in less than 48 hours, but the habitat priority solutions, especially when the harvest volume target was set close to the maximum sustainable limit, all reached the time limit with the gap values between 0.5% and 5.4%. Despite the relatively high gap values, the general spatial configuration of the habitat connectivity patterns stabilized before the cut-off time with little impact on the objective value afterwards.

Because they are highly fragmented, forested areas with extensive *in situ* oil and gas extraction are considered unable to support caribou populations. However, these areas still have sizeable amounts of mature forest that could be harvested for timber. Harvesting trees in areas of oil-and-gas extraction could be viewed as an offset to avoid disturbing areas with intact caribou habitat (Aumann et al. 2007; Yamasaki et al. 2008). To support ongoing discussions about the feasibility of this approach, we compared the optimal solutions for scenarios that only permitted harvesting in forest management agreement areas (FMA scenarios) with scenarios that allowed additional harvest in areas of oil-and-gas extraction, thereby avoiding or deferring the harvesting of sites with prime caribou habitat (FMA-OS scenarios hereafter) (Fig. 3).

RESULTS

We compared the optimal solutions for scenarios that prioritized either harvest or habitat protection. The maximum level of sustainable harvest was 0.51M m^3-yr^{-1} when harvest was limited to forest management agreement areas (FMA scenarios) and just over 0.7 M m^3-yr^{-1} when harvest was also allowed in areas of oil-and-gas extraction (FMA-OS scenarios) (Fig. 4a). The potential habitat network included 5633 nodes in total, of which 2149 were potentially harvestable nodes in the FMA scenarios and 2927 were harvestable in the FMA-OS scenarios. After filtering out disturbed areas, the suitable habitat that could be connected by a habitat network covered approximately 71% of the CLCR area. In harvest priority scenarios, increasing the harvest volume reduced the amount of connected habitat almost linearly, such that the total area of suitable caribou habitat dropped below 65% once the harvest volume exceeded approximately 0.35 M m^3-yr^{-1}. In contrast, prioritizing habitat connectivity maintained the area of connected habitat at over 65% for the entire range of harvest targets, decreasing only as the harvest volume approached the maximum harvestable limit (i.e., 0.5 M m^3-yr^{-1} for FMA scenarios, 0.7 M m^3-yr^{-1} for the FMA-OS scenarios; see Fig. 4a). Our results indicate that it is possible to maintain high levels of spatial habitat connectivity in the CLCR while achieving harvest levels close to the maximum sustainable harvest.

Note that in the FMA-OS scenario, the total amount of connected habitat was approximately the same as in the FMA scenario (Fig. 4a), which indicates that allowing additional harvest in areas of oil and gas extraction does not necessarily lead to an increase of the connected habitat area. This is because the area with the lowest cost of timber and lowest access cost is located in the western part of the CLCR (which also includes prime caribou habitat) and the same area was targeted for harvest first in both the FMA and FMA-OS solutions.

Applying the caribou habitat protection measures led to reallocation of harvest from areas in the western portion of the CLCR with sizeable amounts of high-quality habitat to more distant and less productive forest sites, which added approximately \$1.12-2.04 m^{-3} to the delivered timber unit price (Fig. 4b). The solutions that prioritized habitat protection reported 9-13% lower net revenues than the harvest priority solutions (Table 2). Given the low profit margins of forest mills in today's economic environment, these potential revenue losses could be an important consideration in planning caribou protection measures in areas of active forest management. The impact of caribou protection policies on timber supply cost was noticeable even at low harvest levels and stayed relatively constant over the entire range of harvest volume targets (Table 2). This is because the areas with the cheapest and most accessible wood supply in the western part of the CLCR also have sizeable amounts of suitable caribou habitat, and so any habitat protection measures led to reallocation of harvest from the western part of the range to other areas even when the anticipated harvest levels were low.

Allowing harvest in areas of oil-and-gas extraction did not significantly change the timber supply cost. This is because higher access costs and larger numbers of human disturbances make harvesting in areas of oil-and-gas extraction more expensive than in FMA areas in the western part of the CLCR. However, it enabled harvest of approximately 1.4 times more timber and, at high harvest levels, protected a larger amount of caribou habitat.

We also examined the spatial arrangement of harvest activities in solutions that prioritized harvest versus those that prioritized habitat connectivity. Maps in Figs. 5 and 6 depict examples of harvest selection and habitat connectivity patterns in optimal model solutions that prioritized either harvest revenues (maps a and b in each figure) or habitat connectivity (maps c and d). The maps in Figs. 5a, c and 6a, c present the frequencies of harvest (either once or twice) and the number of time periods identified habitat patches maintained connectivity with other patches over the planning horizon *T*; darker-shaded habitat patches remained connected for a longer period. Maps in Figs. 5b, d and 6b, d depict the time between the beginning of the planning period and the first harvest of a forest stand. Darker-shaded areas indicate immediate harvest and white areas indicate no harvest within the planning horizon *T*. In harvest priority scenario solutions, most harvesting was allocated in the western portion of the CLCR, where access costs are the lowest due to an established network of access roads and easily-convertible seismic lines (Figs. 5a,b 6a,b). Temporal dynamics of the harvest priority solutions revealed that the connected proportion of the range area often fell below the 65% habitat protection target in some periods, especially when the harvest volume target was high (e.g., 0.4M m^3-$year^{-1}$, Fig. 7). Prioritizing habitat protection over maximizing harvest revenues kept the connected portion of the range area above the 65% habitat protection target and near the maximum habitat capacity (Fig. 7). In optimal solutions for habitat protection scenarios, harvest was reallocated from western parts to northern and southern parts of the CLCR with lower-quality habitat and longer access times, thereby protecting caribou habitat in the western part of the CLCR (Figs. 5c, d, 6c, d). Even at moderate harvest levels, the bulk of the harvest was reallocated away from the western part of the range with suitable caribou habitat (close-ups in Figs. 5c, d). At high harvest levels, the optimal solutions showed a small portion of sites in the western part of the CLCR as harvested once over the planning horizon (Fig. 6c, callout I in a close-up map). However, harvest in these sites was deferred for 90 years or longer, so the area was kept intact for most of the planning period (Fig.6d, callout I).

Our optimal solutions show more areas harvested twice in harvest priority scenarios (Fig.8). The sites with two harvests had the lowest hauling costs, generally because they had more roads. Note that at low harvest levels, the habitat priority solutions applied a more intensive harvesting regime within a smaller area in an attempt to increase the area of protected habitat. Thus, an efficient habitat recovery strategy would prescribe setting aside areas with large amounts of intact caribou habitat (or at least postponing harvest for a long period), while increasing the harvest intensity in areas with productive forest but smaller amounts of suitable habitat. This also helps increase the total habitat area that stays connected over the entire planning horizon (i.e., areas shaded in dark green in Figs. 5c and 6c).

DISCUSSION

Reducing the impact of forestry activities to protect caribou habitat

Incorporating landscape connectivity into a forest planning framework helps mitigate the negative impact of forestry activities on caribou habitat in areas with active forest management. Changes in the spatial allocation and timing of harvest could yield a significant increase in the area of protected caribou habitat in the western part of the CLCR. Broadly, more habitat can be protected in the CLCR using a combination of two strategies. The first strategy focuses on reallocating harvest to the northern and southern parts of the CLCR (which already experience disturbance from oil-and-gas extraction but have sizeable amounts of productive forest), while also making the harvest footprint more compact by switching to a more intensive management regime. This more intensive regime may have an added economic benefit of reducing the amount of related maintenance costs to access the harvest sites. The second strategy focuses on deferring harvest in areas that have both low-cost and accessible timber in close proximity to roads (but also large amounts of suitable caribou habitat) close to the end of the planning horizon. Harvest deferral can be effective at low harvest levels, but at high harvest levels it may be insufficient and reallocating harvest to other regions is the only option.

Our results indicate that it is possible in the CLCR to meet the national recovery target for protecting caribou habitat by maintaining habitat connectivity over 65% of the range area while keeping the current levels of harvest operations in the area. This can be achieved by combining the harvest reallocation and deferral strategies to minimize harvest in the western part of the range, although this would lead to a moderate increase of the timber supply cost, on average, by \$1.1-2 m^{-3}. Prioritizing habitat connectivity creates a harvest pattern that is less spatially clustered along the road network, with slightly less area harvested overall but using a more intense management regime that often involves two harvests over the planning horizon.

Insights for forest planning and caribou recovery

The proposed model uses a forward-looking harvest planning approach (following the harvest scheduling model I formulation) and can incorporate caribou habitat connectivity criteria into forest planning. The caribou habitat protection issue is likely to become more important in the future, as the total amount of intact habitat available to support caribou populations in the managed regions of Canadian boreal forests is expected to decline under "business as usual" scenarios (EC 2011). Thus, integrating habitat connectivity into forest management planning may help find solutions for maintaining desired levels of timber harvesting while protecting sufficient amounts of caribou habitat in boreal forest regions. For instance, since our model incorporates feedback from relocating and rescheduling harvest operations on the availability of suitable caribou habitat, it could also assist with estimation of Annual Allowable Cut (AAC) levels in areas with caribou occurrence. The Annual Allowable Cut is the amount of timber that can be harvested yearly on a sustainable basis within a defined forest area. AAC is determined at the provincial level and represents a forecast of the amount of timber that will be available for harvesting over a planned period under a particular forest management regime (such as clear-cut harvesting). The AAC accounts for a combination of current conditions of the managed forest landscape, tree growth rates, current and past management regimes and the extent of past and present natural and anthropogenic disturbances (such as fires, pest and disease outbreaks and harvest). In Alberta, the Ministry of Environment and Sustainable

Resource Development sets the AAC based on models that estimate harvest volumes from tree growth projections while incorporating the allowable cut effect (Schweitzer et al. 1972; Armstrong 2014). Our model incorporates these projections as growth and yield curves, as well as potential losses from fires, when calculating harvest revenue and timber volume projections for harvest prescriptions *i*. Thus, our model could help estimate the potential impacts of caribou conservation policies on the AAC and identify options to achieve the best possible balance between harvest and habitat protection. Note that the cost of habitat protection policies may depend on the legal prescriptions of harvest rights on public forestlands in Alberta. Currently, harvest rights in Alberta are contingent on acceptance of reforestation responsibility (GOA 2016). For some tree species, higher regeneration costs may decrease the profitability of harvest and likely alter the allocation of harvest sites, but so will the selection of sites for caribou habitat protection. Potentially, caribou conservation could be a spark to provide motivation to seek new sources of economic revenue and job creation other than business-as-usual timber extraction, e.g., value-added timber industries (rather than traditional pulp-and-paper or raw log exports), carbon offsets and non-timber forest products as well as activities related to the ecological restoration of degraded landscapes (Mansuy and MacAfee 2019).

The conclusions presented in this study apply to a particular area (Cold Lake, AB) where the spatial configuration of timber hauling costs, forest productivity and suitable habitat patterns determines the allocation of harvest and habitat connectivity patterns in optimal solutions. While our problem formulation is generalizable, its application to other regions would require developing the appropriate spatial datasets on forest productivity, age, habitat availability, timber hauling costs and human disturbances. The use of different spatial data configurations for other regions may also change the magnitude of the trade-off between the harvesting and habitat protection objectives and the impact of caribou protection measures on timber unit price.

Potential model extensions

The model presented in this study facilitates management of both forest harvest regimes and the degree of suitable habitat connectivity, but the approach has high computational costs. Similar to the problem presented in St. John (2016), the proposed MIP model is harder to solve to optimality than harvest scheduling models without habitat connectivity requirements. Nevertheless, the increase in computational burden is justified because the model assists in identifying the benefits of implementing caribou protection measures, characterizing those benefits spatially and assessing their impacts on the timber supply cost and allocation of harvest. These estimates can provide important considerations for decision-makers tasked with implementing large-scale caribou protection measures but who must also be mindful of the potential impacts of these policies on industrial forestry activities.

Our model used an MIP formulation that applied binary decisions to harvesting forested sites. In practice, harvest may take place in only a portion of a forest site. For this reason, our MIP formulation applied some restrictions to the spatial resolution of individual forest patches. In our case, the spatial resolution was also dictated by the minimum habitat area that could comfortably host caribou individuals. St John et al. (2016) acknowledged a similar issue where corridors for reindeer migration in northern Sweden required a certain minimum width to facilitate travel of the animals. Ideally, the size of individual forest patches should be big enough to facilitate the movement of caribou populations through habitat corridors.

Compared to other harvest scheduling models that employ spatial constraints (e.g., McDill et al. 2002; Toth and McDill 2008), our formulation does not impose habitat adjacency criteria on the selection of harvested sites or suitable habitats. Instead, for each time step we solve a network flow problem by finding the connected subgraphs in the habitat network between the suitable habitats. The connected subgraphs are also more sensitive to the spatial arrangement of suitable habitat than formulations based on adjacency criteria.

The combinatorial structure of the network flow problem implies that the time complexity of the proposed model rises exponentially with both the planning horizon T and the number of spatial elements N (which determines the number of arcs connecting the nodes with forest habitat). Potentially, a simpler network model formulation could make the approach applicable for larger datasets. Since most of current caribou recovery policies focus on long-term habitat protection the problem can be simplified to maximizing the amount of suitable habitat that stays connected over a desired time span T_{min} or longer (for example, 60+ years). This would require finding only one optimal connectivity network over the planning period T_{min} or longer and could simplify the formulation. Alternatively, one could use the network model formulation from Jafari and Hearne (2013), which uses a simpler algorithm to ensure connectivity between habitat patches, to track the connected habitat capacity without needing to designate the source and recipient capacities of the connected nodes.

Our approach can be extended in several ways. Incorporating other environmental sustainability constraints, such as maintaining a desired amount of old-growth forest, enforcing habitat connectivity for a portion of the area throughout the entire planning horizon (or minimum desired period), or accounting for possible timber losses due to fire hazard (Stockdale et al. 2019) could make the harvest planning model more realistic. Potentially, other spatial constraints could be added, such as habitat adjacency criteria (see Toth and McDill 2008; Carvajal et al. 2013), but this may further increase the numerical complexity of the problem. The model could also be extended to optimize habitat connectivity for multiple wildlife species, or by linking the harvest scheduling and caribou habitat models with a spatial stochastic fire disturbance model (for example, via the re-planning approach described in Martin et al. 2017). This will be the focus of future work.

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APPENDIX S1. ESTIMATING THE AMOUNTS OF SUITABLE CARIBOU HABITAT FOR A SET OF HARVEST PRESCRIPTIONS.

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Tables:

Table 1. Summary of the model parameters.

Symbol	Parameter / variable name	Description
Sets:		
Θ	Arcs *nm* connecting adjacent nodes *n* and *m* in a landscape	$nm \in \Theta$
N	Nodes (forest patches), *n*	$n \in N$
N_n^-	Nodes-sources of incoming species flow to a node *n*	
N_n^+	Nodes-sources of outgoing species flow from a node *n*	
T	Planning time periods, *t*	$t \in T$
I	Harvest prescriptions, *i*	$i \in I$
Decision variables:		
w_{nt}	Source node selection binary variable	$w_{nt} \in \{0,1\}$
w'_{nt}	Recipient node selection binary variable	$w'_{nt} \in \{0,1\}$
y_{nmt}	Amount of flow between the adjacent nodes *n* and *m* in period *t*	$y_{nmt} \geq 0$
v_{nt}	Unutilized capacity at a selected source node *n* in period *t*	$0 \leq v_{nt} < b_n(1\text{-}\gamma)_t$
v'_{nt}	Unutilized capacity at a selected recipient node *n* in period *t*	$0 \leq v'_{nt} < b'_{nt}(1\text{-}\gamma)$
x_{ni}	Binary selection of a harvest schedule *i* in site *n*	$x_{ni} \in \{0,1\}$
z_{nit}	Product of binary variables w_{nt} and x_{ni}	$z_{nit} \in \{0,1\}$
z'_{nit}	Product of binary variables w'_{nt} and x_{ni}	$z'_{nit} \in \{0,1\}$
Parameters		
b_{nt}	Source node capacity (the amount of flow that could originate from a node *n* in period *t*)	$b_{nt} \geq 0$
b'_{nt}	Recipient node capacity (the amount of flow that could be absorbed by a node *n* in period *t*)	$b'_{nt} \geq 0$
U	Upper bound on the maximum amount of flow through a selected node	$U > 0$
M	Large positive value	$M > 0$
$Q_{t\,\min}, Q_{t\,\max}$	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 merchantable timber available for the harvest at a node *n* in period *t* in harvest prescription *i*	$V_{nit} \geq 0$
Q_t	Volume of timber harvested over a period *t*	$Q_t \geq 0$
R_{ni}	Net revenue associated with harvesting a node *n* according to prescription *i*	$R_{ni} \geq 0$
ε	Allowable increase or decrease in harvest volume in consecutive planning periods *t* and *t* +1	0.02
$E_{T\,min}$	Average target age of forest stands in the managed area at the end of the planning horizon *T*	65
E_{ni}	Forest stand age in a patch *n* at the end of the planning horizon if prescription *i* is applied	0-180
e_n	Postharvest regeneration costs	$e_n > 0$
d_n	Unit volume timber price net of harvest and hauling cost	$d_n > 0$
γ	Minimum proportion of the node's habitat capacity that must be utilized at the selected node	0.05
λ_{nit}	Suitable habitat status for at a node *n* in prescription *i* in period *t*	$\lambda_{nit} \in \{0,1\}$
F,f	Objective scaling factors	$F,f \in [0;1]$

Table 2. Net annual revenues for harvest priority and habitat protection priority solutions.

Harvest scenario	Harvest target, million m^3-year^{-1}	Annual revenues, million $-year^{-1}		Annual difference Net revenues, million $-year^{-1}	Timber unit price difference, $-m^{-3}
		Scenarios: Harvest Priority	Connectivity Priority		
FMA[*]	0.1	1.676	1.473	0.203	2.04
	0.2	3.194	2.833	0.361	1.80
	0.3	4.611	4.030	0.581	1.94
	0.4	5.920	5.177	0.743	1.86
	0.5	6.916	6.353	0.563	1.13
FMA-OS[**]	0.1	1.677	1.475	0.202	2.02
	0.2	3.195	2.803	0.392	1.96
	0.3	4.612	4.106	0.506	1.69
	0.4	5.941	5.284	0.657	1.64
	0.5	7.195	6.517	0.678	1.36
	0.6	8.387	7.319	1.068	1.78
	0.7	9.320	8.476	0.844	1.21

[*] FMA scenario allows harvest in the forest management agreement area only;

[**] FMA-OS scenario allows harvest in both forest management agreement area and areas of current oil and gas extraction

Figures:

Fig.1. Boreal woodland caribou ranges and regions of industrial forestry activities in Canadian boreal forests.

Fig.2. Cold Lake Caribou Range (CLCR) case study model inputs: a) habitat capacity values b_{nit} (example map for no-harvest scenario, $t = 1$, based on Whitman et al. (2017) and Barber et al. (2018) methods); b) map of habitat intactness (used to estimate the habitat capacity values b_{nit}); c) areas of oil and gas exploration with no habitat restoration objectives and areas within 500-m buffers around human disturbances (well pads, routs, pipelines, etc.); d) timber hauling cost.

Fig.3. Area mask for harvest scenarios: a) FMA scenario that allows harvesting in forest management agreement areas only; b) FMA-OS scenario that allows harvest in areas of current oil and gas extraction as well as forest management agreement areas.

Fig.4. Impact of timber harvest target on the area of connected habitat and timber price: a) the connected habitat proportion of the total range area, % vs. timber harvest target, million m^3-yr.$^{-1}$; b) mill gate timber price, \$-m^{-3} vs. timber harvest target, million m^3-yr.$^{-1}$. Solid lines depict the FMA harvest scenarios and dotted / dashed lines depict the FMA-OS scenarios.

Fig.5. Examples of optimal harvest and habitat connectivity patterns – FMA scenarios with harvest target = 0.2 million m^3-yr.$^{-1}$. Harvest priority solutions: a) map of connected habitat and harvest frequencies. Shading indicates the number of periods a node (patch) with suitable habitat maintained connectivity with other nodes with suitable habitat. Darker areas show patches that remained connected over longer periods. Small and large dots indicate that a node (patch) was harvested once or twice, respectively, over the planning horizon T; b) time from the beginning of

the planning period to first harvest. Darker shades indicate more immediate harvest. White areas indicate no harvest over the planning horizon *T*. Habitat protection priority solutions: c) map of connected habitat and harvest frequencies; d) time from the beginning of the planning period to first harvest.

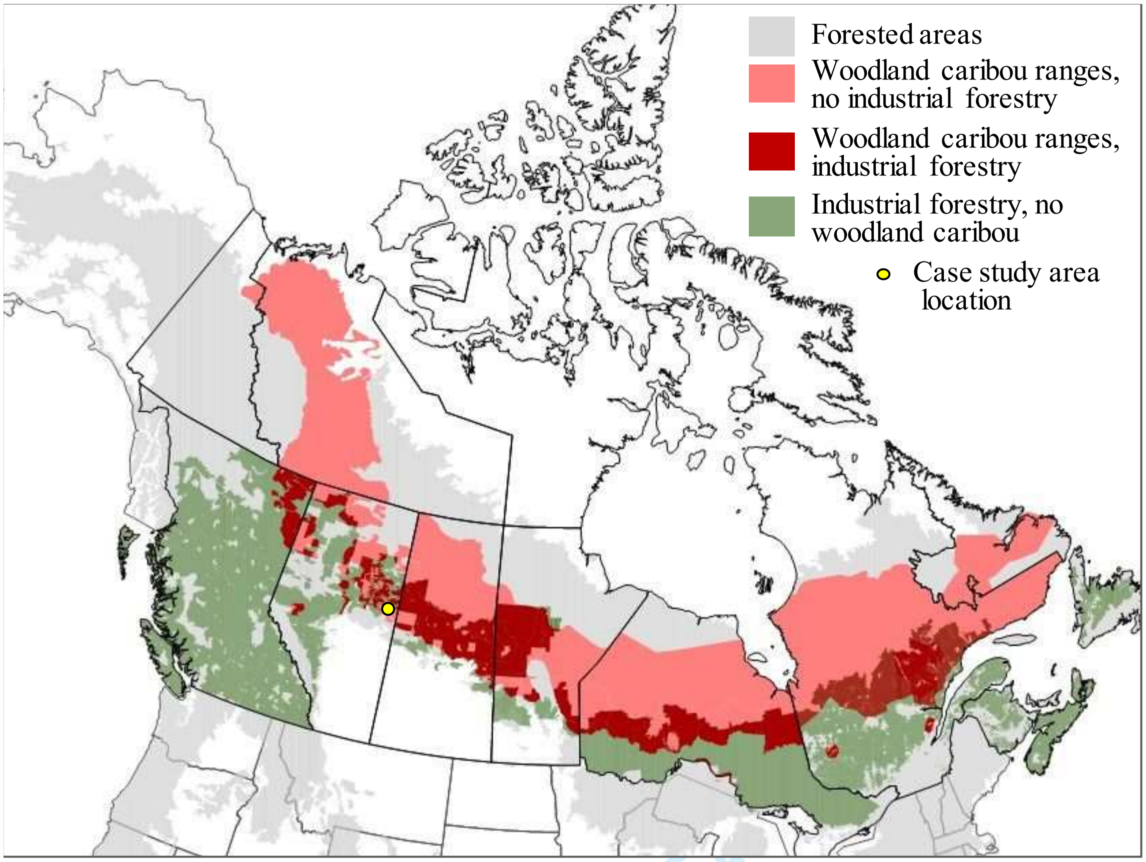
Fig.6. Examples of optimal harvest and habitat connectivity patterns – FMA scenarios with harvest target = 0.4 million m^3-$yr.^{-1}$. Harvest priority solutions: a) map of connected habitat and harvest frequencies. Shading indicates the number of periods a node (patch) with suitable habitat maintained connectivity with other nodes with suitable habitat. Darker areas show patches that remained connected over longer periods. Small and large dots indicate that a node (patch) was harvested once or twice, respectively, over the planning horizon *T*; b) time from the beginning of the planning period to first harvest. Darker shades indicate more immediate harvest. White areas indicate no harvest over the planning horizon *T*. Habitat protection priority solutions: c) map of connected habitat and harvest frequencies; d) time from the beginning of the planning period to first harvest.

Fig.7. Proportion of the CLCR area with connected habitat over 10-year planning periods, *t*: a) FMA scenario; b) FMA-OS scenario. X-axis denotes the planning time periods, years and y-axis denotes the proportion of range area with the connected habitat in a particular period *t*. Bold lines depict the habitat protection priority solutions and thin lines depict the harvest priority solutions.

Fig.8. Total area harvested, ha, over the planning horizon *T* vs. the harvest volume target, million m^3-$yr.^{-1}$: a) FMA scenarios that limit harvest to forest management agreement areas only; b) FMA-OS scenarios that allow harvest in forest management agreement areas and areas of current oil and

gas extraction. Solid lines indicate the total area harvested twice over the planning horizon T and dotted / dashed lines indicate the total area harvested once over the planning horizon.

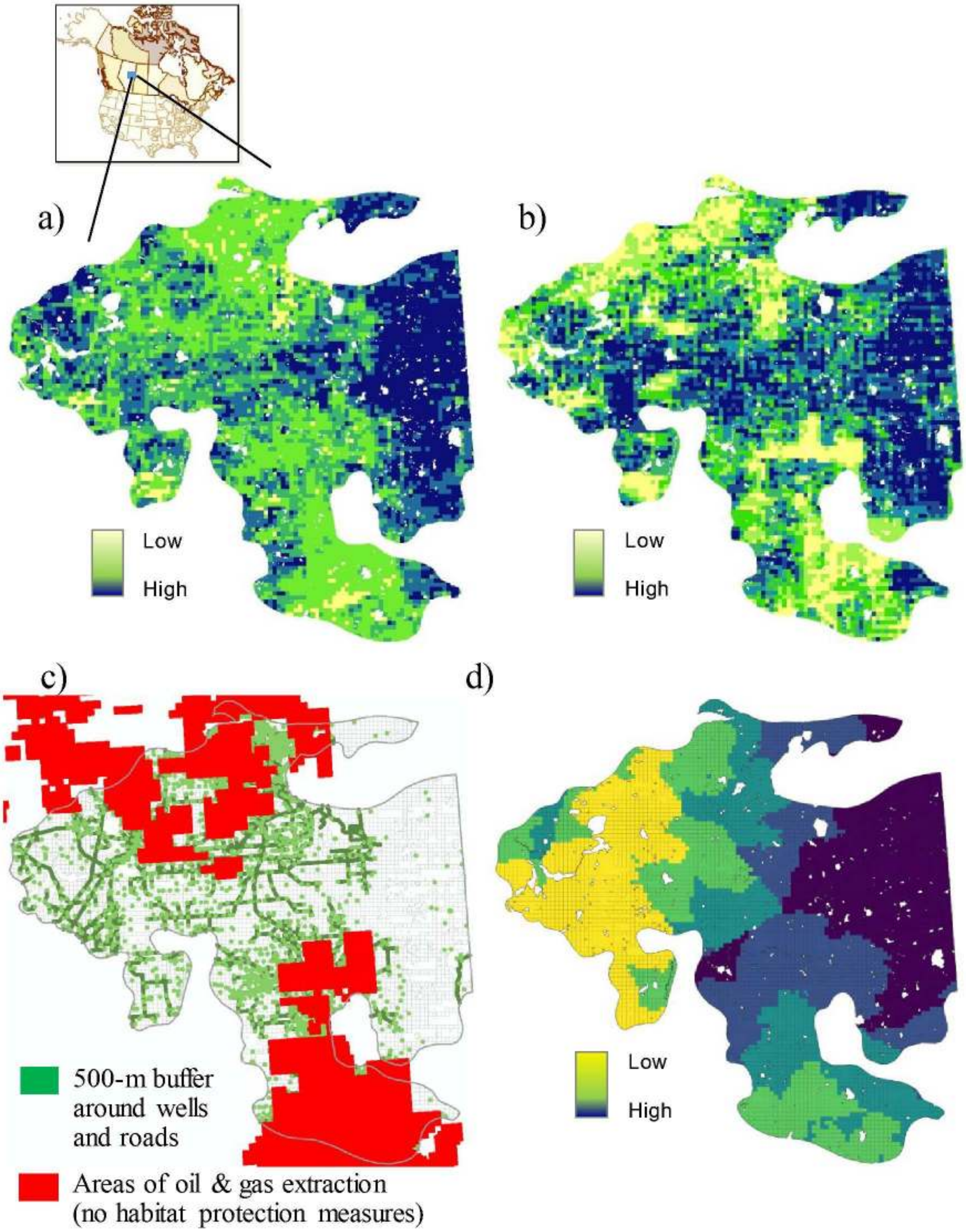
1 **Figures:**



2

3

4 Fig.1.


a)
Low
High
b)
Low
High
c)
500-m buffer around wells and roads
Areas of oil & gas extraction (no habitat protection measures)
d)
Low
High

Fig,2,

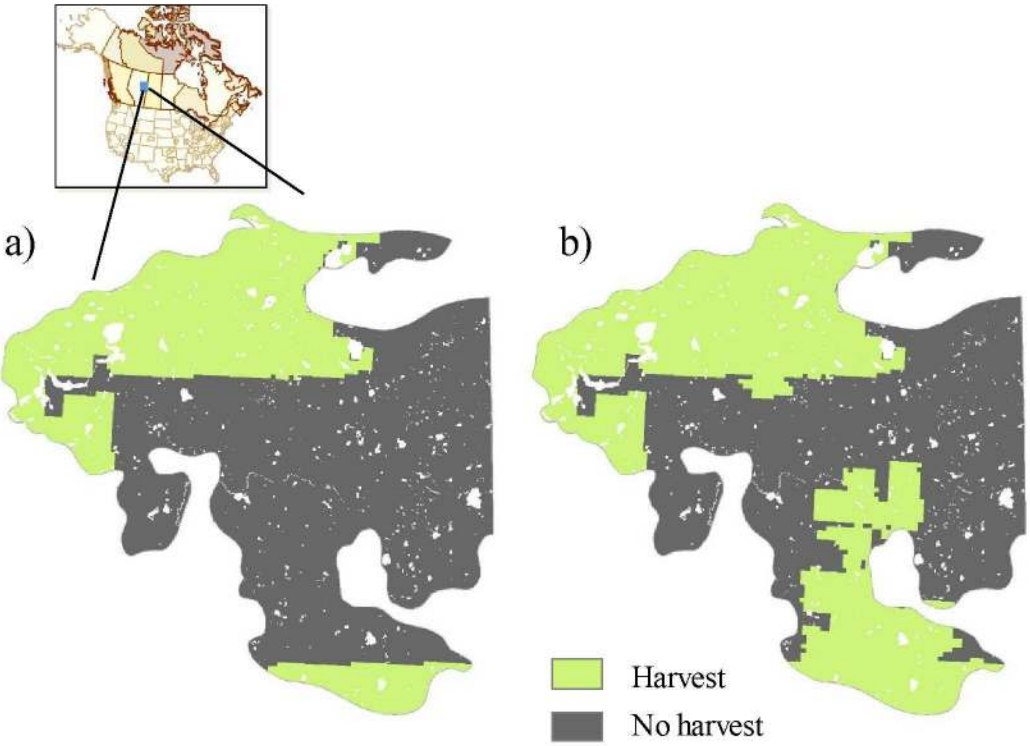


Fig.3.

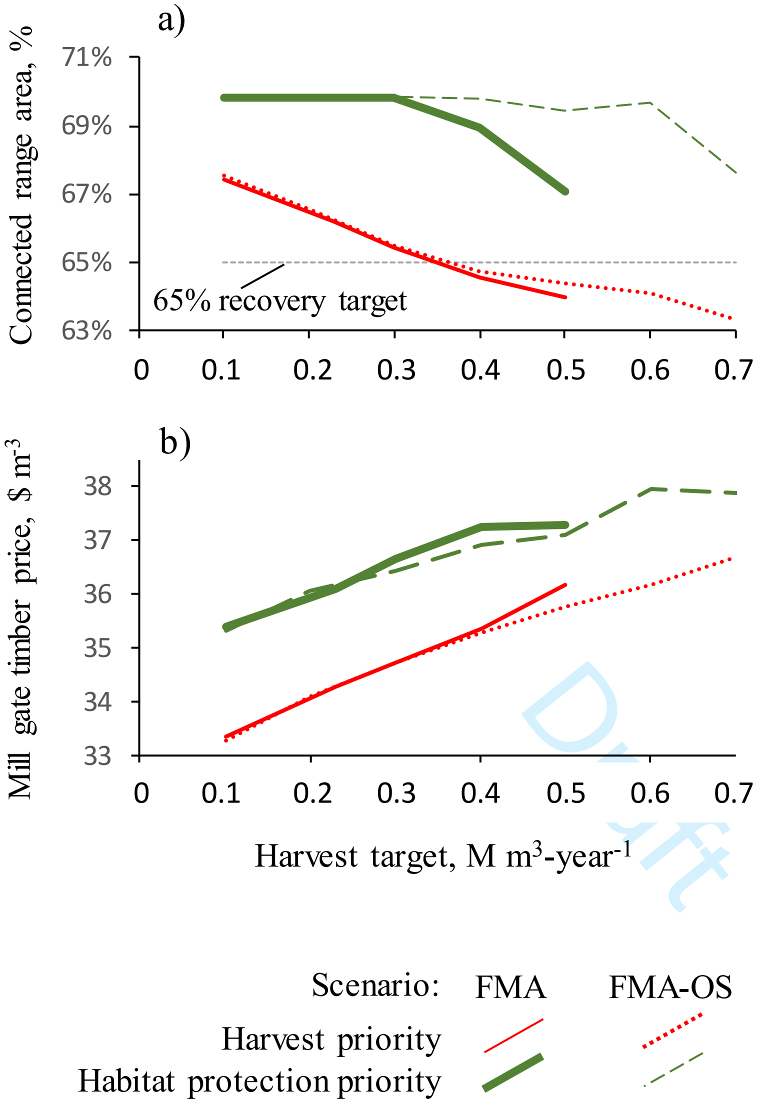

a)
Connected range area, %
71%
69%
67%
65%
63%
65% recovery target
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
b)
Mill gate timber price, $ m-3
38
37
36
35
34
33
Harvest target, M m3-year-1
Scenario:
FMA
FMA-OS
Harvest priority
Habitat protection priority

Fig.4.

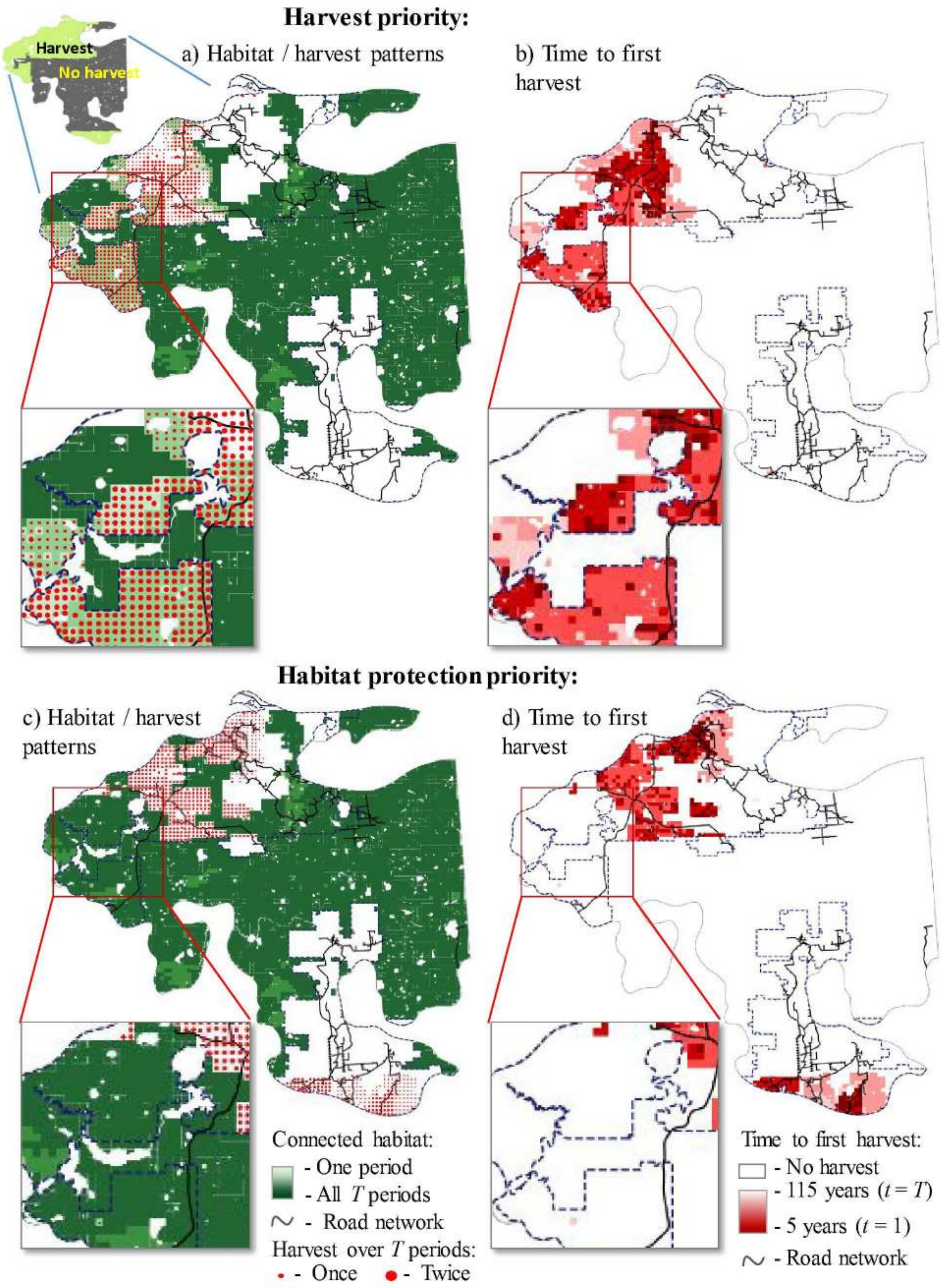

Harvest priority:
Harvest
No harvest
a) Habitat / harvest patterns
b) Time to first harvest
Habitat protection priority:
c) Habitat / harvest patterns
d) Time to first harvest
Connected habitat:
- One period
- All T periods
- Road network
Harvest over T periods:
- Once
- Twice
Time to first harvest:
- No harvest
- 115 years (t = T)
- 5 years (t = 1)
- Road network

Fig.5.

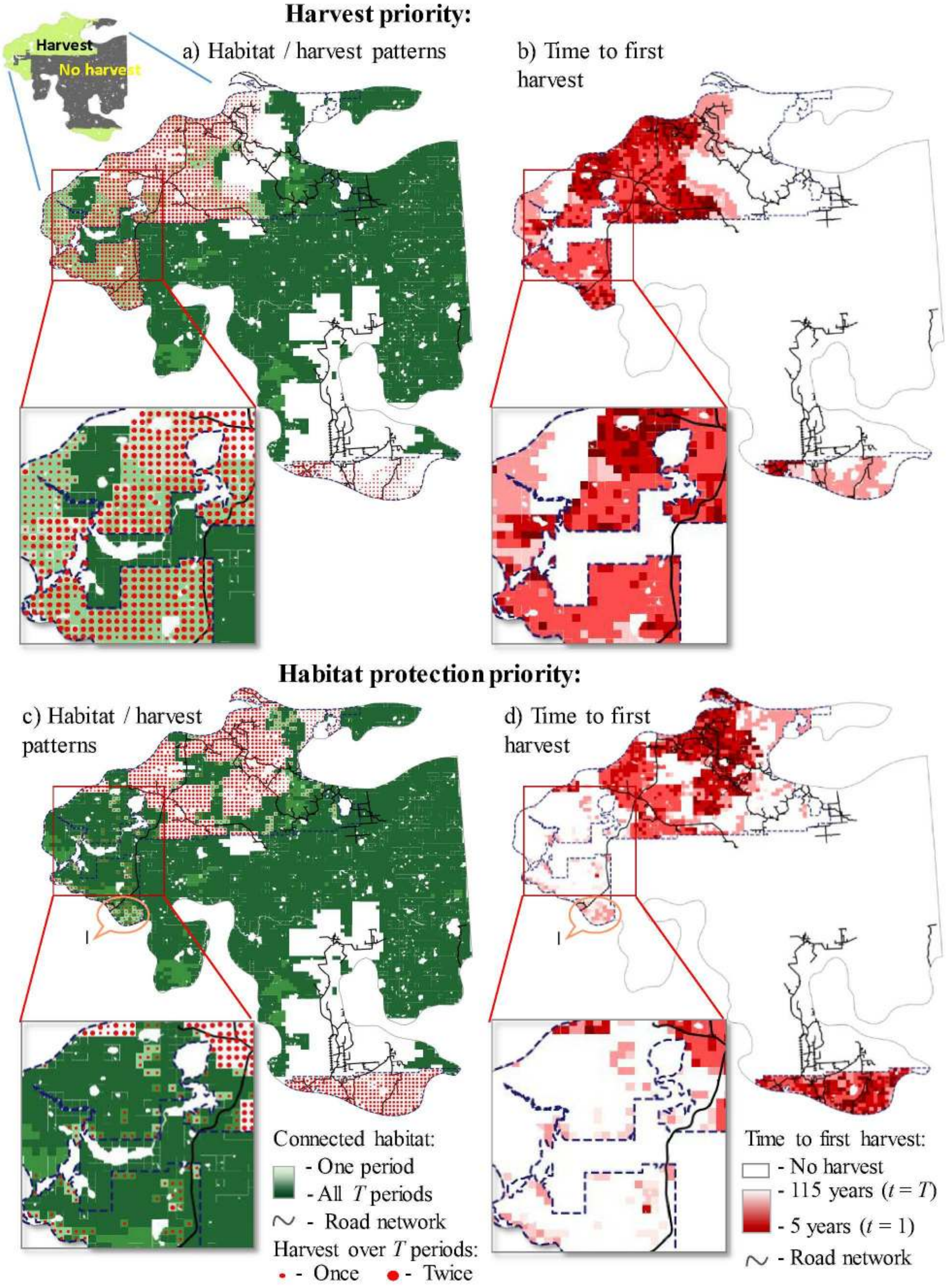

Harvest priority:
Harvest
No harvest
a) Habitat / harvest patterns
b) Time to first harvest
Habitat protection priority:
c) Habitat / harvest patterns
I
d) Time to first harvest
I
Connected habitat:
- One period
- All T periods
- Road network
Harvest over T periods:
- Once
- Twice
Time to first harvest:
- No harvest
- 115 years (t = T)
- 5 years (t = 1)
- Road network

Fig.6.

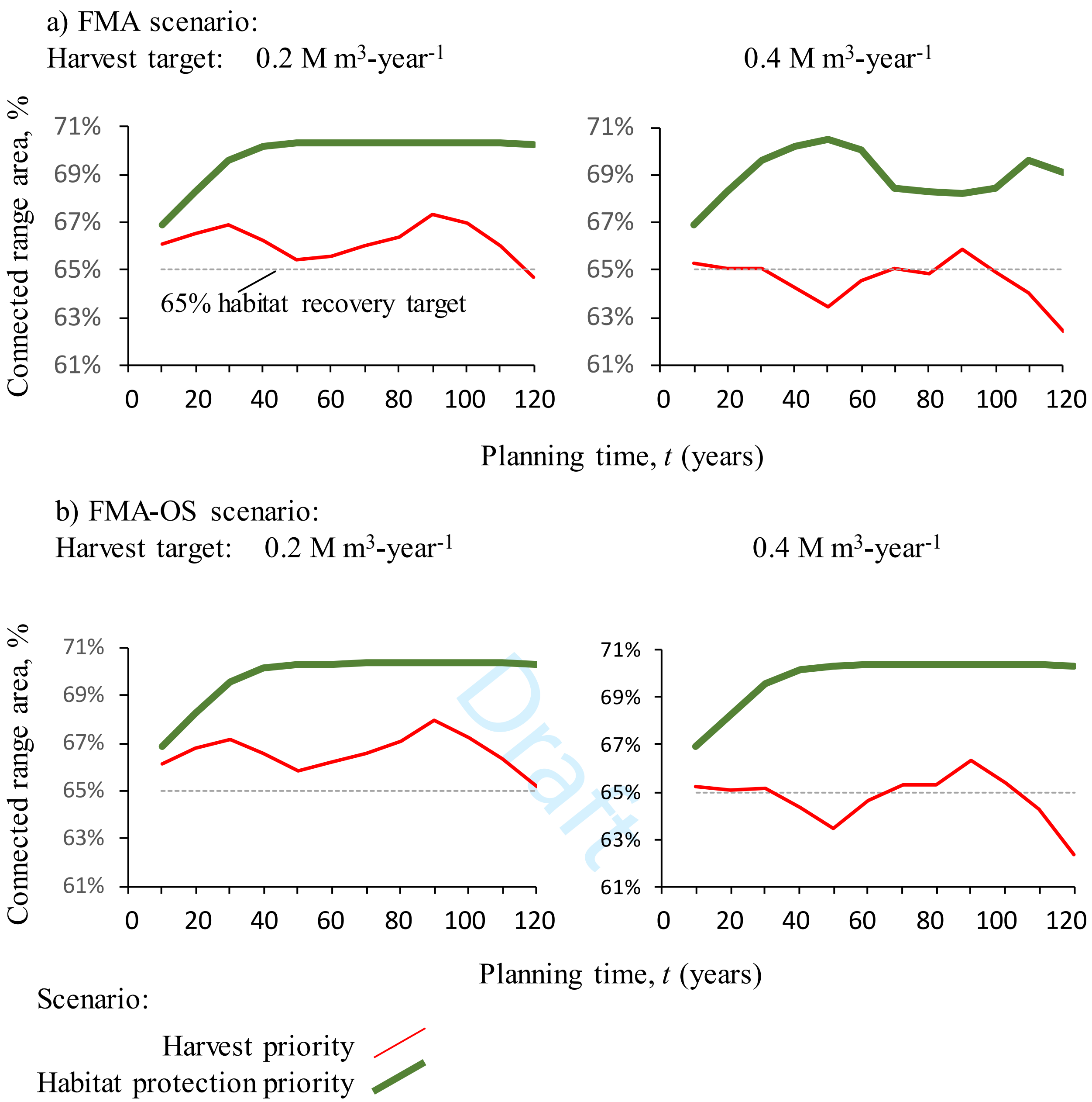

a) FMA scenario:
Harvest target: 0.2 M m3-year-1
0.4 M m3-year-1
Connected range area, %
71%
69%
67%
65%
63%
61%
0
20
40
60
80
100
120
65% habitat recovery target
Planning time, t (years)
b) FMA-OS scenario:
Harvest target: 0.2 M m3-year-1
0.4 M m3-year-1
Connected range area, %
Planning time, t (years)
Scenario:
Harvest priority
Habitat protection priority

Fig.7.

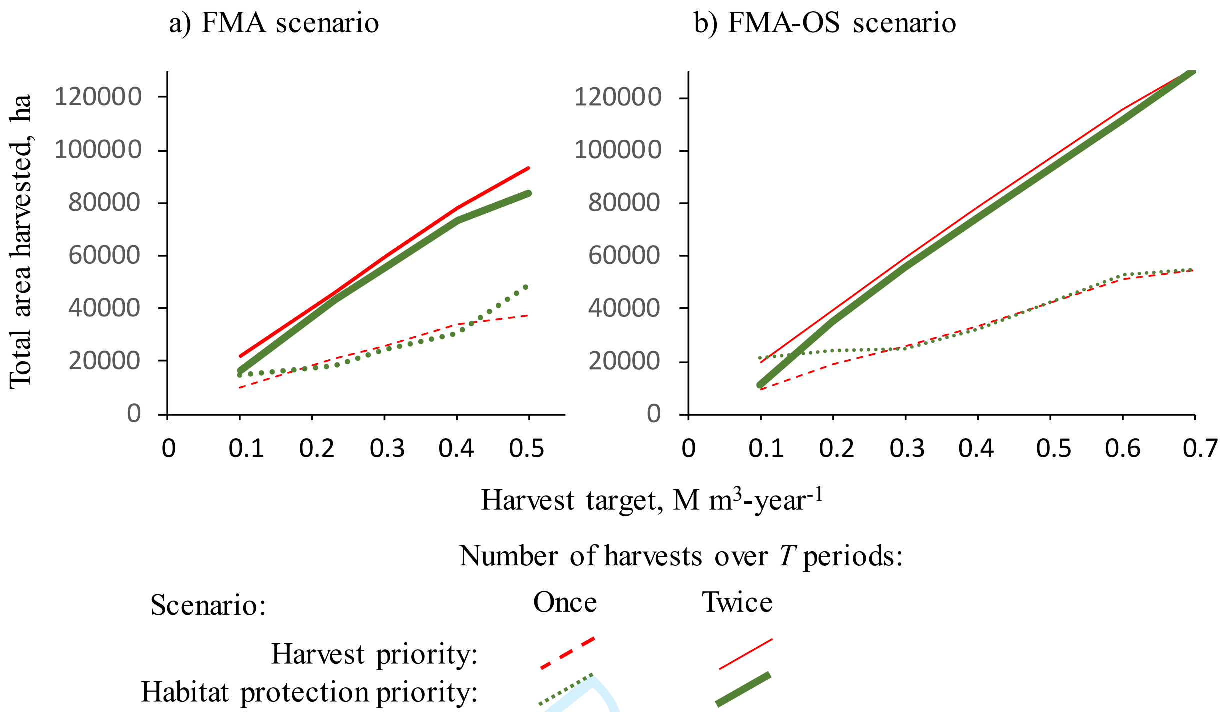

a) FMA scenario
b) FMA-OS scenario
Total area harvested, ha
120000
100000
80000
60000
40000
20000
0
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
Harvest target, M m³-year⁻¹
Number of harvests over T periods:
Scenario:
Once
Twice
Harvest priority:
Habitat protection priority:

Fig.8.