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RESEARCH ARTICLE

Optimal restoration of wildlife habitat in landscapes fragmented by resource extraction: a network flow modeling approach

Denys Yemshanov[1,2], Mackenzie Simpson[1], Frank H. Koch[3], Marc-André Parisien[4], Quinn E. Barber[4], Fabio Campioni[1], Fin Macdermid[5], Salimur Choudhury[6]

Non-renewable resource extraction contributes greatly to degradation of wildlife habitats in boreal landscapes. In western Canada, oil and gas exploration and extraction have left a dense network of linear disturbances (seismic lines) and abandoned well pads that have fragmented boreal forest. Among multiple ecological effects, these disturbances have increased predator access to the preferred habitat of some wildlife taxa, most notably boreal woodland caribou, resulting in population declines. Restoration of seismic lines and abandoned well pads is a critical activity to improve the recovery of woodland caribou populations. We present a linear programming model that optimally allocates restoration efforts to maximize the access of caribou to nearby undisturbed habitat in a fragmented landscape. We applied the model to examine restoration scenarios in the Cold Lake First Nations area in northeastern Alberta, Canada, which includes caribou habitat but also areas of active oil and gas extraction. The model depicts the landscape as a network of interconnected habitat patches and combines three network flow sub-problems. The first sub-problem enforces the spatial connectivity of the remaining network of unrestored sites. The second sub-problem maximizes access to suitable habitat from the restored locations and the third sub-problem ensures the allocation of restoration activities in as few spatially contiguous restoration projects as possible. The approach is generalizable and applicable to assist restoration planning in other resource extraction regions and for other taxa.

Key words: abandoned well pads, access to habitat, mixed integer programming, network flow model, seismic lines, Steiner network, woodland caribou

Implications for Practice

- The proposed methodology can guide practical habitat restoration planning in landscapes fragmented by oil and gas exploration and extraction activities. Optimal restoration solutions maximize local access of a wildlife species to preferred habitat and thus are suited to support fine-scale restoration decisions.
- The approach improves the cost-effectiveness of restoration by controlling the spatial contiguity of restoration projects and minimizing the number of disjunct clusters of restored sites. The optimal solutions maintain access to unrestored features that are still active, making the approach practical for restoration planning in remote regions while ensuring buy-in from industry stakeholders.
- With straightforward modification, the proposed approach can be applied for habitat restoration planning in other landscapes with significant resource extraction activity or for other taxa.

Introduction

Large-scale exploration and extraction of oil and gas deposits in Canada has led to the creation of extensive networks of narrow linear corridors (seismic lines), which were cleared for oil and gas exploration, and well pads (open service areas 1.6–10 ha in size around wells). The resulting fragmentation of boreal forest landscapes has negatively affected the survival of wildlife populations that require large areas of intact forest habitat (Pattison et al. 2016), particularly boreal woodland caribou (*Rangifer tarandus caribou*, caribou hereafter) (Vors & Boyce 2009; Hervieux et al. 2013). Seismic lines alter caribou habitat and facilitate incidental predation risk by increasing abundance of predators such as gray wolves (*Canis lupus*)

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[1]Natural Resources Canada, Canadian Forest Service, Great Lakes Forestry Centre, Sault Sainte Marie, ON, Canada
[2]Address correspondence to D. Yemshanov, email denys.yemshanov@canada.ca
[3]USDA Forest Service, Southern Research Station, Eastern Forest Environmental Threat Assessment Center, Research Triangle Park, Chapel Hill, NC, U.S.A.
[4]Natural Resources Canada, Canadian Forest Service, Northern Forestry Centre, Edmonton, AB, Canada
[5]Cold Lake First Nation, Cold Lake, AB, Canada
[6]Lakehead University, Thunder Bay, ON, Canada

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(Serrouya et al. 2020), thereby increasing their chance of a direct encounter with caribou (Whittington et al. 2011; McKenzie et al. 2012). A network of seismic lines increases the hunting efficiency of predators by allowing them to move farther and faster into caribou refuge habitat (Dickie et al. 2017; Mumma et al. 2017; McKay et al. 2021). The creation of seismic lines also increases the amount of disturbed land with early successional vegetation, which in turn attracts more ungulates and their predators, while also decreasing the area of core intact habitat that can be used by caribou as a refuge (Schneider et al. 2010; Latham et al. 2011*a*, 2011*b*; Wilson & DeMars 2015).

Networks of seismic lines often link to well pads. After 20–30 years of use for resource extraction, the wells are decommissioned (OWA 2019), but the surrounding pads are not always restored, or restoration may only be partly successful (Caners & Lieffers 2014; Janz et al. 2019). Without reclamation, abandoned well pads can cause environmental problems (e.g. impacts to soils) in addition to their contributions to landscape fragmentation (Sechman et al. 2013). Well pads are avoided by caribou and continue to influence the selection of habitat by caribou after human activity ceases (MacNearney et al. 2021).

Caribou are listed as a Threatened species in Canada's Species at Risk Act (SARA 2002). The federal boreal recovery strategy for caribou emphasizes landscape-level planning as a measure to stop population declines (EC 2012). Restoration of seismic lines has been identified as a critical priority for the recovery of caribou populations (ECCC 2017; GOA 2017). Restoration aims to reduce predator use of seismic lines for hunting, and ultimately to reduce the amount of disturbance within a caribou range (Spangenberg et al. 2019). Examples of seismic line restoration activities include replanting trees and creating obstacles to impede the movement of predators (James & Stuart-Smith 2000; Pyper et al. 2014). In practice, when an area of seismic lines is scheduled for restoration, any abandoned well pads in that area should also be restored. This is because access to the unrestored well pads is likely to be cost-prohibitive if the seismic lines connected to them are restored.

Prioritizing where restoration activities should take place improves their cost-effectiveness, especially in situations when a limited budget does not permit restoration of all disturbed sites. Previous efforts to prioritize seismic line restoration in Alberta (ABMI 2017, 2020) ranked potential candidate locations at the township level using multiple criteria, such as the degree of human disturbance, seismic line density, and the amount of recoverable oil and gas resources. Each township was assigned a score based on a weighted average of individual criteria values. While this type of approach provided strategic guidance at the township level, project-level restoration planning also must address many logistical tradeoffs, such as balancing access to restoration sites and currently active wells. Such aspects are beyond the scope of multi-criteria priority rankings and require the use of optimization-based planning tools (Önal & Wang 2008).

In our study, we propose an optimization-based approach that addresses the combinatorial nature of spatial planning of seismic line and abandoned well pad restoration under a limited budget. We use the restoration costs and amount of undisturbed habitat that can be accessed by caribou locally through a restored site to prioritize restoration locations (Nagy-Reis et al. 2020; Serrouya et al. 2020). Our objective is consistent with a key rationale of restoration initiatives, which is reduction of predator access to caribou habitat (Keim et al. 2019; Tattersall et al. 2020).

We consider a number of logistical issues omitted by coarse-scale prioritizations, but which are likely to arise in project-level planning of restoration activities. For example, when a portion of the seismic lines are restored in a region, it is critical to maintain access to the remaining pockets of unrestored sites and resource extraction areas. Budget constraints and the outcomes of pre-treatment seismic line inventory may influence the spatial allocation of restoration activities (Pyper et al. 2014). Logistical considerations also dictate that the restoration must occur over no more than a few contiguous regions. Tracking the aspects mentioned above requires controlling the spatial contiguity between the restored locations. The spatial contiguity between patches of interest in a landscape can be modeled using a network optimization approach (Conrad et al. 2012; Dilkina et al. 2017; Yemshanov et al. 2019). In network optimization, a landscape is depicted as an interconnected network of nodes. In the context of caribou recovery and restoration efforts, controlling the spatial contiguity between nodes selected for restoration may help find configurations that satisfy multiple planning objectives but also allocates the restoration locations in spatially contiguous clusters.

Previously, the control of spatial contiguity when optimizing restoration and conservation planning has been addressed with other approaches, such as enforcing spatial adjacency (Önal & Wang 2008), and connectivity of a protected landscape (Gupta et al. 2019). Network optimization has rarely been used in an ecological restoration context but has been adopted in biological conservation management (Conrad et al. 2012; Dilkina et al. 2017; Yemshanov et al. 2019). In a previous study (Yemshanov et al. 2019), we aimed to maximize the global amount of connected caribou habitat but did not specify where the connectivity between habitats was to be maintained. Furthermore, we did not address the issues of maintaining human access to the unrestored sites and undertaking restoration in spatially contiguous regions.

In this study, we propose a linear programming model that optimizes the restoration of seismic lines and abandoned well pads in an area of interest. Our model helps find restoration strategies in a landscape disturbed by resource extraction, where the planners must account for multiple logistical considerations in addition to the primary wildlife conservation objectives. The model considers spatial contiguity in three contexts. First, our model finds a configuration of restored sites that maximizes the amount of undisturbed habitat that animals can access within a specified distance from a restored site. Second, our model ensures that non-restorable features (such as roads and pipelines) and the remaining unrestored sites are not cutoff by the restoration activities and continue to be accessible. Third, our model allocates restoration in contiguous clusters and minimizes their total number in the landscape.

We applied the model to the problem of restoring seismic lines and abandoned well pads in the Cold Lake First Nations (CLFN) area, Alberta, Canada. Our model finds solutions for a restoration budget set by a decision-maker and accounts for the trade-offs between the budget level, project constraints and restoration objectives. This makes it distinct from previous multi-criteria prioritizations of restoration in the CLFN (ABMI 2017, 2020), which were coarse-scale and more strategic in scope.

Methods

Problem Definition

We conceptualized the fragmented landscape as a lattice of N interconnected patches (nodes). A network of seismic lines, well pads, and roads (the access network Ω hereafter) divides the landscape into fragmented regions with remnant pockets of suitable caribou habitat. We depicted the access network Ω as a set of nodes connected by bi-directional arcs (Fig. 1A).

Each node n may have an amount of suitable caribou habitat b_n, $b_n \geq 0$. We defined the amount of suitable habitat as the combination of three components of habitat (nutritional resources, connectivity, and predation risk) using the methodologies of Whitman et al. (2017) and Barber et al. (2018) (see Supplement S1). We modeled habitat suitability based on broad-scale spatial variation in vegetation and fire likelihood at a regional extent. This type of modeling is meaningful for the study area given the typically large size of wildfires in the region.

Caribou individuals move between nodes containing habitat as part of their foraging and seasonal movement behavior (Stuart-Smith et al. 1997; Rettie & Messier 2001; Hervieux et al. 2013). When the animals cross a seismic line, this increases their exposure to predators who are able to exploit these landscape features (Mumma et al. 2017, 2018; Dickie et al. 2020). Restoration of disturbances in node n allows caribou to move through n with lower predation risk. We assumed that a node becomes natural habitat after restoration but acknowledge that the efficacy of restoration may vary across time and space (Keim et al. 2019; Tattersall et al. 2020).

After some nodes with seismic lines and/or well pads are restored, we must ensure that the remaining nodes in the access network Ω are still connected to at least one location where a road or possibly a seismic line used to access area N enters the landscape. We addressed this aspect with our first network flow sub-problem, which enforced connectivity between the unrestored nodes in network Ω and nodes representing points of entry along the borders of area N. We added an auxiliary node 0 to network Ω that is connected to these entry nodes (Fig. 1A). Node 0 injects flow to the entry nodes (except for entry nodes that are restored; see Fig. 1B), which then is passed to all other unrestored nodes in network Ω. When unrestored nodes receive flow from the entry nodes, this ensures that they are connected to one of the entry points (Fig. 1A). After a node is restored it cannot transmit flow to or receive it from unrestored nodes in network Ω and thus is effectively removed from Ω (Fig. 1B).

A non-negative decision variable, y_{nm}, specifies the amount of flow between nodes n and m and a binary decision variable, x_{nm}, selects arc nm to transmit this flow if both nodes are in network Ω ($x_{nm} = 1$ and $x_{nm} = 0$ otherwise). Each node n in Ω receives flow through a single incoming arc, that is,

$$\sum_{m=0}^{N} x_{mn} = 1$$

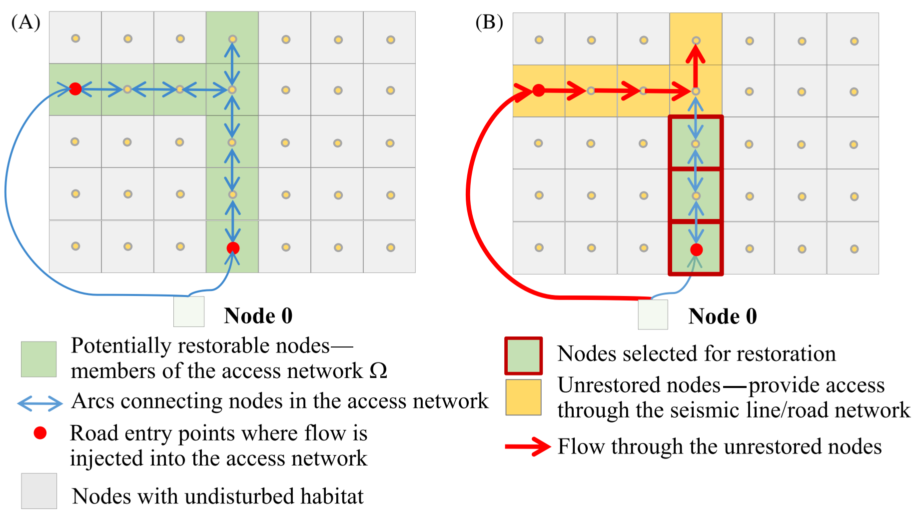

Figure 1. (A) Schematic depiction of site access network Ω, which ensures human access to the remaining unrestored features and permanent disturbances. Blue arrows show arcs connecting nodes that are elements of network Ω. Green cells show nodes with seismic lines (and abandoned well pads) that are potential candidates for restoration and gray cells show nodes with undisturbed habitat. Red dots show the points of access to the study area and where an auxiliary node 0 is connected to the site access network. (B) Red arrows show an example of the flow in site access network Ω from node 0 to the points of entry and then to all unrestored (or non-restorable) nodes. The flow cannot go to restored nodes (outlined in red), which become inaccessible after restoration. Figures 1–3 show the same sample area.

We defined nodes with seismic lines and/or abandoned well pads as eligible for restoration and nodes with other features used specifically to access area N as non-restorable in the near term, but useable to access other nodes in network Ω.

Once a node is restored, caribou can move through that node to neighboring nodes with habitat at reduced risk of predation. To prioritize restoration, we used the amount of suitable habitat, b_n, in nodes n that can be accessed from a potentially restored node. To delineate the habitat *locally* accessible from a potentially restored node n, we find a subset m of nodes with suitable undisturbed habitat connected to n. Our second sub-problem calculated the amount of suitable habitat in nodes connected to restored nodes within a target distance $H_{\max}$. The $H_{\max}$ value defines a distance at which suitable habitat is accessible from a location with anthropogenic disturbance, for example, 500 m, which is the spatial resolution of one node. We defined a habitat network set, Ξ, containing nodes n with seismic lines and/or abandoned well pads (potential candidates for restoration) and nodes m with suitable habitat (Fig. 2A). All n nodes are connected to adjacent m nodes with suitable habitat by unidirectional arcs nm, while all m nodes are connected by bidirectional arcs. To find the number of m suitable habitat nodes connected to a candidate node n, we tracked the flow from node n to nearby m nodes (Fig. 2B). We added an auxiliary node 1 to set Ξ that is connected to all nodes n—candidates for restoration—and serves as a source of the flow from these nodes to m habitat nodes (Fig. 2A & 2B). Only restored nodes can receive flow from node 1 and pass it to adjacent habitat nodes (Fig. 2B). Adjacent habitat nodes pass the flow to other connected habitat nodes and so on. A non-negative decision variable, v_{nm}, specifies the amount of flow between nodes n and m through arc nm in network Ξ, and a binary decision variable, w_{nm}, indicates whether arc nm is selected to transmit flow between n and m, that is, $w_{nm} = 1$ when $v_{nm} > 0$ and $w_{nm} = 0$ when $v_{nm} = 0$. A node in network Ξ becomes connected to other nodes if it receives flow through at least one incoming arc, that is:

$$\sum_{m=1}^{N} w_{mn} > 0$$

Access of caribou individuals to the nearest undisturbed suitable habitat is critical for reducing exposure to predators (Latham et al. 2011*c*; DeCesare 2012; DeCesare et al. 2014); consequently, we considered a small number of proximal habitat nodes connected to each side of a restored node n, as defined by $H_{\max}$. If $H_{\max} = 1$, then a restored node could pass the flow to immediately adjacent habitat nodes (Fig. 2B). We assumed that a habitat node could receive flow from no more than one restored node, which simplifies tracking of the number of nodes with habitat connected to a restored node.

Network nodes define discrete map cells where each cell may include seismic lines and/or abandoned well pads. In this setting, cells including large amounts of potentially suitable habitat and small portions of seismic lines may receive disproportionally high restoration priority. When the total length of these features in node n, l_n, was less than the node's linear size, $l_{\min}$, we adjusted the amount of habitat that could be accessed from the node by a proportion $h_n = l_n/l_{\min}$, $h_n \in [0;1]$. We assumed that $h_n = 1$ if $l_n \geq l_{\min}$. For every habitat node m that was connected to a restored node n, its habitat value, b_m, was adjusted by factor h_n. Because more than one habitat node could be connected to a restored node n, we needed to pass factor h_n to all connected nodes. For each arc nm in the habitat network Ξ we defined a non-negative decision variable, u_{nm}, that passed the adjustment factor h_n from node n to a connected habitat node m via arc

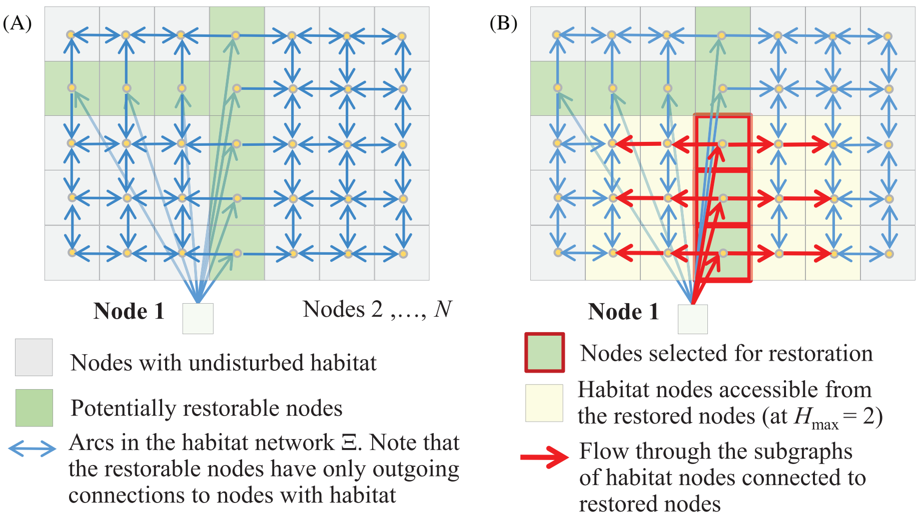

Figure 2. (A) Schematic depiction of habitat connectivity network Ξ. Blue arrows show arcs connecting nodes that are elements of network Ξ. Green cells show nodes with seismic lines (and abandoned well pads) that are potential candidates for restoration and gray cells show nodes with undisturbed habitat. (B) Nodes selected for restoration are outlined in red. Red arrows show the flow from nodes with restored seismic lines (and well pads) to habitat nodes in network Ξ within the chosen distance $H_{\max}$ (two nodes in this example). The flow from the restored nodes to the connected habitat nodes enables tracking of access to habitat at $H_{\max}$ nodes deep.

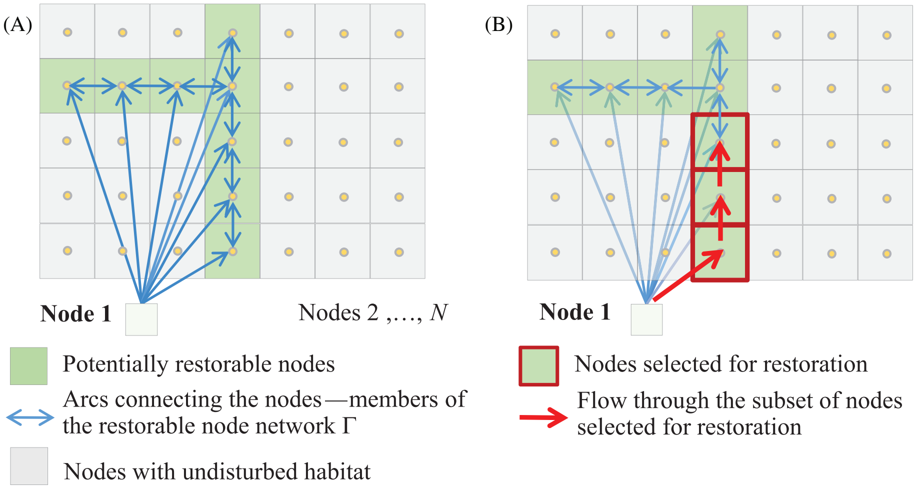

Figure 3. (A) Schematic depiction of potentially restorable node network Γ. Blue arrows show arcs connecting nodes that are elements of seismic line network Γ. Green cells show nodes with seismic lines (and abandoned well pads) that are potential candidates for restoration. (B) Red outlines show nodes selected for restoration. The flow within the restorable node network Γ (red arrows) ensures that the restored area is spatially contiguous.

nm. The h_n value must be passed only to nodes connected to n; therefore, we tracked the product of arc selection between the connected nodes n and m, w_{nm}, and the adjustment factor u_{nm} for that arc, using a non-negative decision variable z_{nm} ($z_{nm} = u_{nm}$ when $w_{nm} = 1$ and $z_{nm} = 0$ otherwise).

We also needed to ensure the spatial contiguity of restored node sets. We defined a network of potentially restorable nodes Γ that included all nodes with seismic lines and abandoned well pads as potential candidates for restoration. These nodes were also members of the access network Ω and the habitat network Ξ. All adjacent nodes in network Γ were connected by bi-directional arcs (Fig. 3A). Our third sub-problem ensured the selection of nodes to be restored in as few connected subgraphs as possible. We introduced an auxiliary node 1 as a source of the flow to the subsets of potentially restorable nodes. Node 1 is connected to every candidate node n in set Γ (Fig. 3A). When a node is restored, it can receive flow from node 1 (or from an adjacent restored node) and pass it to an adjacent restored node, which then passes the flow to another restored node and so on (Fig. 3B). All nodes selected for restoration must receive the flow directly or indirectly from node 1. This ensures the spatial contiguity of the restored node set. A non-negative decision variable, q_{nm}, defines the amount of flow via arc nm between nodes n and m in the network of restorable nodes Γ and a binary decision variable, p_{nm}, selects arc nm to transmit this flow, so that $w_{nm} = 1$ when $v_{nm} > 0$ and $w_{nm} = 0$ when $v_{nm} = 0$.

The number of direct connections from node 1 to restored nodes defines the maximum number of distinct contiguous clusters of restored nodes in landscape N. For example, allowing one direct connection from node 1 creates a single contiguous cluster of restored nodes (Fig. 3B). An upper bound, $V_{\max}$, sets the target number of connections from node 1 to the restored nodes in set Γ.

Problem Formulation

Using the defined sub-problems (1)–(3), we formulated the restoration problem as follows:

$$\max \sum_{n=2,\{1\}}^{N} \sum_{m=2,\{1\}}^{N} (z_{mn} b_n) - Vf \tag{1}$$

s.t.

$$\sum_{n=2,\{0\}}^{N} \left[c_n \left(1 - \sum_{m=2,\{0\}}^{N} x_{mn} \right) \right] \le B \tag{2}$$

$$\Omega_{x_{nm}=1} \text{ connected to entry nodes} \tag{3}$$

$$\sum_{m=2,\{0\}}^{N} x_{mn} \ge R_n \quad \forall n = 2, \ldots, N \tag{4}$$

$$\Gamma_{p_{nm}=1} \text{ connected} \tag{5}$$

$$V \ge \sum_{n=2}^{N} p_{1n} - V_{\max} \tag{6}$$

$$\sum_{m=2,\{1\}}^{N} p_{mn} + \sum_{k=2,\{0\}}^{N} x_{kn} = 1 \quad \forall n = 2, \ldots, N \tag{7}$$

$$\Xi_{w_{nm}=1} \text{ connected to restored nodes} \tag{8}$$

$$v_{nm} \le H_{\max} w_{nm} \quad \forall n = \{1\}, 2, \ldots, N,\ m = \{1\}, 2, \ldots, N \tag{9}$$

$$w_{nm} \le 1 - R_n \quad \forall n = 2, \ldots, N,\ m = 2, \ldots, N \mid R_n = 1 \tag{10}$$

$$\sum_{m=2,\{1\}}^{N} v_{mn} \le \left(1 - \sum_{m=2,\{0\}}^{N} x_{mn} \right) U \quad \forall n = 2, \ldots, N \mid \varphi_n = 1 \tag{11}$$

$$w_{nm} + \sum_{k=2,\{0\}}^{N} x_{kn} \le 1 \quad \forall n = \{1\}, 2, \ldots, N,\ m = \{1\}, 2, \ldots, N \tag{12}$$

$$u_{nm} = h_n w_{nm} \quad \forall n = 2, \ldots, N,\ m = 2, \ldots, N \mid (A_n = 1 \text{ and } A_m = 0) \tag{13}$$

$$u_{nm} = \sum_{k=2}^{N} z_{kn} \quad \forall n = 2, \ldots, N,\ m = 2, \ldots, N \mid (A_n = 0 \text{ and } A_m = 0) \tag{14}$$

$$0 \le u_{nm} \le 1 \quad \forall n = 2, \ldots, N,\ m = 2, \ldots, N \tag{15}$$

$$z_{nm} = u_{nm} w_{nm} \quad \forall n = 2, \ldots, N,\ m = 2, \ldots, N \tag{16}$$

Objective (1) maximizes the amount of undisturbed habitat that is accessible through the restored nodes minus a penalty, V, which defines the number of distinct contiguous clusters of the restored nodes above the target $V_{\max}$ (see constraint (6)). Constraint (2) defines the project budget limit. Parameter c_n denotes the cost to restore seismic lines and abandoned well pads in node n. Equation (3) defines a group of constraints that enforce connectivity between the unrestored nodes in access network Ω and one of the nodes containing a road entry point (Fig. 1A) (see description of (3) in Supplement S2 Equations (S3.1)–(S3.5)). Constraint (4) specifies that nodes with roads, pipelines, and active wells cannot be restored and always remain members of access network Ω. A binary parameter R_n identifies these non-restorable nodes ($R_n = 1$ and $R_n = 0$ otherwise).

Equation (5) defines a group of constraints that guarantee the spatial contiguity of the subsets of restored nodes in network Γ and aim to prevent the selection of individual restored nodes scattered across the landscape (see description of (5) in Supplement S2 Equations (S5.1)–(S5.5)). Together, constraints (5)–(7) control the maximum number of distinct contiguous clusters of restored nodes in landscape N. Constraint (6) defines the non-negative penalty variable V based on the number of direct connections from an auxiliary node 1 (the source of the flow) to restored nodes above the target value $V_{\max}$. According to (6), the objective function (1) is penalized when more than $V_{\max}$ connections to node 1 (and the corresponding contiguous

Table 1. Summary of the model parameters and decision variables. Symbol definitions apply to both the brief problem formulations (1)–(16) and the full formulation in Supplement S2.

Symbol	*Parameter/Variable Name*	*Description*
Sets		
N	Nodes (forest patches) n, m in a landscape N	$n, m \in N$
Ω	Access network—includes nodes with seismic lines, roads, oil-and-gas wells, and an auxiliary node 0	
Γ	Restorable network—includes nodes that are potentially restorable and an auxiliary node 1	
Ξ	Habitat network—includes potentially restorable nodes, nodes with existing suitable habitat and an auxiliary node 1	
Decision variables		
x_{nm}	Binary flow indicator between nodes n and m in the access network Ω	$x_{nm} \in \{0, 1\}$
y_{nm}	Flow through an arc nm between the selected adjacent nodes n and m in the access network Ω	$y_{nm} \ge 0$
w_{nm}	Binary flow indicator between nodes n and m in the habitat network Ξ	$w_{nm} \in \{0, 1\}$
v_{nm}	Flow through an arc nm between the selected adjacent nodes n and m in the habitat network Ξ	$v_{nm} \ge 0$
p_{nm}	Binary flow indicator between nodes n and m in the restorable nodes network Γ	$p_{nm} \in \{0, 1\}$
q_{nm}	Flow through an arc nm between the selected adjacent nodes n and m in the restorable nodes network Γ	$q_{nm} \ge 0$
u_{nm}	Adjustment factor for the amount of habitat that can be accessed after restoring a node n that is passed to a connected habitat node m	$u_{nm} \in [0, 1]$
z_{nm}	Product of binary arc selection variable w_{nm} and variable u_{nm} with the habitat adjustment factor	$z_{nm} \in \{0, 1\}$
V	Penalty for the number of connections from an auxiliary node 1 to the restored nodes in network Γ above the desired threshold $V_{\max}$ (defines the maximum number of spatially contiguous sets of restored nodes in area N above $V_{\max}$)	$V \ge 0$
Parameters		
b_n	Suitable habitat amount in node n	$b_n \ge 0$
h_n	Factor that adjusts the habitat amount in node n when the seismic line length l_n in n is less than the linear node size $l_{\min}$: $h_n = l_n/l_{\min}$ for $l_n < l_{\min}$ and $h_n = 1$ for $l_n \ge l_{\min}$	$h_n \in [0, 1]$
c_n	Cost to restore all seismic lines and abandoned wellpads in node n	$c_n \ge 0$
B	Restoration budget limit	$B > 0$
$H_{\max}$	Maximum number of nodes with suitable habitat that can be accessed from a restored node via arcs extending in each cardinal direction where the adjacent node contains habitat	$H_{\max} \ge 0$
R_n	Binary parameter indicating the non-restorable nodes in the access network Ω with roads, pipelines, active wells or that provide critical access to other non-restorable nodes ($R_n = 1$ and $R_n = 0$ otherwise)	$R_n \in \{0, 1\}$
A_n	Binary parameter indicating potentially restorable nodes in the access network Ω ($A_n = 1$ and $A_n = 0$ otherwise)	$A_n \in \{0, 1\}$
φ_n	Binary parameter indicating potentially restorable nodes in the habitat network Ξ, which may receive flow from auxiliary node 1	$\varphi_n \in \{0, 1\}$
$V_{\max}$	Maximum number of nodes that can be connected to an auxiliary node 1 in the restorable nodes network Γ; defines the maximum number of spatially contiguous subsets of restored nodes in landscape N	1–10
l_n	Total seismic line length in node n	$l_n \ge 0$
$l_{\min}$	Linear size of node n	500 m
f	Scaling factor for penalty V in the objective function equation (1)	$f \ge 0$

restored node clusters) are created. This penalty formulation permits an increased number of distinct restored node clusters to cover multiple areas when existing roads and pipelines prevent the creation of a single cluster. Constraint (7) ensures that a node n containing seismic lines can either be in the pool of restored or unrestored nodes but not in both.

Our last sub-problem estimated the amount of habitat that is accessible through the restored nodes. Equations (8) and (9) control the spatial contiguity of the subgraphs of habitat nodes connected to restored nodes in habitat network Ξ (see description of (8) in Supplement S2 Equations (S8.1)–(S8.4)). Constraint (9) also limits the maximum amount of flow through an arc nm by $H_{\max}$. Constraint (10) ensures that connections to nodes with suitable habitat cannot be established from nodes with roads or other features requiring human access. Constraint (10) is only applied to non-restorable nodes with $R_n = 1$. Constraint (11) ensures that flow from node 1 to node n, a potential candidate for restoration and a member of network Ξ, can

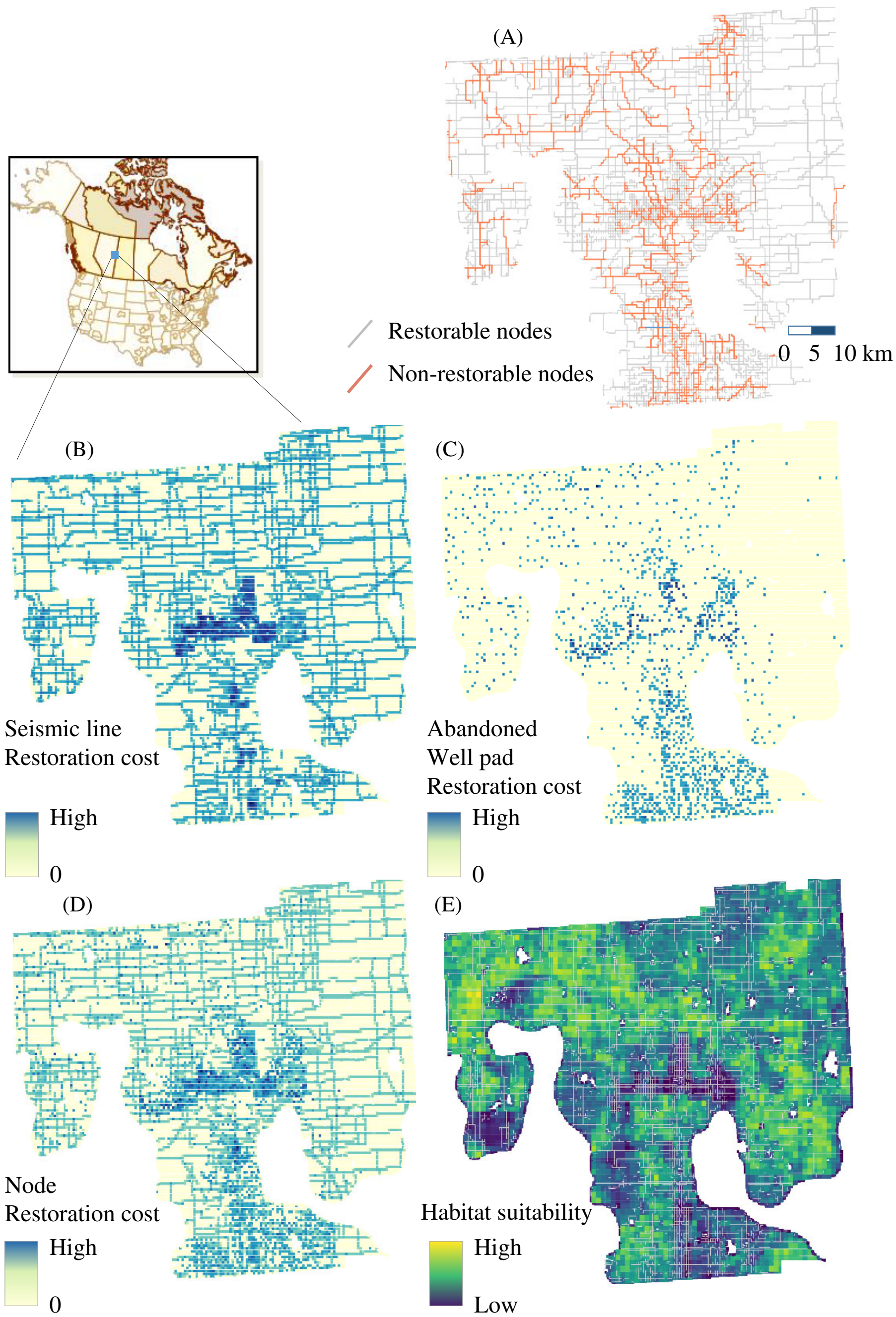

Figure 4. Model spatial inputs: (A) network of non-restorable nodes (containing roads, pipelines, and seismic lines used to access sites with non-restorable wells, in red) and nodes that are candidates for restoration (in light gray); (B) node cost for seismic line restoration; (C) node cost for abandoned well pad restoration; (D) node total restoration cost; (E) a node-based caribou habitat suitability metric.

only occur if that node is restored. A binary parameter φ_n defines the candidate nodes n in network Ξ that may receive flow from node 1 ($\varphi_n = 1$ and $\varphi_n = 0$ otherwise); constraint (11) is only applied to nodes with $\varphi_n = 1$. Constraint (12) specifies that only restored nodes n can be connected to adjacent nodes m with suitable habitat.

Constraint (13) assigns the habitat adjustment factor h_n to arc nm via auxiliary variable u_{nm}, which connects a potentially restorable node n in the access network Ω with habitat node m outside of Ω (i.e. with $A_m = 0$). A binary parameter A_n defines these restorable nodes containing seismic lines and/or abandoned well pads ($A_n = 1$ and $A_n = 0$ otherwise). Constraint (13) ensures that the adjustment factor h_n is passed to all habitat nodes m connected to n. Constraint (14) passes the habitat adjustment factor between the connected habitat nodes n and m, which are located outside of the access network Ω (so $A_n = A_m = 0$). According to (14), the adjustment factor from a restored node k, which is connected to habitat node n (i.e. with arc selection $w_{kn} = 1$), is passed to n via a non-negative decision variable z_{kn}. The z_{kn} value is then passed from node n to node m in the habitat network Ξ via a non-negative decision variable u_{nm}. When nodes n and m are connected, the variable z_{nm}, as a product of variables u_{nm} and w_{nm}, takes the value stored in u_{nm} and passes it to node m. Together, constraints (13) and (14) ensure that the adjustment factor h_n is passed from a restored node n to all habitat nodes connected to n. For each habitat node n, the total amount of suitable habitat is the habitat amount in n, b_n, times the adjustment factor that is passed to n via connecting arcs kn, $\sum_{k=2}^{N} z_{kn}$. Constraint (15) defines the range of auxiliary decision variable u_{mn} and constraint (16) defines the variable z_{nm} as a product of the binary arc selection variable w_{nm} and the non-negative adjustment factor variable u_{nm} (see linearization of (16) in Supplement S2 Equations (S16.1)–(S16.3)). Supplement S2 provides the full problem formulation with expanded definitions of constraints (3), (5), (8), and (16). Table 1 lists the model parameters and variables.

Case Study

We applied the model to explore restoration strategies in the CLFN area in northeastern Alberta (Fig. 4). The CLFN is part of the Cold Lake Caribou Range. The area contains major oil and gas deposits and is fragmented by a dense network of seismic lines (Fig. 4A). Restoration of seismic lines and abandoned well pads has been proposed as a management tool to help prevent further caribou decline (GOA 2017), with a few pilot projects begun in the last decade (Pyper et al. 2014; Tattersall et al. 2020; Dickie et al. 2021).

The spatial data provided by CLFN documented the locations of roads, pipelines, seismic lines, and wells, along with the operational status of the latter: active, abandoned, suspended, leased, or canceled (see full-data description in Supplement S3). We divided the area into a grid of 500 × 500-m nodes. For each node, we estimated the total length of seismic lines and the number of abandoned well pads from the CLFN spatial data. We used these data to estimate the restoration cost values c_n for each node (Fig. 4B & 4D) (see Supplement S3). The seismic line

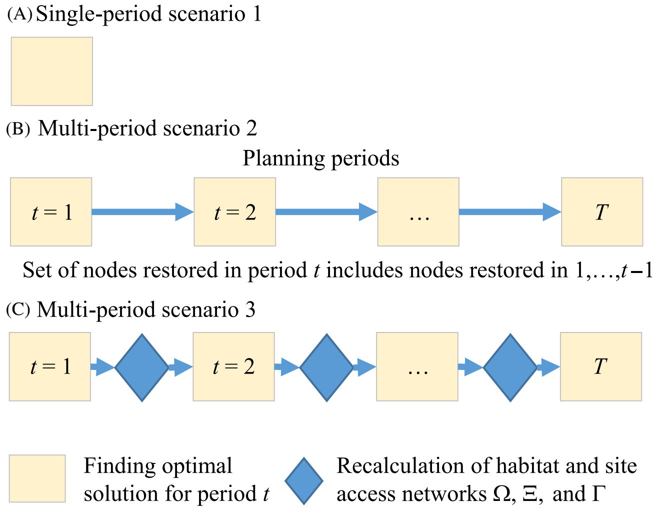

Figure 5. Schematic depiction of scenarios 1–3: (A) single time step scenario 1 (finds an optimal restoration solution for a once-off effort); (B) multi-period scenario 2 without recalculation of networks Ω, Ξ, and Γ after each restoration step. At each period t, the model adds newly restored nodes for that period but also forces the selection of all nodes restored previously in periods 1, …, $t-1$; (C) multi-period scenario 3 with recalculation of networks Ω, Ξ, and Γ after each period. At each period t, the model sees nodes that were restored previously in periods 1, …, $t-1$ as habitat.

restoration unit cost was set to Cdn \$10k km^{-1}, which is within the range of cost estimates for recent pilot restoration projects (Pyper et al. 2014). The average well pad restoration unit cost was estimated at Cdn \$17,622 based on the cost range reported by the Alberta Oil and Gas Orphan Abandonment and Reclamation Association over 2015–2017 (OWA 2015, 2016, 2017). We assumed that only well pads with abandoned status would require restoration. No restoration was allowed for seismic lines used to access roads, pipelines or non-restorable well pads with leased, suspended or active status (Fig. 4A).

We estimated the amounts of suitable habitat, b_n, for each node using the methodology of Whitman et al. (2017) and Barber et al. (2018) (Fig. 4E, see Supplements S1 & S3). Recent assessments for caribou indicated that the animals avoid using undisturbed habitat by at least 500 m from a disturbed site (EC 2012; GoA 2017). Therefore, we set the access distance value $H_{\max}$ to at least one 500 × 500-m node with undisturbed habitat adjacent to a node with seismic lines but also tested scenarios with access distances $H_{\max} = 2$ (1 km) and 3 (1.5 km) nodes (Supplement S3).

Exploring the Restoration Strategies

Our single-period scenario 1 allocated the restoration budget in one planning step (Fig. 5A). We explored a multi-period scenario 2, which allocated the budget over consecutive periods, starting with spending \$2M in the first period, \$3M in the second period, and \$5M in each consecutive period until the entire budget was spent (Fig. 5B). We modeled scenario 2 as a sequence of single-period solutions. In this scenario, the set of restored nodes the current period included locations of all nodes restored in previous periods plus nodes scheduled for immediate restoration. In an alternative multiple-period scenario 3, which resembled scenario 2, all nodes restored in previous periods were converted to suitable habitat in the subsequent period (Fig. 5C). For a given period, the model saw all previously restored nodes as habitat. We also implemented a scenario without spatial contiguity constraints (Fig. 6, dotted lines). While these solutions are impractical because the restored nodes are scattered across the landscape (Fig. 6D), they provide a good frame of reference for assessing the impact of spatial contiguity constraints on model performance.

Results

We first evaluated the optimal restoration solutions without the spatial contiguity constraints (5)–(7) for the clusters of restored nodes. The amount of habitat accessible from the restored nodes as a function of the budget level is shown in Figure 6. As the budget level increased, restoration became less cost-effective as it expanded to areas of the landscape with higher seismic line densities. Adding the contiguity constraints (5)–(7) reduced the amount of habitat accessible from the restored nodes (Fig. 6). The reduction is significant, especially at small budget levels (Table 2). Keeping restoration in contiguous clusters forces the inclusion of nodes with high densities of abandoned well pads and seismic lines. This increases the unit cost of restoration for the same budget level.

Single-Period Versus Multi-Period Solutions

We compared the maps of single-period and multi-period restoration solutions for the habitat access distances, $H_{max} = 1$ (500 m), 2 (1 km), and 3 (1.5 km). Both single- and multi-period solutions selected similar broad regions for restoration in the eastern portion of the CLFN area with the lowest seismic line density (Fig. 7, Supplement S4). However, as the budget level increased, permanent disturbances forced the model to allocate restoration in disjoint clusters (Fig. 7, Supplement S4). For example, the median number of restored node clusters was two in \$2M-budget solutions, six in \$10M and 14 clusters in \$20M-budget solutions (Table 2). The number of distinct clusters increased sharply when the budget approached \$20M.

The maps of optimal solutions for the single-period scenario 1 and multiple-period scenario 2 did not show major differences and the numbers of distinct restored node clusters were similar (Table 2). By comparison, the scenario 3 solutions allocated fewer clusters at large budget levels than the scenarios 1 and 2 solutions (Table 2). This is because the selection of nodes to restore in the next period in scenario 3 was not influenced by the restoration selections in the previous period (like in scenario 2). This allowed selecting larger contiguous areas for restoration than in scenario 2.

A comparison of the scenarios with different H_{max} targets (Fig. 7, Supplement S4) revealed relatively minor differences between the patterns of restored nodes under each scenario. In all scenarios, the selection of nodes for restoration prioritized hotspots with undisturbed habitat (Fig. 4B). Among the three groups of H_{max} scenarios, the scenario with $H_{max} = 3$ (which tracked the farthest potentially accessible habitat) was the most distinct. The impact of increasing H_{max} would be more significant if the area had larger regions of undisturbed habitat.

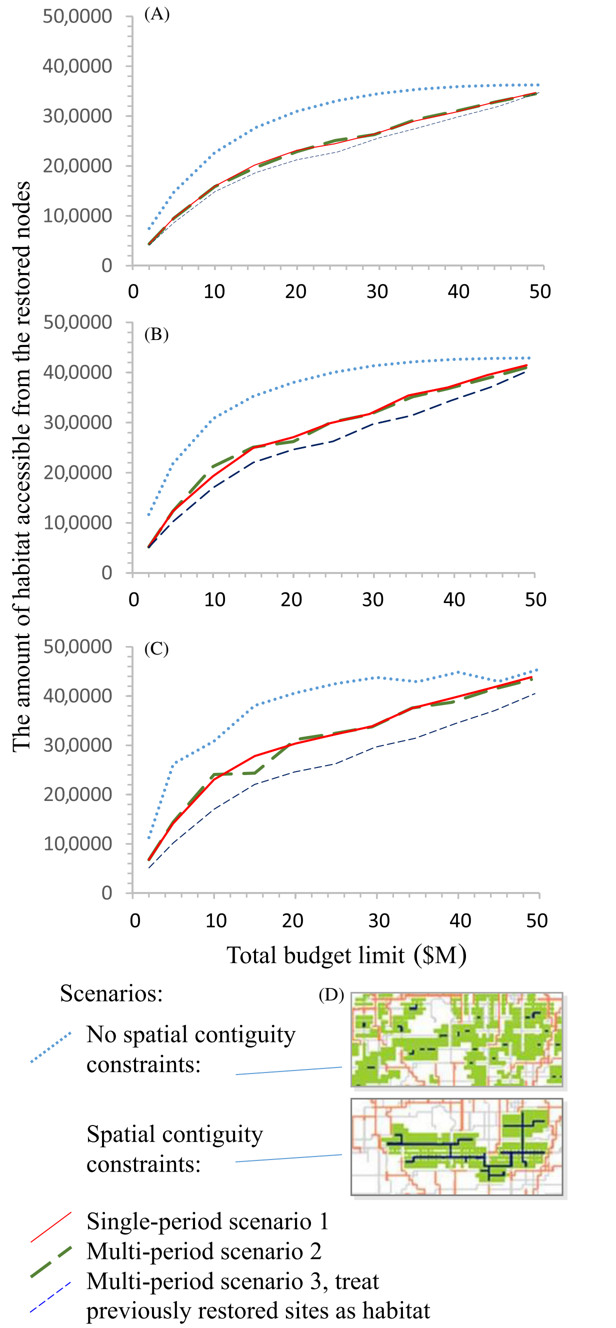

Figure 6. Habitat amount accessible from the restored nodes within H_{max} distance versus total budget spent on restoration. The scenarios: (A) $H_{max} = 1$ (tracking accessible habitat within 500 m of the restored nodes); (B) $H_{max} = 2$ (tracking accessible habitat within 1 km of the restored nodes); (C) $H_{max} = 3$ (tracking accessible habitat within 1.5 km of the restored nodes); (D) close-up with examples of restored node patterns with and without spatial contiguity constraints. Without contiguity constraints, the restored nodes can be scattered across the area. Adding the constraints allocates the restored nodes in spatially contiguous clusters.

Table 2. Area-based summaries of the amounts of habitat, restored node proportions, and the proportions of budget spent on restoration of abandoned well pads. The scenario descriptions are shown in Figure 5. Single-period scenarios report optimal solutions for once-off restoration efforts. In multi-period scenario 2, the model finds new restoration site locations in each period t, but is also forced to include the restoration locations selected previously in periods 1, …, $t-1$. In multi-period scenario 3, the model allocates restored locations for period t only and sees locations restored previously in periods 1, …, $t-1$ as habitat.

Total Budget Limit ($)	*Habitat Amount Accessible from the Restored Sites,* $\sum_{n=2,\{1\}}^{N}\sum_{m=2,\{1\}}^{N}(z_{mn}b_n)$	*Percentage of Total Habitat Amount Accessible from the Restored Sites*	*Percentage of 500 × 500 m Sites with Seismic Lines and Well Pads Restored*	*Number of Contiguous Sets of Restored Sites,* $V+V_{max}$, ($V_{max}=1$)	*Percentage of Total Budget Spent on Restoration of Abandoned Well Pads*	*Percentage of the Habitat Amount Accessible from the Restored Sites vs. the Habitat Amount Accessible in the Solutions with no Contiguity Constraints*
$H_{max}=1$, singe-period scenario 1						
2M	42,222.5	7.5	4.4	2	2.6	34.2
5M	92,488.0	16.4	10.8	3	2.8	32.2
10M	154,817.5	27.4	20.0	6	7.9	28.6
20M	223,517.1	39.6	32.6	14	21.9	25.4
$H_{max}=1$, multi-period scenario 2						
2M	42,222.5	7.5	4.4	2	2.6	41.4
5M	93,103.6	16.5	10.8	3	2.8	35.0
10M	155,412.0	27.6	19.9	5	8.6	29.7
20M	226,449.4	40.1	33.6	16	20.4	25.2
$H_{max}=1$, multi-period scenario 3, treating previously restored sites as habitat						
2M	40,791.6	7.2	4.4	1	0.9	36.5
5M	86,058.3	15.3	10.5	3	3.2	36.9
10M	148,794.6	26.4	19.0	6	11.5	31.4
20M	212,503.3	37.7	31.7	7	23.1	29.1
$H_{max}=2$, singe-period scenario 1						
2M	50,727.4	9.0	4.4	1	0.9	51.0
5M	120,558.4	21.4	10.4	2	5.6	59.5
10M	209,127.9	37.1	20.2	10	7.4	70.2
20M	258,725.4	45.9	32.5	13	22.5	69.7
$H_{max}=2$, multi-period scenario 2						
2M	50,727.4	9.0	4.4	1	0.9	51.0
5M	120,558.4	21.4	10.4	2	5.6	59.5
10M	190,704.2	33.8	19.9	5	8.6	64.0
20M	266,756.6	47.3	32.1	12	23.5	71.9
$H_{max}=2$, multi-period scenario 3, treating previously restored sites as habitat						
2M	51,287.2	9.1	4.5	2	0.9	48.4
5M	102,190.6	18.1	10.6	2	5.3	49.5
10M	170,285.2	30.2	19.9	4	7.9	42.9
20M	246,016.7	43.6	32.5	7	22.7	33.7
$H_{max}=3$, single-period scenario 1						
2M	66,880.9	11.9	4.4	2	2.6	66.6
5M	143,083.2	25.4	10.6	3	3.9	57.6
10M	238,679.2	42.3	20.0	11	8.5	79.9
20M	309,611.0	54.9	34.5	21	18.4	77.3
$H_{max}=3$, multi-period scenario 2						
2M	66,880.9	11.9	4.4	2	2.6	33.4
5M	139,889.1	24.8	10.1	6	7.8	43.7
10M	228,796.0	40.6	19.8	9	9.2	23.4
20M	301,256.9	53.4	34.0	20	19.5	24.8
$H_{max}=3$, multi-period scenario 3, treating previously restored sites as habitat						
2M	57,240.6	10.1	4.3	2	1.8	43.0
5M	114,267.6	20.3	10.0	4	8.1	54.0
10M	182,502.3	32.4	19.4	6	9.0	38.9
20M	242,767.7	43.0	31.7	7	23.0	39.4

Restoration of Abandoned Well Pads Versus Seismic Lines

The budget level influenced the proportions of funds allocated to restoration of seismic lines and abandoned well pads. Theoretical solutions without spatial contiguity constraints (5)–(7) (Fig. 8, dotted line) allocated a smaller portion of the budget to restoring well pads than the solutions that included the constraints (Fig. 8, dashed and solid lines). In small-budget solutions, almost the entire budget was allocated to seismic line restoration (Fig. 8, the curve portions for budget levels below $10M). Well pads are essentially point

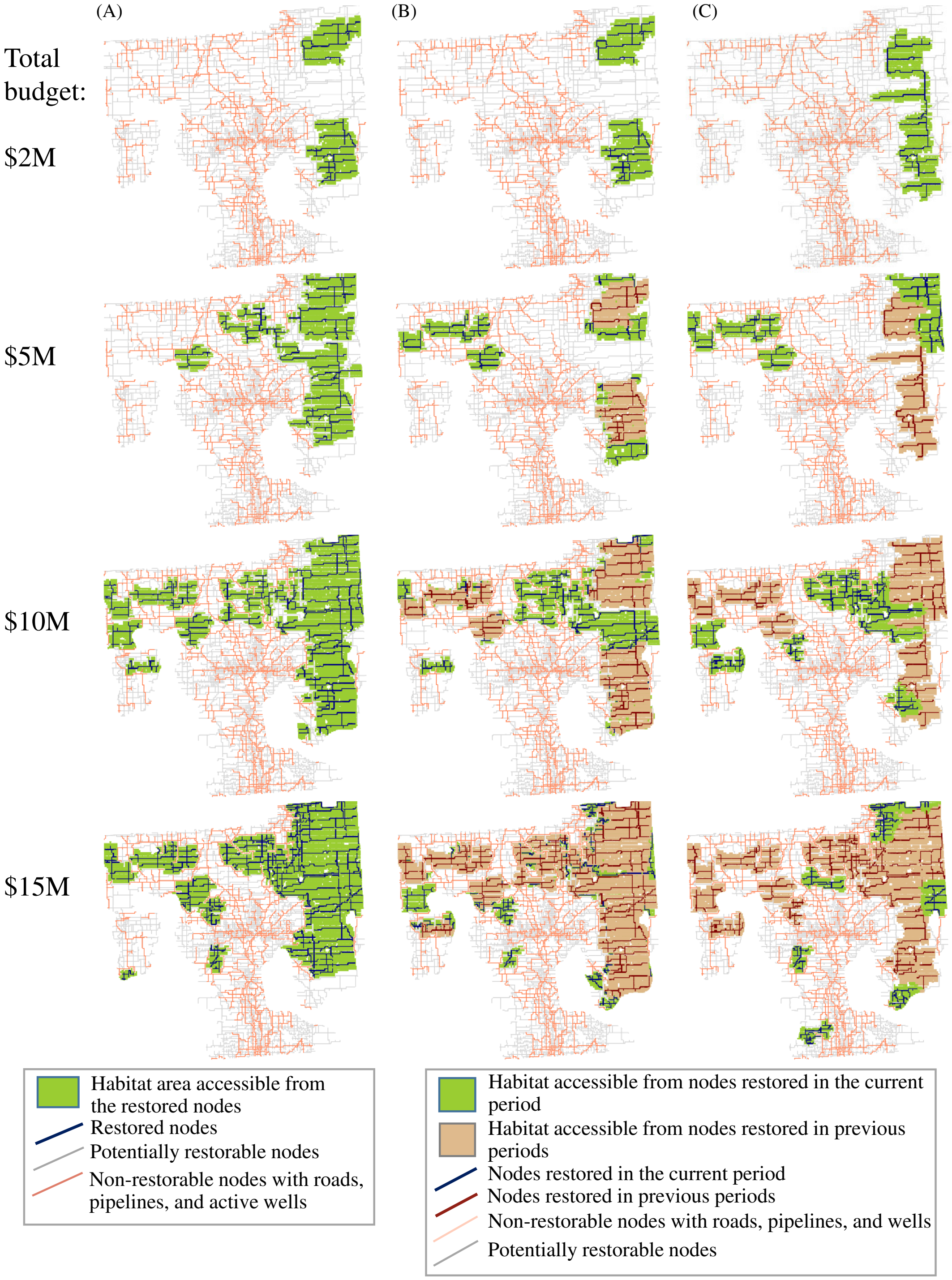

Figure 7. Maps of optimal restoration solutions for scenarios 1–3 (see Fig. 7 for map description). Scenarios with the habitat access distance $H_{max} = 3$ (tracking accessible habitat within 1.5 km of the restored nodes) are shown: (A) single-period scenario 1 for the solution of a once-off restoration effort; (B) multi-period scenario 2 without recalculating the habitat network. At each period t, the model adds newly restored nodes for that period but also forces the selection of all nodes restored previously in periods 1, …, $t-1$; (C) multi-period scenario 3, treating previously restored sites as habitat. At each period t, the model sees nodes that were restored previously in periods 1, …, $t-1$ as habitat.

features; restoring a well pad costs more than restoring an equivalent seismic line area but enables access to less habitat. Thus, the optimal strategy at small budget levels is to minimize the budget portion spent on restoring abandoned well pads (except when the well pads are functionally isolated by seismic line restoration) and prioritize restoration of seismic lines.

In addition, the need to allocate restoration activities in spatially contiguous clusters increased the budget proportion spent on well

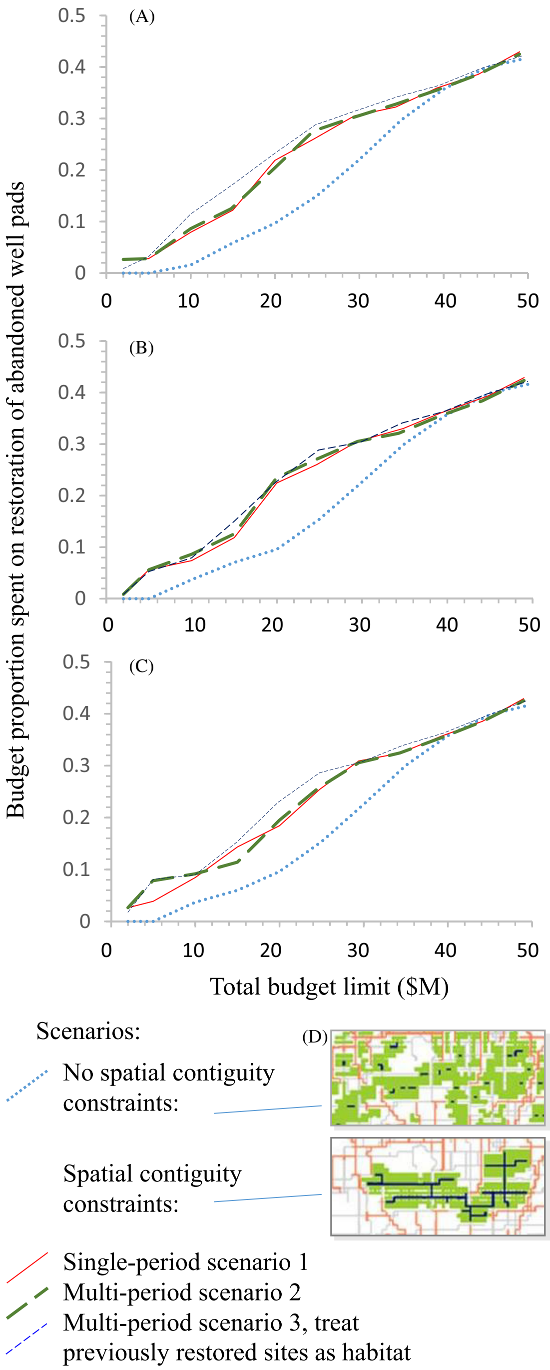

Figure 8. Budget portion spent on restoring abandoned well pads versus total budget level. The scenarios: (A) $H_{max} = 1$ (tracking accessible habitat within 500 m of the restored nodes); (B) $H_{max} = 2$ (tracking accessible habitat within 1 km of the restored nodes); (C) $H_{max} = 3$ (tracking accessible habitat within 1.5 km of the restored nodes); (D) close-ups with examples of restored node patterns with and without spatial contiguity constraints. Without contiguity constraints, the restored nodes can be scattered across the area. Adding the constraints allocates the restored nodes in spatially contiguous clusters.

pad restoration. To keep the restored sites in as few clusters as possible, some sites with high densities of abandoned well pads must be selected. This explains the lower objective value in the solutions with spatial contiguity constraints (Fig. 6) compared to the solutions without contiguity constraints (Fig. 8).

The portion of the budget spent on well pad restoration increases with the budget level (Fig. 8). In large-budget scenarios, restoration activities move into areas with high well densities and so the unit cost increase becomes inevitable. Nevertheless, the optimal strategy to maximize the amount of habitat accessible from the restored sites is to minimize the budget portion spent on restoration of well pads where possible.

Discussion

Our optimization-based approach addresses several important aspects of practical habitat restoration in areas of resource extraction. First, our approach followed a common practice of undertaking restoration activities in spatially contiguous clusters (Pyper et al. 2014; Cenovus 2016). Second, our solutions guaranteed that non-restorable features will remain accessible after restoration. This is useful because a high degree of landscape fragmentation, as in the CLFN area, makes it difficult to plan restoration while managing access to the pockets of unrestored sites. Third, our model emphasized *local* access to habitat from the restored sites according to the access depth defined by the parameter H_{max}. The local access concept in our model is appropriate for tracking the capacity of caribou to utilize restored seismic lines. One of the goals of seismic line restoration is to reduce exposure to predation when caribou are close to disturbed sites (Whittington et al. 2011; McKenzie et al. 2012; Dickie et al. 2020; McKay et al. 2021). In our model, this required tracking the amount of undisturbed caribou habitat close to a restored node. Note that the network of seismic lines in the CLFN area was so dense that almost all habitat was accessible within 1.5 km of the nearest seismic line.

Our model is designed to allocate as few contiguous clusters of restored nodes as possible, which leads to creation of large areas of suitable caribou habitat. Potentially, the distance threshold H_{max} could be used to control the depth of undisturbed habitat accessible from a restored site, enabling prioritization of sites for restoration that provide the most access to core habitat at a distance deemed appropriate by a decision-maker.

Optimal Restoration Solutions Versus Previous Prioritization Efforts

In small-budget solutions, our case study prioritized the northeastern portion of the CLFN area for restoration, which generally agrees with the seismic line treatment locations identified by the recently completed Linear Deactivation (LiDea) project in the Cold Lake Caribou Range (Cenovus 2016; Dickie et al. 2021). When the spatial information collected in practical restoration efforts, such as the LiDea project, becomes available, the new data could be utilized in our model scenarios to find the restoration solutions, which should reduce the cost and better address the logistical limitations.

At a broad scale, our results also agree, in general, with coarse-scale restoration priority rankings developed by the Alberta Biodiversity Monitoring Institute (ABMI 2017, 2020). Both approaches prioritized restoration for the northeastern portion of CLFN. Differences between the prioritizations can be explained by differing methods and objectives. For example, the ABMI prioritizations used an economic valuation criterion based on recoverable oil and gas resources (ABMI 2017, 2020), which we omitted from our objective function. The ABMI ranking solved a partial ordering problem for all elements in a landscape, whereas our model found a combinatorial solution for a subset of locations limited by a defined budget. Furthermore, our methodology incorporated project-level logistics associated with tactical planning (such as maintaining access to unrestored sites). Such considerations are not the focus of strategic prioritizations, which establish broad-scale priority ranks for all sites without considering the budget or logistical constraints. Nevertheless, strategic and project-level prioritizations complement each other because they operate at different decision-making scales (i.e. strategic vs. tactical planning) that are both relevant for large-scope restoration initiatives.

Potentially, our model could take advantage of previous coarser-scale prioritizations. The restoration priority ranks from the ABMI prioritization could be incorporated as an additional term in the objective function. This feedback would guide the model to generally follow the coarse-scale selections suggested by the ABMI effort, whereas the other model components would address the logistical trade-offs. Combining models in this manner could allow decision-makers to make more informed decisions about restoration planning in working landscapes.

Potential Model Extensions

Currently, our model does not allow the presence of unrestored features inside the restored node clusters and avoids non-restorable features to prevent the creation of these isolated segments. Potentially, roads and pipelines could be permitted in restored clusters at a steep penalty, so the model would only select this option if no other alternative allocations were available. It is also possible to use spatially variable cost and restoration success parameters to reflect the costs associated with different ecological conditions when such data become available.

Accounting for the temporal variation of habitat quality and resource extraction activities could be an area of model improvement. Some currently active oil and gas wells may be decommissioned in the future and will require restoration. The current model can be applied sequentially over multiple periods. In each planning period, the habitat suitability map and the network of non-restorable sites could be adjusted to account for temporal changes in habitat suitability and resource extraction locations.

Our model formulation ensured the contiguity of clusters of restored nodes but did not control the shape of the habitat regions around these clusters. Potentially, the formulation could be modified to control the compactness of habitat regions around restored node clusters by minimizing the ratio between the perimeter of a habitat region and its area. This could be a focus of future work.

Acknowledgments

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Supporting Information

The following information may be found in the online version of this article:

Supplement S1. Map of suitable caribou habitat for the cold lake first nations area.

Supplement S2. Full problem formulation.

Supplement S3. Case study data for model scenarios.

Supplement S4. Maps of optimal restoration solutions for scenarios with $H_{\max} = 1$ and $H_{\max} = 2$.

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