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Research article

Restoration of linear disturbances from oil-and-gas exploration in boreal landscapes: How can network models help?

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ABSTRACT

In western Canada, decades of oil-and-gas exploration have fragmented boreal landscapes with a dense network of linear forest disturbances (seismic lines). These seismic lines are implicated in the decline in wildlife populations that are adapted to function in unfragmented forest landscapes. In particular, anthropogenic disturbances have led to a decline of woodland caribou populations due to increasing predator access to core caribou habitat. Restoration of seismic lines aims to reduce the landscape fragmentation and stop the decline of caribou populations. However, planning restoration in complex landscapes can be challenging because it must account for a multitude of diverse aspects.

To assist with restoration planning, we present a spatial network optimization approach that selects restoration locations in a fragmented landscape while addressing key environmental and logistical constraints. We applied the model to develop restoration scenarios in the Redrock-Prairie Creek caribou range in northwestern Alberta, Canada, which includes a combination of caribou habitat and active oil-and-gas and timber extraction areas.

Our study applies network optimization at two distinct scales to address both the broad-scale restoration policy planning and project-level constraints at the level of individual forest sites. We first delineated a contiguous set of coarse-scale regions where restoration is most cost-effective and used this solution to solve a fine-scale network optimization model that addresses environmental and logistical planning constraints at the level of forest patches. Our two-tiered approach helps address the challenges of fine-scale spatial optimization of restoration activities. An additional coarse-scale optimization step finds a feasible starting solution for the fine-scale restoration problem, which serves to reduce the time to find an optimal solution. The added coarse-scale spatial constraints also make the fine-scale restoration solution align with the coarse-scale landscape features, which helps address the broad-scale restoration policies. The approach is generalizable and applicable to assist restoration planning in other regions fragmented by oil-and-gas activities.

1. Introduction

Decades of oil-and gas exploration and extraction in boreal landscapes of western Canada have created a vast network of linear forest disturbances (i.e., seismic lines and roads), which have been implicated in declines of some wildlife populations that were adapted to survive in less fragmented forest (Pattison et al., 2016). In particular, linear disturbances have negatively impacted woodland caribou (*Rangifer tarandus caribou*) (Vors and Boyce, 2009; Hervieux et al., 2013) by allowing predators to travel farther into caribou habitat and increasing their chance to encounter the animals (Whittington et al., 2011; McKenzie et al., 2012; Dickie et al., 2017; Mumma et al., 2017; McKay et al., 2021). These disturbances also promote growth of early seral vegetation that attracts other ungulates, followed by predators, thus further increasing the predation risk to caribou (Schneider et al., 2010; Latham et al., 2011a,b; Wilson and DeMars, 2015).

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Caribou is listed as a threatened species under Canada's Species at Risk Act and provincial laws such as Alberta's Wildlife Act (SARA, 2002; COSEWIC, 2002; GoA, 2023). Restoration of seismic lines has been identified as a critical priority for the recovery of caribou populations (ECCC, 2017; GoA, 2017). Generally, restoration involves replanting trees or creating obstacles to slow the movement of predators (James and Stuart-Smith, 2000; Pyper et al., 2014; Spangenberg et al., 2019). Spatial prioritization of these restoration activities aims to improve their effectiveness but must account for myriad ecological and economic factors.

Seismic lines are widespread in Alberta (Hervieux et al., 2013). Previous efforts to prioritize their restoration (ABMI, 2017, 2020) used multi-criteria analysis to rank coarse-scale spatial units in a landscape. While such an approach helps guide regional planning, it does not address the combinatorial nature of many operational trade-offs in restoration, which instead require the use of optimization-based planning (Önal and Wang, 2008). Furthermore, a successful ecological restoration plan must consider multiple spatial scales ranging from local (i.e., patch-level) to regional and landscape level (Willemen et al., 2012; Arkle et al., 2014; Riato et al., 2023). In conservation management, multi-scale analyses are often included in species-habitat studies because habitat selection by animals is a hierarchical process that ranges from accounting for long-distance species movement to selection of individual sites (Mayor et al., 2009; Lipsey et al., 2017). For restoration of spatially connected habitat, the application of graph theory is deemed to be particularly useful to account for regional, landscape-scale and local habitat characteristics (Tambosi et al., 2014). However, various restoration scales may impose different limitations, which necessitates the use of distinct spatial constraints. For example, project-level planning of restoration requires consideration of various spatial limitations, such as the locations of undisturbed caribou habitat versus the locations of roads that would need to remain in use (Dickie et al., 2023). Addressing these trade-offs requires high-resolution planning to allocate restoration activities at the scale of small forest patches. At the same time, restoration planning is often shaped by general policy considerations at the scale of coarse subdivisions without considering the local complexities at individual sites (ABMI, 2017, 2020). In this situation, a multi-scale planning scheme is required, where a coarse-scale prioritization is introduced to guide the fine-scale restoration planning.

In our study, we address this need with a two-scale approach that employs spatial network optimization. Here, the term "scale" refers to the linear dimensions of the spatial planning units in the landscape, with the fine scale referring to small-size planning units (forest patches) and the coarse scale defining medium-size landscape compartments, each including 40–50 of these small units (patches). We first apply a linear programming model to select a contiguous set of coarse-scale forest regions targeted for restoration. We then use this coarse-scale solution to guide a fine-scale restoration model that optimizes, at the scale of individual forest patches within those regions, for several operational issues that arise in project-level planning but are omitted in coarse-scale prioritizations. Our fine-scale optimization model ensures that when a portion of seismic lines is restored in a chosen region, the remaining pockets of unrestored features remain accessible to managers. The model also helps aggregate restoration into meaningful spatial clusters, which is necessary to relocate equipment and personnel to the project area as efficiently and cost-effectively as possible.

1.1. Ecological restoration as a network flow problem

We applied the spatial network optimization concept to assist with the restoration of seismic lines in the Redrock-Prairie Creek caribou range in northwestern Alberta, Canada, a forest landscape disturbed by decades of oil-and-gas extraction activities. We depict a fragmented forest landscape as a network of disturbed and undisturbed patches and control the contiguity between patches by solving a network flow problem (Sessions, 1992; Conrad et al., 2012; Dilkina et al., 2016; Yemshanov et al., 2019, 2022). The connectivity of patches selected for restoration is managed at two distinct scales: small-size forest patches and medium-size landscape compartments, each including multiple patches. First, we find the contiguous (*cf.* connected) restoration regions that follow broad-scale (i.e., at the range scale) patterns of suitable caribou habitat and human disturbances. Then, at the fine scale, we select sites for restoration that will allow us to meet a desired restoration area target while ensuring that patches with unrestored features are still accessible. We use the amount of *local* habitat that caribou can access through the restored sites as a restoration success metric (Nagy-Reis et al., 2020; Serrouya et al., 2020). This metric follows a common objective of restoration activities to make it harder for predators to access intact caribou habitat when crossing a restored area (Keim et al., 2019; Tattersall et al., 2020).

Spatial contiguity in restoration and biological conservation planning has been managed using various approaches (see Wang et al., 2018), such as minimizing distances and enforcing spatial adjacency between the protected sites (Önal and Briers, 2006; Önal and Wang, 2008; Wang et al., 2018), injecting flow into a network of connected sites set for protection and ensuring that each site receives flow from one adjacent site (Jafari and Hearne, 2013), maximizing the density-weighted connectivity of a protected landscape (Gupta et al., 2019) or maximizing the protected area by selecting from pre-defined habitat clusters (Tóth et al., 2009; Ferguson et al., 2023). Other methods to delineate contiguous protected areas have applied simulated annealing (Ball et al., 2009; Schneider et al., 2012) and network optimization (Conrad et al., 2012; Dilkina et al., 2017; Yemshanov et al. 2020a,b).

The use of network optimization in ecological restoration planning is relatively new (Justeau-Alliare et al., 2021; Yemshanov et al., 2019, 2022). In a previous study (Yemshanov et al., 2022), we used the spatial contiguity concept to minimize the number of disjunct clusters of restored sites in a landscape but only controlled these aspects at the local scale of individual forest patches without considering the broad-scale planning priorities. The solutions, while optimizing the fine-scale features, did not always align with a top-down planning approach which prioritizes restoration activities at the scale of coarse subdivisions and then, after the priority area is approximately defined, proceeds to the scale of planning individual sites (i.e., as a separate step in the planning process). Another major challenge in our previous study was that the fine-scale model performed poorly in large landscapes.

The approach presented in this study accounts for the multi-scale nature of landscape restoration planning and helps reduce the computational burden of solving a fine-scale restoration planning problem in large and complex landscapes. First, the approach finds the coarse-scale allocation of restoration regions that maximizes the amount of suitable habitat in the restored area. This solution serves as a feasible starting point for solving the fine-scale spatial restoration planning model. At the final solution step, the configuration of coarse-scale regions with the restored sites is allowed to change to satisfy the fine-scale project-level constraints. The coarse-scale and fine-scale restoration problems have different degrees of spatial detail. The coarse-scale model aims to estimate the approximate extent of the restored area but does not address the operational needs of controlling access to habitat or unrestored sites, and so is a simpler problem. Using the coarse-scale solution as a warm start to the fine-scale problem produces a feasible solution that is reasonably close to the optimal solution of the fine-scale model. The warm start of the fine-scale problem from this feasible suboptimal solution helps reduce the solution time.

2. Material and methods

2.1. Coarse-scale restoration problem

We consider a landscape with linear disturbances as a network of J coarse-scale regions where each pair of adjacent regions containing seismic lines is connected by arcs. We define regions as hexagons of roughly similar area, with some minor adjustments of hexagon borders to include small-scale features that facilitate access to seismic lines in a given region from adjacent hexagons. Hexagonal regions were chosen over squares as a better depiction of the habitat connectivity pattern; for instance, each hexagonal region is adjacent to six neighbors instead of four. The region size was chosen to correspond to the broad-scale variation of major landscape features in the study area. A region j, $j \in J$, is characterized by the amount of suitable caribou habitat, B_j, which could be accessed by animals through restored seismic lines in j. We assume that the restored caribou habitat must be contiguous to facilitate the movement of animals. We depict a grid of hexagonal units as a network of nodes with suitable habitat which can be connected by linear features (i.e., seismic lines or roads). For a pair of adjacent nodes (hexagons) i and j, a pair of bi-directional arcs ji,ij indicates that i and j are connected.

Our coarse-scale planning problem selects a contiguous subset of regions j with seismic lines, Ψ, for restoration in landscape J to maximize the amount of habitat that can be accessed by caribou through the regions with the restored seismic lines. To keep the restored area contiguous, we need to ensure that the hexagons with restored seismic lines are connected to adjacent regions with undisturbed habitat. We conceptualize the presence of this connection between adjacent regions j and i as a flow through arc ji or ij (Fig. 1a). Bidirectional arcs between adjacent nodes i and j indicate that the flow between i and j could be established either from i to j or from j to i, but we assume that a node can receive flow through one connecting arc only.

We define a binary variable W_{ij} to indicate that flow can pass through arc ij between regions with the restored seismic lines i and j. Because the hexagons with seismic lines are depicted as a connected network, contiguity between the selected restored regions in subset Ψ can be enforced by injecting the flow into one restored region j and ensuring that all other regions selected for restoration receive flow from j (Fig. 1a). To inject flow into subset Ψ of regions with restored seismic lines to maintain their connectivity, we introduce an auxiliary Node 0. Node 0 is connected to all regions j via arcs $0j$ which can be used to inject the flow to any region j selected for restoration (Fig. 1a). Node 0 serves as the flow injection point only, so the flow can only proceed in one direction $0 \rightarrow j$ (Fig. 1a). A non-negative variable Y_{ij} defines the amount of flow between the restored regions through arc ij.

For each region j, we introduce a binary variable R_j to define regions j selected for restoration and therefore included in subset Ψ (i.e., $R_j = 1$ and $R_j = 0$ otherwise). To properly track the flow between the connected restored regions, we assume that a region j that is selected for restoration can receive flow from another region i via a single arc, i.e., $\sum^{i \in \Theta_j} W_{ij} = R_j$, where set Θ_j defines all adjacent regions i or Node 0 connected to j which could transmit flow to j (Fig. 1b). A region j is considered restored (i.e., $R_j = 1$) if it receives flow from any connected region with $R_j = 1$ or from Node 0 (Fig. 1a).

Ensuring connectivity between regions with the restored seismic lines does not preclude that some unrestored regions will be left isolated inside the restored area. Therefore, we also need to ensure the contiguity of the remaining network of unrestored regions. A contiguous subset of regions j, Φ, includes the regions with the unrestored seismic lines or permanent roads in area J. A binary variable V_{ij} defines the connection between the adjacent regions i and j in the subset of unrestored regions Φ (Fig. 1a, yellow arrows) and a non-negative variable Z_{ij} characterizes the amount of flow through arc ij. The subsets of the restored and unrestored regions Ψ and Φ do not overlap except at Node 0 (Fig. 1a) which is only used as a flow injection point.

The coarse-scale restoration problem selects a connected set of regions j in landscape J to maximize B_j, the amount of habitat that is accessible by caribou through the restored features in j, subject to the restoration area target, S, $S \in [1;J]$, i.e.:

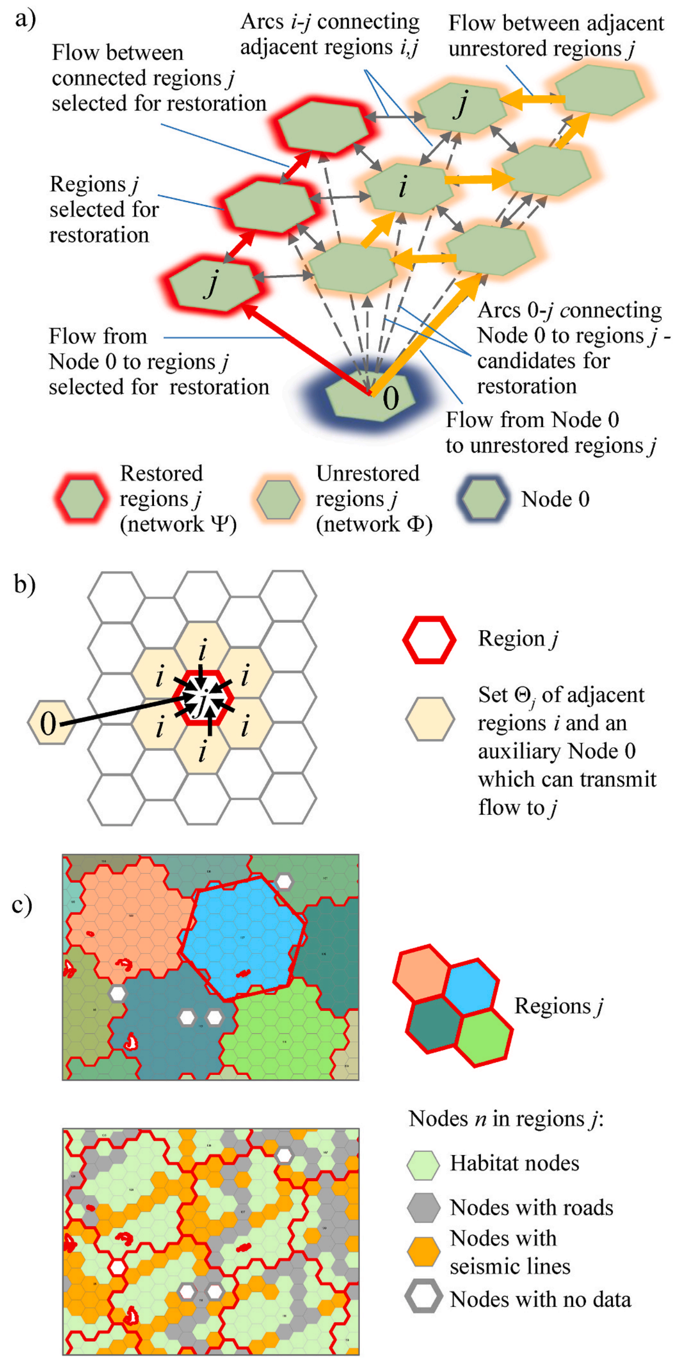

Fig. 1. a) Restoration regions j, connecting arcs ij and a conceptual illustration of network flow between regions j to ensure connectivity of restored and unrestored areas. Dashed lines indicate the connections from Node 0 to nodes j. Hexagons in red outline show regions j selected for restoration (i.e., with $R_j = 1$). Arcs in bold red show the flow from Node 0 to regions j selected for restoration (i.e., with $W_{ij} = 1$), which ensures the contiguity of the subset of restored regions Ψ. Arcs in yellow show the flow from Node 0 to unrestored regions j (i.e., with $V_{ij} = 1$), which ensures the contiguity of the subset of unrestored regions Φ; b) set Θ_j with adjacent regions i that can transmit flow to region j; c) restoration regions j and forest patches (nodes) n.

$$\max \sum^{j\in J} \sum^{i\in\Theta_j} (W_{ij}B_j) \quad (1)$$

s.t.:

$$R_j = 1 \overset{\Psi}{} \ connected \quad (2)$$

$$R_j = 0 \overset{\Phi}{} \ \text{connected} \quad (3)$$

$$\sum^{j\in J} W_{0j} \leq \theta \quad (4)$$

$$\sum^{j\in J} V_{0j} \leq 1 \quad (5)$$

$$\sum^{i\in\Theta_j} W_{ij} = 1 - \sum^{i\in\Theta_j} V_{ij} = R_j \forall j \in J \quad (6)$$

$$\sum^{j\in J} R_j \leq S \quad (7)$$

Table 1 defines all symbolic notation. Objective (1) maximizes the amount of habitat that is accessible through the restored features in the selected regions. Equations (2) and (3) define the constraints that enforce connectivity between the regions with restored (network subset Ψ) and unrestored features (network subset Φ) (Fig. 1a, see description of (2) and (3) in Appendix S1, Eqs. (S1.1)–(S1.3), (S2.1)–(S2.3)). Constraint (4) defines θ, the maximum number of contiguous clusters of regions j selected for restoration, and constraint (5) ensures that the set of remaining unrestored regions Φ is contiguous, with no isolated regions left inside the restored area. Constraint (6) ensures that the networks of restored and unrestored regions do not overlap and relays the selection of flow in the network of restored regions Ψ to a binary variable R_j. Constraint (7) sets the target number of regions for restoration, S.

2.2. Fine-scale restoration problem

Our coarse-scale problem (1)–(7) does not address the restoration of individual sites within the regions j. This aspect is handled by the site-level restoration problem that considers the landscape as a set of small patches with seismic lines, roads and undisturbed habitat at a finer spatial resolution than problem (1)–(7), therefore we define it with different symbolic notation. We depict a landscape of J regions as a network of N small patches (nodes) n, $n \in N$ (Fig. 1c), where each region j includes N_j patches. Nodes with seismic lines and roads fragment the landscape into pockets with undisturbed habitat.

2.2.1. Sub-problem 1: maintaining access to unrestored features

A node with seismic lines or roads can be used to access other nodes scheduled for restoration from the locations where roads enter the area. Similar to our coarse-scale restoration prioritization problem, we depict each pair of adjacent nodes n,m, representing forest sites with roads or seismic lines, as connected by a pair of bidirectional arcs nm,mn. The nodes with roads and seismic lines constitute the *access* network Ω of nodes connected by bi-directional arcs nm, $\Omega \in N$ (Fig. 2a).

Once a portion of nodes with seismic lines is restored, the remaining nodes in network Ω must be accessible from at least one location where roads enter the area. Our first sub-problem enforces connectivity between the nodes with unrestored seismic lines in network Ω (unrestored nodes hereafter) and nodes with points of entry to area N. This is analogous to the group of constraints (2) enforcing the connectivity between restoration regions in our coarse-scale problem (1)–(7) (see Appendix S1, Eqs.S1.1-S1.3). An auxiliary Node 1 works as a flow injection point analogously to Node 0 in the coarse-scale problem(1)–(7) and is connected via arcs $1n$ to nodes n in the access network Ω where roads enter

Table 1
Sets, parameters and decision variables.

Symbol	Parameter/variable name	Description
Sets:	Coarse-scale restoration problem	
J	Restoration regions i,j in landscape J	$J = 172$ regions
Θ_j	Auxiliary Node 0 and regions adjacent to region j which can transmit flow to j	$\Theta_j \in J$
Ψ	Network of regions j selected for restoration (assuming all seismic lines restored in j)	
Φ	Network of the unrestored regions j (assuming no restoration activities in j)	
	Fine-scale restoration problem:	
N	Nodes (landscape patches) n,m in landscape N	$N = 7558$ nodes
N'	Nodes (landscape patches) n,m in landscape N and an auxiliary node 1	
Ω	Access network – includes nodes with seismic lines and an auxiliary Node 1	
Γ	Restorable network – includes nodes that are potentially restorable and an auxiliary Node 1	
Ξ	Habitat network – includes candidate nodes for restoration, nodes with habitat and Node 1	
Decision variables	*Coarse-scale restoration problem:*	
R_j	Binary variable selecting region j for restoration ($R_j = 1$ and $R_j = 0$ otherwise)	$R_j \in\{0,1\}$
W_{ij}	Binary variable indicating the connection between the restored regions i,j in network Ψ	$W_{ij} \in\{0,1\}$
Y_{ij}	Flow through an arc ij between regions i and j in the network of restored regions Ψ	$Y_{ij} \in [0; J]$
V_{ij}	Binary variable indicating the connection between the unrestored regions i,j in network Φ	$V_{ij} \in\{0,1\}$
Z_{ij}	Flow through an arc ij between regions i and j in the network of unrestored regions Φ	$Z_{ij} \in [0; J]$
	Fine-scale restoration problem:	
x_{nm}	Binary flow indicator between nodes n and m in the human access network Ω	$x_{nm} \in\{0,1\}$
y_{nm}	Flow through an arc nm between the selected adjacent nodes n and m in access network Ω	$y_{nm} \geq 0$
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 habitat network Ξ	$v_{nm} \geq 0$
p_{nm}	Binary flow indicator between nodes n and m in the restorable network Γ	$p_{nm} \in\{0,1\}$
q_{nm}	Flow through an arc nm between the selected adjacent nodes n and m in restorable network Γ	$q_{nm} \geq 0$
u_{nm}	Adjustment factor for the habitat amount 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 arc selection variable w_{nm} and variable u_{nm} with the habitat adjustment factor h_n	$z_{nm} \in [0; 1]$
g_{mn}	Binary variable that defines whether the habitat node that is accessible from another restored node within distance $H_{\max}$ is adjacent to an unrestored node m	$g_{mn} \in [0; 1]$
P_1	Penalty for the number of connections from an auxiliary node 1 to the restored nodes in network Γ above the desired threshold $\omega_{\max}$ (defines the maximum number of spatially contiguous sets of restored nodes in area N above $\omega_{\max}$)	$P_1 \geq 0$
P_2	Penalty for the number of cases when a habitat node that is accessible from one restored node becomes adjacent to an unrestored node the distance of $H_{\max}$ nodes	$P_2 \geq 0$
Parameters:	*Coarse-scale restoration problem:*	
B_j	Habitat amount which can be accessed through all the restored nodes in region j	$B_j \geq 0$
S	Restoration area target (the number of regions j to restore)	$S \in [0; J]$
	Fine-scale restoration problem:	
b_n	Suitable habitat amount in node n	$b_n \geq 0$

(*continued on next page*)

Table 1 (*continued*)

Symbol	Parameter/variable name	Description
h_n	Factor that adjusts the amount of habitat in node n according to the seismic line length l_n in n	$h_n \in [0; 1]$
c_n	Cost to restore all seismic lines in node n	$c_n \geq 0$
c_{fix}	Fixed cost to relocate personnel and equipment to a disjunct restored node cluster	$c_{fix} \geq 0$
C	Restoration budget limit	$C > 0$
H_{max}	Maximum number of connected habitat nodes which be accessed through a restored node in each cardinal direction	$H_{max} = 3$
χ_{nj}	Binary parameter that identifies nodes n located in coarse-scale region j	$\chi_{nj} \in \{0,1\}$
ξ_{mn}	Binary parameter that indicates when an unrestored node m is adjacent to a habitat node n	$\xi_{mn} \in \{0,1\}$
ω_{max}	Maximum desirable number of disjunct clusters of restored nodes that can be created without penalizing the objective function value	$\omega_{max} \geq 1$
δ_n	Binary parameter indicating the non-restorable nodes in access network Ω ($\delta_n = 1$)	$\delta_n \in \{0,1\}$
A_n	Binary parameter defining nodes n that are potential candidates for restoration in networks Ω, Ξ and Γ ($A_n = 1$ and $A_n = 0$ otherwise)	$A_n \in \{0,1\}$
f_1, f_2	Scaling factors for penalties P_1, P_2 in the objective function	$f_1, f_2 \geq 0$

the area. Node 1 is used to inject the flow to the nodes with entry points to the area (Fig. 2a). The flow is passed from entry points to adjacent unrestored nodes in network Ω and so on until all unrestored nodes receive flow (and so remain connected to one of the entry points). A restored node cannot receive flow from unrestored nodes and effectively removed from network Ω (Fig. 2b).

A non-negative variable, y_{nm}, specifies the amount of flow between nodes n and m, while a binary variable, x_{nm}, selects arc nm to transmit this flow if both nodes are in access network Ω ($x_{nm} = 1$ and $x_{nm} = 0$ otherwise). Each node n in network Ω can receive flow through at most a single incoming arc. All nodes with seismic lines can be restored but some nodes with roads may stay in use and so always remain in network Ω.

2.2.2. Sub-problem 2: estimating the habitat amount that is accessible from the restored nodes

Each node n may include suitable habitat. Caribou constantly move between nodes with habitat as part of their foraging behavior. When caribou cross a seismic line or road, this increases their exposure to predators who uses these disturbances to gain access to core caribou habitat (Dickie et al., 2020; Mumma et al., 2017, 2018). In this context, the restoration of seismic lines in node n reduces the risk of predation when caribou cross that node (Dickie et al., 2021) and so can be characterized by the local amount of undisturbed habitat, b_n, that animals can access through that node after restoration. To delineate the amount of habitat that is *locally* accessible from n, we find a subset of nodes m with habitat (habitat nodes hereafter) which are connected to n within an access distance H_{max}. Unimpeded access to the nearest undisturbed habitat is critical for a reduction of predation risk on caribou (Latham et al., 2011c; DeCesare, 2012; DeCesare et al., 2014), therefore we only consider access to habitat within a relatively short distance, i.e., 0.5–1.5 km, which translates to $H_{max} = 3$ nodes (Fig. 2c and d) (EC, 2012; GoA, 2017). To avoid overestimation of the accessible habitat from the restored nodes, we assume that a habitat node could receive flow from no more than one restored node. We define a habitat network Ξ, which includes nodes n that are candidates for restoration and all nodes m with suitable habitat (Fig. 2c). Nodes n with seismic lines are connected to adjacent habitat nodes m by unidirectional arcs $n \rightarrow m$, while the adjacent habitat nodes are interconnected by bidirectional arcs.

For each restored node n, we track the flow from n to a sequence of $\leq H_{max}$ connected habitat nodes using a network flow formulation that is analogous to the connectivity sub-problem for access network Ω. An auxiliary Node 1 in set Ξ is connected to all n nodes with seismic lines – candidates for restoration (Fig. 2c) – and serves as a source of the flow from each restored node to $\leq H_{max}$ connected habitat nodes. Only the restored nodes can receive flow from Node 1 and pass it to habitat nodes (Fig. 2d). An adjacent habitat node can pass the flow to another habitat node, and so on until the number of nodes connected to the restored node n reaches H_{max}. A non-negative variable, v_{nm}, defines the amount of flow between nodes n and m through arc nm in network Ξ, and a binary variable, w_{nm}, selects arc nm to transmit flow between n and m (i.e., $w_{nm} = 1$ when $v_{nm} > 0$). A node in network Ξ becomes connected to other nodes if it receives flow from other nodes or Node 1.

In our network of discretized forest patches, some patches adjacent to large habitat pockets may include small seismic line segments and so their restoration value may be inflated. We use the following method to compensate for this effect of spatial discretization. When the length of seismic lines in node n, λ_n, is less than the node's linear width, λ_{min}, we adjust the amount of habitat accessible from n by the ratio $h_n = \lambda_n / \lambda_{min}$ ($h_n = 1$ for $\lambda_n \geq \lambda_{min}$). For every habitat node m that is connected to a restored node n, the amount of habitat b_m that can be accessed from n is adjusted by factor h_n. Thus, the value of h_n at a restored node n must be passed to all habitat nodes connected to n within an H_{max} distance. For each arc nm in network Ξ, we define a non-negative decision variable, u_{nm}, $u_{nm} \in [0; 1]$, that passes the adjustment factor h_n from the restored node n to a connected habitat node m via arc nm. Since the h_n value must be passed only to nodes connected to a restored node n, we track the product of the arc selection variable between the connected nodes n and m, w_{nm}, and the passed adjustment factor u_{nm} for that arc, using a non-negative variable z_{nm}, $z_{nm} = u_{nm} w_{nm}$.

In areas with high disturbance densities, the pockets of undisturbed habitat may be too small to guarantee a desired habitat access depth H_{max}. When the cross-sectional width of a habitat pocket is less than H_{max}, habitat that is accessible from one side of the pocket may end up bordering an unrestored feature within H_{max} on the other side of the pocket. This habitat has little value for caribou as a refuge; instead, restoration should favor nodes adjacent to habitat with a cross-sectional width above H_{max}. To address this aspect, we track adjacency between nodes with linear features (seismic lines or roads) and undisturbed habitat. For each arc mn in habitat network Ξ, we define a binary parameter ξ_{mn} that indicates whether node m with linear disturbances is adjacent to habitat node n ($\xi_{mn} = 1$ and $\xi_{mn} = 0$ otherwise). For a pair of adjacent nodes m and n with $\xi_{mn} = 1$, a binary variable g_{mn} defines whether n (the habitat node) is adjacent to an unrestored node m but accessible from a restored node within distance H_{max} (i.e., $g_{mn} = 1$ and $g_{mn} = 0$ otherwise). Occurrences of $g_{mn} = 1$ penalize the objective function and attempt to avoid situations when a habitat node that is accessible from one restored node within H_{max} borders an unrestored node.

2.2.3. Sub-problem 3: seismic line restoration in contiguous clusters

Practical considerations (e.g., available personnel or resources) may restrict restoration to one or a few contiguous clusters. To ensure the contiguity of the restored node clusters, we defined a network of restorable nodes Γ (restorable network hereafter) that included all nodes with seismic lines as candidates for restoration. All adjacent nodes in network Γ are connected by bi-directional arcs (Fig. 2e). Our third sub-problem controls the contiguity of the restored nodes and is analogous to the site access sub-problem in network Ω. An auxiliary Node 1 injects the flow to the connected subset(s) of nodes and is connected to every node n that is a candidate for restoration in network Γ (Fig. 2e). A restored node must receive flow from Node 1 or an adjacent restored node and can pass it to another adjacent restored node (Fig. 2f), which guarantees the contiguity of the subset. A non-negative variable, q_{nm}, defines the amount of flow via arc nm between nodes n and m in restorable network Γ and a binary variable, p_{nm}, selects arc nm to transmit this flow, so that $p_{nm} = 1$ when $q_{nm} > 0$. The number of connections from Node 1 to the restored nodes n in network Γ, ω_{max}, sets the maximum desirable

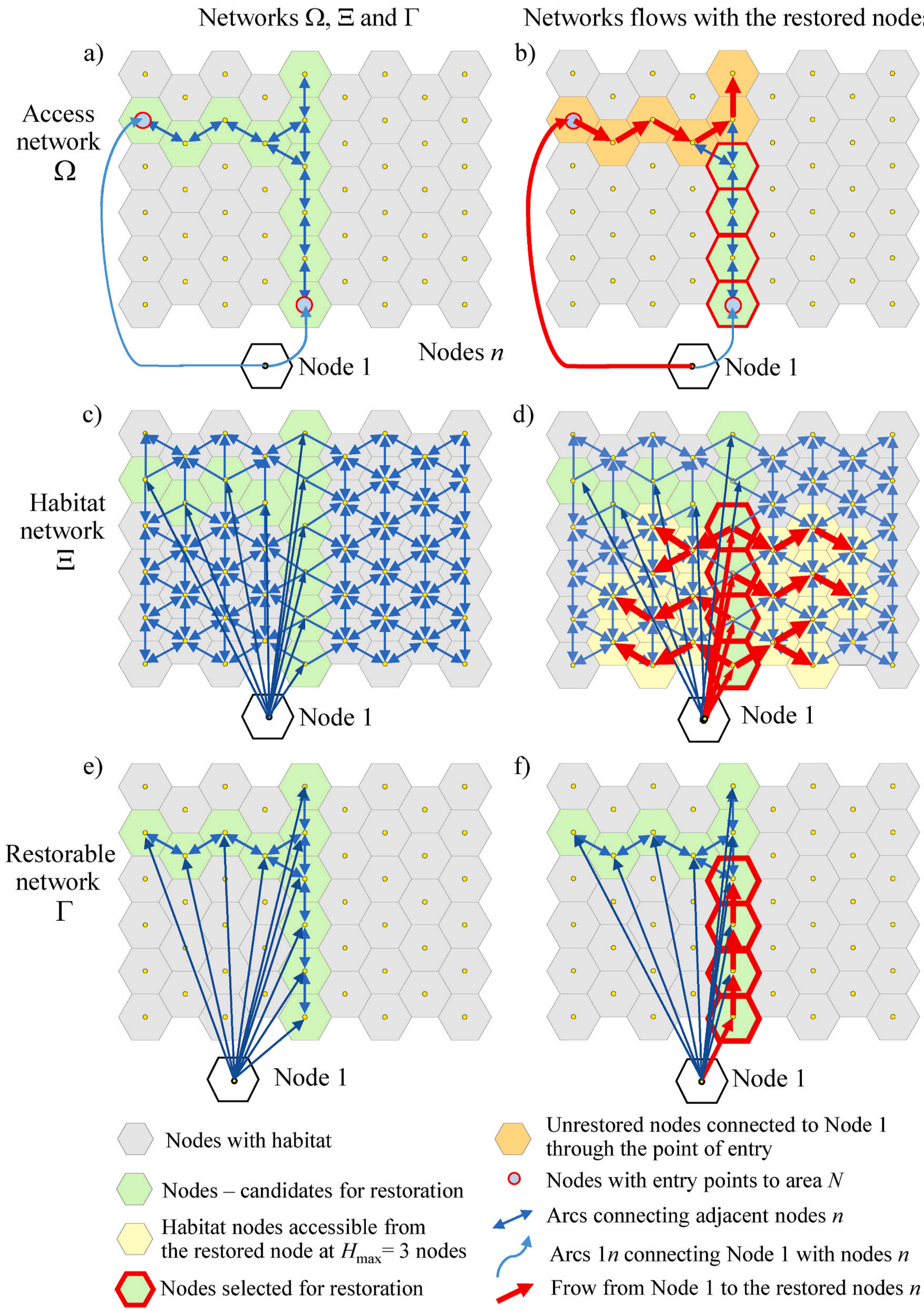

Fig. 2. a) Access network Ω, comprised of nodes with linear features that facilitate access to the restoration sites. Adjacent nodes of network Ω with seismic lines and roads are connected by arcs (blue arrows). Red arrow from Node 1 injects flow into the network of unrestored nodes; b) example of flow injected from Node 1 to access network Ω and passed to all unrestored nodes (bold red arrows); c) habitat network Ξ. Restorable nodes are connected to adjacent habitat nodes, which are interconnected by arcs (blue arrows); d) example of network flow from Node 1 through the restored nodes to the adjacent habitat nodes (bold red arrows). The flow from a restored node is passed to $H_{max} \leq 3$ nodes (yellow hexagons); e) restorable network Γ. Blue arrows connect adjacent nodes that are candidates for restoration; f) Example of flow node 1 to the restored nodes (bold red arrows) to enforce the contiguity of the restored area. Red outline shows the restored nodes. Habitat nodes are shown in gray. Nodes that are potential candidates for restoration are shown in green.

number of disjunct restored node clusters (Fig. 2f).

2.2.4. Fine-scale problem formulation

Using the defined sub-problems 1–3 we formulate the fine-scale restoration problem as follows:

$$\max \sum^{n\in N'}\left(b_n\sum^{m\in N'} z_{nm}\right) - P_1 f_1 - P_2 f_2 \tag{8}$$

s.t. :

$$\overset{\Omega}{x_{nm}=1}\ \text{is connected to through nodes with entry points to auxiliary Node 1} \tag{9}$$

$$\sum^{m\in N'} x_{mn} \geq \delta_n \forall n\in N \tag{10}$$

$$\overset{\Gamma}{p_{nm}=1}\ \textit{is connected to auxiliary Node 1} \tag{11}$$

$$P_1 \geq \sum^{n\in N} p_{1n} - \omega_{max} \tag{12}$$

$$\sum^{m\in N'} p_{mn} + \sum^{k\in N'} x_{kn} = 1\forall n\in N \tag{13}$$

$$\overset{\Xi}{w_{nm}=1}\ \textit{is connected through the restored nodes to auxiliary Node 1} \tag{14}$$

$$v_{nm} \leq H_{max} w_{nm} \forall n,m\in N \tag{15}$$

$$\sum^{m\in N'} w_{mn} \leq 1-\delta_n \forall n\in N \,\Big|\, \delta_n = 1 \tag{16}$$

$$\sum^{n\in N'} v_{mn} \leq \left(1-\sum^{m\in N'} x_{mn}\right) N \forall n\in N \,\Big|\, A_n = 1 \tag{17}$$

$$w_{mn} \leq 1-\sum^{k\in N'} x_{kn} \forall n,m\in N \tag{18}$$

$$u_{nm} = h_n w_{nm} \forall n,m\in N \mid A_n = 1, A_m = 0 \tag{19}$$

$$u_{nm} = \sum^{k\in N} z_{kn} \forall n,m\in N \,\Big|\, A_n, A_m = 0 \tag{20}$$

$$z_{nm} = u_{nm} w_{nm} \forall n,m\in N \tag{21}$$

$$P_2 \geq \sum^{n\in N}\left(\sum^{m\in N} g_{mn}\xi_{mn}\right) \forall \xi_{mn} = 1 \tag{22}$$

$$g_{mn} = \sum^{k\in N} w_{kn}\left(\sum^{l\in N} x_{lm}\right) \forall m,n\in N, \xi_{mn} = 1 \tag{23}$$

Objective (8) maximizes the amount of habitat within $\leq H_{\max}$ nodes that can be accessed through the restored nodes minus the rescaled penalties P_1 and P_2 (described below). Set N' includes an auxiliary Node 1 and set N with all other nodes n. Equation (9) defines a group of constraints that enforce connectivity between the unrestored nodes in access network Ω and at least one node where roads enter the area N (Fig. 2a and b, Appendix S1, constraints (S9.1)–(S9.5)). Constraint (10) specifies that nodes with permanent roads (defined by a binary parameter $\delta_n = 1$) remain in access network Ω.

Equation (11) defines a group of constraints that ensure the connectivity of the restored nodes in network Γ and are analogous to the group of constraints (9) (see Eqs. (S11.1)–(S11.5) in Appendix S1). Constraint (12) defines the non-negative penalty variable P_1 as the number of direct connections from auxiliary Node 1 to restored nodes above the target value $\omega_{\max}$. Penalty P_1 keeps the problem feasible when a complex landscape configuration forces restoration in more than $\omega_{\max}$ disjunct clusters. Complex landscapes may include multiple hotspots with suitable habitat. When constrained by budget or the restored area target, the model seeks the most cost-effective solution that maximizes access to habitat. At some point, when the restored area (or budget) limit increases, continuing the restoration in a single cluster after all cost-effective sites around the habitat hotspot are restored may be too costly because it would force restoration of sites with little access to habitat. Thus, there is a trade-off between creating a new cluster where restoration is more cost-effective versus keeping all restored sites in one cluster. Controlling the number of restored clusters with a penalty constraint (12) helps address this issue. Setting the penalty P_1 coefficient f_1 to a high value instructs the model to keep as few restoration clusters as possible but allows creation of a new restoration cluster if a complex landscape configuration does not permit the expansion of an existing cluster or this expansion is cost-prohibitive.

Constraint (13) ensures that a node n containing seismic lines can have either restored or unrestored status but not both. Constraints (14)–(21) control the amount of habitat and the number of habitat nodes that can be accessed through the restored nodes. Equation (14) defines the group of constraints that ensure that a restored node n is connected to $\leq H_{\max}$ habitat nodes and works analogously to the group of constraints (11) (see Eqs. (S14.1)–(14.4), (S15)] in Appendix S1). Constraint (15) limits the maximum amount of flow through each arc connecting a restored node n and an adjacent habitat node by $H_{\max}$.

Constraint (16) prevents connections between nodes with habitat and nodes with roads and is only applied to non-restorable nodes with roads identified by the binary parameter $\delta_n = 1$. Constraint (17) prevents the flow from auxiliary Node 1 to node n, a candidate for restoration, if node n is not restored. A binary parameter A_n defines the nodes n that are candidates for restoration in network Ξ and thus may receive flow from Node 1 (i.e., $A_n = 1$ and $A_n = 0$ otherwise). Constraint (18) specifies that only restored nodes n can be connected to adjacent habitat nodes m.

Constraints (19)–(21) adjust the amount of habitat that is accessible from a restored node n according to the adjustment factor h_n, which is based on the seismic line length in n. Constraint (19) assigns adjustment factor h_n to an arc u_{nm} that connects a potentially restorable node n (i.e., with $A_m = 1$) and habitat node m (i.e., with $A_m = 0$). Constraint (20) passes the habitat adjustment factor between the connected nodes n and m through arc nm, when both nodes are located outside of the access network Ω (i.e., $A_n = A_m = 0$). The adjustment factor from a restored node k that is connected to habitat node n (i.e., with $w_{kn} = 1$) 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 the non-negative decision variable u_{nm}. As noted earlier, the variable z_{nm} is the product of decision variables u_{nm} and w_{nm} and takes the value stored in u_{nm} and passes it to node m when nodes n and m are connected. Together, constraints (19) and (20) pass the adjustment factor h_n from a restored node n to all habitat nodes connected to n, where it is multiplied by the habitat amount b_n. Constraint (21) defines the variable z_{nm} as a product of the binary arc selection variable w_{nm} and the adjustment factor variable u_{nm} and is linearized in equations (S21.1)–(S21.3) in Appendix S1.

Constraint (22) defines the penalty P_2 to objective (8) as the number of times when a habitat node m that is accessible from one restored node within $\leq H_{\max}$ nodes becomes adjacent to another unrestored node n. Constraint (23) defines the decision variable g_{mn} for an arc mn as the product of two binary terms that define the unrestored status of node m, $\sum^{l\in N} x_{lm} = 1$, and whether a habitat node n that is adjacent to m is accessible from another restored node within $H_{\max}$ nodes, $\sum^{k\in N} w_{kn} = 1$. Constraint (23) is linearized in equations (S23.1)–(S23.3) in Appendix S1.

2.3. Full problem formulation

Our coarse-scale and fine-scale problems use different spatial resolutions for regions j and nodes n, respectively. After finding a coarse-scale solution to problem (1)–(7) for a restoration target of S regions, we forced the fine-scale model to find the configuration of restored nodes n within the contiguous regions j prioritized by the coarse-scale solution (i.e., with $R_j = 1$). We introduced the binary parameter χ_{nj} that identifies whether node n is located in region j ($\chi_{nj} = 1$ and $\chi_{nj}=0$ otherwise). The selection of coarse-scale region j for restoration implies that only the sites n located within that region (i.e., with $\chi_{nj} = 1$) can be selected for restoration. We added constraint (24) to restrict the selection of nodes n for restoration to regions j that were prioritized in the coarse-scale problem solution, i.e.:

$$\sum^{m\in N'} p_{mn} \le \sum^{j\in J} R_j \chi_{nr} \forall n \in N \tag{24}$$

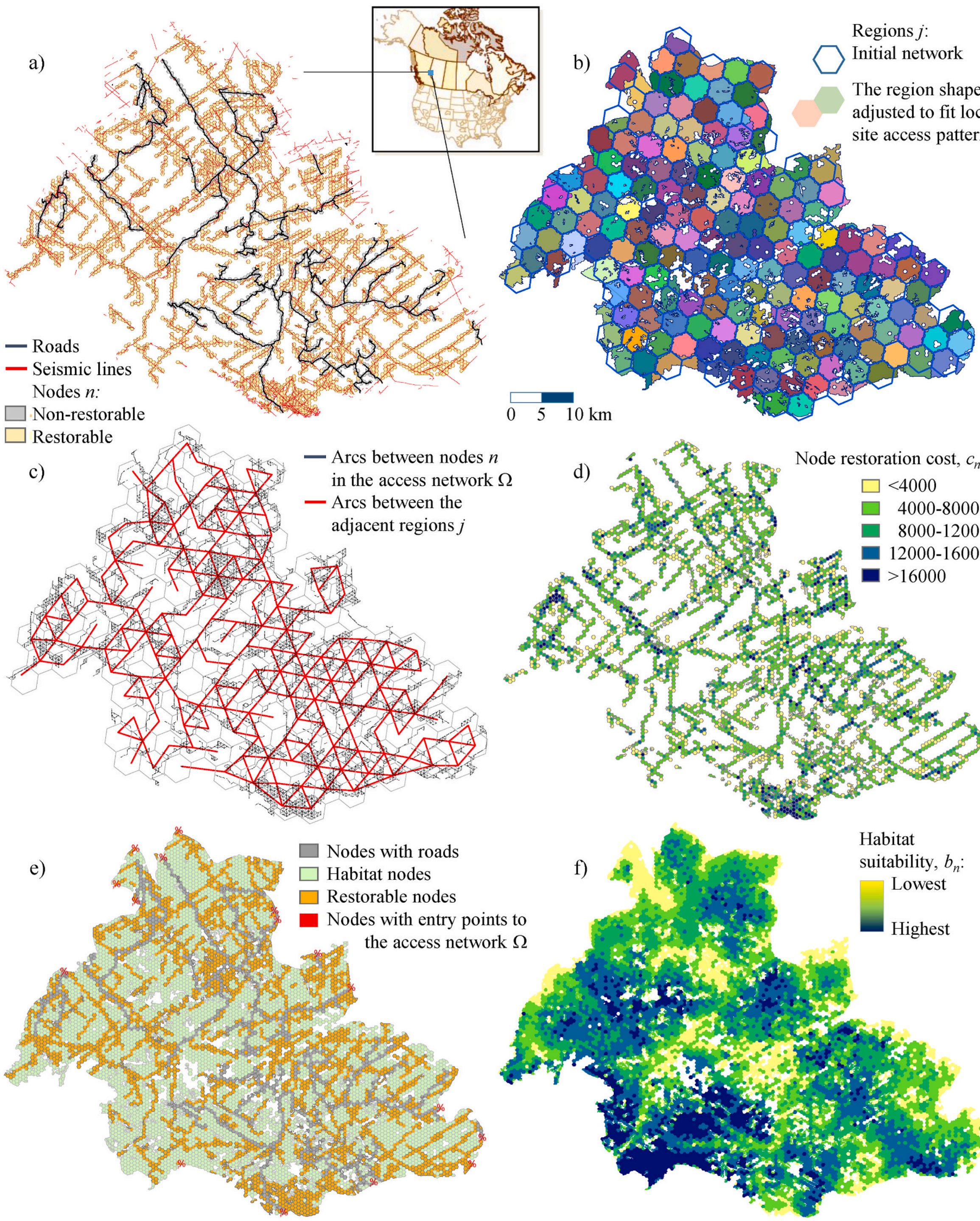

Fig. 3. Spatial inputs: a) linear features (seismic lines and roads); b) restoration regions j; c) arcs connecting adjacent nodes n in access network Ω and the adjacent regions j in networks Ψ and Φ. (The arc arrows are not shown); d) node restoration cost; e) nodes with roads which are expected to remain in use in the "roads" scenario (in gray), nodes with seismic lines (in orange), nodes with undisturbed habitat (in light green) and nodes where permanent roads enter the access network Ω (in red); f) caribou habitat suitability estimates, b_n.

Solving the fine-scale restoration problem (8)–(24) using the fixed values $R_j = 1$ from the coarse-scale solution allocates the pattern of fine-scale restored nodes n within the regions j selected for restoration in the coarse-scale (1)–(7) solution. However, this is a suboptimal solution to the full problem because the configuration of regions j in the coarse-scale problem solution does not account for the fine-scale connectivity constraints (9), (10) and (14)–(23). Consequently, we solved the full problem with objective (8), subject to constraints (2)–(7), (9)–(24) that enforce the connectivity of the restored nodes at both coarse and fine scales. We used the solution to the fine-scale problem (8)–(24) with fixed R_j values to warm start the full-size problem. Since this solution was reasonably close to the near-optimal solution to the full problem, this reduced the full problem solution time. The model was composed in the General Algebraic Modeling System (GAMS, 2022) and solved with the GUROBI linear programming solver (GUROBI, 2022).

2.4. Budget-constrained scenarios

The area-constrained model can be reformulated as a budget-constrained problem by adding constraint (25) to the fine-scale problem (8)–(23), i.e.:

$$\sum^{n\in N}\left[c_n\left(1-\sum^{m\in N'}x_{mn}\right)+p_{1n}c_{fix}\right]\leq C \tag{25}$$

where symbol c_n denotes the cost of restoring all seismic lines in node n and C is the restoration budget limit. The budget-constrained problem is not guided by the solution to the coarse-scale problem (1)–(7). We assumed that restoring a contiguous cluster of nodes n requires a setup cost c_{fix}. For each node n in restorable node network Γ, the value of the binary variable $p_{1n} = 1$ denotes a connection from Node 1 to a disjunct contiguous cluster of restored nodes n (which we used to track a setup cost c_{fix} in equation (25)). The inclusion of the setup costs guides the selection of as few disjunct node clusters as possible.

2.5. Case study

We applied the model to explore restoration strategies in the Redrock-Prairie Creek caribou range of northwestern Alberta (Fig. 3). The landscape is a part of the Redrock-Prairie Creek caribou range and has been fragmented by oil-and-gas exploration activities which created a network of seismic lines (Fig. 3a). The Government of Alberta has initiated planning efforts to restore caribou habitat in the area (GoA, 2016, 2017, 2022a,b).

2.5.1. Data

We mapped the locations of seismic lines and roads in the Redrock-Prairie Creek from data provided by Alberta Environment and Protected Areas, Provincial Geospatial Centre (GoA, 2022c) and a human footprint dataset (ABMI, 2019) that documents all human disturbances in the province (Fig. 3a). The human footprint dataset provides digitized maps of anthropogenic disturbances (including linear features) on the Alberta land base, as digitized from SPOT6 satellite imagery. We discretized the landscape into a network of 7758 24-ha hexagonal nodes n. For each node n, we estimated the length of seismic lines and roads, and the amount of suitable caribou habitat. The network of coarse-scale regions j consisted of 172 1170-ha hexagons, each including, on average, 49 nodes n (Fig. 3b). If a region j included a few isolated nodes n with seismic lines which could only be accessed from an adjacent region, these nodes were reassigned to that adjacent region. Some seismic line segments were overgrown by vegetation and were not visible in the human footprint map. To link isolated seismic line segments to the nearest seismic line features in ABMI's human footprint dataset, we used visual assessments of aerial imagery in web search engines to check for the presence of overgrown seismic lines adjacent to the isolated segments. The nodes with seismic lines and roads comprised the access network Ω (Fig. 3c). The arc connections between coarse-scale hexagons j generally followed the arcs in access network Ω (Fig. 3c). For each node n with linear features (i.e., seismic lines and temporary roads that are similarly restorable), the restoration cost c_n was defined proportional to the linear feature length in n times the Cdn \$13k-km^{-1} unit cost (Fig. 3d). The restoration unit cost was based on the average unit cost of recent seismic line restoration efforts in Alberta.

We used Alberta's forest inventory database (ASRD, 2005) to delineate the extent of useable caribou habitat, b_n, in each node. To calculate the b_n values, we estimated the suitability of caribou habitat using resource selection functions (RSF), which describe the selection of resources by caribou within a seasonal home range and compare the distribution of locations that animals used to those that were available to them (Manly et al., 2002) (Fig. 3f, see Appendix S2). The use of forest patches by caribou was estimated as a function of landscape attributes, including the proportion of conifer species, forest age, elevation, the presence of linear disturbances and water bodies (Table S2.1 Appendix S2). We calculated the RSFs using mixed model logistic regression for four seasons: calving (May–June), fall (October–November), early winter (December–January) and later winter (February–April) and used the average of the four-season values to calculate the habitat suitability index. The use of logistic regression to relate environmental and geographical variables to wildlife species location information is a common approach to calculate RSFs (Boyce et al., 2002; Manly et al., 2007). Note that most of the caribou GPS relocations are outside of the study area in summer. For each node n, the amount of useable habitat b_n is equal to the habitat area in n times the habitat suitability index based on the RSFs. The habitat access depth $H_{\max}$ was set to three nodes (~1.5 km) according to assessments of the avoidance of human disturbances by caribou (EC, 2012; GoA, 2017), which varies from 500 m to 1.5 km from a disturbed site. The lower 500-m minimum caribou avoidance threshold was used to select the size of hexagonal nodes n.

To estimate the amounts of habitat B_j that can be accessed by animals after all nodes with seismic lines are restored in region j, we solved the fine-scale restoration problem (8)–(23) by setting the restoration area target to one region j at a time (Fig. 4a,c). The solution was found by restricting the scope of the node restoration variable p_{mn} to nodes located in chosen region j, $m,n \in N_j$. We also estimated the cost-effectiveness of restoring a region j as the ratio between the accessible habitat amount B_j and total seismic line restoration cost in j (Fig. 4b and c).

2.5.2. Scenario planning sequence

We allocated restoration in a sequence of planning steps t with an incremental restoration target of $S = 10$ regions (Fig. 5). A sequence of single-period problems was used because the fine-scale multi-period problem was too complex to solve for the area in reasonable time. In the sequential scenario, the target area S that is restored in step t is treated as habitat with some degree of suitability at the next planning step t+1 and then, a new target area S is restored and so on (Fig. 5).

Restoring the seismic lines in as few clusters as possible is often desirable for practical reasons, but at some point, permanent disturbances (such as roads) may no longer permit continuing restoration in just a few clusters and the planner must consider increasing the desired number of restored clusters, $\omega_{\max}$. Thus, the sequential planning process resembles a decision tree where the planner evaluates, at each planning step, the alternative options to conduct restoration in different numbers of disjunct clusters (Figs. 6 and 7, Figs.S1, S2 in Appendix S3). Since the whole tree of scenarios was too large to report, we only presented the scenario sequences with the best objective values, assuming that the planner aims to maintain restoration in as few disjunct clusters as possible (Figs. 6 and 7).

2.5.3. Area-constrained vs. budget-constrained restoration strategies

We compared solutions with the restored area target S (which included both fine-scale and coarse-scale connectivity constraints) with

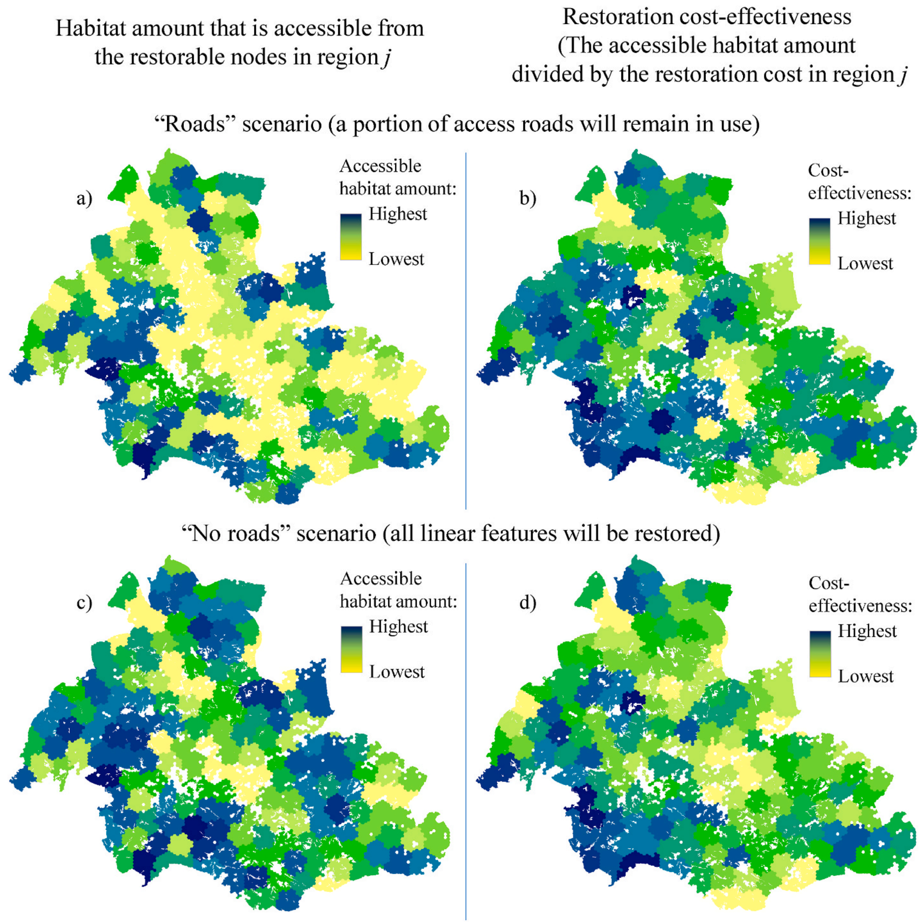

Fig. 4. Region-specific estimates. The "Roads" scenario (assumes that a portion of roads will remain in use after restoration): a) habitat amount, B_j, that can be accessed through the restored nodes in region *j*, after restoring all seismic lines in *j*; b) restoration cost-effectiveness (the amount of accessible habitat B_j divided by the restoration cost of seismic lines in region *j*). The "No roads" scenario (assumes that all linear features to be restored): c) habitat amount, B_j, that can be accessed through the restored nodes in region *j* after restoring all linear features in *j*; d) restoration cost-effectiveness.

solutions constrained by the restoration budget limit *C*. The budget-constrained problem considers habitat connectivity at the scale of individual sites *n* only (i.e., is limited to the fine scale) and does not include the coarse-scale constraints, so it only makes short-distance decisions at the scale of these sites when optimizing the access to habitat. By comparison, the area-constrained problem uses the coarse-scale solution as a warm start and includes both coarse- and fine-scale connectivity constraints, which controls the configuration of the restored area at both scales. Fig. 8 compares the budget-constrained solutions with the comparable-cost area-constrained solutions, for budget limits up to $9M. Note that the need to manage restoration in contiguous clusters without the guiding coarse-scale connectivity constraints makes the budget-constrained problem combinatorically hard. To reduce the solution time, we first solved the problem without the contiguity penalty P_1 in objective (8) and used this solution to warm start the full problem with penalty P_1 (Fig. 5b).

2.5.4. "Roads" versus "no roads" scenarios

We evaluated two groups of practical scenarios (Fig. 4). The "roads" scenario assumes that some existing roads will remain in use after restoration (Figs. 3a and 4a,c). The nodes with permanent roads received the value $\delta_n = 1$ and their locations were provided by Alberta Environment and Protected Areas (Fig. 3e). A theoretical "no roads" scenario assumes that all roads and seismic lines can be restored at the same restoration unit cost and helps assess the relative impact of retaining a portion of roads on restoration efficiency (Fig. 4c and d).

3. Results

We have compared the sequences of model solutions in Figs. 6 and 7. In all scenarios, restoration starts in the least disturbed area with high quality habitat near the southwest range border. Once that area is restored the scenarios expand to other regions in the southern and north-central portions of the range. The preservation of permanent roads reduces the total amount of habitat that could be made accessible from the restored features by almost half (Table 2). This reduction is most significant at intermediate restoration steps when less than 30% of all seismic lines are restored. Eventually, the scenarios converge by coalescing the restored clusters into larger regions with high-quality habitat, however the restored areas in the scenarios with retained access roads are more fragmented than the restored areas in the theoretical "no roads" scenarios (Figs. 6 and 7). The no roads scenarios allow creation of higher-quality habitat clusters because roads aren't disrupting connectivity to better habitat. The total amount of potentially accessible habitat in the "roads" scenarios is significantly lower than in the "no roads" scenarios. The fragmentation by roads creates more habitat pockets with a small cross-sectional width that are adjacent to permanent roads and therefore forced to be omitted by the model constraints (22) and (23).

3.1. Multi-scale (area-constrained) vs. fine-scale (budget-constrained) solutions

The optimal solutions for the budget-constrained and area-

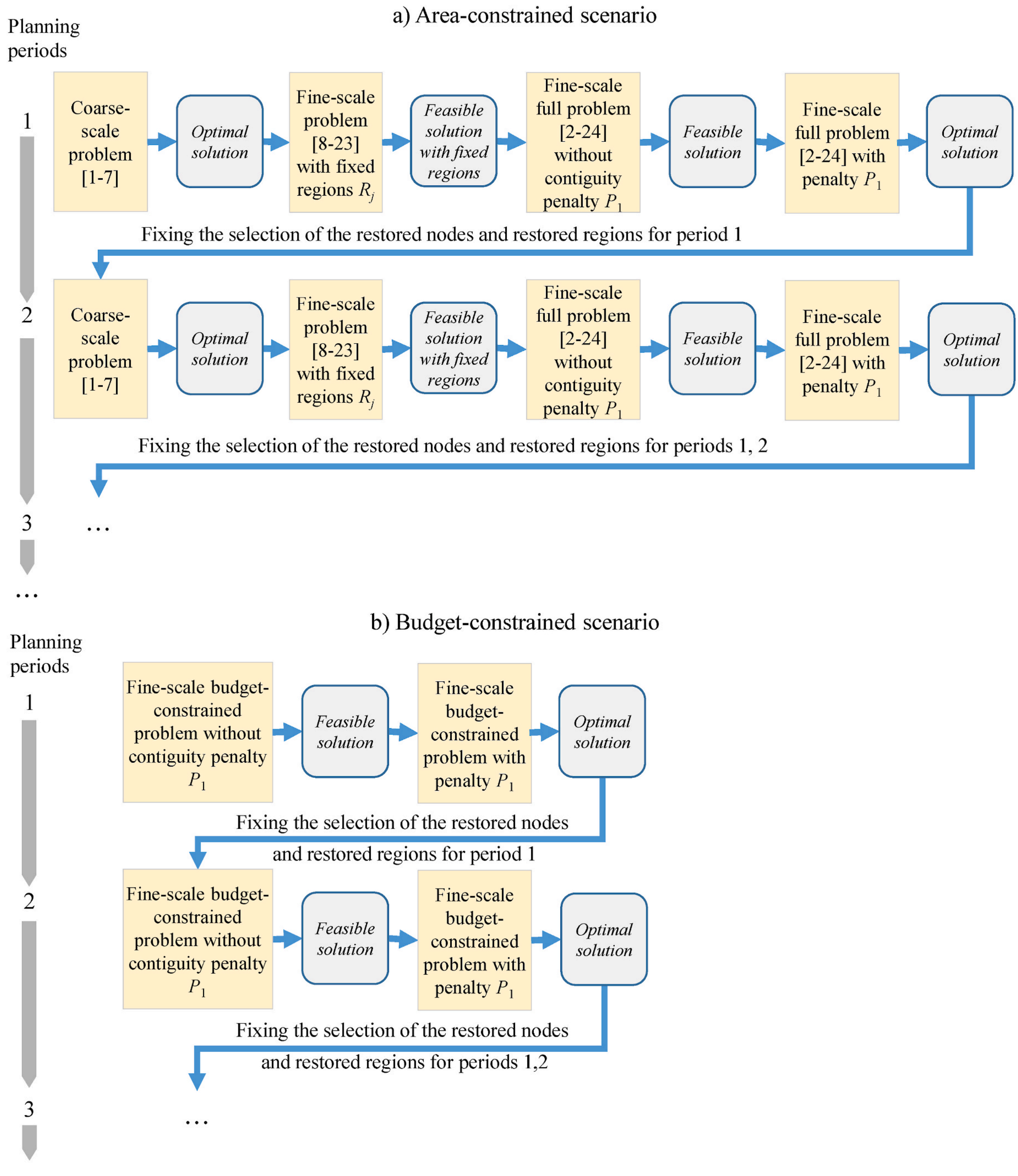

Fig. 5. Sequences of budget-constrained and area-constrained scenarios: a) area-constrained scenario; At each planning period, we first solved the coarse-scale restoration model and used its solution to solve the fine-scale model while keeping the region selection variables R_j fixed. This solution was used as a warm start to solve the fine-scale problem. The fine-scale model was solved first without the contiguity penalties, to find a feasible solution, which is then used as a warm start for the full model; b) budget-constrained scenario sequence.

constrained scenarios revealed distinct restoration strategies (Fig. 8, Table 2). The budget-constrained solutions did not include the coarse-scale habitat connectivity constraints and tended to select multiple restored node clusters in locations with low seismic line densities that were adjacent to large pockets of undisturbed habitat. The area-constrained solutions included the coarse-scale connectivity constraints and so tended to allocate larger contiguous areas with pockets of suitable habitat, but not as effectively as in the budget-constrained solutions (Fig. 9a–c, callout I). To satisfy the area-based constraint and keep the restored area contiguous at both coarse and fine scales, the restored node clusters included some sites with high seismic line densities which the budget-constrained solutions tended to exclude (Fig. 9a and b). The budget-constrained solutions were more cost-effective than the area-constrained solutions (Fig. 9c), but the selected restored node clusters were scattered across the entire landscape (Fig. 8). When selecting the restoration locations adjacent to pockets of undisturbed habitat, the budget-constrained model created twice more disjunct clusters of restored nodes than the area-constrained model (Figs. 8 and 9d, Table 2). While the area-constrained solutions were not as cost-effective as the budget-constrained solutions (Fig. 9c, Table 2), their spatial contiguity and better alignment with the coarse-scale prioritization make them a more practical choice with fewer logistical

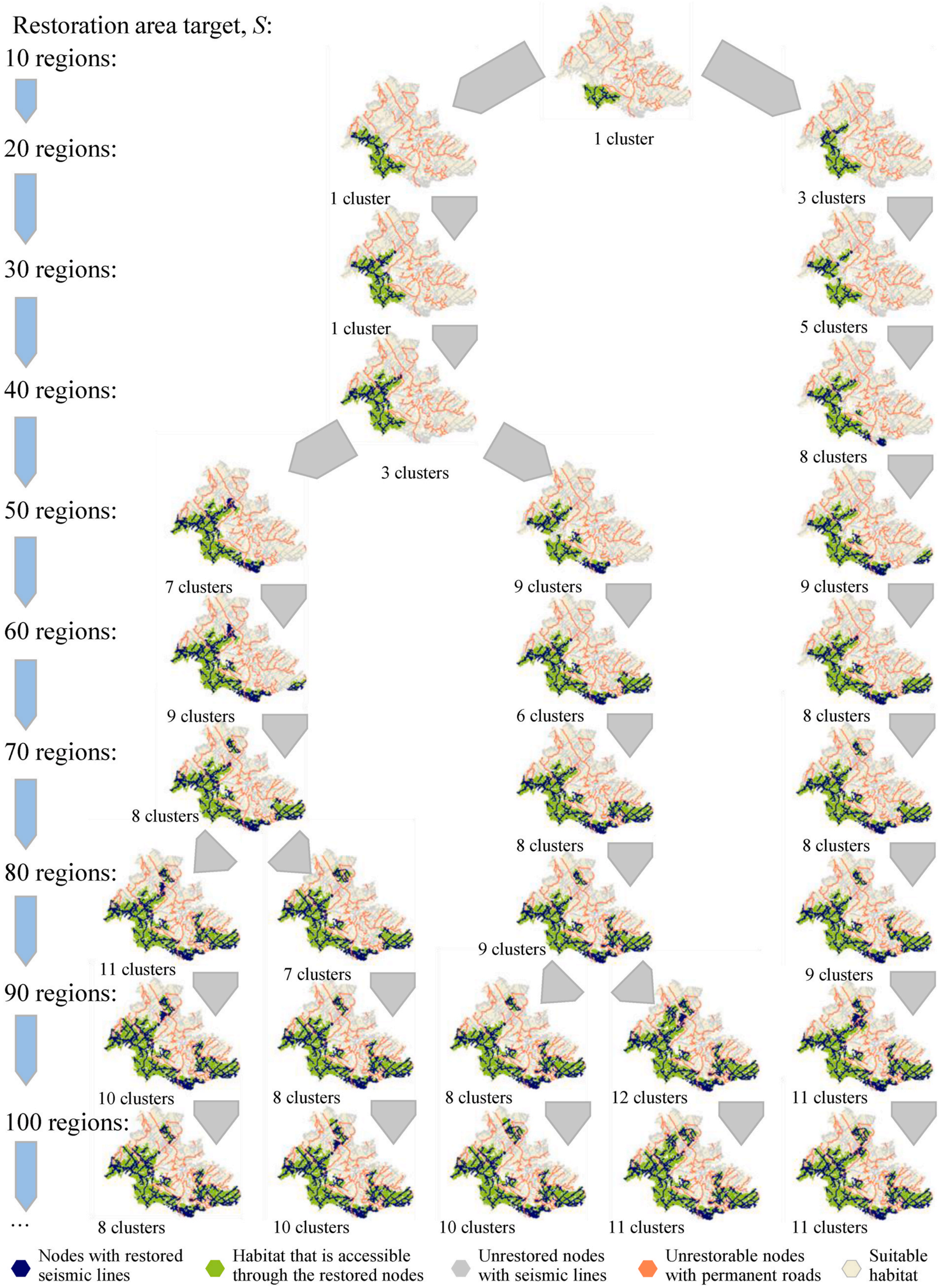

Fig. 6. A trimmed scenario tree for the area-constrained problem in the "roads" scenario (see full scenario tree in Fig.S3.1 in Appendix S3).

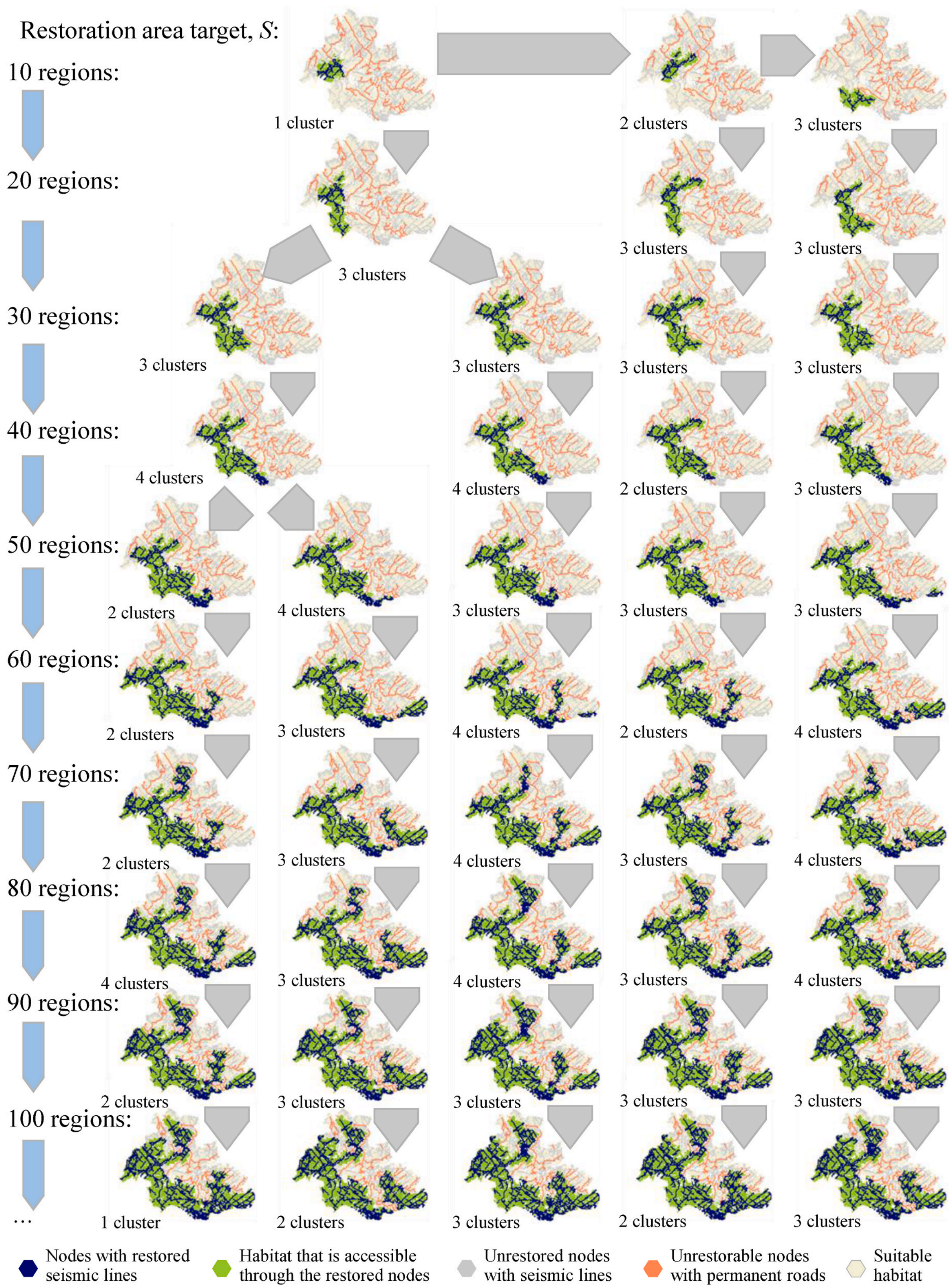

Fig. 7. A trimmed scenario tree for the area-constrained problem in the "no roads" scenario (see full scenario tree in Fig.S3.2 in Appendix S3).

obstacles and resource allocation constraints.

The cost-effectiveness of restoration shows the rule of diminishing returns. In area-constrained solutions, the rule of diminishing returns holds until approximately 450 km of linear features are restored (which is equivalent to a cost of $6M, or approximately 50 regions, Figs. 8 and 9c, Table 2). After this point, the hotspots of eligible features close to the best-quality habitat have been already restored, and restoration moves to areas with higher disturbance densities and poorer habitat overall. The point when the cost-effectiveness curve stabilizes and no longer follows the rule of diminishing returns (Fig. 9c, callout II) is a useful

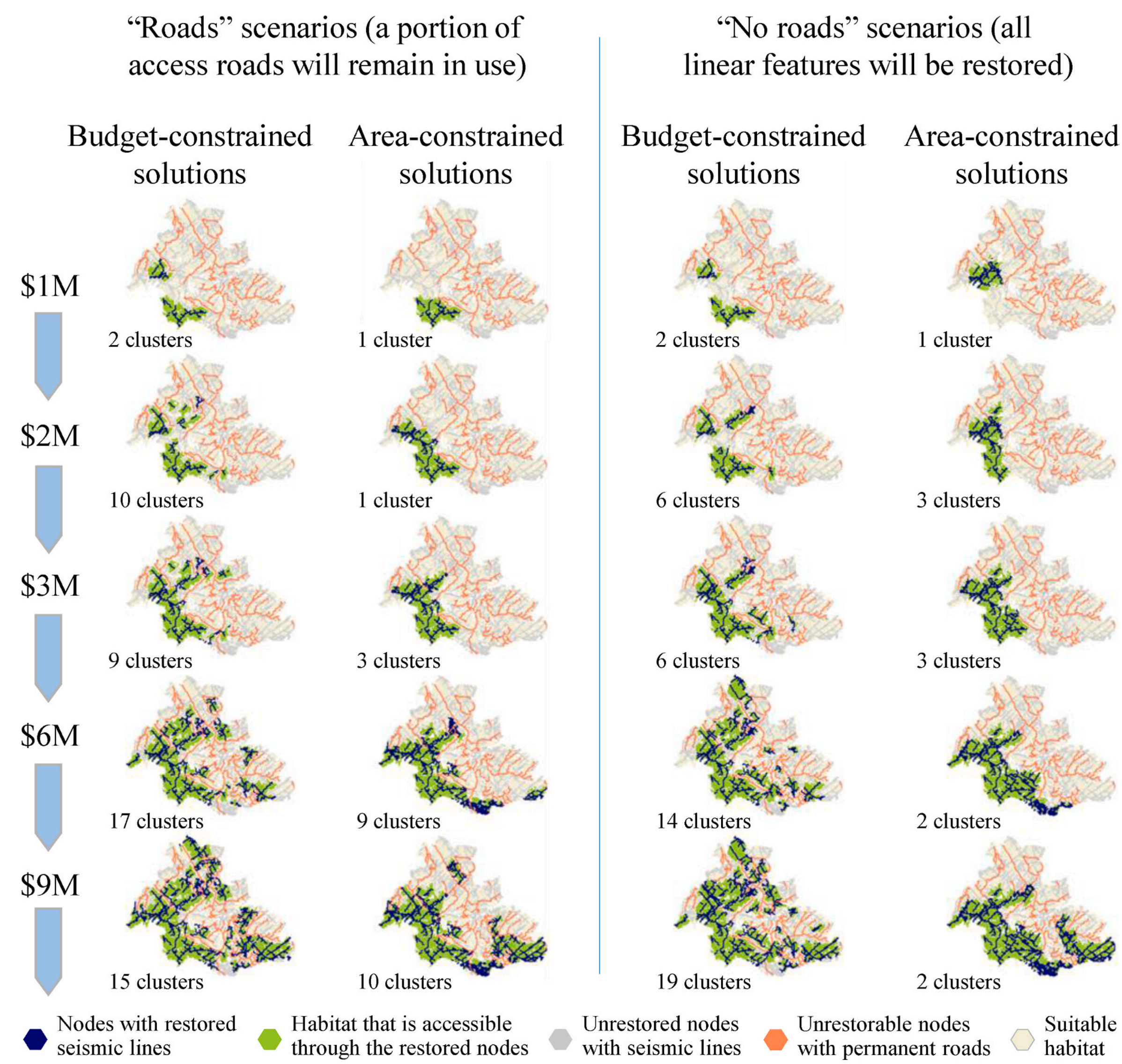

Fig. 8. Budget-constrained vs. the equivalent-cost area-constrained solutions. The sequential scenarios with the approximate restoration budget of $1M, $2M, $3M, $6M and $9M are shown for the "roads" and "no roads" scenarios. The area-constrained scenarios are shown for the sequences with the lowest number of disjunct restoration clusters (i.e., the leftmost branches in the scenario sequence trees in Figs. 6 and 7).

indicator in situations when the decision-maker needs to assess the possible budget range for cost-efficient solutions.

The budget-constrained solutions produced more instances where the restoration of seismic lines from one side of a small habitat pocket left this pocket adjacent to unrestored seismic lines (or roads) on the other side (Fig. 10). Such occurrences are addressed by the penalty P_2, which is meant to restrict the number of habitat pockets with a cross-sectional width of $\leq H_{max}$ nodes that are encircled by seismic lines, but only some of them are restored. The area-constrained solutions show fewer of these occurrences (Fig. 10a) but also lower P_2 penalty values (Fig. 10b) because they create a more contiguous restored space with fewer isolated clusters than the budget-constrained solutions (Fig. 9d). Once the budget limit increases the restoration proceeds to the areas where seismic lines fragment the landscape into smaller pockets of undisturbed habitat and so the P_2 penalty value increases (Fig. 10b).

3.2. Multi-cluster restoration solutions

In areas with high road densities, pockets of undisturbed habitat divided by roads may force managers to restore seismic lines in multiple isolated clusters. For each planning step, we compared solutions aimed at restoring different numbers of node clusters (Figs. 6 and 7). The requirement to keep restoration in as few disjunct clusters as possible reduces cost-effectiveness because it forces the restoration of some nodes with higher seismic line densities to maintain cluster contiguity. However, this reduction is moderate (Fig. 9c and d, Table 2). The impact of decisions regarding the number of restored node clusters was only noticeable in "no roads" solutions with a budget below $3M (Fig. 9c, callout III). As the area with restored seismic lines increases, the number of isolated restored node clusters stabilizes (Fig. 9d callout IV). In a practical context, allowing a larger number of disjunct clusters can be useful in landscapes with a high degree of fragmentation or the presence of natural barriers because it offers flexibility when attempting to establish connectivity between small pockets of habitat divided by areas where restoration is costly or impractical.

3.3. "Roads" versus "No roads" restoration scenarios

The presence of permanent roads in the area reduces the total amount of caribou habitat that can be accessed through the restored sites. This implies that the same amount of habitat that is accessible from the restored sites in the "roads" scenario would represent a higher

Table 2
Summaries of the amounts of habitat, the total costs and the number of disjunct clusters of restored nodes for the budget-constrained and the area-constrained scenario sequences.

	Budget-constrained scenarios					Area-constrained scenarios					
Budget size $	Accessible habitat amount (% of total accessible habitat)[a]	Accessible habitat area, ha	Approx. cost, $M[b]	Cost-effect.[c]	Number of disjunct restored clusters[d]	Number of restored regions, S	Accessible habitat amount[a] (% of total accessible habitat)[e]	Accessible habitat area, ha	Approximate cost, $M[b]	Cost-effectiveness[c]	Number of disjunct restored clusters[d]
	"Roads" scenario										
1M	10,011 (16.1%)	16,010	1.0	9.64	2	10	8744-8745 (14.1%)	13,132–13133	0.91	9.39–9.39	1–1
3M	22,087 (35.6%)	40,145	3.0	6.99	9	30	16,189-17998 (26.1–29.0%)	27,172–31367	2.5–2.7	6.32–6.39	1–5
6M	34,996 (56.4%)	67,374	6.0	5.64	17	50	22,263-26509 (35.9–42.8%)	45,667–48380	5.2–6.1	4.18–4.32	7–9
9M	45,801 (73.9%)	92,289	9.0	4.95	15	80	35,887-37550 (57.9–60.6%)	68,937–73742	8.7–9.3	3.94–4.05	9–11
	"No roads" scenario										
1M	10,036 (9.0%)	15,906	1.0	9.54	2	10	6119-8404 (5.5–7.5%)	11,689–13434	0.98–1.3	4.59–8.26	1–3
3M	21,567 (19.3%)	39,769	2.95	6.93	6	30	20,270-20950 (18.2–18.8%)	35,859–37891	3.4–3.5	5.69–5.84	3–3
6M	35,185 (31.6%)	70,180	5.9	5.74	14	50	28,104-29119 (25.2–26.1%)	52,301–54027	5.9–6.9	4.14–4.68	2–3
9M	46,326 (41.5%)	95,597	8.95	5.00	19	70	38,659-39248 (34.7–35.2%)	77,186–78478	9.7–10.3	3.74–3.94	2–4

[a] Calculated as $\sum^{n\in N}(b_n \sum^{m\in N} z_{mn})$ analogously to objective (8). The value in brackets show the proportion of the total accessible habitat that can be accessed through the restored nodes within $H_{\max}$ distance. The "roads" scenario assumes that a portion of roads will remain in use, hence the total amount of potentially accessible habitat does not include the habitat that can be accessed from permanent roads. The "no roads" scenario assumes that all linear features can be restored, so the total amount of accessible habitat includes the habitat accessible from all linear features (i.e., both seismic lines and roads). The total amount of habitat accessible though all restored nodes was estimated by solving the full problem without the target area constraint (7).

[b] Calculated as $\sum^{n\in N}[c_n(1-\sum^{m\in N} x_{mn})p_{1n}c_{fix}]$ analogously to Eq. (25).

[c] The total amount of accessible habitat divided by the total restoration cost. Higher values indicate better cost-effectiveness.

[d] The penalty value P_1 in Eq. (12).

[e] The total amount of accessible habitat was estimated by solving the full problem with no restored area restriction.

proportion of the total accessible habitat than in the "no roads" scenario (Table 2). In the "roads" scenarios, the restored area was not as compact as in the "no roads" scenarios (Figs. 6–8). Differences between the "roads" and "no roads" solutions were relatively minor in the small-budget solutions but increased once restoration expanded to areas with a higher density of permanent roads (Fig. 8). Permanent disturbances divide the landscape into multiple compartments and force restoration activities into multiple disjunct clusters (Table 2, Fig. 9d). Restoring a disjunct node cluster has a fixed startup cost, hence solutions with a larger number of disjunct clusters have higher costs. This explains the lower cost-effectiveness of the "roads" solutions compared to the "no roads" solutions for the same restored area target (Table 2). Once a significant portion of the area that is adjacent to large pockets of undisturbed habitat is restored, restoration proceeds to heavily disturbed areas and so the cost-effectiveness drops (Fig. 9c). Thus, the optimal strategy is to start restoration from the areas adjacent to the largest pockets of undisturbed habitat near the southwestern border of the range and gradually expand the restored space to encircle the regions with high disturbance densities in the central part of the range, which should be restored at the last step (Figss. 6–8).

4. Discussion

Our two-scale planning approach helps address several important aspects of practical restoration in landscapes disturbed by oil-and-gas exploration and extraction activities, which our previous work (Yemshanov et al., 2022) omitted. First, the use of a coarse-scale planning model to guide restoration activities at the fine scale better aligns with common planning practice where restoration is prioritized first at the scale of coarse landscape units (e.g., ABMI, 2016) and then followed by operational planning at the scale of individual forest sites (Pyper et al., 2014; Cenovus, 2016). Second, our approach addresses the numerical challenge of solving a fine-scale restoration planning problem for large landscapes. In heterogenous landscapes, the budget-constrained model tends to prioritize sites with low seismic line densities that are adjacent to large pockets of undisturbed habitat. While this strategy uses the budget most effectively, it creates a circuitous configuration of pockets of restored sites surrounded by areas with unrestored seismic lines, and so is impractical. In sequential planning, these complex configurations evolve into an unwieldy pattern of restored sites and their further expansion could only be achieved by restoration of the multiple small pockets of seismic lines which were left unrestored during the previous restoration planning steps. At this stage, the budget-constrained problem gets increasingly hard to solve and quickly becomes intractable. Adding the coarse-scale solution and switching to an area-constrained formulation with both coarse- and fine-scale connectivity constraints helps the model to see the "big picture" (i.e., a coarse-scale configuration of the restored area) and find a feasible solution for the fine-scale problem quickly while reducing the time to find the full problem solution.

4.1. *Keeping restoration in contiguous clusters while maintaining access to the unrestored sites*

The requirement to keep restoration in contiguous clusters while maintaining access to unrestored sites greatly increases the problem complexity. However, this is an important aspect of restoration planning in large landscapes, such as in the Redrock-Prairie Creek caribou range.

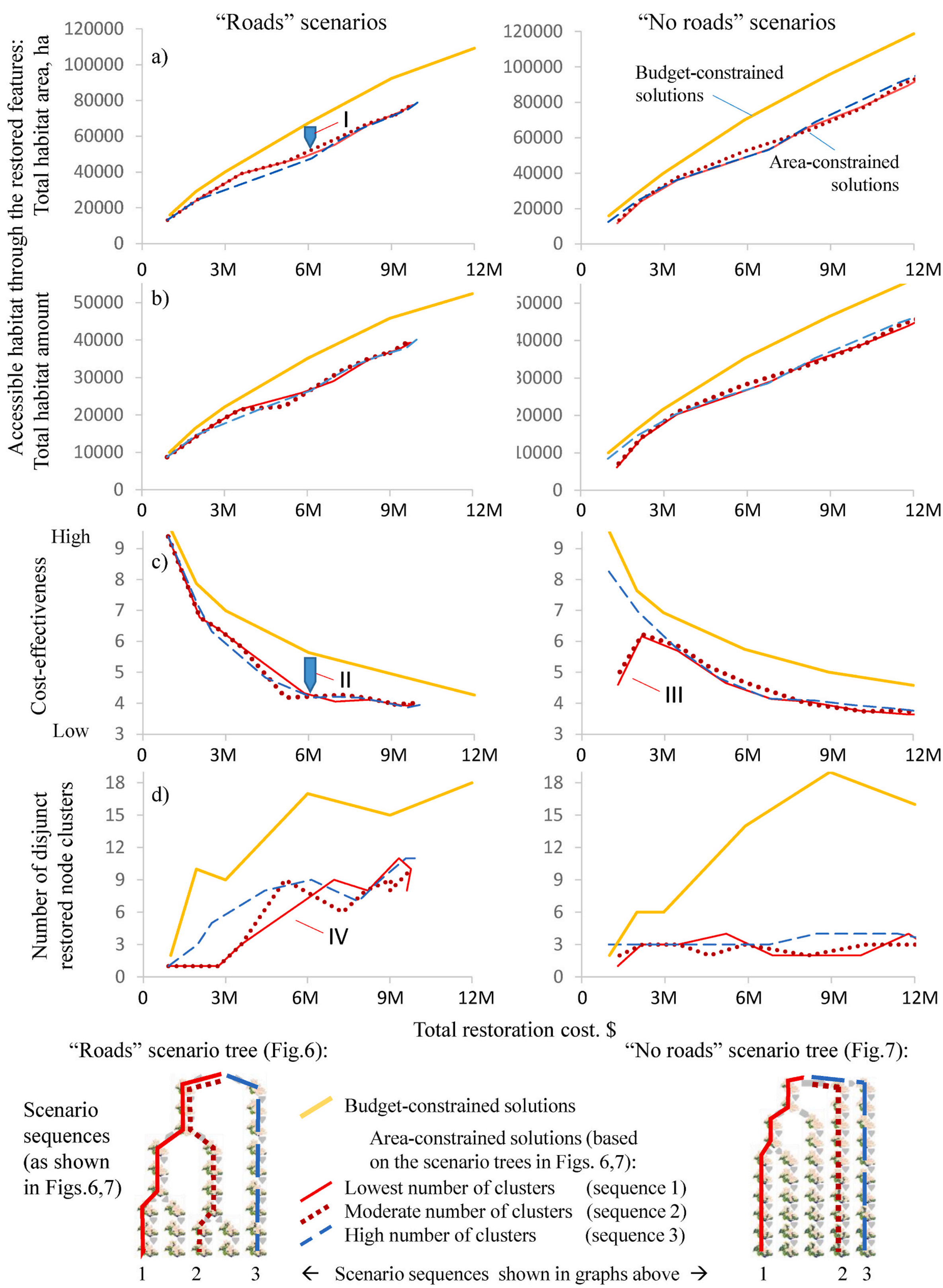

Fig. 9. The amount of habitat that can be accessed through the restored sites, the cost-effectiveness of restoration and the number of disjunct restored node clusters as a function of the total restoration cost: a) the area of undisturbed habitat that is accessible through the restored features vs. the total restoration cost. Callout I indicates the performance of the area-constrained solutions vs. the budget-constrained solutions; b) the total amount of habitat that is accessible through the restored features vs. the total cost; c) cost-effectiveness of restoration (i.e., the total amount of accessible habitat divided by the restoration cost) vs. the restoration cost. Callout II indicates the budget size when the cost-effectiveness levels off and no longer follows the rule of diminishing returns. Callout III shows the low budget "no roads" solutions which are forced to create one-two contiguous clusters; d) the number of disjunct restoration node clusters vs. the total restoration cost. Callout IV shows the point when the number of restored node clusters tends to stabilize.

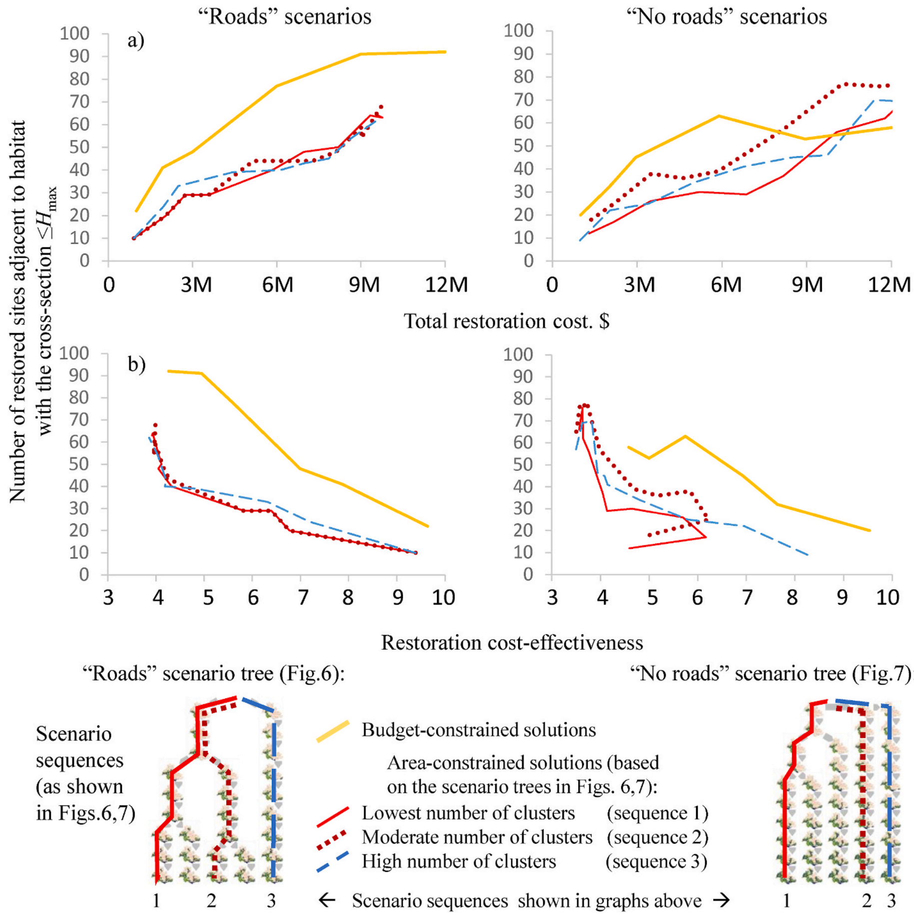

Fig. 10. a) The impact of penalty P_2, as represented by the number of cases where the restoration of seismic lines from one side of an undisturbed habitat pocket leaves this pocket adjacent to unrestored disturbances within $\leq H_{max}$ nodes on its other side (Y-axis) vs. the total restoration cost (X-axis); b) the impact of penalty P_2 (Y-axis) vs. cost-effectiveness of restoration (X-axis).

Managing access to unrestored sites is important in sequential planning, when a decision-maker aims to avoid blocking access to remnant pockets of unrestored sites which may be restored at a later stage. Our solutions ensure that the unrestored and non-restorable features remain accessible after a portion of sites with seismic lines is restored.

4.2. Local access to habitat as a metric of restoration success

Our model emphasizes the amount of undisturbed habitat that caribou can access *locally* when moving through the restored sites. The concept of local access to habitat (as defined by the access depth H_{max}) emphasizes the capacity of caribou to utilize the restored sites to travel between undisturbed habitats at a reduced risk of predation compared to moving through an unrestored open space. This required estimating the local access to habitat through each node that was a potential candidate for restoration, which further increased the numeric complexity of the problem. Potentially, the problem can be simplified by estimating the approximate amount of habitat accessible *locally* through a restorable node n within radius H_{max} and using this habitat amount as an attribute of node n instead of finding the subgraph of H_{max} habitat nodes connected to n. However, this approach would overestimate the amounts of accessible habitat when a cluster of adjacent nodes is restored because the habitat areas associated with each of the adjacent nodes within H_{max} radius would overlap. We addressed this issue by tracking the non-overlapping subgraphs of the connected habitat nodes but, as noted, this came at the cost of higher complexity.

4.3. Coarse-scale prioritization vs. other priority schemes

Compared to previous prioritizations of seismic line restoration activities in the area (ABMI, 2017, 2020), our model used smaller restoration regions j (i.e., 11.8 vs. 25 km^2). While the locations of coarse-scale priorities are in general agreement with previous prioritizations by the Alberta Biodiversity Monitoring Institute (ABMI, 2017, 2020), our coarse-scale model solutions provide a better account for the practical needs to manage the restored area as a contiguous space. Potentially, the maps depicting the habitat amounts B_j, the seismic line restoration costs and the cost-effectiveness of restoration (in Fig. 4) could guide other strategic prioritizations. Alternatively, the prioritizations based on multi-criteria ranking, e.g., ABMI (2020), could be enhanced by adding the constraints to maintain the connectivity of the priority areas. Previous prioritizations (such as ABMI, 2017, 2020) were limited to a static aggregation of multiple spatial parameters (such as the presence of suitable caribou habitat, the proportion of human disturbances, or the presence of oil and gas deposits) and did not control the spatial properties of the selected priority areas (such as contiguity of the restored and unrestored areas or spatial links to critical migration corridors). This aspect would require solving the connectivity problem analogous to our coarse-scale model (1)–(7). A strategic prioritization, such as that done by ABMI (2020) could potentially be linked to our model if it is formulated as a connectivity problem. Furthermore, our approach can be used to make high-level restoration policies operationally feasible at the fine scale, for example, keeping the restored area contiguous at a broad scale while allowing multiple restoration projects at a fine scale to account for local landscape heterogeneity and operational limitations.

Potentially, our coarse-scale regional model could utilize another performance metric that incorporates economic criteria, for example, the value of oil-and-gas deposits or the extent of human disturbances (ABMI, 2016, 2017). These criteria could also be formulated as masking constraints aimed to exclude some locations with poor ratings from the restoration plan. Adding other criteria that characterize the habitat quality in the restored areas, such as the feasibility of restoration based on edaphic site conditions or the degree of overlap between caribou and predator habitats (ABMI, 2016; Finnegan, 2018), could adapt the model to develop more balanced restoration strategies that account for both conservation goals and economic objectives.

Effective recovery of caribou populations in landscapes disturbed by hydrocarbon extraction requires coordination between site-specific restoration activities and coarse-scale assessments at the caribou range scale (Ray, 2014). While federal and provincial caribou recovery policies prescribe range-scale planning to guide caribou habitat restoration (EC, 2012; GoA, 2017), most restoration efforts are undertaken at the scale of individual forest patches (or, in some cases, individual seismic line segments). Accordingly, our optimization-based approach provides the capacity for integrative planning at both the scale of forest patches and at the landscape scale. In addition, it facilitates accounting for complex spatial trade-offs between various biophysical, economic and operational constraints, which makes it a promising tool to support the planning of large restoration programs, such as under the new restoration framework of the province of Alberta (GoA, 2017).

4.4. Potential model extensions

For small landscapes, our sequential single-period model can be updated to a multi-period formulation to account for the temporal dynamics of human use of the area. However, for large landscapes, a fine-scale multi-period problem would be numerically intractable. The problem size could be reduced by using nodes of different size, such as aggregating nodes in the core habitat areas or combining multiple adjacent nodes with seismic line into longer segments. However, these transformations would increase the workload to prepare the network sets Ω, Γ and Ξ and would require careful judgment with respect to the scale of spatial aggregation.

Our formulation did not consider the spatial variation of site quality and the likelihood of seismic line restoration success. Site conditions may evolve over time due to changing climate, which is likely to influence the success of restoration efforts. Potentially, restoration success rate could be included in the model to adjust the restoration efficiency and costs in a node n due to changes in climate or other environmental factors.

Author contributions

DY conceived the research, secured the funding, wrote the model and the first draft; DY, FK and AP developed the study; NL prepared the network-based datasets; MS performed the modeling experiments; AP, VH and CM prepared the geospatial input data; EN developed the caribou habitat suitability model, AP, CC and GD contributed the scenario development; all coauthors contributed to editing the manuscript.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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Supplementary data

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