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Implementation resistance and the human dimensions of connectivity planning

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Abstract

1. Conserving species' ability to traverse the landscape is vital for maintaining biodiversity in the face of global change. Connectivity conservation requires identifying important pathways for species' movements and aligning societal support for conservation of those pathways. Contemporary connectivity analyses emphasize the impacts of topography, vegetation and human footprint on species' movements; but largely ignore the role that attitudes, economics and institutions play in practitioners' ability to conserve those movements.
2. We introduce implementation resistance as an analogue of biophysical resistance that combines social, economic and institutional factors that promote or impede connectivity conservation. We demonstrate the utility of integrating implementation resistance as a means of choosing between competing connectivity conservation strategies using wolves in Colorado (USA) as a case study.
3. Our analysis of five potential corridor locations based on biophysical costs revealed substantial differences in the social costs associated with implementing each corridor despite relatively minimal differences in the biophysical costs.
4. Our comparison of hypothetical interventions to reduce implementation resistance illustrates that interventions that reduce conflicts between land use and wolves may substantially reduce overall resistance, those reductions are not as well aligned with connectivity priorities as those resulting from changes in land management agency policy.
5. Our results highlight the need to design conservation interventions that fit both the social and ecological landscape and provide a framework for developing robust, interdisciplinary methods that facilitate implementable connectivity conservation.

KEYWORDS
circuit theory, conservation social science, human dimensions, institutional capacity, least-cost path, wildlife connectivity

1 | INTRODUCTION

Most of the Earth's land consists of shared landscapes, where human settlements and intensive agriculture are interspersed with areas of high biodiversity value (Ellis, 2019). In these complex landscapes, conservation practitioners focus increasingly on maintaining or restoring ecological connectivity as a key biodiversity conservation and climate adaptation strategy (Heller & Zavaleta, 2009; Littlefield et al., 2017; Nuñez et al., 2013). The substantial growth in connectivity conservation plans reflects this growing emphasis globally (Keeley et al., 2019). Contemporary efforts to model connectivity focus on identifying how variation in biophysical elements of the landscape and their spatial juxtaposition restrict or alter movement into order to identify key locations for conservation or restoration (Dickson et al., 2019; Whittington et al., 2022). Conserving connectivity, however, requires not only identifying the most important pathways that species will traverse but also designing interventions that are likely to be supported by people affected by those conservation interventions (Epstein et al., 2015). Designing connectivity conservation strategies with people in mind necessitates an approach capable of integrating social and ecological dimensions in ways that facilitate scenario testing and actionable decision-making. Here, we introduce an analytical framework for integrating the optimal movement pathways through a biophysical landscape with the sociopolitical costs associated with conserving those pathways. We argue this approach will lead to connectivity conservation institutions that better align with the interests, values and needs of people (i.e. social fit) while also addressing the spatial, temporal and functional characteristics of species movement (i.e. ecological fit, Epstein et al., 2015). Improving the social–ecological fit of connectivity conservation institutions is vital given the increasingly human-influenced, sociopolitically fragmented landscapes that prevail worldwide.

Connectivity conservation is rooted in fundamentals of island biogeography (MacArthur & Wilson, 1967) and metapopulation dynamics (Hanski, 1994). Large, connected habitats should permit greater diversity and reduce the likelihood of population extinction. Initial efforts to characterize isolation focused on the presence of biogeographic barriers and the role of dispersal distances in determining the degree of isolation between patches (McRae, 2006). Patch area and simple metrics of isolation, however, are often poor predictors of population dynamics (Prugh et al., 2008; Taylor et al., 1993). Recognition that landscape heterogeneity leads to spatial variation in movement pathways coupled with an exponential increase in the availability of datasets describing that heterogeneity has facilitated increasingly sophisticated approaches for determining if/how habitats remain connected based on the costs of moving across the landscape (Cushman et al., 2010). Estimates of the relationship between landscape features and the costs of movement have been developed using generic assumptions (e.g. Belote et al., 2016; Theobald, 2013), expert opinion (e.g. Dickson et al., 2013) and animal travel times and based on telemetry (e.g. Zeller et al., 2014). In many contemporary connectivity conservation plans, practitioners rely on models that incorporate spatial depictions of these costs to anticipate species' movements to identify areas where substantial connectivity exists or where targeted restoration might improve connectivity (McRae et al., 2012; Panzacchi et al., 2016; Peck et al., 2017).

Implementing the conservation interventions necessary to conserve or improve connectivity in shared landscapes, however, requires reconciling the needs of biodiversity (e.g. identified via connectivity models and plans) with the politics of a place (Agrawal & Redford, 2009) and the preferences, values, and demands of human actors (Epstein et al., 2015). Indeed, the willingness and capacity of society to adopt conservation interventions vary across space, and often independently of the biophysical value of an intervention (Neeson et al., 2015). The importance of many of these social dimensions is evident in a variety of conservation planning approaches (e.g. systematic conservation planning, structured decision-making; Schwartz et al., 2018) which attempt to identify optimal conservation actions given a suite of objectives and costs. These approaches, however, do not readily accommodate the complex spatial dependence, dynamic ecological flows, or social–ecological interactions inherent in connectivity conservation especially across broad spatial extents (Daigle et al., 2020). Despite being critical to conservation success, the integration of social factors into the conservation connectivity models that underlie connectivity conservation plans is lacking.

Although the assumptions and objectives underlying analysis of biophysical models of connectivity and assessments of social–ecological fit vary, they rely on the methodological foundations of graph (or network) theory to understand how the structure of networks affects their function (Bodin, 2017; Bodin & Crona, 2009; Rayfield et al., 2011). Biophysical connectivity analyses use least-cost or circuit-theoretic algorithms that explicitly incorporate the impacts of landscape heterogeneity outside of habitat patches to identify potential movement pathways among source and destination areas and estimate the centrality of source patches in a network. Similarly, assessments of social–ecological fit apply network algorithms to characterize repeated patterns of connections between actors (Bodin & Crona, 2009; Guerrero et al., 2015) and the degree to which the strength of connections across actors facilitates access to information, sharing of resources, collaborative management, or resilience to environmental change (Barnes et al., 2019, 2020). Wildlife connectivity analyses focus on the physical process of moving across the network in a spatially explicit way while social–ecological fit analyses focus on network structures that treat space implicitly or rely on measures of adjacency. Although the role of scale in both ecological and social networks remains an important consideration (e.g. Cash et al., 2006; Laliberté & St-Laurent, 2020), their shared methodological foundation provides a means of integrating the two in a way that addresses calls for more integration of social and ecological data in conservation planning (Carter et al., 2020; Ghoddousi et al., 2021). Moreover, overcoming sociopolitical and institutional barriers to connectivity conservation is likely to require governance networks to soften spatial boundaries in existing institutional (e.g. land tenure, management jurisdictions) arrangements (Cash et al., 2006; Fischer, 2018). Finally, emergence of the study of the landscape ecology of institutions provides a coherent framework for integrating ecological and institutional landscapes into the same analysis (Cumming & Epstein, 2020).

Spatially explicit integration of the biophysical costs of movement with the sociopolitical costs of conservation interventions is particularly important for connectivity conservation. Although any single intervention may improve connectivity locally, failing to implement all (or most) of the necessary interventions along the entirety of an identified corridor or movement pathway may result in ecological dead ends where large portions of a habitat (or protected area) network remain inaccessible to organisms unable to access those locations without traversing the human-dominated matrix (Guerrero et al., 2015; Runge et al., 2014). As such, the cumulative biophysical (e.g. energetic and mortality risk) and implementation (e.g. sociopolitical and economic) costs of the completed route rather than that of any individual patch is the relevant cost to minimize (Etherington & Holland, 2013). Resistance surfaces, two-dimensional lattices (i.e. rasters) that capture the costs of moving across the landscape, provide the foundation for estimating these costs for biophysical analyses of connectivity (Fletcher Jr et al., 2019; Sawyer et al., 2011; Zeller et al., 2012). These resistance surfaces typically capture costs to the animal (e.g. energy used, time spent, opportunities lost and exposure to mortality risk). The logic of resistance surfaces could be extended to incorporate the sociopolitical costs that practitioners face when trying to implement connectivity conservation due to the spatial arrangement of the formal and informal institutions that govern wildlife conservation (Cumming & Epstein, 2020) to permit estimation of the cumulative costs (in terms of social or political capital) of conservation and facilitate analyses of the trade-offs associated with different connectivity conservation strategies.

We describe an approach for integrating the concepts of social–ecological fit into connectivity conservation planning by leveraging the shared reliance on graph theory for estimating wildlife connectivity and characterizing social–ecological fit. We introduce implementation resistance as an extension of the biophysical resistance concept that underlies the bulk of contemporary connectivity modelling. Just as biophysical resistance surfaces attempt to represent the cost of movement across the landscape by integrating biophysical elements and anthropogenic factors (Zeller et al., 2012), implementation resistance attempts to capture the sociopolitical costs that make the enacting of conservation difficult. We use a case study based on grey wolf (*Canis lupus*) conservation in the US Rocky Mountains to illustrate a variety of metrics that can aid practitioners in identifying corridors that are both biophysically important and sociopolitically feasible. Finally, we clarify how implementation resistance can help researchers and practitioners facilitate a more systematic, transparent evaluation of the trade-offs between different conservation interventions.

1.1 | Societal impacts on connectivity

Implementation resistance extends the ideas of biophysical resistance to consider the 'costs' a conservation practitioner may face in trying to move from connectivity planning to action. Just as topography or land cover may make parts of the landscape more costly for an animal to move through, the spatial juxtaposition of ecological, institutional and social factors makes some locations sociopolitically more costly than others for implementing conservation actions (Williamson et al., 2018). Although these factors may not affect the costs an animal incurs as it moves across the landscape, they affect the sociopolitical environment that conservation practitioners must navigate in their attempts to translate connectivity conservation plans to actions (i.e. achieve social fit). Implementation resistance surfaces provide a means for understanding how these costs accumulate along routes between habitats and allow synoptic assessment of biological and social trade-offs associated with potential conservation actions to achieve social–ecological fit (Figure 1). We outline several key societal factors to consider as a starting point for building implementation resistance surfaces including: human values and attitudes, economics and institutional capacity.

Conservation emerges from the values and attitudes that people hold in relation to particular species or places, and their governance preferences (Kinzig et al., 2013). For example, routing corridors through portions of the landscape where human attitudes towards a species are negative may result in higher human-induced mortality for individuals of that species (Carter et al., 2012, 2014). Similarly, community cultural norms may preclude conservation interventions that affect individual property rights in some areas (Inwood & Bonds, 2017; McCurdy, 1984). While outreach and education can be used to change local values and norms to support conservation efforts, we argue that incorporating these considerations directly into connectivity modelling at the outset will improve conservation outcomes and ease of implementation. Spatially explicit estimates of values and attitudes are increasingly available for wildlife (Manfredo et al., 2021), climate change policy (Howe et al., 2015), and ecosystem services (Faccioli et al., 2020) making it possible to incorporate these abstract concepts into connectivity models more directly.

In addition to social support for connectivity interventions, the economic feasibility of protecting biophysical corridors may mean altering their paths to avoid expensive parcels or incompatible land uses (Parrott et al., 2019). The growth of conservation planning approaches that maximize the conservation return on investment reflects the impact of economics in determining where conservation happens (Boyd et al., 2015). Land prices provide one means of incorporating the direct cost of connectivity conservation into planning efforts by trying to optimize connectivity benefits and land purchase costs (Armsworth et al., 2020; Naidoo et al., 2006; Nolte, 2020). Unlike protected area designation, additional opportunities for connectivity conservation may be possible without outright purchase of the parcel. For example, forest management can be adjusted to maintain particular habitat configurations or reduce road development along important movement pathways (Williamson et al., 2020). Targeting parcels of land for wildlife-friendly management may avoid costs associated with parcel purchase; however, regional dependence on natural resource-based economic sectors (e.g. forestry, mining or outdoor recreation; Ford et al., 2020) may

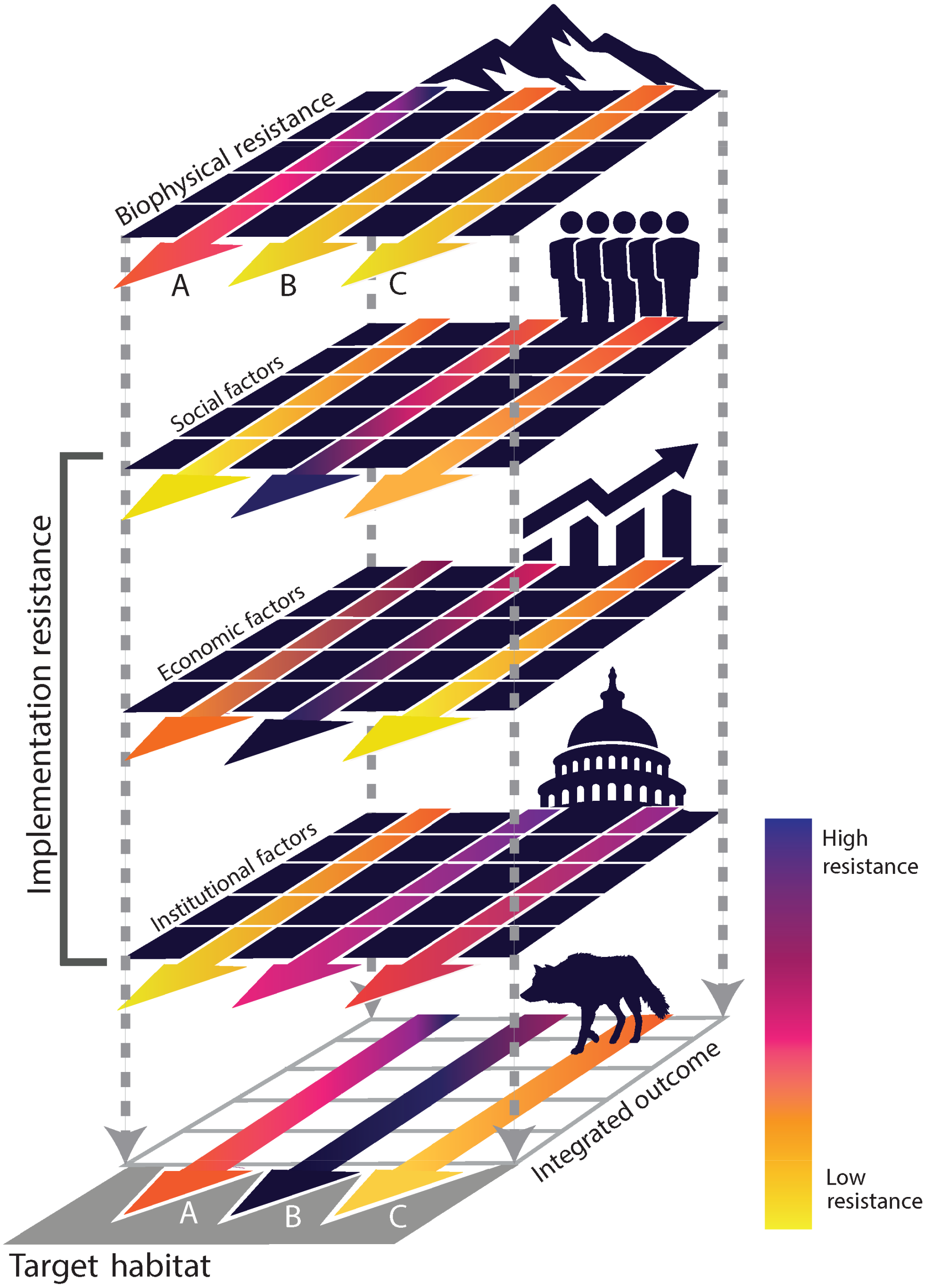

FIGURE 1 An illustration of how the spatial arrangement of social, economic and institutional factors (i.e. implementation resistance) combine to alter the relative priority of different biophysical linkages. Paths B and C are equally viable linkages with respect to their biophysical resistance (i.e. they provide ecological fit); however, variation in the factors that comprise implementation resistance suggests that paths A and C achieve greater social fit than path B. Integration of biophysical resistance with implementation resistance illustrates that path C provides the greatest social–ecological fit and is likely the most appropriate choice for conservation practitioners. We have depicted each resistance surface as a stylized raster with equal resolutions. In practice, these may vary depending on the scale of data collection and the nature of sociopolitical boundaries.

create important opportunity costs that constrain where connectivity conservation occurs (Naidoo et al., 2006; Schneider et al., 2011). Incorporating both acquisition and opportunity costs is component of systematic conservation planning for protecting habitats (Schneider et al., 2011). By integrating acquisition and opportunity costs into implementation resistance surfaces and applying connectivity modelling frameworks, we can assess and minimize the accumulation of costs along the entirety of the route.

Finally, institutional arrangements and the capacity of management agencies can affect the conservation of connectivity as preserving species' ability to move requires restoring or maintaining linkages across large portions of a species' range which span multiple jurisdictional or political boundaries (Smith et al., 2016). Developing cohesive conservation strategies across these political boundaries requires coordination and action by multiple government actors. Consider the plains bison (*Bison bison*) whose status changes from wildlife to livestock, from endemic to extirpated, and pest to cultural icon simply by crossing the socially constructed borders of US states, Canadian provinces, and Indigenous territories (Gates et al., 2010; Hessami et al., 2021). The authority for managing species' movements or coordinating with other jurisdictions may be unclear or lacking in these cross-boundary situations, creating important implementation barriers due to institutional capacity and characteristics regardless of social support (Cumming & Epstein, 2020). Capacity limitations are compounded in multi-jurisdictional landscapes where disparate budgets, the presence of competing mandates, constituencies, and tenure agreements require substantial coordination (Cumming & Epstein, 2020; Runge et al., 2014; Stahl et al., 2020). Recent efforts to map the institutional landscape with respect to capacity (e.g. budgets or employees [Williamson et al., 2018] or legal authority [Stahl et al., 2020]) provide a starting point for understanding how jurisdictional fragmentation affects our ability to conserve important linkages. These efforts could be further expanded by applying fragmentation metrics from landscape ecology to characterize the effects of the spatial juxtaposition of these different jurisdictions and the variation in their missions, mandates and capacities.

2 | METHODS

We illustrate the construction of implementation resistance surfaces and their integration into connectivity conservation planning using wolves in the central Rocky Mountains of the United States as a case study. After listing under the US Endangered Species Act in 1978, efforts to recover the species in the United States led to their reintroduction in Yellowstone National Park in 1995. Those reintroduced populations eventually expanded into the states of Idaho, Washington, Oregon and California resulting a variety of societal responses. Years of contentious debate about wolf management in Idaho recently culminated in the state's legislature passing a bill in 2021 removing the limit on the number of wolves that can be hunted with a licence. Motivating this decision was antagonism towards wolves by some interest groups who argued wolves negatively impacted livestock production and populations of game species that people hunted. In contrast, residents of the state of Colorado voted to require the Colorado Parks and Wildlife Commission to develop a plan to reintroduce wolves to the western portion of the state. Voting patterns were linked to political support for presidential candidates in 2020 and participation in game hunting, indicating that sociopolitical factors can underlie behaviours towards wildlife (Ditmer et al., 2022). Although wolves have proven capable of navigating the biophysical landscape, the sociopolitical landscape has been historically much more difficult to traverse making the issue of identifying where connectivity conservation achieves socioecological fit a key consideration for conservation practitioners.

Our goal with this case study is to illustrate an approach for exploring the effects of social, economic, and institutional factors on connectivity conservation rather than identifying the exact locations of quality wolf habitat or the connections between those locations. We treat Yellowstone National Park (MT/WY) and Weminuche Wilderness Area (CO) as the nodes/cores to be connected in this analysis due to Yellowstone's status as the founder population for wolves in the western United States and the Weminuche Wilderness status as the largest (~202,000 ha) federally designated wilderness area within the potential reintroduction area. Maintaining or enhancing connectivity between the Colorado population(s) and the Yellowstone population should help prevent reintroduced wolves from being genetically isolated from the remaining populations. By integrating implementation resistance with the oft-used biophysical resistance surface, we quantify the accumulation of sociopolitical costs along important linkages, evaluate trade-offs in terms of both potential connectivity and feasibility, identify locations where connectivity conservation is both important and implementable and explore the ability of hypothetical conservation interventions to implementation resistance.

2.1 | Building implementation resistance surfaces

We characterized the biophysical resistance of our study area using Theobald's (Theobald, 2013) human modification index (HMI) and the slope as these two sources of resistance are common in several multispecies connectivity modelling efforts in the United States (Belote et al., 2016; Dickson et al., 2017; Theobald et al., 2012). The HMI is a quantitative, empirically based estimate of landscape integrity designed for landscape-level assessments that combines multiple potential stressors (e.g. residential development, roads, energy development) into a single index (ranging from 0 to 1) using a fuzzy sum approach to account for compensatory and additive effects of human impacts on land use and land cover (Theobald, 2013). We used a similar approach to construct implementation resistance surfaces that depict the ability for practitioners to successfully conserve a route. We include the fair market value of land (Nolte, 2020) for private lands as land cost is an oft-cited factor in determining where conservation occurs and is frequently incorporated in many spatial conservation planning algorithms. We included differences in federal organizational mandates by creating an additional surface depicting the degree to which the land management agency has a stated connectivity or conservation mandate (Table 1). We integrated the potential challenges that arise from conflicting land use based on the value of livestock sales for each county as connectivity for predators is likely to be viewed negatively in areas of high livestock productivity (USDA National Agricultural Statistics Service, 2017). Finally, we considered social support for wolves by generating US Census tract-level post-stratified estimates of the proportion of the population within a tract that responded that

TABLE 1 Resistance values used for lands managed by federal agencies in the case study region. The US Department of Agriculture's Forest Service was given the lowest value as they are the only agency with a national mandate to plan for connectivity (giving them the most institutional capacity to implement connectivity conservation). Slightly higher resistance values were given to agencies whose mission includes the conservation of species, but that lack any formal policy for maintaining or conserving connectivity. Moderate resistance values were given to agencies with multiple use mandates that may prioritize the production of other natural resources at the expense of wildlife connectivity. Highest values were given to agencies whose priorities do not include natural resource management of any kind.

Agency	Area (ha)	Resistance value
Bureau of Land Management	24,182	0.8
Bureau of Reclamation	17,063	1
Department of Defence	1626	0.7
Department of Energy	83	1
Fish and Wildlife Service	33,719	0.3
Forest Service	32,327	0.2
National Park Service	25,393	0.3
Natural Resource Conservation Service	309	0.5

they would prefer to see wolf populations increase over the next 5 years (all participants provided written consent via the web survey; UBC Behavioral Research Ethics Board protocol H19-02427 and Boise State Institutional Review Board protocol 090-SB20-141; Supporting Information). These factors represent starting points for our hypothetical example analysing the role that the spatial configuration of institutions shapes implementation, the choice of which variables are appropriate for a given region may vary for different species/conservation practices. Data for elevation, HMI and housing prices were available at 90, 270 and 480 m, respectively, and were aggregated to 1-km resolution using bilinear interpolation. Data for county-level cattle sales, public land ownership and census tract-level wolf opinions were available as vectors and converted to 1-km rasters. We chose 1-km resolution to facilitate combination of the data as described below and reduce computation time for a multi-state analysis.

We combined the land use conflict, institutional capacity and social support surfaces into a combined social cost index (SCI) by normalizing each surface to a 0:1 range. We used a fuzzy sum algebraic approach to combine the implementation layers following Theobald (2013):

$$B_{\text{sum}} = 1.0 - \Pi_{j=1}^{k}\left(1 - b_i\right)$$

where the value (B_{sum}) at each cell, i, is based on the scaled values (b_i) for $j = 1 \ldots k$ data layers with values ranging from 0.0 (no cost) to 1.0 (high cost). The fuzzy sum method ensures that values for the combined surface were at least as high as the largest contributing cell, without exceeding one (Theobald, 2013). We then created the biophysical and implementation resistance surfaces following Dickson et al. (2017) wherein:

$$R_{\text{biophys}} = (1 + \text{HMI})^{10} + \text{slope} / 4$$

We treated land value similar to elevation, as land value refers to an actual quantity (not an index) and we wanted to maintain the resistance structure used in the biophysical surface for the purpose of this example. Hence, implementation resistance was estimated as:

$$R_{\text{implement}} = \left(1 + B_{\text{sum}}\right)^{10} + \text{land value} / 4$$

2.2 | Metrics for integrating biophysical and implementation resistance

We imagine that conservation practitioners make decisions about connectivity conservation strategies based on the costs (both biophysical and sociopolitical) and probability of success (in terms of both successful dispersal and successful conservation of dispersal paths). As such, we combined least-cost corridor analysis, which assesses the cumulative costs of all paths between two nodes (Adriaensen et al., 2003), with circuit-theoretic analysis, which produce current densities analogous to the probability that a random walker passes through a pixel connecting two nodes (McRae et al., 2008), to understand the potential implications of implementation resistance on wolf connectivity. All least-cost corridor analyses and data preparation were conducted in the R Environment for Statistical Computing (R Core Team, 2021) using the raster (Hijmans, 2022), gdistance (van Etten, 2017) and igraph (Csardi & Nepusz, 2006) packages. All circuit-theoretic analyses were conducted in Julia (Bezanson et al., 2017) using the Circuitscape package (Anantharaman et al., 2020).

2.2.1 | Choosing among competing corridors

Connectivity conservation planning often focuses on identifying key 'corridors' for wildlife movement. Although corridors may not encompass the entirety of the landscape that provides connectivity or fully reflect the movement process, they do provide areas with discrete boundaries where management and policy interventions can be focused to conserve important routes for species movement. Least-cost corridor analysis typically involves identifying the least-cost path (based on biophysical resistance) and then buffering that path by either a fixed distance or a resistance threshold (e.g. Beier et al., 2009; LaRue & Nielsen, 2008).

To reflect a conservation planning scenario wherein practitioners must choose between competing corridors, we identified five distinct least-cost corridors by iteratively estimating the least-cost path, buffering by 4000 m (sensu Ford et al., 2020) and updating the resistance surface such that the least-cost path identified in the previous step was given a high resistance value. This approach allows identification of biologically relevant least-cost corridors while ensuring that each represented a distinct corridor choice.

2.2.1.1 | *Estimating corridor conservation costs*

To illustrate the trade-offs involved in conserving the five least-cost corridors, we compared each corridor based on both their ease of implementation and their biological efficacy using the biophysical and implementation resistance rasters. We extracted both the biophysical and implementation cost values for all pixels within each least-cost corridor within 10 km of the destination (Yellowstone National Park) to ensure that cost values reflected those of the complete implementation of a given corridor. We calculated the cost/km for both the biophysical costs and implementation costs. We also calculated a trade-off index (TO) for each least-cost corridor as:

$$\mathrm{TO}_i = \frac{1 + \left(\max(B) - B_i\right)}{1 + \left(\max(I) - I_i\right)}$$

where the trade-off index (TO) for least-cost corridor *i* is the ratio of the difference between maximum total biophysical cost across all least-cost corridors and the total biophysical costs for least-cost corridor$_i$ (B_i) to the difference between the maximum total implementation costs across all least-cost corridors and the total implementation costs for least-cost corridor$_i$ (I_i) and. We add 1 to both the numerator and denominator to avoid division by zero when least-cost corridor$_i$ has the maximum total implementation costs. Values greater than 1 indicate a least-cost corridor where the increased biophysical costs outweigh the reduction of implementation costs associated with implementing that corridor. Similarly, values less than 1 indicate a least-cost corridor where implementation cost savings outweigh the increased biophysical costs incurred along that corridor.

2.2.2 | Connectivity conservation as a probability

We ran Circuitscape analyses on both the biophysical and implementation resistance surfaces. We estimated the probability of movement through a pixel and that the pixel would be conserved by comparing the cumulative current flow surface resulting from a Circuitscape analysis based solely on the biophysical resistance surface to that resulting from an analysis based solely on the implementation resistance surface. Current flow in a circuit-theoretic analysis of connectivity provides an estimate of the net number of times that a random walker passes along a branch connecting two nodes in a network and provides an estimate of the probability of passage through each pixel. When using a biophysical resistance surface, this probability reflects the likelihood that an animal will move through a given pixel as it traverses the network via random walk (McRae et al., 2008). We extended this interpretation by considering the current density that results from an analysis based solely on an implementation resistance surface as the probability that a connectivity conservation action will occur within that pixel as practitioners attempt to conserve routes between the two nodes. We classified each current surface into quintiles and assessed current evenness (i.e. congruence between the quintiles for each surface) at each pixel using a bivariate choropleth map to illustrate areas where probabilities of movement are high, probabilities of implementation are high and where both are high.

Finally, because low current flow can result from conditions where there are multiple, redundant paths and from conditions where movement (or implementation) is impeded, we normalized the current surfaces from the implementation analysis to identify areas of impedance (i.e. areas where movement or implementation is reduced due to the presence of barriers) and channelization (i.e. areas where the surrounding landscape forces movement through a particular location). We divided the current flow produced by the Circuitscape analysis using the implementation resistance surface by the current flow produced from a uniform resistance surface with all values set to the minimum of the implementation resistance surface (McRae et al., 2016). Locations where this ratio is less than 1 are areas where current flow is lower than that produced by a 'null' resistance surface (i.e. impeded) and areas where this ratio is greater than 1 are areas where flow is higher than predicted by a 'null' surface and reflects areas where the surrounding implementation landscape 'channels' current flow through a location (McRae et al., 2016). For our analysis, we considered areas where flow was 20% lower or higher than expected given the null (i.e. the value of the normalized surface was less than 0.8 or greater than 1.2) to be impeded or channelized respectively.

2.3 | Evaluating the effects of potential conservation interventions

We imposed two hypothetical conservation interventions to illustrate the utility of our approach for conservation practitioners. First, we considered a situation where the US Bureau of Land Management (BLM) adopted an agency-wide mandate to include connectivity in land use planning similar to that of the US Forest Service (Williamson et al., 2020). The BLM manages the largest portion of high-resistance land within the state and is also the largest public land manager in the United States. We imposed this jurisdictional scenario by assigning the BLM and Forest Service the same resistance values (0.3) and recalculating the fuzzy sum and resistance values following the equation above. Second, we considered a situation where the impact of livestock production as a land use on implementation resistance is reduced by 15%. Although we do not specify the type of intervention, a 15% reduction is consistent with the upper range of the effect of messaging strategies for increasing pro-wolf sentiment (Niemiec et al., 2020). We imposed this scenario by multiplying the existing livestock resistance value by 85% and recalculating the fuzzy sum as above. We compared the effects of these hypothetical interventions by recalculating the cost ratios and trade-off index within the least-cost corridors, estimating the change in implementation probability quintiles by characterizing the change in current density that results from the use of the updated resistance surfaces, and evaluating spatial patterns of impedance and channelization.

3 | RESULTS

We identified five spatially distinct least-cost corridors connecting the Weminuche Wilderness to Yellowstone National Park (Figure 2). Although these corridors traverse different portions of the landscape, there is relatively little difference between the corridors with respect to their biophysical costs. Euclidean distance between the highest and lowest cost least-cost corridor differed by 20 km. Comparison of the trade-off index values (Table 2) and cost per kilometre estimates (Figure 3) suggests slightly larger differences between the five least-cost corridors with the intermediate corridor being 'cheaper' with respect to the sociopolitical costs of implementation than the other corridors. Examination of the bivariate choropleth map highlights a substantial swath of ecologically important and implementable landscape along the Rocky Mountain crest, but also illustrates spatial mismatches between areas where movement is likely, but implementation is not (Figure 4).

Results of our hypothetical scenario highlight the fact that the effectiveness of any connectivity conservation intervention is highly dependent on the spatial configuration of existing institutions both with respect to the ecological needs of the species and the objectives of surrounding land managers. In our example, national-level intervention in the missions and mandates of the Bureau of Land Management substantially reduces the social costs of implementing the various least-cost corridors, but not as much as an intervention that changes the relationship between land use (in this case livestock

TABLE 2 Trade-off index values for the top five least cost corridors between the Weminuche Wilderness Area (CO, USA) and Yellowstone National Park (MT/WY, USA) under baseline conditions and after introducing hypothetical conservation interventions that reduce the impact of land use on the resistance to connectivity conservation or that or create a connectivity conservation mandate for the US Bureau of Land Management. Larger values indicate conditions where the increased biophysical costs of the corridor outweigh any reductions in implementation resistance. Path 3 minimizes the biological and social trade-offs across all scenarios.

Cost rank	Trade-off index (baseline)	Trade-off index (land use scenario)	Trade-off index (policy scenario)
1	1.0055	1.0063	1.0055
2	1.0057	1.0066	1.0057
3	1.0049	1.0057	1.0048
4	1.0059	1.0068	1.0059
5	5.7640	61.3772	5.7638

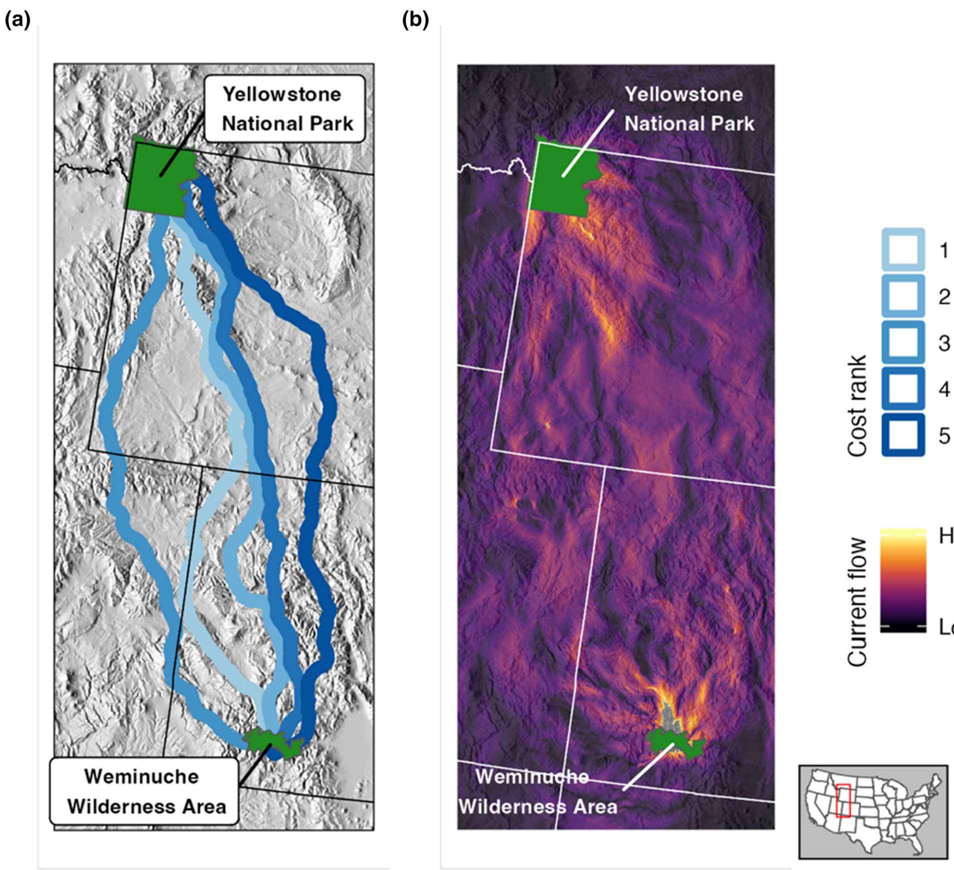

FIGURE 2 Least-cost corridors (a, based on the least-cost path and buffered by 4000 m) and circuit theoretic-derived current flow based solely on a biophysical resistance surface (b) for the case study connecting Yellowstone National Park (WY, USA) and the Weminuche Wilderness Area (CO, USA).

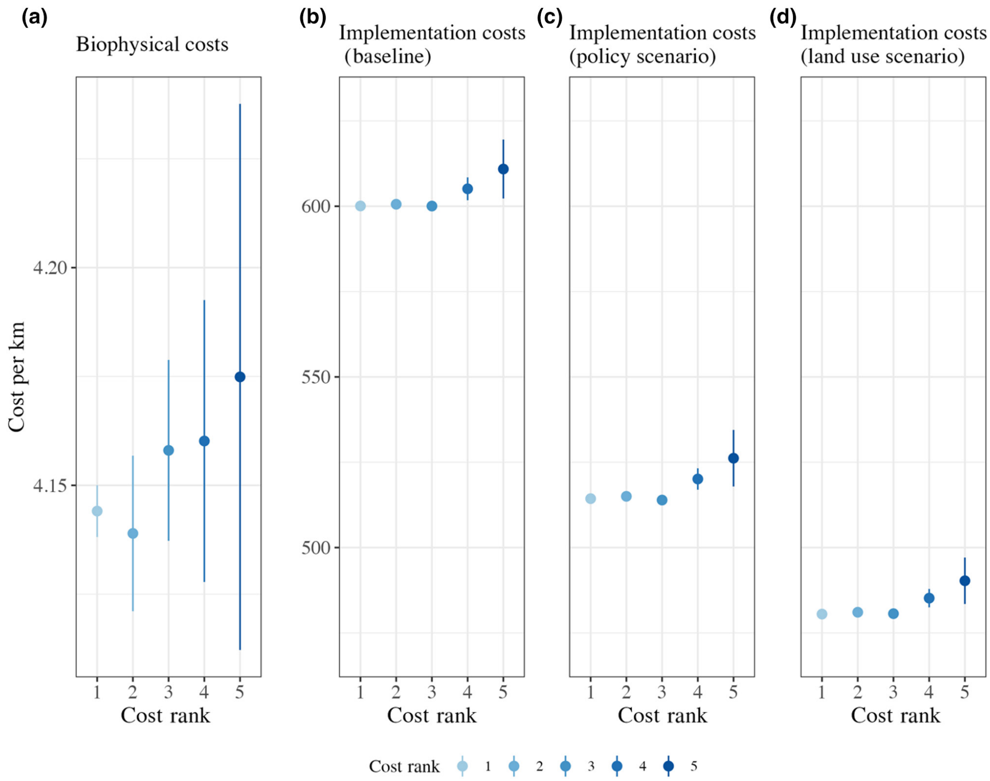

FIGURE 3 Comparing the cost per kilometre of the five lowest cost corridors connecting Yellowstone National Park and the Weminuche Wilderness Area based on the biophysical costs conditions (a), the baseline implementation costs (b), the hypothetical reduction of implementation resistance due to a policy change at the Bureau of Land Management (c) and the hypothetical reduction of implementation resistance due to a change in the contribution of land use (livestock production) to implementation resistance (d). Path 2 has the lowest biophysical cost per kilometre whereas path 3 has the lowest implementation costs per kilometre.

production) and implementation resistance (Figure 3). Although the changes in the relations between land use and implementation have a larger impact on the cost ratio, the spatial location of their effects (as measured by the changes in current flow produced by the updated implementation resistance surface) is peripheral to the high joint probability core area along the Rocky Mountain crest. In contrast, changes to the BLM connectivity mandate increased the implementation probability in several regions that align with high joint probability core areas (Figure 4). Mapping of impedance and channelization yielded similar results. The change in resistance due to changes in land use resulted in more area considered 'channelized' and less area considered 'impeded' than under current conditions or the BLM scenario, but the spatial locations of those changes were at the periphery of the study area. In contrast, the BLM scenario yielded increased channelization in the core of the current connectivity zone despite having a smaller effect on the rest of the landscape (Figure 5).

4 | DISCUSSION

Planning for connectivity conservation implementation requires choosing interventions and institutions that align with both the sociopolitical and ecological landscape (i.e. achieve socioecological fit (Epstein et al., 2015) across broad spatial extents). Given the need to align multiple dimensions of the biophysical and sociopolitical landscape, it is not surprising that few contemporary connectivity plans are fully implemented (Keeley et al., 2019). We introduced implementation resistance as a means of synthesizing multiple dimensions of the sociopolitical landscape into a two-dimensional surface that is compatible with contemporary graph theoretic methods for spatially explicit estimation of connectivity. Our simple case study using wolf reintroduction illustrated how consideration of the spatial arrangement of sociopolitical factors that promote connectivity conservation allowed comparison of the relative feasibility of ecologically comparable connectivity conservation strategies, evaluation of potential conservation interventions and formal expressions of both the likelihood that wildlife move through a particular location of the landscape and the likelihood that the humans responsible for managing those locations take actions to conserve those movements. Given that existing protected areas are unlikely to provide sufficient habitat for many species as climate changes (e.g. Littlefield et al., 2017; Parks et al., 2023; Ward et al., 2020), the ability to evaluate different connectivity conservation strategies both in terms of their ecological benefits and potential for implementation is critical.

At a minimum, implementation resistance surfaces allow practitioners to explicitly state assumptions about the sociopolitical landscape in which they operate, be transparent about the weighting of

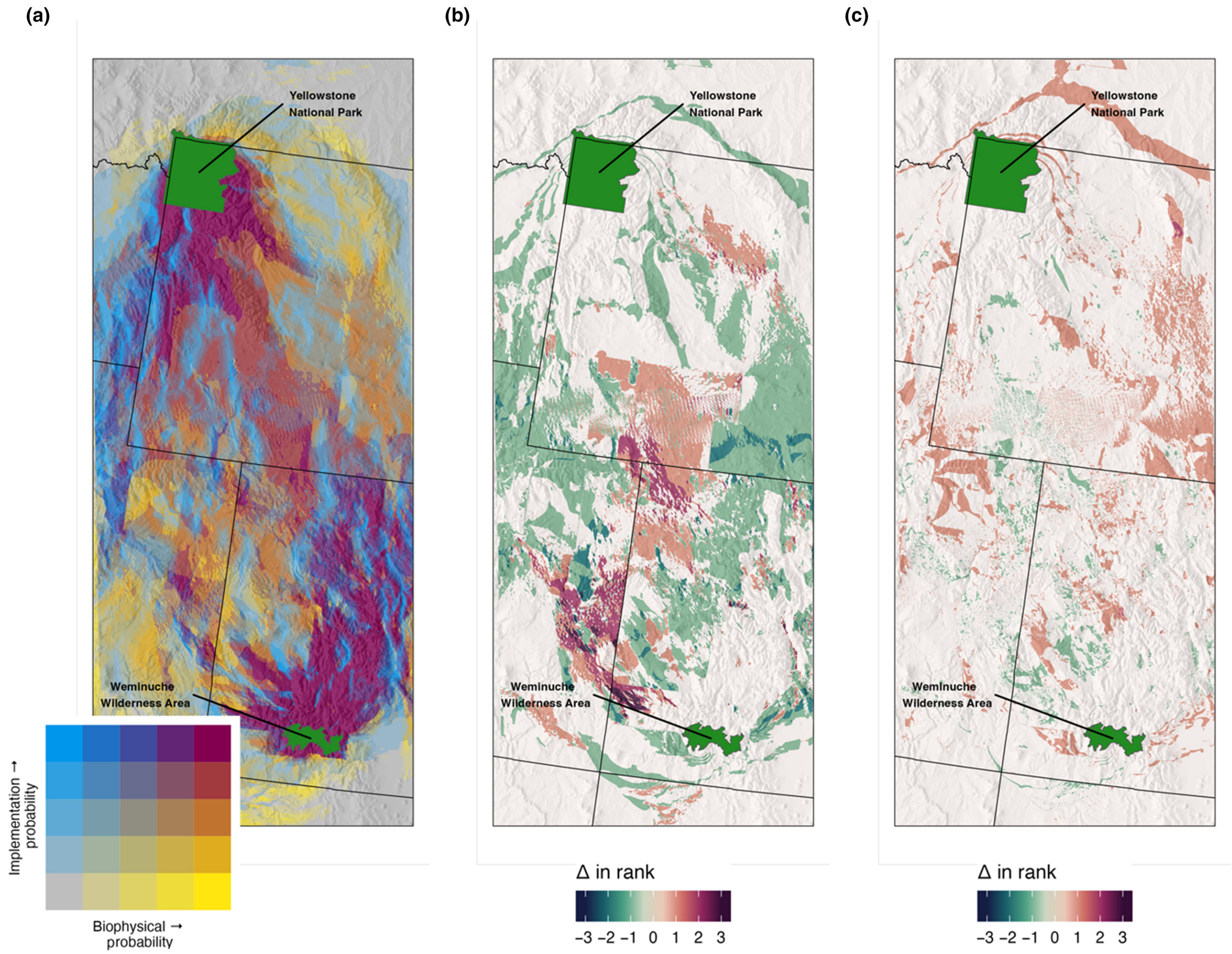

FIGURE 4 Bivariate choropleth (a) depicting the quintiles (i.e. rank) of the probabilities of movement (based on biophysical resistance) and implementation (based on implementation resistance) resulting from a Circuitscape analysis. Areas in red indicate locations where the probability of movement and the probability of implementation are both high. Panels (b and c) depict the change in the probability of implementation rank resulting from a hypothetical change in policy by the US Bureau of Land Management to emphasize connectivity conservation (b) and a reduction in the amount of implementation resistance due to land use (c).

different social factors, and evaluate the sensitivity of a strategy to those assumptions and weighting schemes. Empirical validation of the outcome of implementation resistance-based assessments will be critical for designing institutions that conserve connectivity. Indeed, analyses of connectivity models indicate that habitat suitability-based resistance surfaces do not always reliably predict species movement (Scharf et al., 2018). Similar empirical analyses are necessary to evaluate the role of implementation resistance in determining the difference between where connectivity conservation is planned and where it is ultimately implemented. Spatial regression of implemented connectivity conservation plans (e.g. Carter et al., 2020; Williamson et al., 2018) provides one potential approach for parameterizing implementation resistance. Comparing current flows or measuring distances between planned and implemented connectivity conservation actions and evaluating which components of biophysical or implementation resistance best-predict differences in locations could provide another promising approach.

We used cost ratio, current evenness and impedance/channelization as a means of characterizing the potential efficacy of different implementation strategies because these metrics are easily calculated using least-cost corridor and circuit theoretic approaches familiar to practitioners and because they account for the cumulative nature of both energetic and sociopolitical costs. Our impedance/channelization results highlight the fact connectivity conservation interventions may dramatically alter the landscape of implementation resistance highlighting the need to account for the dynamic interplay between implementation and conservation outcomes over time (e.g. Cumming & Epstein, 2020). These metrics, however, rely on assumptions (e.g. perfect knowledge of the landscape for least-cost corridors and random traversal of the landscape for circuit theoretic models) that are likely unrealistic for both wildlife and conservation practitioners (Panzacchi et al., 2016). Although less frequently used, randomized shortest paths (Saerens et al., 2009) provide a promising approach for

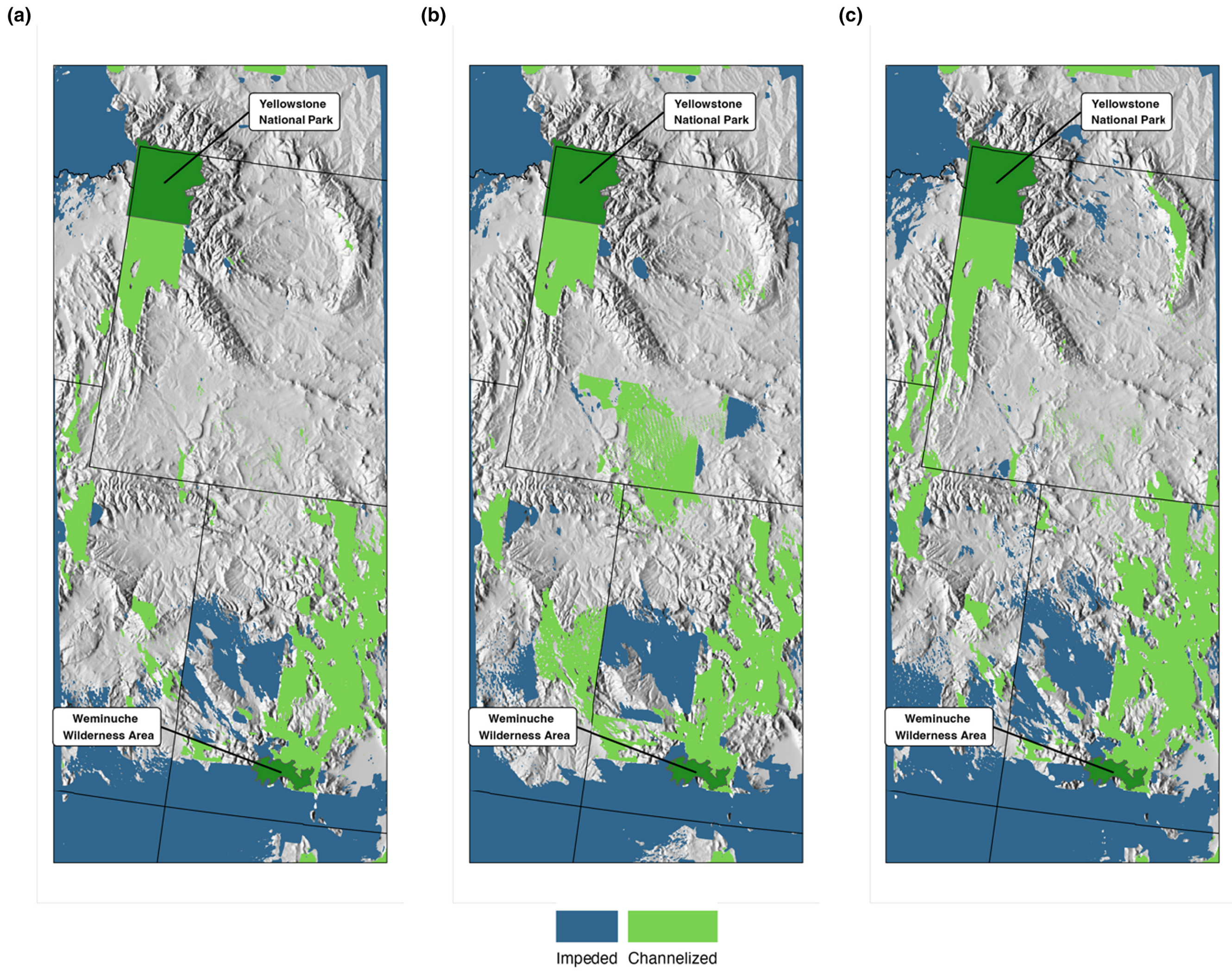

FIGURE 5 Channelization (i.e. areas where resistance of the surrounding landscape forces current through a particular location) and impedance (i.e. areas current flow is low because the landscape impedes movement rather than due to the presence of multiple, low-resistance paths) based on baseline implementation resistance (a), a hypothetical change in policy by the US Bureau of Land Management (b) and a hypothetical change in the relations between land use and implementation resistance (c). Areas in green (channelized) highlight locations where connectivity conservations actions are more likely primarily because of the resistance of the surrounding landscape. Areas in blue (impeded) highlight areas where probability of implementation is low due to the presence of sociopolitical barriers.

unifying the analyses by allowing both wildlife and practitioners to vary in their exploration of the environment.

Our approach relies on the availability of geographic information depicting institutional boundaries and publicly available data describing the mandates or objectives associated with each of those institutions. In countries where land tenure is still contested or changing rapidly, these data may simply be unavailable. Our example relied on formal institutions (i.e. government agencies) which may be only a subset of the relevant parties responsible for or capable of affecting wildlife connectivity. Mapping informal institutions (e.g. the presence of norms, variation in social capital, history of cross-boundary collaboration) would be an important addition to our approach. Social–ecological archetype analysis, wherein quantitative and qualitative data are combined to identify recurrent patterns in institutional arrangements at an intermediate level of abstraction (sensu Oberlack et al., 2019), provides a promising opportunity to develop spatial representations of these complex institutions to facilitate their incorporation into implementation resistance. Finally, static representations of resistance do not capture the dynamic evolution of public opinion or policy and may not fully capture the complexity that practitioners face in working in those regions. Additional work is necessary to explore how temporal variation in both the social and ecological landscapes affects the validity of connectivity modelling in general.

Our example also relied on a large, international survey of resident opinions about the management of multiple species combined with multilevel regression and post-stratification to generate spatial depictions of potential resistance to efforts to restore wolves. There are a number of contemporary efforts to survey wildlife values across broad spatial extents (e.g. Jacobs et al., 2022; Manfredo et al., 2021) that could be used to generate similar implementation resistance surfaces. Alternatively, the growing field of conservation culturomics which uses quantitative analysis of word frequencies and sentiments in large bodies of text (sensu Ladle et al., 2016) may provide additional pathways for developing spatially explicit estimates of public attitudes toward different species. In most cases, generating these estimates is likely to require modelling of the outcome of interest (i.e. wildlife management preferences) as a function of demographic and ecological variables. Because wildlife preferences may not be well predicted by demographic variables, evaluating the performance models within various demographic categories will be critical to ensuring that the resulting surfaces are valid before they are incorporated into consequential decisions.

Beyond analytic concerns, scale mismatches must be considered when developing social resistance surfaces for connectivity planning (Cumming et al., 2006). Connectivity conservation is likely to engage a variety of government levels and governance preferences (Cash et al., 2006; Fischer, 2018). The ability of surrogate variables (e.g. education levels, policy mandates, etc.) to accurately characterize implementation resistance at each scale of governance is vital and should expand well beyond those proxies used here. Globally, the cultural and social contexts that characterize if and how connectivity will be supported is an area of growth for conservation science and is key for moving these tools from being conceptually interesting to strategically useful (Guerrero et al., 2018). In addition to more sophisticated characterizations of social context, reconciling differences in scales between the social and ecological components of connectivity will be important for operationalizing their integration (Cumming & Epstein, 2020). Here, we used 1-km resolution for practical reasons; however, this decision could be informed by the ecology of the species in question, theoretical considerations or both. In the absence of better methods for integrating data at differing resolutions into existing connectivity modelling software, analysts should evaluate the sensitivity of their results to the resolution chosen for analysis.

Much of the literature on overcoming the planning–implementation gap is focused on the role of structured, transparent processes (e.g., Open Standards, Structured Decision Making, Systematic Conservation Planning). Although such processes are vital for building trust, increasing buy-in and fostering shared learning, the nature of connectivity conservation makes them difficult to deploy at the necessary spatial extents. We envision our framework as complementing these process-based approaches by highlighting key social 'pinch points' in achieving broader connectivity conservation objectives. By targeting investment in incentives, collaboration and institutional development in these high-resistance locations, we can build social overpasses to overcome persistent barriers to conservation. These 'social overpasses' may be as important for maintaining a species' ability to access habitats, find mates or avoid climate impacts as much-publicized physical overpasses that help wildlife cross roads.

Designing and evaluating social interventions to conserve connectivity is as critical as contemporary efforts to evaluate the effectiveness of physical overpasses. The growing body of literature on environmental behavioural interventions and the rich literature on institutional development provide excellent starting points for such research, but are rarely considered in designing connectivity plans for regions that vary spatially in terms of both their ecological importance or their sociopolitical context. Despite the complexity involved in characterizing implementation resistance, failing to do so means failing to implement. Instead, navigating this complexity can lead to successful conservation outcomes on the vast and growing portion of the Earth's land shared by wildlife and people.

AUTHOR CONTRIBUTIONS

Matthew A. Williamson. Lael Parrott, Neil H. Carter and Adam T. Ford conceived the ideas. MAW designed the methodology, collected and analysed the data; MAW and ATF led the writing of the manuscript. All authors contributed critically to the drafts and gave final approval for publication.

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CONFLICT OF INTEREST STATEMENT

None of the authors have a conflict of interest to declare.

DATA AVAILABILITY STATEMENT

All data used for producing the example analysis described here are available at https://github.com/SpaSESLab/Williamson_Implementation-resistance/ (doi: https://doi.org/10.5281/zenodo.8172751). US Census data for producing the MRP estimates were obtained from the 2020 American Community Survey (U.S. Census Bureau, 2021) retrieved using the tidycensus (Walker & Herman, 2021) package in the R Statistical Computing Environment.

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SUPPORTING INFORMATION

Additional supporting information can be found online in the Supporting Information section at the end of this article.

Data S1. Additional information describing the survey and Multilevel Regression and Postratification (MRP) methodology are available in the Supporting Information.

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