

Abstract

The spatial distribution of public lands in the western U.S. is an artifact of 19th century land-disposition policies. While this legacy is sometimes an impediment to conservation, it may also provide novel opportunities to spatially reorganize public conservation lands within realistic budget constraints. Here we seek to understand the conservation potential of strategically rearranging inaccessible ("stranded") public land in Montana, US. We use conservation reserve network design and consider coarse- and fine-filter conservation features—land cover types and predicted habitat for 12 umbrella species, respectively—and incorporate habitat connectivity corridors into one reserve design scenario. All conservation reserve network designs are constrained by a budget equal to the current value of stranded public land parcels and seek to meet or exceed the extent of conservation currently provided by stranded parcels with respect to land cover type and predicted species habitat. We find that each conservation reserve simulation expands the total protected area in Montana within the realistic budget constraint. Two maximum coverage scenarios, which exhaust the budget, result in reserve designs that substantially exceed coarse- and fine-filter conservation targets. All reserve designs provide landscape connectivity benefits. Our results illustrate notable and practical opportunities to develop conservation reserve networks in the western US that account for landscape connectivity and that benefit both private landowners and biodiversity conservation efforts through land trades and acquisitions.

1. Introduction

Habitat fragmentation, degradation, and loss are leading causes of worldwide declines in biodiversity (Butchart et al., 2010; Chapin III et al., 2000; Hansen et al., 2004; Krauss et al., 2010; Newbold et al., 2015). While much attention has focused on mitigating the effects of development, deforestation (Barlow et al., 2016), and agricultural intensification (Butler et al., 2007), the legacy of historical land policy has been an underappreciated conservation challenge. Understanding the impacts of historically determined public lands and the conservation potential of spatially reorganizing these lands within realistic budget constraints may provide novel conservation opportunities that align with contemporary conservation objectives.

Public lands comprise the majority of protected areas in the western United States (Gergely & McKerrow, 2013). Although in practice these protected areas form the basis of critical habitat for a variety of species, their extent and spatial configuration is more often a result of convenient or ad-hoc placement rather than the outcome of strategic conservation planning (Creech and Williamson 2019; Joppa and Pfaff 2009). One reason for this is that each of the various public land agencies has a unique mission grounded in its authorizing legislation and historical origins. Broadly, national parks were created to preserve especially stunning landscapes and recreational locales. National forests were formed with a goal of more effective timber management, while organized grazing districts were the original rationale for other U.S. Forest Service lands, much of the land now overseen by the Bureau of Land Management (Loomis, 2002). Ultimately, though, many public lands consist primarily of parcels left unclaimed by settlers during Westward expansion and spatially uniform but ad hoc 1-mi^2 land grants made to railroads and states (Leonard & Plantinga, 2022). Across the western U.S. there are regions where the legacy of spatially uniform land grants is evident in checkerboarded 1-mi^2 public and private land parcels, as shown in Figure 1B. Given the haphazard way in which public lands were designated in the western U.S., protected areas meant to protect and conserve biodiversity often fall short of providing high-quality critical habitat to a variety of species, limiting their contributions to biodiversity objectives (Jenkins et al., 2015).

The ad hoc and fragmented nature of large swaths of public land is underscored by the fact that many of these lands are not even legally accessible to the public or to agency managers. In the western US for example, there are thousands of small, isolated public land parcels, surrounded on all sides by private lands, that are not directly or indirectly reachable by road, and hence are inaccessible both to the public and to agency managers (Leonard & Plantinga, 2022). The lack of access has established economic costs, due to limits on resource development, protection, and recreation, which results in reduced private land values in the surrounding area (Leonard and Plantinga, 2022). Yet, the spatial distribution of stranded lands is likely to have impacts beyond local economies because the configuration of these lands—often in checkerboard patterns—results in fragmented habitat with many edges typically accompanied by fences that restrict many species' movement (Xu et al., 2021). Fragmented habitats have been linked to obstructed gene flow (Schlaepfer et al., 2018), inhibited migration (Harris et al., 2009; Wilcove & Wikelski, 2008), reduced habitat quality (Didham, 2010), and altered microclimates (Wilson et al., 2016). Agency managers' inability to access stranded lands may further impact habitat quality by preventing active management activities including habitat restoration, invasive species management, and fire prevention efforts (Leonard, Plantinga and Wibbenmeyer, 2021).

However, there is increasing interest in improving public land access through reconfiguration of public and private land parcels. For example, the US Great American

Outdoors Act (GAOA) of 2020 permanently funded the Land and Water Conservation Fund in the amount of $900 million annually to improve access to public lands through land acquisitions and exchanges with private landowners. Federal land swaps often lead to large increases in public acreage, in addition to resolving fragmentation issues. In many cases, swaps convert thousands of acres of checkerboarded private land into public ownership, while just a few hundred acres of public land convert to private ownership (Fitzgerald, 2000). Such reconfiguration of stranded public land could benefit conservation efforts by consolidating land managed for biodiversity. However, for these benefits to be realized the swaps need to be ecologically strategic. For instance, trading public lands dominated by old growth forests for previously clear-cut private land is unlikely to yield conservation benefits.

Public-private land swaps also must be economically and politically feasible. Such land swaps would affect a variety of stakeholders including landowners directly involved in exchanges, other landowners whose lands may be adjacent to both stranded and non-stranded land, recreational users seeking expanded access to public land, and members of the broader public who may ascribe existence value to affected landscapes and species. This paper focuses on the potential conservation benefits of land swaps, taking as given that such swaps are likely to leave the parties directly involved no worse off economically.

There are several reasons why land swaps are likely to produce net benefits for local residents. First, landowners who currently enjoy access to adjacent stranded lands are unlikely to lose the use of these lands. To the contrary, land swaps would involve transferring many stranded lands to the adjacent private landowners who currently use them. Second, recent research shows that stranded land reduces average land values at the county level and adjacent land values at the parcel level (Leonard and Plantinga, 2022, Blomqvist et al. 2022), suggesting that land swaps are likely to benefit landowners. Indeed, where they have occurred, land swaps have typically been seen as a windfall for the landowners and communities involved but have proved politically controversial because of uncertain public benefits. This paper addresses the latter issue in the specific context of biodiversity conservation through expansion and/or consolidation of high-quality, protected areas (Fitzgerald, 2000; Government Accountability Office, 2000).

We analyze the conservation potential of strategically reconfiguring stranded public lands using conservation reserve network design, a toolset commonly used in Systematic Conservation Planning (SCP) (Kukkala & Moilanen, 2013; Schloss et al., 2011). We consider both coarse- and fine-filter conservation features (i.e., land cover types and twelve umbrella species, respectively) and focus on Montana, US, as nearly 6% of the state's extensive public land area (approximately 773,000 hectares) is stranded. After characterizing the current conservation and monetary value of Montana's 7,637 stranded public land parcels, we evaluate one minimum cost and two maximum coverage conservation reserve network design scenarios: (1) an economically efficient reserve network that must contain at least the amount of predicted species habitat and land cover types currently contained in stranded parcels at the least cost, (2) a reserve network that maximizes coverage of all conservation features and is constrained by a budget equal to the current stranded land value, and (3) a reserve network that maximizes habitat protection within the budget of current stranded land value and that accounts for habitat connectivity. We find that each scenario's reserve design protects as much or more of each focal species' predicted habitat and of each land cover type as is currently held in stranded land. Our results illustrate the conservation potential of spatially reorganizing stranded public land parcels within realistic budget constraints.

2. Methods

The goal of our analyses is to understand how strategic land trades and acquisitions (hereafter 'land trades') could increase conservation outcomes in Montana, as proxied by the amount and connectivity of predicted species habitat and natural land cover types. We conduct our analyses separately for each county, to ensure that costs and benefits of land trades and conservation reserves are distributed equitably across the state. We first divide each county in Montana into planning units and assess the current conservation and economic values of each planning unit. We then estimate the conservation value provided by stranded public land parcels in each county, in terms of coarse- and fine-filter conservation features, and use these estimates as the minimum conservation value to be achieved by each conservation reserve design scenario. Finally, we compare results of the three stranded public land redistribution scenarios with respect to coarse- and fine-filter conservation features, habitat fragmentation, total cost of land trades, and landscape connectivity within counties and across the state.

2.1. Planning Units

Due to the original allocation of public land grants, many stranded public land parcels began as 2.6 km^2 (1-mi^2) Public Land Survey System (PLSS) Sections, often arranged in checkerboard patterns (Leonard and Plantinga, 2022; Figure 1). Based on this historical context, and computational feasibility, we use PLSS Section polygons as a spatial template for planning units, hereafter referred to as PUs. Using a smaller planning unit would create computational difficulties without providing additional insights because there is relatively little variation in public vs. private land ownership within PLSS sections. Using larger planning units would create an increased risk that a given planning unit could contain multiple distinct habitat types. The conservation value of each PU depends on its availability (land cover type and/or overlap with protected areas), its cost, and its contributions towards our conservation goals (or "targets").

2.1.1. Planning unit availability

We assign each planning unit (PU) an availability status to indicate whether it can be included in the conservation reserve, cannot be included ("locked out", e.g., highly developed land/high degree of human modification), or must be included ("locked in" e.g., existing conservation areas) in the final reserve (Figure 2). All PUs overlapping major protected areas are considered "locked in" . PUs overlapping major roadways, or urban areas are "locked out". In one of the three reserve design scenarios, we also lock out all PUs that do not overlap with connectivity corridors (Figure 2C; Figure 3).

To identify PUs overlapping major protected areas, we first apply a negative 100-meter buffer to protected area polygons and a positive 100-meter buffer to major urban areas and roadways. The negative buffer on major protected areas minimizes the number of PUs that are considered overlapping with those areas when the overlap is very small. The positive buffer on urban areas and roadways prevents PUs likely to be impacted by roads and urbanization from being included as available to a reserve design. We then use the '*st_join'* function from R's sf package (Pebesma, E., 2018) to spatially join the protected area and urban/roadway shapefiles to the planning unit shapefile, allowing us to assign either a "locked in" or "locked out" status if any portion of a PU polygon overlapped with any portion of a protected area or urban polygon, respectively. When a PU polygon overlapped with both a protected area and urban area polygon, we assigned a "locked out" value. All planning units that are not given a "locked in" or "locked out" status can be included in reserve designs. For reserve design scenario 3, only PUs overlapping with habitat connectivity corridors can be included in the final reserve design (see Section 2.7).

2.1.2. Planning unit monetary value

We use a Montana cadastral polygon shapefile to estimate the total monetary value of each planning unit in 2020 dollars. The cadastral data report the Fair Market Value, which is an estimate of the price a property would sell for in a market transaction. An alternative is the estimates of sale price from Nolte (2020), which are shown in a national analysis to approximate conservation costs. We use the Montana data because 1) Fair Market Value data are also shown in Nolte (2020) to provide a good approximation of conservation costs and 2) the Montana cadastral data provide land price estimates specifically for our study region.

To assign monetary values to each PU, we sum the value of all overlapping cadastral parcels, accounting for cadastral parcels that overlap with multiple PUs. Cadastral parcel polygons and planning units (PU) have different geometries. To determine the total value of each PU, we first crop cadastral parcels to the outline of each PU and adjust the value of the cropped cadastral parcels based on the cropped area relative to the total original area. If at least 95% of a cadastral parcel overlapped with one planning unit, we considered it entirely within that unit. We then perform a spatial join between PUs and cropped cadastral parcels and sum the value of all cadastral parcels overlapping each PU to find each PU's total value. For use as a budget constraint in our reserve scenarios, we find the total value of stranded land parcels per county. This is consistent with actual land swaps, which are based on the value of parcels prior to land exchanges that do not reflect anticipated increases in land value that may result from the exchange itself (Fitzgerald 2000, Government Accountability Office, 2000). Prior to performing the spatial join, we apply a negative 50-m buffer to cadastral parcels, which leads to completely removing very small, stranded parcels (< 50-m^2) and minimizing false matches between stranded and cadastral parcels with miniscule overlap. As a result, our PU values and the conservation budget estimate are conservative. The average size of dropped stranded parcels is 3.2 hectares, and the total dropped area is less than 1% of all stranded public land area.

2.1.3. Planning unit conservation value

To assess the conservation value of planning units (PUs), we focus on 18 conservation features including species-specific features (i.e., fine filters) and land cover and vegetation characteristics (i.e., coarse filters). We choose 12 umbrella species and species of conservation interest which collectively represent major habitat types across Montana, including forest and alpine habitats (black bear (*Ursus americanus),* grizzly bear *(Ursus arctos),* mountain lion *(Puma concolor),* elk *(Cervus elaphus),* lynx *(Lynx canadensis),* moose *(Alces americanus),* wolverine *(Gulo gulo)*), grassland and shrubland habitats (black-tailed prairie dog (*Cynomys ludovicianus),* pronghorn *(Antilocapra americana),* swift fox (*Vulpes velox*)), and shrub-steppe habitats (pygmy rabbit (*Brachylagus idahoensis),* greater-sage grouse *(Centrocercus urophasianus*)).

We choose to focus on a selected suite of species for two reasons. First, the selected species have been identified as at-risk species, species of conservation interest, or umbrella/surrogate species in previous Montana-focused conservation research (Carroll et al., 2021; Cushman et al., 2013; Montana Fish, Wildlife & Parks, 2015). Second, focusing on this suite of species allows us to illustrate biodiversity benefits and conservation gains captured by each conservation reserve scenario without adding unnecessary complexity. We do not intend for the results of each reserve design scenario to be interpreted as species-specific conservation plans for any of the focal species, but rather a demonstration of conservation benefits that can result from rearranging stranded land parcels through land trades in such a way that prioritizes biodiversity protection. Other similar studies have used a 'generic species' approach, combining traits and habitat requirements of multiple species (Williamson et al., 2020), or have included a larger suite of individual species. However, conservation reserve designs associated with the set of representative conservation features we have chosen can demonstrate potential biodiversity and habitat protection benefits while avoiding unnecessary complexity.

To proxy each PU's potential contribution to conservation targets, we find the total coverage of each species' predicted habitat as well as the land cover composition. To estimate the amount of species habitat per planning unit, we use predicted habitat raster data from the USGS Gap Analysis Project and sum the number of 30-m habitat pixels per species per PU. To estimate the land cover composition of each PU, we use the 2016 National Land Cover Database (NLCD) Land Cover dataset. We first aggregate NLCD raster data from 30-m to 270-m resolution using the nearest-neighbor method for computational efficiency. We then reclassify land cover classes into six categories representing different natural habitats (water, snow, forest, scrubland, grassland, and wetland (Table S1)) then sum the number of 270-m pixels per planning unit of each of the six land cover types.

2.2. Reserve design scenarios

We consider three conservation reserve scenarios in each county. The first is a cost-effective scenario which maintains the status quo of protection currently offered by stranded public land parcels for each conservation feature while reducing cost (scenario 1; A minimum set problem in SCP terms). The second is a maximum coverage scenario (scenario 2; A 'maximum coverage'/'maximum gain' problem in SCP terms) in which we require the reserve design solution to exhaust our budget by maximizing coverage of each conservation feature. To do so requires that we increase the conservation targets to make the budget constraint binding. The third is a spatially restricted maximum coverage scenario (scenario 3) that expands on scenario 2 by confining the reserve design to planning units that overlap habitat connectivity corridors (Figure 3 and Section 3.3).

To simulate stranded public land redistribution under these different scenarios, we use the *R* package *Prioritzr* (Hanson et al., 2020) with the Gurobi optimizer (Gurobi Optimization, LLC, 2021). *Prioritzr* uses integer linear programming to find an exact conservation reserve design solution, rather than a set of near-optimal solutions as in the similar and commonly used software Marxan. *Prioritzr* is increasingly used in strategic conservation planning to identify optimal networks of reserve parcels that achieve biodiversity goals at the least cost ("minimum set problem") or that achieve maximum biodiversity conservation subject to a budget constraint ("maximum coverage problem"; SI).

2.3. Assessing changes in conservation potential

To assess changes in conservation potential among our three reserve design scenarios and the current stranded public land distribution, we first compare changes in protected area and the representation of each conservation feature in our three reserve design solutions. We look specifically at changes in total protected area, in coverage of each land cover type, and in total protected habitat for each of the 12 umbrella species. We complement these habitat metrics with two additional landscape metrics— fragmentation and connectivity. To assess fragmentation of stranded public land and each reserve design scenario, we calculate mean patch size, total core area, and edge density (Hargis et al., 1998) using the R package *landscapemetrics* (Hesselbarth et al., 2019)(SI). We then use the R package *estimatr* (Blair et al., 2021) for a county-level heteroskedasticity-robust linear regression comparing county-level habitat connectivity associated with each reserve design solution relative to estimated connectivity under the current arrangement of stranded public land parcels and protected areas. We use log-transformed average cost-weighted distances of protected areas (CWD)—the accumulated 'cost' of travel an organism accumulates while moving across a landscape—as the habitat connectivity response variable (SI).

2.4. Selecting major protected areas

In our study, "protected area" refers to land parcels within Montana, mostly public, that are managed for biodiversity. We relied on three publicly available databases to identify protected areas: the Protected Areas Database of the United States (PAD-US), the National Wilderness Preservation Database, and the Montana Fish, and Wildlife and Parks (MFWP) spatial data. We include PAD-US parcels with GAP status I or II, both of which are defined as being managed for biological diversity and 'natural value' protection. Wilderness areas are, by definition, managed to support the 'natural condition' and minimize anthropogenic disturbance within their boundaries. Lastly, we include MFWP parcels, some of which are managed strictly for species or habitat protection and some of which are managed according to conservation easements that simultaneously promote the use of rangelands and protection of species and habitat (MFWP land designations in Table S3).

We place minimum size requirements on protected areas parcels (>40 km^2) to reduce the total number of discrete protected area parcels, for computational feasibility (Belote et al. 2016). In particular, the Circuitscape and Linkage Mapper Software run notably slower with each additional protected area. However, since our analysis is at the county level, we require protected areas in each county, but the above protected area size criteria left 12 of 56 counties without at least one protected parcel. For each of those 12 counties we select the largest protected area overlapping with or completely within that county, resulting in at least one protected area polygon per county.

2.5. Connectivity Corridors

Given the value of habitat connectivity to biodiversity conservation and reserve efficacy (Crooks & Sanjayan, 2006; Mcdonald et al., 2008; Wilson et al., 2016) we include a reserve scenario that restricts the conservation reserve design to planning units within habitat connectivity corridors. Landscape connectivity analyses require the development of a resistance surface that represents the energetic cost and mortality risk experienced by an individual moving across different characteristics of landscape. Each cell of a resistance raster is assigned a resistance value based on land cover type and ‘naturalness’. To develop a multi-species resistance surface that represents the ‘naturalness’ of landscapes, we generally follow methodologies used by Theobald (2013) and Belote et al. (2016). ‘Naturalness’ is meant to represent permeability, or the resistance faced by organisms crossing the matrix of land cover between protected areas (Theobald et al., 2012), as a function of the degree of human development.

To develop the multi-species resistance surface, we integrate spatial data representing land cover types, roadways, urban imperviousness, rivers, canopy cover and slope angle. NLCD land cover, canopy cover, and urban imperviousness datasets are aggregated from 30-m to 270-m. The NLCD land cover raster was aggregated using the ‘nearest neighbor’ method, as is appropriate for rasters with categorical data, while the canopy cover and urban imperviousness rasters, both of which represent their respective features on continuous scales from 0 to 100, were aggregated using bilinear interpolation. The reclassified and aggregated NLCD land cover raster was assigned resistance values ranging from 10 to 1000 according to Table S2. Values in the NLCD urban imperviousness raster were multiplied by 10 to stretch values from 0 to 1000. USGS digital elevation model rasters were compiled for all of Montana, converted to a slope angle raster using the ‘*terrain’* function in R’s raster package, then aggregated to 270-m resolution (Hijmans, R., 2022). Shapefiles of Montana’s major roadways and rivers were rasterized (270-m) then assigned resistance values ranging from 500 to 1000 according to Table S2. Assigned resistance values for all rasters ranged from 0 to 1000. To develop the final resistance surface, we overlaid rasters of land cover, imperviousness, roadways, and rivers, took the maximum value for each cell, then adjusted the maximum value using canopy cover and slope angle such that resistance and slope are positively correlated while resistance and canopy cover and negatively correlated (eq. 1).

$$resistance\ value_{cell\ i} = \max(land\ cover, urban\ imperviousness, roadways, rivers) * (1 + slope - canopy)$$

Final resistance values ranged from 5 to 1450, where natural, undeveloped, low-angle, forested, and/or terrestrial landscapes had the lowest values, and highly developed, steep landscapes, major roadways, and/or open water had the highest values. Resistance values assigned to specific land cover features and types before being adjusted for slope and canopy cover are shown in Table S2 and the final resistance surface is shown in Figure S1.

We use Linkage Mapper (McRae & Kavanagh, 2011) to model connectivity corridors between the protected habitat areas described in the “*Selecting Protected Areas*” section above. Other studies have incorporated connectivity into conservation reserve designs using a ‘connectivity modifier’ similarly to a boundary length modifier (Beger et al., 2010), but that approach posed computational constraints due to the spatial scale of our analyses, namely the number of planning units within larger counties and across the state of Montana.

3. Results

3.1. Summary of Stranded Public Land Parcels

Stranded public land parcels exist in all 56 counties in Montana (Figure 1), though the amount and arrangement vary. For example, ~10% of Custer County is stranded land, much of which is arranged in a checkerboard pattern, while less than 1% of Madison County consists of stranded parcels in a relatively random spatial arrangement. Most stranded parcels are grassland (~60%) and shrubland (~26%), with a small percentage designated as forest (~8%) and other land cover types (Figure S2). Relative to the entire state, stranded public land contains larger proportions of shrubland and grassland, and lower proportions of all other NLCD land classes (Figure S2).

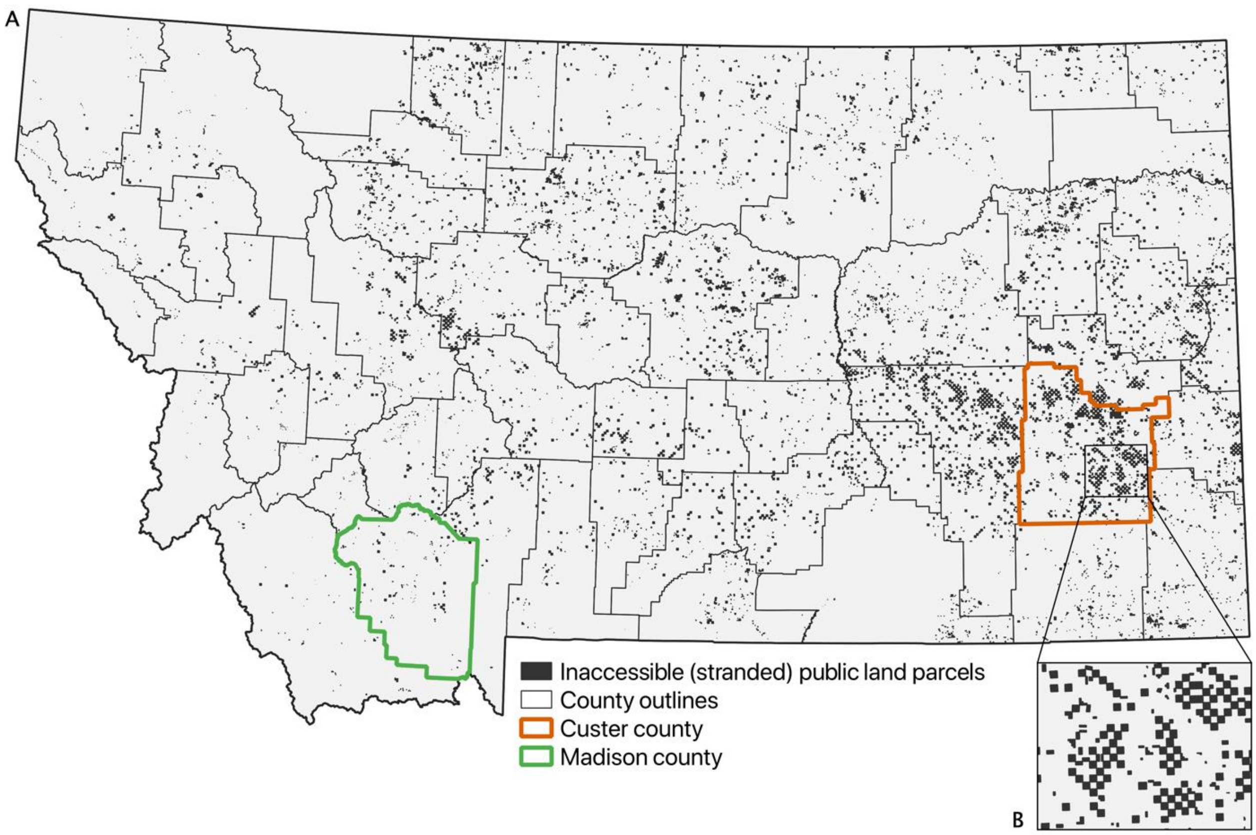

Figure 1. Panel A shows the distribution of stranded public land parcels (dark grey) across Montana, US. Madison County (green outline) and Custer County (orange outline) highlight variation in spatial patterns of stranded public land, from sparse and random to a concentrated checkerboard arrangement, respectively. Panel B shows an example of the checkerboard pattern.

3.2. Value of stranded land parcels

We conservatively estimated the total value of stranded public land parcels across Montana at approximately \$207.5 million (2020 dollars), with county-level totals ranging from ~\$62,000 (Deer Lodge County) to ~\$30 million (Cascade County).

3.3. Comparing Conservation Reserve Design Scenarios

We evaluate three conservation reserve design scenarios, to determine if redistribution of Montana's stranded public land parcels could increase habitat conservation and biodiversity protection, and in the process, decrease fragmentation and improve connectivity. All reserve designs increase the amount of species' habitat contained within the protected area network relative to the amount currently contained in stranded land parcels (Table 1). Additionally, we find that each conservation reserve design expands the total protected area in Montana while meeting or exceeding all conservation targets within the budget (Tables 1&2). The two maximum coverage scenarios, which exhaust the budget, produce reserve designs that substantially exceed most conservation targets.

3.3.1. Cost-effective conservation reserve networks (scenario 1)

Our goal in the cost-effective conservation reserve scenario was to test the feasibility of meeting all 18 conservation feature targets within the specified budget of $207.5 million (assessed value of stranded public lands in 2020 dollars). The conservation targets used in this scenario characterize the current protection offered to each conservation feature—six NLCD land cover types and 12 umbrella species—by the current arrangement of stranded public land parcels (Table 2). Thus, a reserve design that meets these targets equates to rearranging stranded land parcels in such a way that maintains the status quo of protection for each conservation feature while reducing costs. We find this requires only 28% of the budget, leaving nearly $150 million dollars remaining, and demonstrating that it is indeed possible to maintain the current conservation value of stranded parcels more efficiently (Figure 2D). However, our goal was to explore the possibility of increasing biodiversity and habitat protection through strategic redistribution of stranded public land parcels, which we demonstrate in two maximum coverage scenarios.

3.3.2. Maximum coverage conservation reserve networks (scenarios 2 & 3)

Our goal in the maximum coverage scenarios was to increase protection for each conservation target by exhausting the reserve budget, $207.5 million. All conservation targets were met in the cost-effective scenario well within the budget, so for scenarios 2 and 3 we increased the targets until the cost of the reserve solutions were nearly equal to $207.5 million. For scenario 2, this meant increasing conservation targets by a factor of 3.1. The reserve design for this scenario used over 99.5% of the budget and exceeded all conservation targets (Table 2; Figure 2E).

In the second maximum coverage reserve design scenario (scenario 3) we again sought to expand habitat and biodiversity protection by exhausting the budget while adding the constraint that solutions must be confined to habitat connectivity corridors (Figure 2C; Figure 3). To use all $207.5 million in scenario 3, conservation feature targets were increased by a factor of 2.7. Targets were again exceeded, though not as notably as in scenario 2. In particular, increases in protected habitat for swift fox, pronghorn antelope, and black-tailed prairie dog were smaller for scenario 3 than for scenario 2.

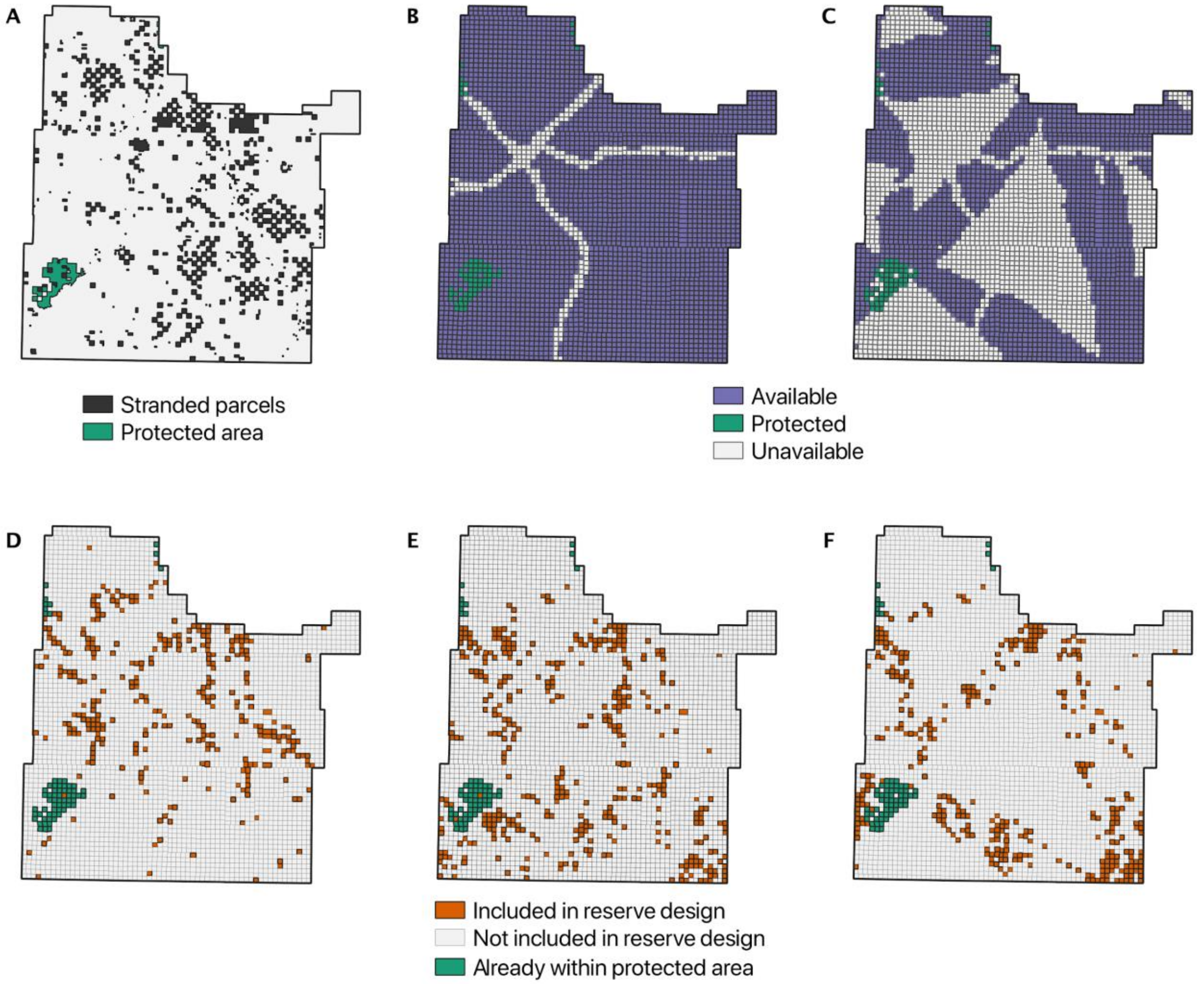

Figure 2. Custer County Panel A shows stranded parcels (dark grey) and a major protected area (green) in Custer County, Montana. Panels B and C show the distribution of planning unit statuses (available to be included, not available, or already protected) for the cost-effective and maximum coverage reserve design scenarios (Panel B), and maximum coverage with corridors scenario (Panel C). Panels D-F show reserve design solutions (orange) with previously protected areas (green) for each of the three reserve design scenarios: cost-effective, maximum coverage, and maximum coverage with corridors, respectively.

3.3.3. Landscape metrics

We compare average patch size, total core area, and edge density for current stranded public land parcels and the three solutions to the reserve design scenarios (Table 3). Edge density is similar for the two maximum coverage scenarios and current stranded parcels, but total core area and mean patch size are more favorable for all reserve designs than for stranded parcels.

3.3.4. County-level habitat connectivity comparisons

Habitat connectivity corridors (Figure 3) are based on a multi-species resistance surface of Montana (SI) and depict cost-weighted distances (CWD), or the cost of movement (energy expenditure and/or mortality risk) accumulated by organisms traveling across a landscape. Low

CWD values correspond to places near the single-most efficient path connecting core, protected habitat patches.

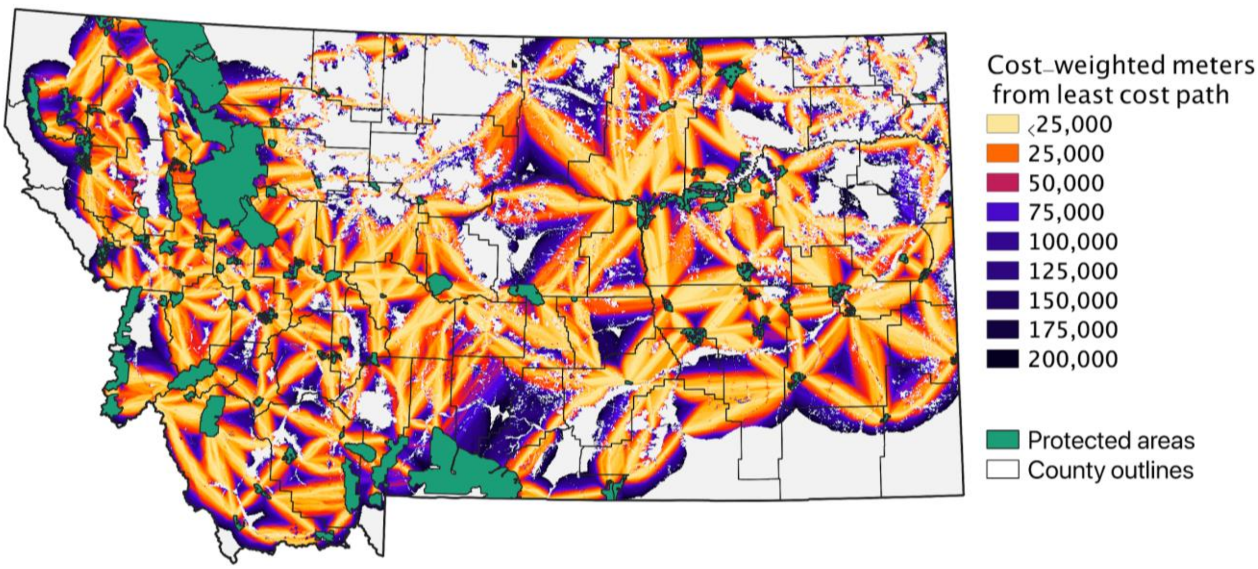

Figure 3. Habitat connectivity corridors between major protected areas (green) in Montana, US from low (yellow) to high (black) accumulated cost-weighted travel distance.

Average county-level CWD values were 46% lower for scenario 3 relative to the current distribution of stranded public land parcels and protected, which was expected given the scenario's design (Table 4). However, average CWD values were also lower for scenarios 1 and 2 though not statistically significant. The reserve designs for the cost-efficient scenario resulted in an 11% average decrease in CWD, and the scenario 2 reserve design resulted in a 7% average decrease in CWD, so though not always statistically significant, each reserve design improved county-level habitat connectivity.

4. Discussion

Inaccessible public land covers over 2.4 million hectares across the western U.S. (Leonard & Plantinga, 2022). The fragmented nature of these parcels combined with their inaccessibility and resulting lack of management limits their ecological and economic value. In this study we have demonstrated how strategic reconfiguration of stranded public land parcels could increase protected multi-species habitat across Montana, the state with the highest proportion of stranded lands. These increases in protected area could be achieved under a realistic budget, set by a conservative estimate of the current value of stranded parcels. Our cost-effective reserve design scenario showed that the current conservation value of stranded parcels could be achieved in a more economically efficient manner with 72% of the total budget remaining. Additionally, we showed that if the entirety of the budget were used to expand the total area managed for biodiversity conservation, protected habitat for all 12 umbrella species could increase substantially, whether or not we confine reserve designs to habitat connectivity corridors. Lastly, all three reserve networks show improved connectivity metrics relative to stranded parcels.

These findings have positive implications for both umbrella species with large home ranges or migratory patterns as well as smaller mobile species with relatively localized habitat requirements.

Historical land policies can be an impediment to conservation. For example, public irrigation projects, levee building, and infrastructure investment have increased the value of private lands, and thus the costs of conservation, in addition to having substantial direct negative effects on the environment. Nevertheless, conservation planning that adequately considers both social and environmental management goals have resulted in win-win conservation solutions that secure both biodiversity protection and ecosystem services gains (Tallis et al., 2008). Here we present a potential win-win biodiversity conservation framework for Montana that seeks to increase protected multi-species habitat within a tangible and realistic budget while also providing economic benefits to private landowners.

Despite the potential for win-wins, land trades, particularly trades between public and private entities, are not without socio-political challenges related to who benefits and who pays (Hegwood et al., 2021; Tallis et al., 2008). Yet, the current policy environment presents several opportunities to overcome past challenges. For example, President Biden’s Executive Order #14008 charges federal agencies to conduct a “comprehensive review and reconsideration” of current policies and outlines the goal of conserving 30% of the country’s land and water by 2030, presenting an opening for revisiting land trades as a potential tool to advance conservation outcomes if supported by the type of analysis undertaken here. Moreover, the bi-partisan Great American Outdoors Act endowed the Land and Water Conservation Fund with a $900 million annual budget to pursue additional land acquisitions, presenting another mechanism to promote habitat conservation and connectivity if traditional trades remain elusive.

There are three important limitations to our study. First, we rely on predicted species habitat from the USGS GAP database rather than direct measures of species abundance or movement. For a study of our spatial scope, it is unlikely that sufficient data would be available for even one well-studied species. Nevertheless, ground-truthing modeling approaches with observations from surveys or citizen science is a promising direction. Second, our approach to multi-species habitat connectivity modeling relies on the assumption that the ‘naturalness’ of a landscape adequately represents its permeability, and that permeability is similar for the 12 species considered (Belote et al., 2016; Theobald, 2013; Theobald et al., 2012). Third, land use, trades, and redistributions are local decisions that involve myriad stakeholders. Our modeling results are not intended to be prescriptive, but rather illustrative of the potential conservation and cost-saving benefits of strategic land trades or acquisitions. Despite these limitations, we illustrate here that strategic redistribution of stranded public land parcels offers an opportunity to achieve beneficial outcomes for both ecological and human communities coexisting on limited land resources, making these methods worthy of refinement to match local knowledge and decision making.

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Data

The following publicly available data were used to develop planning unit monetary and conservation value data for the conservation reserve design scenarios:

- Predicted species habitat data was downloaded from the U.S. Geological Survey Gap Analysis Project (Wilson et al., 2016)
- National Land Cover Database (NLCD) 2016 Land Cover Conterminous United States was downloaded from https://www.mrlc.gov/data/nlcd-2016-land-cover-conus
- Montana cadastral data was downloaded from ftp://ftp.geoinfo.msl.mt.gov/Data/Spatial/MSDI/Cadastral/
- Montana administrative boundary shapefiles were downloaded from http://ftp.geoinfo.msl.mt.gov/Data/Spatial/MSDI/AdministrativeBoundaries/

The following publicly available data were used to locate large, protected areas in Montana and to model habitat connectivity corridors (methods in SI):

- Protected Areas Database (shapefile): https://www.usgs.gov/core-science-systems/science-analytics-and-synthesis/gap/science/pad-us-data-download?qt-science_center_objects=0#qt-science_center_objects
- National Wilderness Areas: https://wilderness.net/visit-wilderness/gis-gps.php
- Montana Fish, Wildlife, and Parks parcel data (shapefile): https://gis-mtfwp.opendata.arcgis.com/search?tags=mtfwp%20open%20data
- Digital Elevation Model (raster): https://viewer.nationalmap.gov/basic/?basemap=b1&category=ned,nedsrc#productSearch
- NLCD USFS Tree Canopy Cover (raster): https://www.mrlc.gov/data/nlcd-2016-usfs-tree-canopy-cover-conus
- NLCD Urban Imperviousness (raster): https://www.mrlc.gov/data/nlcd-2016-developed-imperviousness-descriptor-conus
- Montana Transportation (shapefile): http://ftp.geoinfo.msl.mt.gov/Data/Spatial/MSDI/Transportation/
- Montana Hydrography (shapefile): http://ftp.geoinfo.msl.mt.gov/Data/Spatial/MSDI/Hydrography/

Stranded public land parcel data is available at figshare.com: https://doi.org/10.6084/m9.figshare.16832746.v1

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Table 1. Comparison of total protected habitat for each species in Montana to protected habitat in current protected areas, stranded public land parcels, and conservation reserve designs

Species	Predicted habitat in MT (ha)	% in protected areas	% in stranded parcels*	% in scenario 1 solution	% in scenario 2 solution	% in scenario 3 solution
Black bear	10,008,144	15.6	0.6	5.2	7.2	3.8
Black-tailed prairie dog	10,946,163	1.6	2.7	2.7	6.5	5.6
Grizzly bear	4,558,530	24.5	0.4	5.7	8.3	2.8
Cougar	20,011,230	9.1	1.5	4.0	7.7	5.5
Elk	17,944,819	10.6	1.0	3.6	7.0	4.6
Lynx	4,560,675	14.7	0.3	9.7	10.8	5.0
Moose	10,706,585	15.6	0.5	5.0	7.1	4.0
Pronghorn	20,440,174	3.1	2.5	2.7	6.8	5.9
Pygmy rabbit	805,018	2.9	0.4	0.5	3.0	2.4
Greater-sage grouse	3,105,512	3.1	0.9	1.1	5.2	3.9
Swift fox	1,503,325	0.2	0.6	0.6	1.4	1.4
Wolverine	3,910,352	27.9	0.2	2.1	3.4	2.1

* % in stranded public land parcels after parcel sizes reduced with 50-m buffer, consistent with the rest of the study, to deal with tiny parcels and more precisely match stranded parcels with cadastral parcels. '% in Scenario' columns exclude the currently protected portion of reserve design solutions (Figure 2D-F).

Table 2. Conservation feature representation: Current protected areas and in each reserve design scenario

Conservation feature	Currently in stranded parcels/ Conservation feature target (ha)	Current protected area (ha)	Protected area in cost-efficient reserve (ha)	% Change	Protected area in maximum coverage reserve (ha)	% Change	Protected area in maximum coverage + corridors reserve (ha)	% Change
Umbrella Species								
Black bear	46,711	1,561,644	2,095,353	34.2	2,304,840	47.6	1,974,795	26.5
Black-tailed prairie dog	240,278	175,184	474,945	171.1	890,474	408.3	797,033	355.0
Brown bear	13,434	1,121,706	1,383,501	23.3	1,504,162	34.1	1,260,464	12.4
Cougar	243,274	1,829,332	2,638,436	44.2	3,407,532	86.3	2,978,671	62.8
Elk	144,107	1,899,093	2,556,888	34.6	3,177,881	67.3	2,772,380	46.0
Lynx	9,609	673,499	1,119,786	66.3	1,174,177	74.3	916,582	36.1
Moose	41,229	1,679,372	2,225,047	32.5	2,458,814	46.4	2,142,337	27.6
Pronghorn antelope	422,129	625,784	1,177,586	88.2	2,032,680	224.8	1,857,907	196.9
Pygmy rabbit	2,163	23,243	27,607	18.8	48,225	107.5	42,676	83.6
Greater-sage grouse	22,681	95,364	129,481	35.8	259,867	172.5	221,407	132.2
Swift fox	6,586	3,254	12,323	278.7	24,633	657.0	23,759	630.1
Wolverine	6,971	1,092,953	1,175,192	7.5	1,234,868	13.0	1,187,652	8.7
NLCD Land Cover Types								
Water	919	37,208	63,029	69.4	99,873	168.4	70,822	90.3
Snow	0	933	933	0.0	940	0.8	933	0.0
Forest	43,259	1,182,883	1,658,665	40.2	1,813,672	53.3	1,549,861	31.0
Scrub	136,943	584,920	821,007	40.4	1,235,917	111.3	1,117,010	91.0
Grassland	314,746	606,594	1,031,280	70.0	1,541,740	154.2	1,417,242	133.6

Wetland	3,732	25,464	33,979	33.4	64,225	152.2	56,585	122.2

Conservation feature targets are equal to the amount of predicted species habitat or land cover currently contained in public stranded land parcels; 'Current protected area' is the amount of predicted species habitat and land cover currently in protected areas. Subsequent columns show the amount of predicted species habitat and land cover contained in each reserve design scenario (current protected areas included) and the % change in protected area for each conservation feature under a given scenario's solution.

Table 3. Landscape Metrics for the current arrangement of stranded parcels and the three conservation reserve scenarios

Scenario	Mean patch size (ha)	Edge density	Total core area (ha)
Current stranded parcels	121	0.61	485,466
Reserve scenario solution, excluding currently protected (locked in) PUs			
Cost-effective (Scenario 1)	851	0.35	983,372
Maximum coverage (Scenario 2)	911	0.72	1,936,985
Maximum coverage in habitat connectivity corridors (Scenario 3)	799	0.60	1,435,473

Table 4. County-level Log Average CWD Regression Results

	Estimate (Standard Error)
Intercept	11.30*** (0.13)
Scenario 1: Cost-effective	-0.12 (0.087)
Scenario 2: Maximum coverage	-0.07 (0.091)
Scenario 3: Maximum coverage within connectivity corridors	-0.61*** (0.102)
R^2	0.8235
Adj. R^2	0.7638
N	224
*** $p < 0.001$, * $p < 0.1$	

Figure Captions

Figure 1. Panel A shows the distribution of stranded public land parcels (dark grey) across Montana, US. Madison County (green outline) and Custer County (orange outline) highlight variation in spatial patterns of stranded public land, from sparse and random to a concentrated checkerboard arrangement, respectively. Panel B shows an example of the checkerboard pattern.

Figure 2. Custer County Panel A shows stranded parcels (dark grey) and a major protected area (green) in Custer County, Montana. Panels B and C show the distribution of planning unit statuses (available to be included, not available, or already protected) for the cost-effective and maximum coverage reserve design scenarios (Panel B), and maximum coverage with corridors scenario (Panel C). Panels D-F show reserve design solutions (orange) with previously protected areas (green) for each of the three reserve design scenarios: cost-effective, maximum coverage, and maximum coverage with corridors, respectively.

Figure 3. Habitat connectivity corridors between major protected areas (green) in Montana, US from low (yellow) to high (black) accumulated cost-weighted travel distance.

Highlights

- Reconfiguring stranded public land parcels can increase conservation in Montana, US
- 3 conservation reserve designs, confined by budget, increase habitat conservation
- All reserve designs increase county-level landscape connectivity

Running Head

Reconnecting stranded public lands

Title

Reconnecting stranded public lands is a win-win for conservation and people

Authors, affiliations, emails

L. Claire Powers, claire.powers@colorado.edu,
BioFrontiers Institute, University of Colorado, Boulder, Colorado 80309, USA,
Environmental Studies Program, University of Colorado at Boulder, Boulder, CO, 80309, USA

Ashley E. Larsen, larsen@bren.ucsb.edu
Bren School of Environmental Science and Management, University of California, Santa Barbara, USA

Bryan Leonard, bryan.leonard@asu.edu
School of Sustainability, Arizona State University, Phoenix, Arizona

Andrew J. Plantinga, plantinga@bren.ucsb.edu
Bren School of Environmental Science and Management, University of California, Santa Barbara, USA

Open Research Statement
Montana stranded public land spatial data is available on figshare.com at https://doi.org/10.6084/m9.figshare.16832746.v1. All other data used in this study are published and publicly available (see 'Data' section following 'Acknowledgements'). Our research was done in the R environment using well-documented functions and packages which are cited throughout the manuscript. As such, final versions of the code have not been published in a public repository, but we would be happy to do so upon request.

Keywords

Biodiversity conservation
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Author Statement
AJP, BL, AEL conceived of the study, LCP analyzed the data and wrote first draft. All authors contributed to revisions.

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