A Conservation Prioritization Tool for the Missouri Headwaters Basin

Project Summary and User Guide

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See also: A Conservation Prioritization Tool for the Missouri Headwaters Basin: Quick-Start Guide.

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Overview

Both terrestrial and freshwater aquatic management practices contribute to maintaining a healthy, connected landscape, yet these two ecological realms are often managed independently rather than as intertwined components of a single system. Cross-realm management, which explicitly considers the connections between terrestrial and aquatic realms, is a promising new direction in natural resource management that has great potential to benefit ecosystem functions that are not realm-specific, such as connectivity, and to inform more efficient management decisions by identifying co-benefits: management actions that benefit both the terrestrial and aquatic realms. However, examples of successful applications of cross-realm management frameworks remain rare. This prioritization tool and user guide are the products of a project funded by the National Fish and Wildlife Foundation to support, integrate, and build on existing efforts towards terrestrial and freshwater management in the Missouri Headwaters Basin (MHB) of southwestern Montana and northwestern Wyoming. The objectives of the project were to (1) examine how joint actions can be prioritized and applied on the ground, and (2) pilot a repeatable approach that can be applied to other areas.

We first developed a conceptual model of ecological integrity in the MHB that identified relationships between key conservation targets, threats to those targets, and potential management actions that can address identified threats. The conceptual model was developed collaboratively with regional stakeholders from state and federal government agencies, NGOs, and academia. We selected five conservation targets to describe ecological integrity in the MHB (stream health, normative flow regime, upland vegetation composition and structure, riparian potential, and within-habitat connectivity) and nine conservation or restoration actions that could be applied in the MHB to preserve or improve the condition of these targets (fuels management, grazing management, soil health management, irrigation adjustment, road decommissioning, bridge and culvert upgrades, stream and riparian restoration, land protection, and woody encroachment control). We compiled spatial data representing the condition of conservation targets, threats to those targets, and possible locations for implementing conservation or restoration actions.

We then integrated the conceptual model and spatial data into a conservation prioritization tool to allow stakeholders to identify areas where conservation actions can simultaneously yield the greatest benefits for multiple conservation targets, and to do so in a quantitative, repeatable, and defensible way. We made use of an existing systematic prioritization algorithm and software tool (Zonation; Moilanen et al. 2014), creating a custom application with simple user interface tailored to the MHB. Zonation is a powerful spatial prioritization method, made more powerful by its ability to integrate and consider the impacts of directed connectivity in freshwater systems when identifying priority areas. This means, for example, that conservation and restoration of headwater streams with potential to benefit downstream targets can be prioritized more highly. Our hope is that the tool will help resource managers and conservation practitioners working in the MHB to quickly, easily, and flexibly evaluate where to implement conservation action to achieve the greatest co-benefits for a variety of desired conservation targets, in both terrestrial and freshwater realms.

Background

Both terrestrial and freshwater aquatic management practices are key contributors to maintaining a healthy, connected landscape. Despite being heavily siloed in research and management (Stoms et al. 2005), the terrestrial and freshwater realms are not two independent systems, but intertwined components of a single system that should be considered holistically. For instance, disruptions to the intactness and health of stream networks, including wetlands, riparian zones, floodplains, and uplands, influence water cycling and flow regimes that greatly impact terrestrial habitat (e.g., Poff et al. 1997; Lake et al. 2007; Hauer et al. 2016). Similarly, intactness of the terrestrial landscape influences water quality and quantity through a variety of mechanisms including overland flow, infiltration, percolation, and horizontal flow.

Cross-realm management, which explicitly considers the connections between terrestrial and aquatic realms, is a promising new direction in natural resource management that has great potential to benefit ecosystem functions that are not realm-specific, such as connectivity, and to inform more efficient management decisions that affect these functions. The justifications for and advantages of integrating terrestrial and freshwater management are manifold. Threats to ecosystems (e.g., urbanization, pollution, grazing) are often shared across realms or propagated between realms, and their impacts can be best addressed by considering both realms simultaneously (Adams et al. 2014). Many ecological or geophysical processes rely on connections between terrestrial and freshwater systems (e.g., sedimentation, nutrient pollution; Beger et al. 2010). Some species occupy both terrestrial and freshwater realms at different times of day, in different seasons, or at different points in their life cycle. For instance, amphibians use wetlands during the breeding season but terrestrial uplands for the remainder of the year, and some waterfowl forage in freshwater but nest in uplands. Connectivity between realms is critical for such species (Beger et al. 2010).

Cross-realm management also allows for the identification of co-benefits: management actions that benefit both the terrestrial and aquatic realms. For example, livestock exclusion from riparian zones benefits terrestrial wildlife and plants, but also improves water quality in streams by reducing sedimentation and nutrient inputs associated with grazing (Pusey & Arthington 2003; Adams et al. 2014). Suurkuukka et al. (2014) found that protection of riparian forests in Finland that were selected for high terrestrial biodiversity also enhanced stream macroinvertebrate biodiversity. Amis et al. (2009) found that priority areas for conservation selected using an integrated assessment of terrestrial and freshwater biodiversity provided greater target achievement than did separate assessments for each realm. These studies demonstrate that a better understanding of the co-benefits resulting from interactions between terrestrial and freshwater ecosystem components can help to prioritize joint actions that increase efficiencies and yield greater benefits to the system as a whole.

The challenges of cross-realm conservation are strongly tied to organizational and geographic divisions, where agency jurisdiction, expertise, and management techniques are highly segregated between the freshwater and terrestrial realms (Beger et al. 2010). Technical barriers also exist, such as poor availability of data on cross-realm processes, the need to modify existing decision-support tools geared toward a single realm, and uncertainty about effects of actions that influence multiple realms (Alvarez-Romero et al. 2015). Progress has been made towards addressing these challenges in recent years, and several conceptual frameworks for cross-realm conservation planning have been proposed (Amis et al. 2009; Beger et al. 2010; Adams et al. 2014; Alvarez-Romero et al. 2015). However, examples of successful applications of these frameworks remain rare.

This project was intended to support, integrate, and build on existing efforts towards terrestrial and freshwater management in the High Divide, with two major objectives: (1) examining how joint actions can be prioritized and applied on the ground, and (2) piloting a repeatable approach that can be applied to other areas. Specifically, we sought to develop a robust, practicable model that integrates key conservation targets pertaining to terrestrial and freshwater Integrity, highlights key threats that may impact multiple targets, and identifies key conservation and restoration actions available to address threats and achieve targets.

Missouri Headwaters Basin

The Missouri Headwaters Basin encompasses 36,000 km^2 in southwestern Montana and northwestern Wyoming (Fig. 1). The region is known for its spectacular natural areas, abundant wildlife, and blue-ribbon trout streams, but it is also experiencing ecological stresses associated with human population growth, natural resource use, and climate change. Approximately 40 percent of the basin is public land that is managed primarily by the U.S. Forest Service, National Park Service, and Bureau of Land Management (Fig. 2), much of it high-elevation forests. Private lands comprise the remaining 60 percent of the basin and tend to be concentrated in major river valleys and at lower elevations. Although human population density remains low throughout most of the MHB, the Gallatin Valley in the northeastern corner of the basin has experienced rapid population growth in recent years and is projected to continue growing for the foreseeable future.

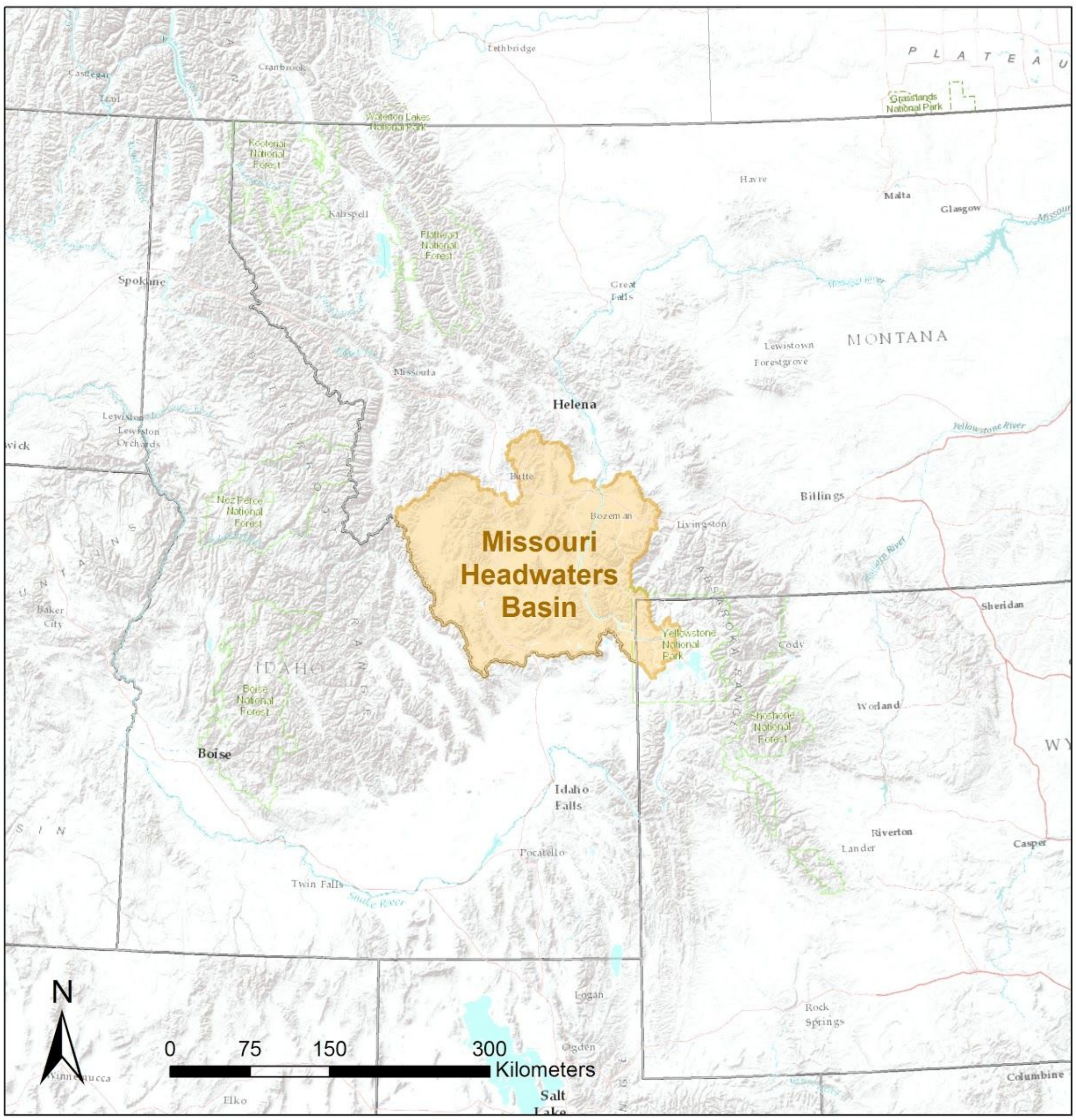

Figure 1. Location of the Missouri Headwaters Basin in the Northern Rocky Mountains.

The MHB is currently the focus of efforts by many stakeholders to improve or maintain ecological integrity. Non-governmental conservation organizations such as The Nature Conservancy, Trout Unlimited, Wildlife Conservation Society, Gallatin Valley Land Trust, and Heart of the Rockies Initiative are actively implementing conservation and restoration actions on the ground. Local watershed groups in each of the eight sub-basins of the MHB (Beaverhead, Bighole, Boulder, Gallatin, Jefferson, Madison, Red Rock, and Ruby) play an important role in local-scale conservation efforts. State and federal agencies such as Montana DNRC, USFS, NPS, and BLM carry out conservation and restoration programs within the lands and waters they manage.

The MHB is also the site of several national-level conservation campaigns. The Great Northern Landscape Conservation Cooperative has identified the MHB as an important focal area for connectivity conservation because it includes some of the best remaining linkages between three critical ecosystems in the western United States: the Greater Yellowstone, Salmon-Selway, and Crown of the Continent. The MHB also hosts one of two demonstration projects for the National Drought Resilience Partnership, a group of federal departments and agencies that works with state and local stakeholders to build long-term drought resilience.

A tool allowing for objective, science-based spatial prioritization of such efforts could benefit many of these groups as they decide how best to allocate limited conservation resources. By allowing for simultaneous prioritization of actions based on their benefits to aquatic and terrestrial targets, the tool should help practitioners take full advantage of potential cross-realm co-benefits.

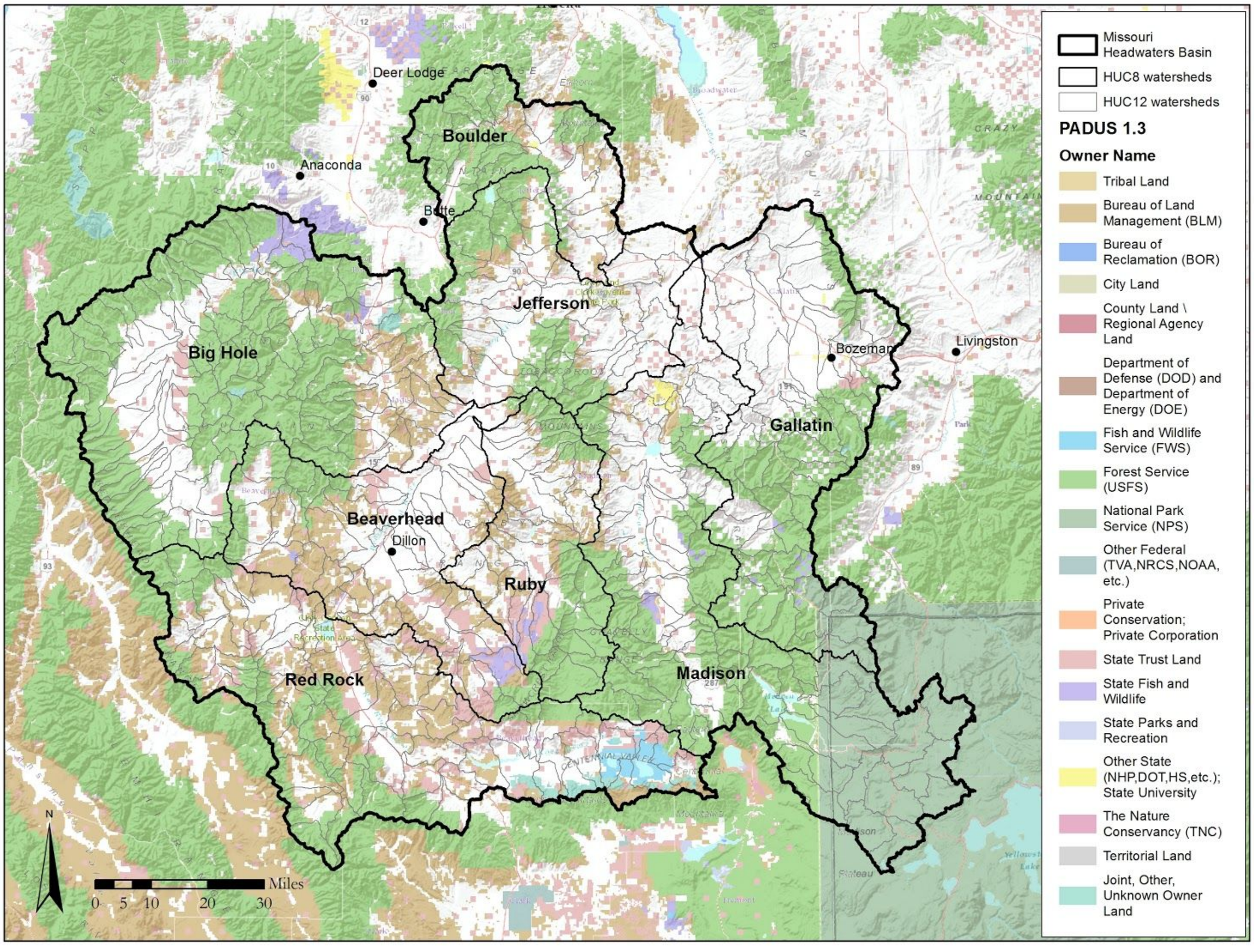

Figure 2. Hydrologic units and land ownership in the Missouri Headwaters Basin of southwestern Montana and northwestern Wyoming.

Conceptual Model

The initial step in this analysis was to develop a conceptual model of ecological integrity in the MHB that identified relationships between key conservation targets, threats to those targets, and potential management actions that can address identified threats (after Margoluis et al. 2009). The conceptual model was developed collaboratively with representatives of interested practitioners and stakeholders currently working in the region, including Montana Department of Natural Resources and Conservation, Montana State University, Montana Department of Environmental Quality, Wildlife Conservation Society, The Nature Conservancy, Natural Resources Conservation Service, U.S. Forest Service, Montana Water Center, U.S. Fish and Wildlife Service, Great Northern Landscape Conservation Cooperative, Science for Nature and People Partnership's Ecological Drought Working Group, and National Fish and

Wildlife Foundation. This approach was designed to ensure that the conceptual model was informed by local and expert knowledge such that the most important components were included, and that the process remained aligned with the needs of existing planning initiatives in the region (Cross et al. 2012).

Process

We convened a stakeholder workshop in Bozeman in April 2017 to generate an initial conceptual model. This workshop was focused on identifying (1) a limited number of conservation targets that adequately capture the most important elements of ecological integrity in the MHB, (2) conservation and restoration actions that have been or could be implemented in the MHB to maintain or improve the condition of these targets, and (3) ecological threats and stresses that negatively affect conservation targets and can be ameliorated through conservation actions. Although many of the links between actions and targets identified in the workshop were not very strong or direct, the initial conceptual model we generated (Fig. 3) served as a useful starting point for narrowing the focus of our prioritization tool to include only the most important link for which sufficient spatial data were available.

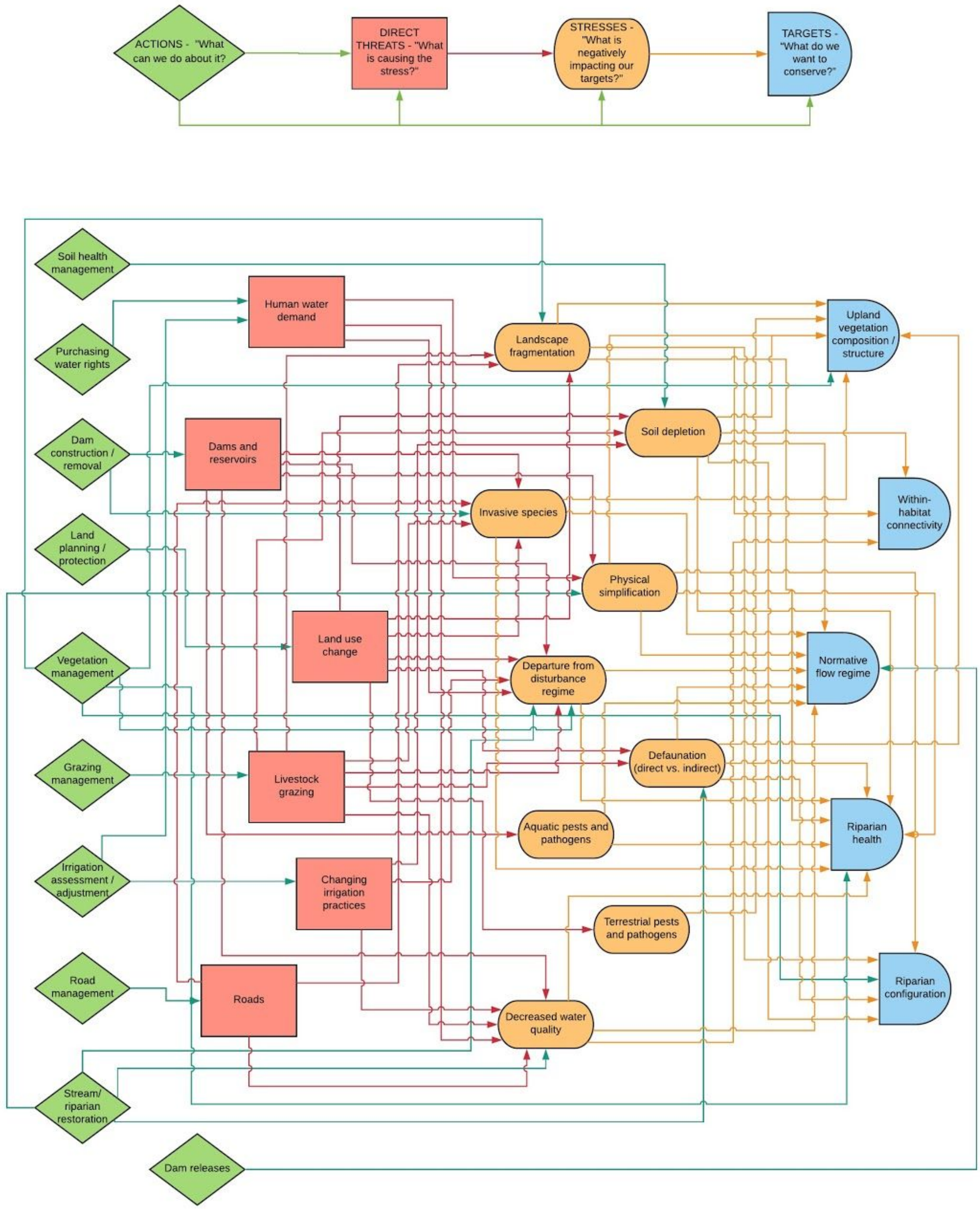

Figure 3. Initial conceptual model resulting from advisory council brainstorming workshop.

We pared down our initial conceptual model to a manageable size and level of complexity in several ways. First, we compiled all available spatial data relating to conceptual model components; many components lacked spatial data of sufficient spatial extent or resolution to be included in a quantitative prioritization analysis (e.g., invasive species distribution) and were therefore removed. Second, we reviewed the scientific literature on conceptual model links to determine which had the greatest scientific support and were thus of sufficient importance to include in the final model. Third, we had further discussions with several stakeholder representatives to determine which conservation targets, threats/stressors, and actions were of greatest interest to stakeholders and practitioners in the MHB. Based on these exercises, we produced a simplified conceptual model of the most important actions and targets and the links among them (Fig. 4). Detailed descriptions of actions and targets, as well as the relationships between actions and targets, are provided in later sections of this user guide.

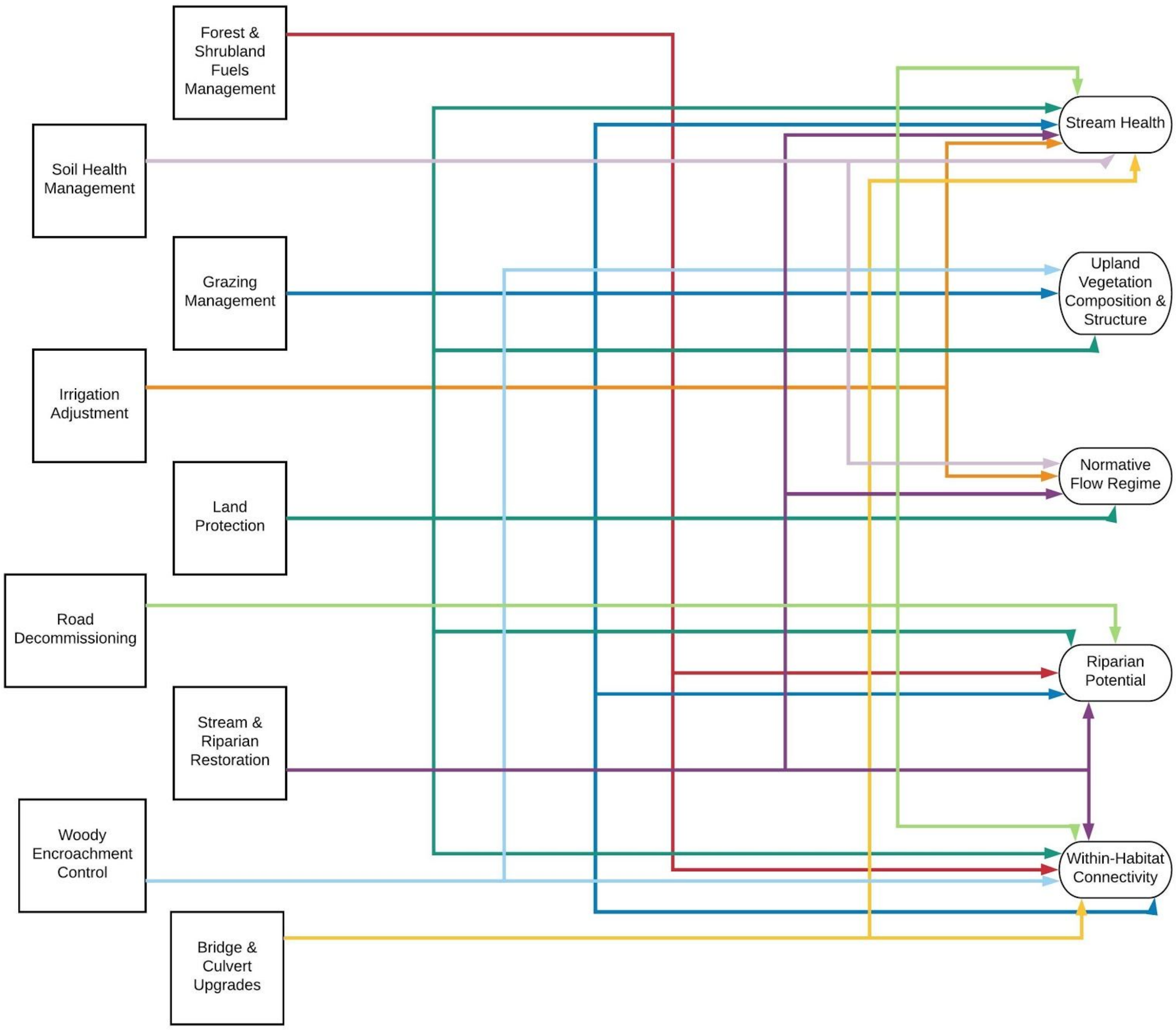

Figure 4. Simplified conceptual model of links between actions and targets included in the prioritization tool.

Targets

We selected five conservation targets to describe ecological integrity in the MHB. Many of these are broad proxies for a variety of more specific aspects of ecological integrity. Below, we provide a description of each target and the spatial data we used to quantify that target. Additional information on spatial data sources is available in Appendix A.

Stream Health

What is it? Healthy streams are critical for maintaining or restoring communities of native aquatic organisms. Defining stream health precisely is challenging because many characteristics of streams influence their ability to support aquatic communities. Water temperature, pH, flow rate, dissolved oxygen content, nutrients and pollutant concentrations, stream bed composition, channel structure, presence of woody debris, and many other factors are known to influence stream biotic communities (Norris and Thoms 1999). Beyond its importance for ecological integrity, stream health has direct impacts on human well-being. Healthy streams provide clean drinking water, irrigation water, and recreational opportunities such as fishing (Meyer 1997). Although the MHB contains an abundance of healthy streams, human impacts associated with population centers and agricultural activities have compromised stream health in many of the major river valleys.

How can we measure it? Benthic macroinvertebrates are commonly used as indicators of stream health because they spend all or most of their life cycle in water, are sensitive and respond in predictable ways to human disturbance, and have limited ability to move to escape poor stream conditions, such that their diversity and abundance reflect the effects of multiple stressors integrated over time (EPA 2017). We used a modeled biotic condition index developed from field data on benthic macroinvertebrate assemblages collected for the U.S. Environmental Protection Agency’s National Rivers and Streams Assessment. The model used geospatial data on nearby and upstream land use, land cover, climate, and other landscape characteristics to predict biotic condition of individual streams where field data were not available (Hill et al. 2017). Although stream assessments and management plans for the MHB have typically focused on fish populations and fish habitat (McEvoy et al. 2018), we believe using macroinvertebrates as a stream health indicator provides a more comprehensive perspective.

Riparian Potential

What is it? Riparian areas comprise only a small percentage of the MHB but play an essential role in maintaining ecological integrity and providing ecosystem services. Riparian areas serve as habitat and dispersal corridors for a vast array of wildlife species; act as buffers between uplands and streams by filtering sediments and nutrients; maintain stable stream channel morphology; lower stream temperatures by providing shade; reduce flooding impacts; regulate streamflow; and promote water storage (Theobald et al. 2010). As the interface between aquatic and terrestrial systems, riparian zones are at the heart of cross-realm processes. However, they are often subject to human impacts in the MHB because their productivity, gentle topography, and proximity to water make them attractive sites for development and agriculture.

How can we measure it? Mapping riparian zones can be challenging due to their dynamic nature and physical and biological complexity (Theobald et al. 2010). Field-based assessments allow greater accuracy but are not feasible at large spatial extents such as the MHB, while remote sensing-based approaches can be applied to large extents but tend to have coarse spatial and thematic resolution. To minimize the effects of seasonal and inter-annual variability in riparian vegetation configuration and biases associated with classifying riparian vegetation from remotely-sensed imagery, we used a very simple definition of potential riparian area based on the area of valley bottom as modeled using topographic characteristics (Harrison-Atlas et al. 2017).

Portions of many valley bottoms have been heavily modified and no longer have natural riparian vegetation or connected floodplains, so we use information on the degree of human modification (Theobald et al. 2012) to better estimate valley bottom area that is likely to have intact riparian cover when evaluating the need for conservation actions. For restoration actions, we also consider how threats to riparian areas (e.g., roads, grazing allotments) overlap with existing riparian areas.

Finally, we consider the sinuosity of streams as a component of riparian potential when evaluating the need for some stream and riparian restoration actions. Sinuosity is a measure of a stream's tendency to meander back and forth across its floodplain, and lower-gradient streams such as those flowing through large valleys tend to be naturally sinuous in the absence of human alterations to the stream channel. Sinuous streams are thus associated with minimally modified riparian zones. We used sinuosity data from the National Hydrography Dataset for stream reaches within the MHB.

Within-habitat Connectivity

What is it? Connectivity refers to the degree to which a landscape facilitates or impedes movement by organisms among habitat patches (Taylor et al. 1993). Connectivity is beneficial or even necessary for a wide range of ecological processes including animal migration, gene flow, natal dispersal, habitat recolonization, and range shifts in response to climate change (Crooks and Sanjayan 2006). A review of over 20 years worth of scientific studies found that increasing landscape connectivity was the most commonly recommended action for preserving biodiversity in the face of climate change (Heller and Zavaleta 2009). We focus on within-habitat connectivity (i.e., the ability of organisms that prefer a particular biome to move among patches of that same biome type) for the purposes of this tool.

How can we measure it? We used a model of connectivity among core areas of grassland, shrubland, or forest created by Dave Theobald for the Great Northern Landscape Conservation Cooperative (GNLCC) based on the approach described in Theobald et al. (2012). The model iteratively generates least-cost paths among pairs of core areas of a given biome type, with resistance to movement defined by the degree of human modification across the landscape, then uses a network centrality metric to quantify the relative importance of each landscape cell to keeping the GNLCC-wide network of cores connected. Connectivity routes with high centrality (i.e., "flowlines") indicate highly permeable connections between core areas. This connectivity dataset was generated for the Northern Rocky Mountain region and was intended to highlight areas that are predicted to support ecological connectivity at this broad scale. Flowlines are not species-specific, but they are specific to a biome (grassland, forest, or shrubland).

Upland Vegetation Composition & Structure

What is it? Vegetation composition refers to the plant species present in an area, while vegetation structure describes the morphological characteristics of plants and plant communities (van der Maarel 2005). Together, composition and structure define a variety of upland vegetation communities in the MHB, including various forest, shrubland, and grassland assemblages. Ecologically intact upland vegetation serves as habitat for terrestrial wildlife species and provides critical ecosystem services such as cycling of nutrients, energy, and water, carbon sequestration, flood risk prevention, and air and water quality regulation (Bonn et al. 2009). Although vegetation in many upland areas of the MHB remains similar to historic conditions, some upland areas have been altered by activities such as residential and commercial development, crop cultivation, grazing, timber harvest, and fire suppression.

How can we measure it? We used the 2011 National Land Cover Database (Homer et al. 2015) to identify areas of natural upland vegetation within the MHB. NLCD uses remotely sensed imagery and decision tree models to assign pixels to various thematic classes such as forests, grassland, shrubland, crops, and residential areas. Because this thematic classification allows for significant differences in the condition of upland vegetation types within a class, we supplemented NLCD with an index of human modification (Theobald 2013, Theobald et al. 2016) that integrates the effects of multiple anthropogenic stressors (e.g., energy production, invasive species, pollution, transportation infrastructure) to estimate overall level of modification. We used estimates of the area extent of natural upland cover types with low modification (when considering conservation actions) or high modification (when considering restoration actions) to measure upland vegetation composition and structure of planning units within the MHB.

Normative Flow Regime

What is it? Flow regime describes the characteristic pattern of a stream's flow timing, quantity, and variability. There are five key components of flow regime: (1) the magnitude of discharge in a given time interval; (2) the frequency of occurrence of a flow of a given magnitude; (3) the duration of time associated with a given flow condition; (4) the timing (i.e., predictability) of flows of a given magnitude; and (5) the rate of change (i.e., flashiness) of flow magnitude (Poff et al. 1997). Flow regime influences biodiversity and ecological integrity of aquatic and riparian ecosystems through a variety of mechanisms. For instance, frequency and intensity of high flows affect species composition and abundance; many plant and animal species life cycles are synchronized with periods of high or low flow; changes in duration of inundation or annual flow volume affect abundance of plant cover types; and seedling establishment for riparian tree species such as cottonwoods is highly sensitive to flashiness of stream flows (Poff et al. 1997).

Human modification of hydrologic processes has altered aspects of the natural flow regime in the MHB. Dams, diversion structures, levees, and groundwater pumping have directly modified stream flows, while land-use activities such as timber harvest, agriculture, and urbanization have indirectly modified flows. We therefore focus on the "normative flow regime" - one that resembles the natural flow regime sufficiently to sustain native species and ecosystems - rather than natural flow regime as a conservation target, recognizing that restoring pre-settlement hydrologic conditions is not feasible in this landscape.

How can we measure it? We used a modeled dataset of flow characteristics for streams in the western U.S. (Wenger et al. 2010) to measure normative flow regime in the MHB under future climate scenarios. We focused on a metric called center of flow mass (CFM), defined as the day of the year at which half of the annual flow has been exceeded, because the timing of flows (particularly late-summer flows) emerged during our conceptual modeling workshop as an especially important influence on ecological integrity. CFM integrates information on several aspects of flow regime, including type and timing of precipitation, timing of snowmelt, and duration of summer low-flow season (Regonda et al. 2005). We calculated the predicted shift in CFM (i.e., how many days earlier or later CFM is predicted to occur in the 2040s relative to the present) as a measure of the anticipated threat to normative flow in streams across the MHB. The shift in CFM is positively correlated with other flow metrics of interest, including change in mean summer flow volume.

Actions

We identified eight types of conservation or restoration actions that could be applied in the MHB to improve ecological integrity. Although there are many other potential actions that could be pursued, we focused on those for which (1) there are clear links to conservation targets in our conceptual model, and (2) stakeholders have expressed interest in implementing within the MHB. These actions vary with respect to the geographic footprint within which they could effectively be implemented. We used a variety of spatial data sources (Appendix A) to identify the subset of lands and waters in the MHB where each action could occur. Below, we provide a short description of each action and how we determined its geographic footprint.

Land Protection

What is it? Many public lands already prohibit or limit land use practices that are most ecologically detrimental, such as minerals extraction, timber harvest, and residential or commercial development. On private lands, however, these practices are generally permissible. Conservation easements - legally binding agreements that limit land uses or prevent development on a private parcel in perpetuity while the land remains privately owned - have emerged as an effective means of conserving ecologically intact private lands (Gustanski and Squires 2000). Because most conservation easements specifically prohibit the most ecologically destructive practices, easements benefit a wide variety of aquatic and terrestrial conservation targets. In some cases, outright fee purchases of lands by a land trust or other conservation organizations are used to ensure that lands are managed in a manner that promotes ecological integrity.

Where could it be implemented? We focused on land protection via conservation easements and land purchases, which are implemented on privately owned lands. The geographic subset for land protection included all privately owned lands that were not already under conservation easement or owned by a private conservation organization (e.g., a land trust).

Bridge & Culvert Upgrades

What is it? Bridges and culverts can impact both the hydrological and ecological characteristics of streams. They are associated with increased flow turbulence, scouring, and downstream bank erosion, which can reduce habitat quality for aquatic organisms (Richardson and Richardson 1999). High flow velocities and "perched culverts" (those with an outlet elevated above the downstream water surface) can present barriers to upstream passage for fish and other aquatic species, effectively isolating upstream and downstream populations. However, culverts can be retrofitted or replaced with new structures designed to minimize these negative impacts to stream ecosystems (Federal Highways Administration 2007), and such upgrades are now widely pursued (Roni et al. 2008).

Upgrading or replacing road-crossing structures can also be an opportunity to improve connectivity for terrestrial wildlife. Many wildlife species use riparian zones as movement corridors, and can cross roads beneath bridges if these underpass areas are of sufficient dimensions. Bridges crossing rivers and riparian zones can be designed such that their span is extended to include unsubmerged land on either side of a stream, which facilitates use as an underpass by terrestrial species (Macdonald and Smith 1999). Road crossings, including bridges and culverts, are often upgraded as part of road maintenance by state transportation departments.

Where could it be implemented? Spatial data quantifying ecological impacts of individual bridges and culverts are not available for the MHB, nor are detailed structural data that could be used to identify individual bridges best suited for upgrades to improve aquatic or terrestrial connectivity. Thus, we used points of intersection between streams (from the National Hydrography Dataset) and roads (from the US Census Bureau's TIGER/Line roads dataset) to infer locations of bridges and culverts that could potentially be upgraded to improve connectivity and/or reduce impacts on streams. We supplemented these road-stream intersections with bridges mapped for the Department of Homeland Security's National Bridge

Inventory, which included bridges >20 feet in length that span obstructions or topographic depressions (i.e., not necessarily streams).

Road Decommissioning

What is it? Road decommissioning is "the physical treatment of a roadbed to restore the form and integrity of associated hillslopes, channels, and flood plains and their related hydrologic, geomorphic, and ecological processes and properties" (Switalski et al. 2004). Treatment methods vary widely according to objectives and available resources, and include practices such as blocking entrances, revegetation, waterbarring, removing fills and culverts, establishing drainageways, removing unstable road shoulders, and even full obliteration by recontouring and restoring natural slopes (Napper 2007). Reasons for decommissioning roads are numerous and include restoring fish and wildlife habitat, reducing erosion, restoring landscape connectivity, restoring natural drainage patterns, increasing slope stability, and restricting human access (Switalski et al. 2004). Road decommissioning is a common action on National Forests within the MHB; since the mid-1990s, approximately 400 miles of roads on the Beaverhead Deerlodge NF and 1000 miles on the Gallatin NF have been decommissioned in some form (Environmental Quality Council 2015).

Where could it be implemented? We focused on three types of roads in the U.S. Census Bureau's TIGER roads database that we considered most suitable for road decommissioning: vehicular trails (i.e., four-wheel-drive roads), service drives along public access highways, and private roads for service vehicles (logging, oil fields, ranches, etc.). These road types tend to have relatively low traffic volume, are often built to serve for a limited time period (e.g., logging roads), and are typically surfaced with natural materials that make them easier to decommission. We considered only those roads on public lands, where opportunities and resources for road decommissioning are greater.

Grazing Management

What is it? Grazing management practices reduce the impacts of domestic livestock on ecological systems by altering the timing and intensity of grazing pressure on the landscape. One such practice is rotational grazing, in which livestock are regularly shifted between different portions of a pasture called paddocks, allowing ungrazed paddocks to "rest" and recover from grazing impacts. Rotational grazing has numerous ecological benefits including reduced erosion and runoff, improved forage plant diversity and production, increased water infiltration of soils, increased water quality, and increased wildlife habitat diversity (Undersander et al. 2002). Impacts of grazing on streams and riparian areas are especially acute, so riparian exclusion is another common grazing management practice. Riparian exclusion involves construction of fences or other physical barriers to prevent livestock from accessing riparian areas, and can reduce stream bank erosion and inputs of sediments and nutrients associated with riparian grazing (George et al. 2011).

Where could it be implemented? Information on where, when, and how intensely lands in the MHB are grazed by domestic livestock is very limited, particularly for private lands. We utilized grazing allotment boundaries provided by the U.S. Forest Service, Bureau of Land Management, and Montana Department of Natural Resources and Conservation to identify areas where grazing may occur on federal and state lands.

Soil Health Management

What is it? Soil health management actions are designed to improve water capacity, increase productivity, and decrease erosion potential of soils - outcomes that lead to fewer detrimental impacts to and demands on surrounding natural systems. Common soil management practices that could be implemented in the MHB include: (1) Cover cropping, the planting of crops in a season when fields are normally fallow. The presence of a crop layer reduces soil erosion potential by preventing wind and water erosion; improves soil productivity by reducing nutrient runoff and increasing nitrogen if the cover crop is a nitrogen fixer; and improves soil water capacity by preventing soil compaction and slowing runoff velocity to allow greater infiltration (Fageria et al. 2005). (2) Conservation tillage, a cultivation method that leaves the previous year's crop residue on fields before and after planting the next crop, including “no-till,” “ridge-till,” and “mulch-till” practices. Crop residues increase soil water capacity by shielding soil from wind, which reduces evaporation at the soil surface, and by creating a more porous soil structure that holds more water. Crop residues also increases soil productivity by decomposing and contributing organic matter to the soil (Busari et al. 2013). (3) Crop rotation, the practice of planting different crops in a particular order over multiple years in the same location. This can decrease soil erosion if the rotation includes crops that provide good erosion control (e.g., small grains, hay), and can improve soil productivity if nitrogen fixers are included in the rotation to replace the nutrients used by other crops (NRCS 1996).

Where could it be implemented? Lands on which soils have been modified by agricultural practices are most likely to benefit from soil health management actions. We identified agricultural lands using the 2011 National Land Cover Database (Homer et al. 2015), and included those lands classified as "cultivated crops" or "pasture/hay."

Stream & Riparian Restoration

What is it? The goals of stream and riparian restoration include enhancing habitat for fish and wildlife, improving water quality, restoring dynamic channel processes, increasing channel complexity, preventing bank erosion, restoring native vegetation, and reconnecting streams with their floodplains (Yochum 2017). A wide variety of practices are currently employed to restore streams and riparian zones to more natural conditions that support ecological processes. One of the most promising new approaches being implemented in the MHB is beaver mimicry, in which channel-spanning structures made of natural materials are installed within streams to simulate the effects of a beaver dam. Although research on effectiveness of beaver mimicry is still limited, possible benefits include groundwater recharge, floodplain connectivity, trapping of sediment, increased aquatic habitat diversity, and creation of riparian and wetland habitat (Pollock et al. 2015). Other practices that are commonly implemented to restore streams and riparian areas in the MHB include planting native riparian vegetation (e.g., willow and cottonwood), channel reconstruction, bank stabilization, and addition of large woody debris (DNRC 2016).

Where could it be implemented? We considered all streams in the MHB to be potential candidates for restoration actions. We used the National Hydrography Dataset Plus Version 2 to identify streams within the basin. To identify areas eligible for riparian conservation or restoration, we used a modeled valley bottom dataset produced by Conservation Science Partners (Harrison-Atlas et al. 2017; D. Theobald, pers. comm.), in which valley bottom extents were delineated based on slope derived from the USGS National Elevation Dataset (10 m resolution) and stream mean annual discharge (USGS NHDPlus).

Irrigation Adjustment

What is it? Irrigation practices have large impacts on the timing and volume of streamflow available to support ecological processes. A number of strategies are currently being used in the

MHB to reduce water use for irrigation by managing water more carefully, including: installing devices that use water more efficiently, such as drip irrigation systems and overhead sprinklers; regulating and increasing efficiency of water delivery by installing automatic headgates that measure and control the flow of irrigation water to fields, converting open irrigation ditches to closed pipes to reduce evaporative loss, or lining earthen ditches to reduce loss to seepage; and instituting water sharing agreements in which water rights holders are compensated for reducing their water use during times of water shortage. Both center pivot and flood irrigation systems are employed in the MHB, with different hydrological consequences. Center pivot and other drip/sprinkler systems are more efficient in that they divert less water from streams and reservoirs for irrigation, but nearly all of this water is utilized by crops and does not infiltrate to the water table for longer-term storage and groundwater recharge. Flood irrigation, in contrast, requires larger water diversions, but much of this water infiltrates the soil and is stored in the water table, supporting late-summer streamflows (Kendy and Bredehoeft 2006).

Where could it be implemented? Irrigation methods (e.g., center pivot versus flood) vary across the MHB, but data on irrigation methods utilized on particular parcels are not available. We therefore considered all irrigated lands, regardless of irrigation method, as potential targets for irrigation adjustment. We used modeled data from the U.S. Geological Survey based on remotely sensed land cover and vegetation greenness information (Pervez and Brown 2010) to identify irrigated areas in the MHB.

Forest & Shrubland Fuels Management

What is it? Increases in the density of woody plants (trees and shrubs) as a result of fire suppression over the past century are fueling larger and more destructive wildfires that pose threats to both ecological systems and human safety and property (Ryan et al. 2013). Several techniques are commonly used to reduce the amount of these fuels on the landscape and the associated risk of wildfire. Prescribed fire is the practice of intentionally burning areas in a controlled manner to meet resource management objectives. In addition to reducing fuels, prescribed fire can also be used to restore historic vegetation conditions (e.g., open forests with lower tree density) and maintain diverse wildlife habitat. Fuels reduction can also be achieved through thinning, the mechanical removal of trees and shrubs to reduce woody plant density (Jain et al. 2012).

Where could it be implemented? Fuels management actions such as prescribed fire and mechanical thinning are most needed in areas predicted to have relatively high risk for wildfires. We used a Wildfire Hazard Potential dataset (Dillon et al. 2015) produced by the U.S. Forest Service to identify these areas, retaining all areas classified as "High Risk" or "Very High Risk."

Woody Encroachment Control

What is it? Shrubs and trees are encroaching upon and replacing grasslands in southwest Montana and many parts of the western U.S., likely driven by a combination of grass herbivory by livestock, reduction in fire frequency, and climatic changes (Van Auken 2009). Encroachment into grasslands results in habitat loss for grassland wildlife species, reduced forage availability, increased fuel loads, and reduced plant species richness (Symstad and Leis 2017). Woody encroachment into shrublands is also a conservation concern in the MHB, primarily because of impacts on the greater sage-grouse (*Centrocercus urophasianus*), a year-round sagebrush community obligate that was recently a candidate for listing under the Endangered Species Act. Sage-grouse populations are highly sensitive to encroachment of conifers into sagebrush habitat (Baruch-Mordo 2013), and conifer removal has been shown to increase sage-grouse survival (Severson et al. 2017). Conifer removal may also benefit a variety of other grassland obligate birds and mammals (Noson et al. 2006, Woods et al. 2013).

Woody encroachment control can be achieved through multiple treatment methods, including mechanical removal (e.g., mastication, cutting) and prescribed fire (Williams et al. 2017). In Montana, both of these methods are used to restore grassland and shrubland habitat.

Where could it be implemented? Fine-scale spatial data depicting where woody encroachment has occurred or is likely to occur in the future in Montana are not available. We therefore used a very broad definition of areas at risk of encroachment, based on cover types represented in the 2011 National Land Cover Database. For encroachment into grasslands, we considered all grasslands within 500 m of an edge between existing grassland and woody vegetation (forest or shrubland) cover types as potential areas for woody encroachment control. For encroachment into shrublands, we considered all shrublands within 500 m of an edge between existing shrub and forest cover types as potential areas for woody encroachment control. This method likely overestimates areas of encroachment, but is useful for coarse-scale identification of areas where encroachment control actions may be warranted.

Links Between Actions and Targets

The heart of our cross-realm prioritization approach is establishing mechanistic links between conservation actions and conservation targets. These links allow us to combine spatial data representing the condition of targets, threats to those targets, and areas where actions could be implemented to assess the relative opportunity for conservation actions to influence targets for individual planning units (hereafter, “conservation opportunity”) within the MHB.

For purposes of the MHB prioritization tool, our planning units consisted of subwatershed units (HUC12). These units represent the smallest units that (A) were supported by the quality and resolution of the available data and (B) met all needs associated with the structure of the tool. Our use of subwatersheds as the unit of analysis means that all lands and water within each unit were scored and prioritized together - in other words, whole units were assigned a single value representing its conservation opportunity for applying a given action to a given target, and the tool assigns priority ranks at the level of whole units. This was necessary because in many cases, actions and the threats they address apply to different footprints on the landscape than the conservation targets they affect. For example, grazing management seeks to mitigate destructive grazing on grazing allotments that may be impacting health of adjacent streams. These linkages among actions, threats, and targets can only be quantified by summarizing the relevant data across planning units that contains both the action/threat footprint and the target footprint. Furthermore, consideration of downstream impacts of conservation and restoration actions requires that upstream/downstream relationships be defined. This information is readily available for subwatershed units.

We used inverse but equivalent strategies for assessing opportunity associated with conservation actions (i.e., those actions intended to preserve targets that are currently in favorable condition) versus restoration actions (i.e., those actions intended to improve targets that are currently in unfavorable condition). Nearly all of the actions included in this tool are employed primarily as restoration actions to reverse the effects of anthropogenic stressors such as water use, roads, floodplain development, and grazing pressure on conservation targets. For these restoration actions, we designed the prioritization tool to assign higher priority to subwatersheds where the target of interest is in poorer condition (or more threatened) and thus more likely to benefit from restoration. Only one of the actions we consider - land protection - is typically employed as a conservation action to protect areas where conservation targets remain in good condition and have not been significantly degraded by anthropogenic stressors. For conservation actions, we designed the prioritization tool to assign higher priority to subwatersheds where the target of interest is in better condition (or less threatened) and thus more likely to merit protection.

We note one exception to this prioritization approach: for our within-habitat connectivity target, we prioritized both conservation and restoration actions in areas predicted to have higher connectivity value (i.e., better target condition). We did so because the flowline centrality data we used to estimate connectivity value aimed to highlight paths that, at broad scale, are important for connecting large, intact cores of a particular biome throughout the Northern Rockies. Although high-centrality (i.e., high importance) flowlines tend to pass through areas of low resistance (i.e., high intactness), they are often not strongly influenced by highly localized, low-severity human impacts on the landscape such as specific grazing practices or the presence of an unpaved road. Therefore, there is ample opportunity to improve connectivity through many of the restoration actions we consider along flowlines hypothesized to be critical to broad-scale connectivity. And, perhaps more importantly, localized restoration actions in places with *low* centrality are generally not expected to increase broad-scale connectivity value, which is strongly influenced not only by local impacts, but also by the context of a particular location within the landscape as a whole. By focusing conservation actions on these high-connectivity regions, we prioritize connectivity conservation in areas that are known to be important for wildlife movement at a broad scale and thus merit protection. By focusing restoration actions on these same high-connectivity regions, we seek to address local gaps in connectivity within regions expected to serve as important wildlife corridors, rather than restore connectivity in local areas that are surrounded by unsuitable dispersal habitat and thus unlikely to be regionally important.

Below, we provide a brief description of the mechanisms by which conservation or restoration actions are linked to targets. We also describe the metric we used to assign a relative conservation or restoration value of a given action for a given target in each subwatershed.

Action: Land Protection

Target: Stream Health

How are they linked? Land protection prevents land use change that could result in decreased water quality through sedimentation, introduction of pollutants, or other changes to the stream biotic community.

How did we quantify conservation value? We assigned highest value to subwatersheds with the greatest value-weighted length of streams predicted to have higher-than-average biotic condition value on private, non-conserved lands.

Target: Riparian Potential

How are they linked? Land protection prevents fragmentation of riparian habitat via land use change that removes or increases disturbance to natural riparian vegetation.

How did we quantify conservation value? We assigned highest value to subwatersheds with: (1) largest area of valley bottom within private, non-conserved lands with lower-than-average human modification; and (2) highest stream sinuosity within these areas. These two factors were given equal weights when assigning conservation value.

Target: Normative Flow Regime

How are they linked? Land protection prevents land use change that could result in increased human water demand and/or changes in vegetation that could alter stream recharge.

How did we quantify conservation value? We assigned highest value to subwatersheds with the greatest length of streams predicted to experience lower-than-average shift in center of flow mass toward early-season flow on private, non-conserved lands.

Target: Upland Vegetation Composition & Structure

How are they linked? Land protection prevents habitat loss and fragmentation via land use change that removes or increases disturbance to natural habitat.

How did we quantify conservation value? We assigned highest value to subwatersheds with the greatest area of uplands with lower-than-average human modification on private, non-conserved lands.

Target: Within-habitat Connectivity (Forest, Grassland, Shrubland)

How are they linked? Land protection prevents fragmentation via land use change that removes or increases disturbance to natural habitat.

How did we quantify conservation value? We assigned highest value to subwatersheds with the greatest total centrality value summed over all connectivity flowlines on private, non-conserved lands.

Action: Bridge & Culvert Upgrades

Target: Stream Health

How are they linked? Upgrading bridges and culverts can remove some of the physical stressors associated with these structures for aquatic organisms. For instance, well-designed culverts or bridges minimize scouring, erosion, and flow acceleration that are problematic for many aquatic species, and they facilitate both upstream and downstream passage.

How did we quantify restoration value? We assigned highest value to subwatersheds with the greatest value-weighted length of streams predicted to have lower-than-average biotic condition value within 100 m of a bridge.

Target: Within-habitat Connectivity (Forest, Grassland, Shrubland)

How are they linked? Bridges with a wide span that encompasses upland areas on either side of stream can allow many wildlife species to safely cross beneath roads that would otherwise serve as barriers to movement.

How did we quantify restoration value? We assigned highest value to subwatersheds with the greatest concentration of high-centrality connectivity flowlines within 1 km of a bridge.

Action: Road Decommissioning

Target: Stream Health

How are they linked? Roads influence stream health through their effects on sediment input, pollutant input, streamside vegetation, and aquatic connectivity (e.g., culverts where roads cross streams). Decommissioning roads can reduce the impacts of these stressors on aquatic communities.

How did we quantify restoration value? We assigned highest value to subwatersheds with the greatest value-weighted length of streams predicted to have lower-than-average biotic condition value within 1 km of a decommissionable road.

Target: Riparian Potential

How are they linked? Road decommissioning in riparian zones can restore riparian vegetation, hydrologic function, and connectivity between streams and floodplains.

How did we quantify restoration value? We assigned highest value to HUC12 units with the greatest length of decommissionable roads within valley bottoms.

Target: Within-habitat Connectivity (Forest, Grassland, Shrubland)

How are they linked? Roads serve as barriers to movement for many wildlife species. Decommissioning roads that are no longer needed can restore connectivity, particularly when decommissioning efforts include restoration of native vegetation to the road bed.

How did we quantify restoration value? We assigned highest value to subwatersheds with the greatest total centrality value summed over all connectivity flowlines within 1 km of a decommissionable road.

Action: Grazing Management

Target: Stream Health

How are they linked? Livestock grazing impacts stream health through changes to streambank soil characteristics, departure from disturbance regime, and potential introduction of invasive species. Grazing can lead to stream bank erosion and sedimentation of streams, as well as introduce stream pollutants through runoff; it may also alter impacts of flood flows on streams due to changes in stream channel morphology. Grazing management actions to benefit stream health could include exclusion or reduction of grazing access to valley bottoms, particularly streambanks.

How did we quantify restoration value? We assigned highest value to subwatersheds with the greatest value-weighted length of streams predicted to have lower-than-average biotic condition value within public grazing allotments.

Target: Riparian Potential

How are they linked? Livestock grazing impacts riparian potential through landscape fragmentation due to reduction of riparian vegetation cover and/or changes in stream channel morphology. Grazing management actions to reduce fragmentation could include exclusion or reduction of grazing access to riparian areas.

How did we quantify restoration value? We assigned highest value to subwatersheds with the greatest area of valley bottom within public grazing allotments.

Target: Upland Vegetation Composition & Structure

How are they linked? Grazing can fragment landscapes through changes in vegetation composition and diversity; change soil characteristics by reducing water capacity through compaction, increasing erosion potential through cover reduction, and reducing soil productivity through nutrient removal; and introduce a new source of disturbance while reducing fire fuel loads. Grazing management actions such as rotational grazing can minimize these impacts to uplands by reducing their intensity.

How did we quantify restoration value? We assigned highest value to HUC12 units with the greatest area of uplands within public grazing allotments.

Target: Within-habitat Connectivity (Forest, Grassland, Shrubland)

How are they linked? Grazing management reduces grazing pressure and associated detrimental effects on soils and vegetation that can reduce habitat quality for grassland, shrublands, and forest wildlife species. By promoting habitat quality, grazing management reduces landscape fragmentation and improves ecological connectivity.

How did we quantify restoration value? We assigned highest value to subwatersheds with the greatest total centrality value summed over all connectivity flowlines within public grazing allotments.

Action: Soil Health Management

Target: Stream Health

How are they linked? Soil health management actions such as cover cropping, crop rotation, and conservation tillage can reduce soil erosion potential, which improves habitat quality for aquatic organisms because less sediment and nutrients enter streams via runoff. These practices may also increase soil productivity, which reduces the need to apply fertilizers that are eventually washed into streams.

How did we quantify restoration value? We assigned highest value to subwatersheds with the greatest value-weighted length of streams predicted to have poorer-than-average biotic condition value within cultivated lands.

Target: Normative Flow Regime

How are they linked? Cover cropping improves soil water capacity by preventing soil compaction and increasing infiltration of water. Conservation tillage increases soil water capacity because crop residue reduces evaporation at soil surface, and organic matter added by crop residue creates a more porous soil structure that holds more water. Both practices can help preserve the normative flow regime by storing more water in the soil and reducing the flashiness of runoff that occurs after storm events or major snowmelt events.

How did we quantify restoration value? We assigned highest value to subwatersheds with the greatest length of streams predicted to experience higher-than-average shift in center of flow mass toward early-season flow within cultivated lands.

Action: Stream & Riparian Restoration

Target: Stream Health

How are they linked? Actions such as beaver mimicry and willow planting restore riparian habitat that can keep stream temperatures cooler (via shading and subsurface water storage), which favors many aquatic organisms including native salmonids. These actions can also increase channel complexity, reduce stream bank erosion, filter sediment, and contribute organic matter to streams - all of which positively influence habitat quality for many aquatic organisms.

How did we quantify restoration value? We assigned highest value to subwatersheds with the greatest value-weighted length of streams predicted to have poorer-than-average biotic condition value.

Target: Normative Flow Regime

How are they linked? Stream and riparian restoration actions such as beaver mimicry slow the passage of water downstream and increase water storage, recharging groundwater by allowing surface water to more fully infiltrate the water table. This allows for higher summer base flows and may help maintain late-season flows through more gradual release of stored groundwater into streams.

How did we quantify restoration value? We assigned highest value to subwatersheds with the greatest length of streams predicted to experience higher-than-average shift in center of flow mass toward early-season flow.

Target: Riparian Potential

How are they linked? Actions such as beaver mimicry and planting willows can restore riparian vegetation, reconnect streams to floodplains, increase channel complexity, and otherwise restore hydrological and ecological processes that support riparian habitat.

How did we quantify restoration value? We assigned highest value to subwatersheds with: (1) largest area of valley bottom with higher-than-average human modification; and (2) lowest stream sinuosity within these areas. These two factors were given equal weights when assigning conservation value.

Target: Within-habitat Connectivity (Forest, Grassland, Shrubland)

How are they linked? Actions such as beaver mimicry and planting willows can restore riparian habitat that is used for dispersal by a wide variety of wildlife species, including many that typically occupy non-riparian habitats.

How did we quantify restoration value? We assigned highest value to subwatersheds with the greatest total centrality value summed over all connectivity flowlines within valley bottoms.

Action: Irrigation Adjustment

Target: Stream Health

How are they linked? Irrigation practices affect stream health through their effects on flow regime - presumably streams with conditions closer to historic flow regimes, without excessive water use, and with irrigation practices that sufficiently recharge groundwater, will be healthier in terms of a variety of stream biotic condition metrics. Pivot irrigation makes more efficient use of water and pulls less total water from the stream, but does not water deeply and thus does not recharge groundwater, which can lead to reduced late-season flows and perhaps less intact/healthy biotic communities. Irrigation adjustment actions to restore normative flow regime, and thus stream health, may consist of switching from pivot to flood irrigation practices (or otherwise adjusting timing of irrigation to increase depth of watering and enable groundwater recharge).

How did we quantify restoration value? We assigned highest value to subwatersheds with the greatest value-weighted length of streams predicted to have lower-than-average biotic condition value within irrigated lands.

Target: Normative Flow Regime

How are they linked? Irrigation practices affect the volume and timing of stream/river flow as a function of how much water removal is pulled from the stream for irrigation, and when. Although pivot irrigation methods reduce water usage for irrigation by reducing the total water removed from the stream, pivot irrigation does not redistribute enough water to the land surface to recharge groundwater, and thus can lead to late-season dry conditions and reduced late-season flows as the water that would have recharged groundwater and bolstered late-season flows continues downstream. Irrigation adjustment actions to restore normative flow regime may therefore consist of switching from pivot to flood irrigation practices (or otherwise adjusting timing of irrigation to increase depth of watering and enable groundwater recharge).

How did we quantify restoration value? We assigned highest value to subwatersheds with the greatest length of streams predicted to experience higher-than-average shift in center of flow mass toward early-season flow within irrigated lands.

Action: Forest & Shrubland Fuels Management

Target: Riparian Potential

How are they linked? Fuels management can remove encroaching woody vegetation from riparian zones and reduce the likelihood of high-severity wildfires that could damage riparian vegetation communities.

How did we quantify restoration value? We assigned highest value to subwatersheds that contained the largest area of valley bottom classified as "high risk" or "very high risk" for wildland fire.

Target: Upland Vegetation Composition & Structure

How are they linked? Fuels management actions can restore historic vegetation conditions (e.g., open canopy forest) in upland areas and reduce the likelihood of high-severity wildfires that could destroy vegetation communities.

How did we quantify restoration value? We assigned highest value to subwatersheds that contained the greatest area of uplands classified as "high risk" or "very high risk" for wildland fire.

Target: Within-habitat Connectivity (Forest, Grassland, Shrubland)

How are they linked? Fuels management actions can restore historic vegetation conditions to forests, grasslands, and shrublands, improving habitat quality and facilitating movement of organisms that utilize these biomes. In addition, fuels management can reduce the likelihood of high-severity wildfires that would destroy vegetation communities and fragment these habitats.

How did we quantify restoration value? We assigned highest value to subwatersheds with the greatest concentration of high-centrality connectivity flowlines in areas classified as "high risk" or "very high risk" for wildland fire.

Action: Woody Encroachment Control

Target: Upland Vegetation Composition & Structure

How are they linked? Woody encroachment control can restore natural vegetation conditions to shrublands (by removing encroaching conifers) and grasslands (by removing encroaching shrubs and conifers.

How did we quantify restoration value? We assigned highest value to subwatersheds with the greatest area of uplands within 500 meters of an edge between (A) grassland and conifer or shrubland cover types, or (B) shrubland and conifer cover types.

Target: Within-habitat Connectivity (Grassland, Shrubland)

How are they linked? Connectivity of grassland and shrubland specialist species is compromised when woody encroachment occurs and fragments previously connected habitat. Encroachment control actions can maintain or restore preferred habitat structure in grasslands and shrublands and facilitate movement among habitat patches.

How did we quantify restoration value? We assigned highest value to subwatersheds with the greatest concentration of high-centrality grassland connectivity flowlines within 500 m of an edge between grassland and conifer or shrubland cover types (for grassland connectivity target), or the greatest concentration of high-centrality shrubland connectivity flowlines within 500 m of an edge between shrubland and conifer cover types (for shrubland connectivity target).

Prioritizing Conservation Action

A variety of systematic approaches have been developed for spatially prioritizing conservation actions across the landscape (Moilanen & Kujala 2006; Watts et al. 2009; Tallis et al. 2011). Prioritization is necessary because resources for implementing conservation solutions are typically limited and a balance between conservation and production targets is usually required. Systematic prioritization methods aim to identify an optimal set of site-specific actions that jointly maximize achievement of conservation targets, often while simultaneously minimizing conservation costs.

Implementation of systematic prioritization algorithms is nontrivial in the terrestrial and marine systems to which they have commonly been applied, despite the fact that they represent spatial relationships among planning units fairly simply as non-directional and distance-based. The problem becomes far more complex in freshwater aquatic systems because water flow is directed and connectivity is determined by stream length and topology (Moilanen et al. 2008; Hermoso et al. 2011). This means, for example, that a downstream target may be strongly influenced by the condition of geographically distant headwaters, but not vice versa.

Several prioritization algorithms have been adapted for freshwater systems in order to accommodate this added complexity. Moilanen et al. (2008) modified the Zonation algorithm and software (Moilanen & Kujala 2006) to prioritize rivers and streams on New Zealand's North Island for conserving fish biodiversity. Hermoso et al. (2011) adapted Marxan (Watts et al. 2009) to prioritize fish biodiversity conservation among catchments of the Guadiana River basin in the Iberian Peninsula. Terrado et al. (2015) extended the InVEST model (Tallis et al. 2011) to the assessment of anthropogenic impacts on both terrestrial and aquatic habitats. Although none of these applications addressed precisely the same targets or objectives as those present in the MHB, each of these methods offers flexibility for adaptation to this system. For example, varying costs of alternative actions in alternative locations can be incorporated, different conservation targets can be assigned different weights of importance, connectivity can be parameterized in target-specific ways (e.g., accounting for upstream connectivity, downstream, or both), land and water management actions can be considered simultaneously, and alternative scenarios of change in land use, climate, or socioeconomic context can be compared.

The Zonation prioritization algorithm

Zonation is an advanced algorithm and software tool for spatially prioritizing conservation actions. It identifies areas where conservation actions can simultaneously yield the greatest benefits for multiple conservation targets. Although it is designed primarily to inform conservation of biodiversity by identifying places that are important for maintaining habitat for multiple species, it can also be applied to other types of conservation targets (e.g., land cover types, ecosystem services, or in our case, various attributes of a functional terrestrial-freshwater system).

The Zonation algorithm produces a hierarchical and balanced prioritization of the landscape, accounting for complementarity of priority areas (i.e., conservation targets not fully achieved by a given priority area are achieved by another) (Moilanen et al. 2014). It iteratively removes the least valuable units from the landscape, while minimizing overall loss of conservation value across targets, maintaining connectivity among remaining units in user-defined ways (including directed connectivity along stream networks), and accounting for user-defined priorities among conservation targets. It produces a map of priority rank, identifying both optimal conservation areas for achieving a given set of targets and areas that may be least useful, where other uses of lands and waters may have minimal impact.

Missouri Headwaters Prioritization Tool

Zonation is a powerful tool, with many options for tailoring the prioritization process to a particular place and conservation need. However, this functionality and adaptability also makes for a steep learning curve and a complex setup process to use Zonation for identifying conservation priorities. Our aim was to do most of this legwork in advance for conservation practitioners working in the MHB.

We have built a custom application of the Zonation prioritization software for the MHB, with a tailored, easy-to-use graphical interface. We have produced the necessary data layers (described above), identified the most appropriate algorithm parameters, and translated settings that users may wish to control into non-technical terms. Our hope is that this will allow users facing conservation and management decisions in the MHB to quickly and easily evaluate where to implement conservation action to achieve the greatest co-benefits for desired terrestrial and/or freshwater conservation targets, without any need for technical knowledge about how to parameterize and run the Zonation software itself. However, it is still critical that users understand (in non-technical terms) what the algorithm and key settings mean for interpretation of their results.

For further details about the Zonation algorithm and settings used in the MHB prioritization tool, see Appendix B. For complete details about the algorithm and software itself and all implementation options, see the Zonation v4.0 User Manual. 'A Quick Introduction to Zonation' is an excellent resource for quickly setting up and running an example prioritization using the Zonation software package, and the 'Running a Zonation Planning Project' e-book places application of Zonation for prioritization into a broader planning process context. The following tool setup and use instructions are also available in a standalone Quick-Start Guide.

System Requirements and Setup

The MHB prioritization tool is powered by the R statistical programming environment (www.r-project.org; R Core Team 2017). Although there is no need for users to have any familiarity with R, users do need to download and install R (version 3.0.1+) as well as the RStudio software (version 1.0+) to run the tool. Unfortunately, because the Zonation software is Windows-only, the MHB prioritization tool can only be run on Windows operating systems.

To install the necessary software on your computer:

1. Download and install the current version of R for Windows here. The link will download an .exe file; open it to be guided through the install process.
2. Download and install the current version of RStudio for Windows here. Open the downloaded .exe file to be guided through setup of RStudio on your computer.
3. If you are already an RStudio user, please ensure that you have updated to version 1.0 or later. These instructions highlight the most straightforward means of updating R as well as RStudio on Windows machines.

Accessing the Tool

In order to download and open the MHB prioritization tool on your computer:

1. Download the zip file containing the prioritization tool and all necessary data here. Save the file to a permanent directory of your choosing; do **NOT** simply save to your Downloads folder.
2. Unzip the zip file to your preferred location on your computer. (If you do not already have a means of opening compressed zip files, we recommend the free, open-source 7-Zip.)
3. In the unzipped tool folder, double-click the file 'MHB_ToolSetup.R' to open the setup file. This only needs to be run once prior to your first use of the tool (Fig. 5).

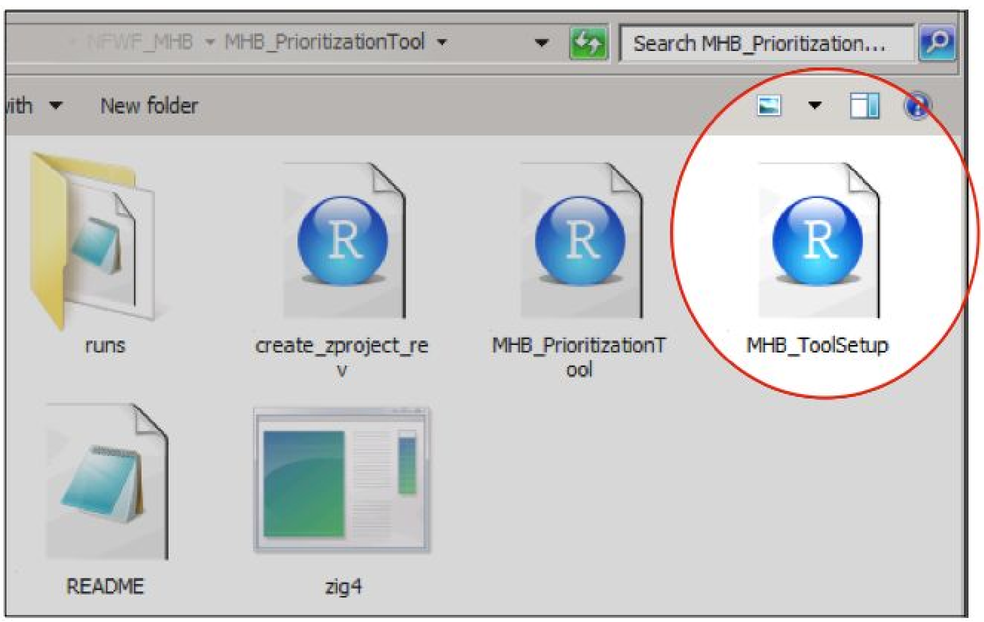

Figure 5. To set up R to run the tool, first open 'MHB_ToolSetup.Rmd' in the main tool directory.

4. A short install script will open in RStudio - **DON'T PANIC!** All you need to do is click the 'Source' button in the header bar (Fig. 6). The script will install the necessary R packages to support the tool. This will take about 5-10 minutes, and only needs to be run the first time you use the tool.

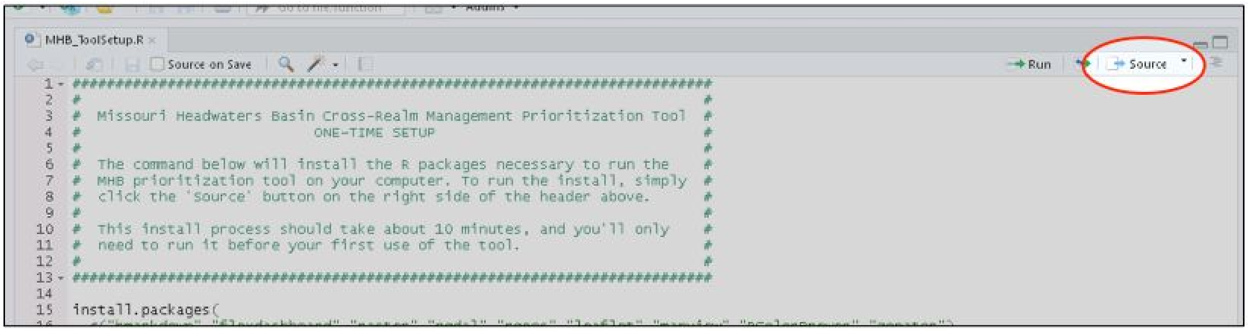

Figure 6. Run the short tool setup from RStudio by clicking the 'Source' button.

5. To run the prioritization tool itself, double-click the file 'MHB_PrioritizationTool.Rmd' to open.
6. The script underlying the tool will open in RStudio - **DON'T PANIC**! You can ignore the code and simply click the 'Run Document' button in the header bar (Fig. 7).

Figure 7. Run the prioritization tool user interface from RStudio by clicking the 'Run Document' button.

7. If prompted further to "Install Required Packages", click "Yes". This will only be required the first time you run the tool.
8. The user-friendly tool interface will open in a browser window (Fig. 8).

Using the Tool

The tool interface allows you to first specify options for your prioritization run (Fig. 8), then to explore the map results. To set up your run:

1. Name your prioritization run. Run names should not contain spaces or slashes. Your run settings and output will be saved under the name you choose in the 'MHB_PrioritizationTool/runs' directory.

   Hint*: If you expect to run several versions of your prioritization (e.g., with different actions, targets, or weights), it may be helpful to use names that specify these choices.*

2. Select your conservation action of interest. You will see the list of conservation targets change with your selection to reflect which targets could be linked directly to the chosen action in the Conceptual Model.

   For further description of each action and its links to conservation targets, see Links Between Actions and Targets.

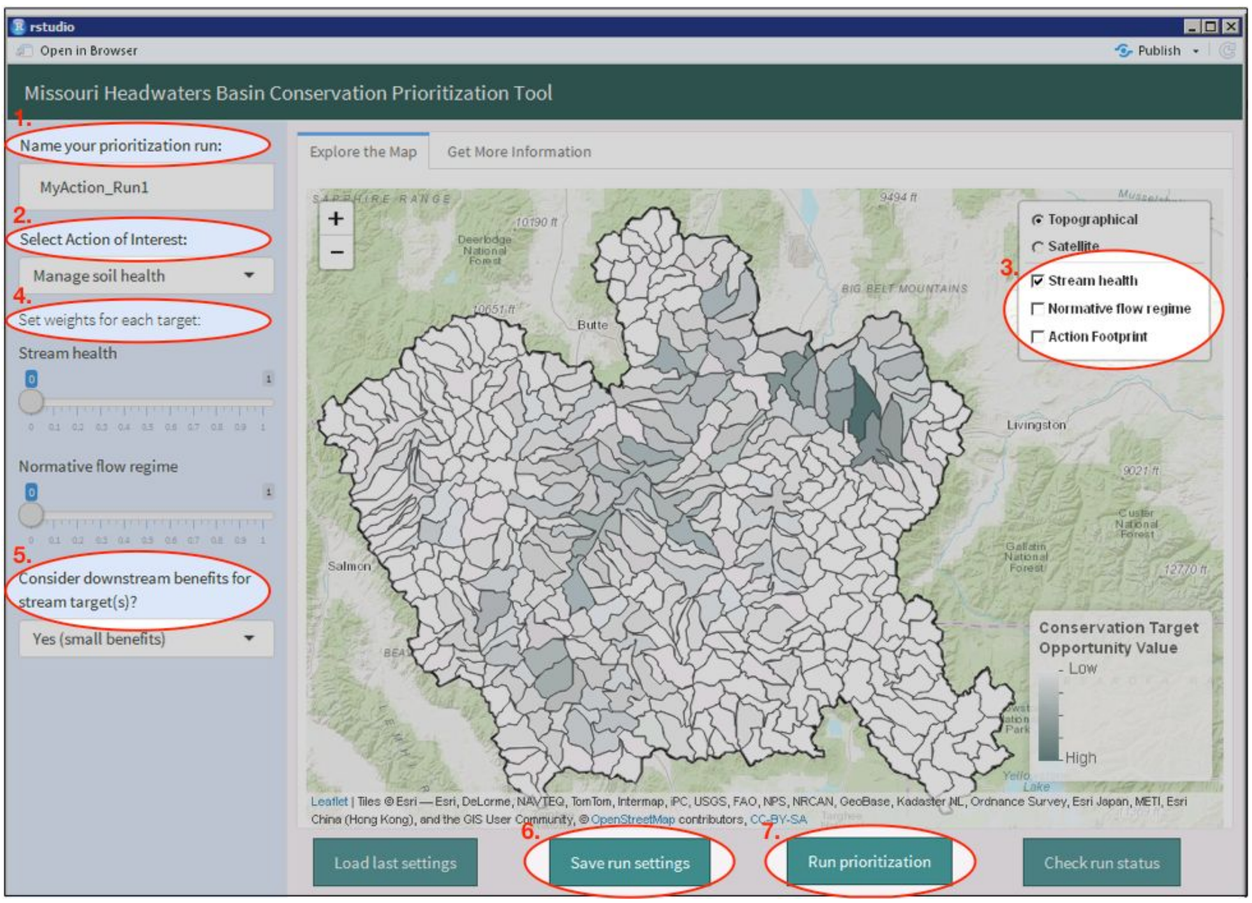

Figure 8. Steps for running the prioritization tool from the user interface.

3. Explore the target condition layers associated with the selected action on the map. Layers can be turned on and off in the legend. The 'Action Footprint' layer can be turned on to view the areas in which your action of interest can be applied.

   Remember that 'Conservation Target Opportunity Value' for each subwatershed unit was calculated in a way that accounts for the area available for the action of interest within the unit (see Links Between Actions and Targets). A unit may have low Opportunity Value because it contains no areas to which the action of interest can be applied.

4. Select weights for each conservation target associated with your action of interest. Targets that are very important to you should receive higher weights; a target that is not at all important to you can be assigned a weight of zero to be ignored. Weights need not sum to 1, but this might make interpretation easier.

   ***Hint**: If you are running several slightly different iterations of a prioritization, it might be helpful to use the 'Load last-used settings' option. This will reload the action and weights selected the last time the tool was used.*

5. If your selected action is applicable to stream-based targets (stream health and/or normative flow regime), choose whether and how strongly potential downstream benefits of the action will be considered. If downstream benefits are considered, headwater units with high target value that are upstream of other units with high target value will be prioritized more heavily.

   ***Hint**: It may be helpful to run the same prioritization with different downstream benefits options implemented for comparison.*

6. Save your settings, then run the prioritization using the buttons at the bottom of the interface window.

7. Monitor the status of your run. A console window will appear and display the progress of the Zonation algorithm (Fig. 9). Do not close this window, or the run will be canceled!

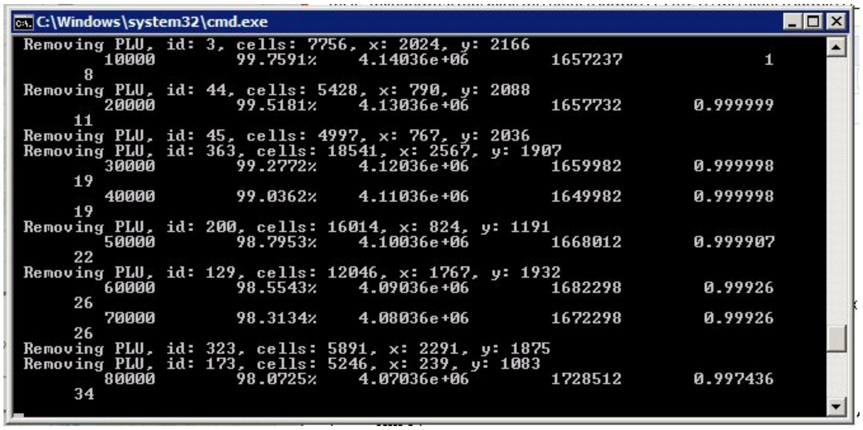

Figure 9. Pop-up console window displaying progress of prioritization run.

8. Check the status of your run using the 'Check run status' button. When the run is complete, clicking this button will load the result on the map interface to explore (Fig. 10).

   Prioritizations typically take less than 5 minutes to complete, but may take up to 10 minutes, depending on settings used and processor speed. If for any reason you need to interrupt and/or restart a running prioritization, you can do so by selecting the console and entering 'Control+C' or simply closing the console window.

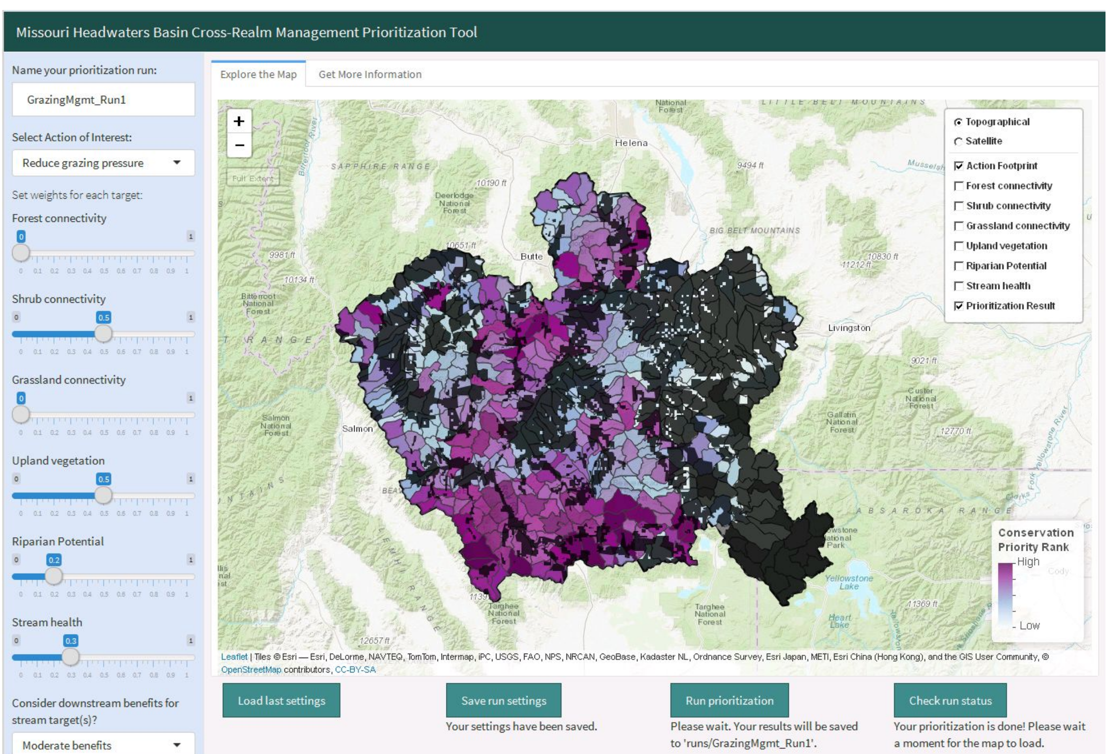

Figure 10. Example result map after completion of prioritization run.

9. For GIS users, the result file is available for import to ArcMap or other GIS software for further viewing, custom symbolization, comparison with results from other runs, and further analysis in the context of other available data for the region. To access the result file, go to 'MHB_PrioritizationTool/runs/[yourRun]/[yourRun]_out/' and select the geoTiff file ending in 'rank.compressed.tif' (Fig. 11). Higher raster values indicate higher priority rank.

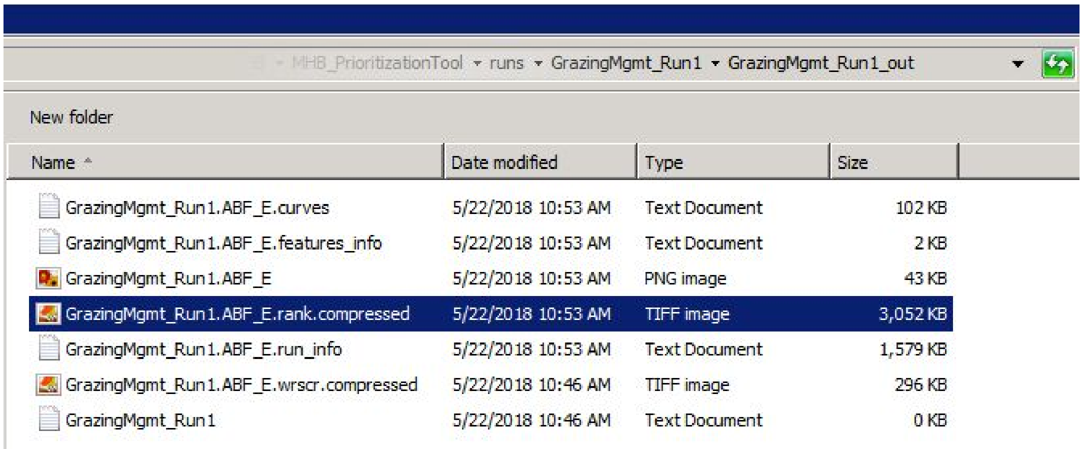

Figure 11. Example of output geoTiff file for use in GIS software.

Interpreting Results

When the prioritization is complete, clicking the 'Check run status' button will display your results on the map interface. Higher values (shown in darker purple) reflect higher priority units, given the weights and settings selected for the run. These units are predicted to offer the greatest opportunity for achieving the greatest benefit to multiple conservation targets across the MHB. Note that differences in area among subwatersheds have been accounted for: results represent conservation or restoration value per unit area.

It is very important to fully understand the data sources used in the tool, how target opportunity values were derived, and implications of run settings (e.g., consideration of downstream benefits) in order to assess whether the result captures useful aspects of action-target relationships for your individual goals and applications. We strongly recommend reviewing the relevant data sources (Appendix A: Spatial Data Sources), how 'Conservation Target Opportunity Value' was calculated for each action-target combination of interest (Links Between Actions and Targets), and descriptions of key settings (Appendix B: Zonation Parameterization) to ensure that the results of the tool meet your needs.

We suggest exploring and comparing results of similar prioritization runs to understand impacts of choices in weights and directed connectivity setting on the prioritization outcome. Multiple outputs can't currently be loaded on the map simultaneously, but you can view result images in the output directory created for your run. These image layers can also be opened with ArcGIS or other GIS software to view, symbolize, and overlay (see Step 8 above).

Zonation is a powerful tool, but when prioritization runs get complex (many targets with varying weights, downstream benefits considered), results can become more difficult to interpret. We recommend a few paths by which you might explore the impact of different run settings:

- Try running prioritizations of single targets (set a single target weight to 1, with others set to 0), then comparing these to your multiple-target result.
- Try making small adjustments to the relative weights assigned to multiple targets to understand how sensitive the result is to weight choices. Which units have high priority regardless of changes in weights? Which change in priority?
- Try running the same prioritization (consistent targets and weights) with different downstream benefit settings to better understand how this feature changes your results.

Ultimately, we recommend that you choose the prioritization result that best captures the values you place on targets and your understanding of the system, not which produces a result most like what you expect or want to see. Exploration of alternative settings are intended to promote understanding of how the tool operates and how selected settings affect the result, not to achieve a preconceived output.

Troubleshooting

Help! Where do I go to open the tool?

First, you'll need to download the tool package here. Then follow the instructions above (Accessing the Tool) to unzip the downloaded folder, run the tool setup, and open the MHB_PrioritizationTool.Rmd file.

I can't open 'MHB_PrioritizationTool.Rmd'.

The prioritization tool is powered by the R and RStudio software. If you do not have R and RStudio, or if you are not running the current versions, follow the instructions above (System Requirements and Setup) to install or update these applications.

Also note that the prioritization tool is currently Windows-only. If you are a Mac user, you will need to run the tool on a Windows machine instead.

I just see a bunch of code when I open the tool. What do I do?

Don't panic! This is what you should see, but there is no need to understand or interact with the code. You can ignore it and simply click 'Run Document' in the header bar (see Accessing the Tool instructions above). The user-friendly graphical interface will open in a browser window.

I get an error that 'flexdashboard' or another package does not exist or cannot be found when I try to run the tool.

Did you run 'MHB_ToolSetup.R' before attempting to open the tool? This short script installs the R packages necessary to run the tool and must be run before opening the tool (see Accessing the Tool instructions above).

I get an error that the 'create_zproject_rev' source file does not exist or cannot be found when I try to run the tool.

This can happen if you downloaded the tool to a temporary directory, like your Downloads folder. Move the entire tool package to a permanent directory on your computer and try again.

The tool interface grays out and I see error messages in RStudio when I open the tool.

This is generally an indication that the tool script did not find something it was looking for. If this is the first time you are running the tool, did you choose 'Yes' when asked to install packages? Did you accidentally alter any of the code before you clicked 'Run Document'? Did you delete, rename, or reorganize any files within the tool folder? If any of these things may have happened, try downloading a fresh copy of the tool.

The tool interface grays out and I see error messages in RStudio when I select a new action from the drop-down menu.

This is an indication that the tool is not finding the map layers it is looking for. Did you delete, rename, or reorganize any files within the tool folder? If any of these things may have happened, try downloading a fresh copy of the tool.

The tool interface grays out and I see error messages in RStudio when I save my run settings.

This can happen when run names contain slashes ('/'). Restart the tool and choose a run name that does not contain spaces or slashes.

The 'Load last settings' button doesn't work.

This option will not be functional until you've saved settings for at least one prioritization run. Try it again after saving your settings.

Nothing happens when I hit 'Run', or my prioritization stopped running without producing any results.

The tool will create an output directory and necessary run files but immediately fail if the run name contained spaces. Try again with a name that does not use spaces or slashes.

This will also happen if no targets were assigned non-zero weights. Make sure that you have given at least one target a weight greater than zero.

This may also happen if Zonation does not find the data files it is looking for. If you have deleted, renamed, or rearranged any files downloaded with the tool package, we recommend downloading a fresh copy of the tool.

My result won't load on the map.

An error may have occurred that prevented the tool from running (see previous issue). You can check to see that a result file was successfully produced by going to 'MHB_PrioritizationTool/runs/[yourRun]/[yourRun]_out/' and looking for the geoTiff file ending in 'rank.compressed.tif'.

If you entered a new run name into the interface after your prioritization began, the tool will not be able to find the results file in the appropriate location and it will not load on the map. In this case, you have several options:

1. You can re-enter the run name for the result you'd like displayed, then hit 'Check Run Status'. This should allow the tool to look for your result in the appropriate directory.
2. You can open the result file directly. The .tif file can be opened and manipulated in GIS software, or you can view the result image in any photo viewer that supports tiff files (lighter shades represent higher priority).
3. You can rerun the prioritization with the same settings, this time without changing any settings before the prioritization is complete, and your result should load on the map successfully.

I want to run another prioritization but nothing happens when I hit 'Run'.

It should generally be possible to start a new run in the same window after a previous run has been completed. However, if the new run does not start, you may need to close and reopen the tool.

How do I see my results after I've closed the tool?

The result file is available for import to ArcMap or other GIS software for further viewing, custom symbolization, comparison with results from other runs, and further analysis in the context of other available data for the region. To access the result file, go to 'MHB_PrioritizationTool/runs/[yourRun]/[yourRun]_out/' and select the geoTiff file ending in 'rank.compressed.tif'. Higher raster values indicate higher priority rank.

You can also view the result image in any photo viewer that supports tiff files. Lighter shades in the tiff image represent higher priority.

I still have an issue that isn't addressed here.

If you've followed all instructions and are still experiencing an issue that is not resolved by the above guidance, please let us know. You can contact Meredith McClure or Tyler Creech for further assistance.

Model Limitations and Future Improvements

It is important to recognize that the tool uses the best available data that was consistent across the MHB and was thought to capture action-target relationships in broadly relevant and applicable ways. Some action-target links are represented more broadly than others. Please review the data sources (Appendix A: Spatial Data Sources) and how 'Conservation Target Opportunity Value' was calculated for each action-target combination (Links Between Actions and Targets) to ensure that results of the prioritization process meet your needs and that the results are interpreted and applied appropriately.

Not all actions, targets, or action-target links identified in the original stakeholder-driven conceptual model are included in the tool due to lack of appropriate data, limited published evidence for links, or relative weakness of links. A future iteration of the model could be more inclusive as additional data and information become available.

Results of this prioritization tool should be viewed as complementary to local knowledge and on-the-ground field assessments of conservation and restoration opportunities. Results are generated at the scale of subwatershed units (HUC12), and although overlay of action footprints can help to focus in on more specific places within priority units where an action may be advantageous, the coarseness and/or generality of some datasets and our calculation of target opportunity value will generally still call for more localized assessment of conservation or restoration opportunities. The goal of this tool is to help practitioners to narrow down areas of the MHB where these time- and energy-intensive local assessments may be most valuable.

In short, we strongly encourage interpretation and application of tool results in the context of other available information, field assessment of potential priority areas identified by the tool, and consideration of the social, political, and management context of potential conservation and restoration actions, which may offer opportunities for or barriers to action depending on the time and place.

References

Adams, V. M., J. G. Alvarez-Romero, J. Carwardine, L. Cattarino, V. Hermoso, M. J. Kennard, S. Linke, R. L. Pressey, and N. Stoeckl. 2014. Planning across freshwater and terrestrial realms: cobenefits and tradeoffs between conservation actions. Conservation Letters **7**:425–440.

Alvarez-Romero, J. G., V. M. Adams, R. L. Pressey, M. Douglas, A. P. Dale, A. A. Augé, D. Ball, J. Childs, M. Digby, R., Dobbs, and N. Gobius. 2015. Integrated cross-realm planning: a decision-makers' perspective. Biological Conservation **191**:799–808.

Amis, M. A., M. Rouget, M. Lotter, and J. Day. 2009. Integrating freshwater and terrestrial priorities in conservation planning. Biological Conservation **142**:2217–2226.

Beger, M., H. S. Grantham, R. L. Pressey, K. A. Wilson, E. L. Peterson, D. Dorfman, P. J. Mumby, R. Lourival, D. R. Brumbaugh, and H. P. Possingham. 2010. Conservation planning for connectivity across marine, freshwater, and terrestrial realms. Biological Conservation **143**:565–575.

Bonn, A., M. Rebane, and C. Reid. 2009. Ecosystem services: a new rationale for conservation of upland environments. *In:* Drivers of environmental change in uplands. Bonn, A., T. Allott, K. Hubacek, and J. Stewart, eds. Routledge, New York.

Busari, M. A., S. S. Kukal, A. Kaur, R. Bhatt, and A. A. Dulazi. 2015. Conservation tillage impacts on soil, crop and the environment. International Soil and Water Conservation Research **3**:119-129.

Crooks, K. R., and M. Sanjayan, eds. 2006. Connectivity conservation (Vol. 14). Cambridge University Press.

Cross, M. S., E. S. Zavaleta, D. Bachelet, M. L. Brooks, C. A. Enquist, E. Fleishman, L. J. Graumlich, C. R. Groves, L. Hannah, L. Hansen, and G. Hayward. 2012. The adaptation for conservation targets (ACT) framework: a tool for incorporating climate change into natural resource management. Environmental Management **50**:341–351.

Dillon, G. K., J. Menakis, and F. Fay. 2015. Wildland fire potential: a tool for assessing wildfire risk and fuels management needs. *In:* Proceedings of the large wildland fires conference, May 19-23, 2014, Missoula, MT. Keane, R .E., M. Jolly, R. Parsons, and K. Riley (eds). U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station, Fort Collins, CO. Proc. RMRS-P-73:60-76.

DNRC [Montana Department of Natural Resources and Conservation]. 2016. Guidance for landowners and practitioners engaged in stream and wetland restoration activities. Water Resources Division.

Environmental Quality Council. 2015. Summary of road information for Montana's National Forest System. URL http://leg.mt.gov/content/Committees/Interim/2015-2016/EQC/Meetings/Sept-2015/hj-13-summary-road-info-mt-usfs.pdf

EPA [U.S. Environmental Protection Agency]. 2017. National Aquatic Resource Surveys home page. URL https://www.epa.gov/national-aquatic-resource-surveys

Fageria, N. K., V. C. Baligar, and B. A. Bailey. 2005. Role of cover crops in improving soil and row crop productivity. Communications in Soil Science and Plant Analysis **36**:2733-2757.

Federal Highway Administration. 2007. Design for fish passage at roadway-stream crossings: synthesis report. United States Department of Transportation. Pub. No. FHWA-HIF-07-033.

George, M. R., R. D. Jackson, C. S. Boyd, and K. W Tate. 2011. A scientific assessment of the effectiveness of riparian management practices. *In:* Conservation benefits of rangeland practices: assessment, recommendations, and knowledge gaps. Briske, D. D. (ed). United States Department of Agriculture, Natural Resources Conservation Service, Washington, DC. pp. 213-52.

Gustanski, J. A., and R. H. Squires. 2000. Protecting the land: conservation easements past, present, and future. Island Press, Washington, D.C.

Harrison-Atlas, D., D. M. Theobald, B. G. Dickson, V. Landau, and I. Leinwand. 2017. Description of the approach, data, and analytical methods used to evaluate river systems in the western U.S. Conservation Science Partners, Truckee, CA.

Hauer, F. R., H. Locke, V. J. Dreitz, M. Hebblewhite, W. H. Lowe, C. C. Muhlfeld, C. R. Nelson, M. F. Proctor, and S. B. Rood. 2016. Gravel-bed river floodplains are the ecological nexus of glaciated mountain landscapes. Science Advances **2**:e1600026–e1600026.

Heller, N. E., and E. S. Zavaleta. 2009. Biodiversity management in the face of climate change: a review of 22 years of recommendations. Biological Conservation **142**:14-32.

Hermoso, V., S. Linke, J. Prenda, and H. P. Possingham. 2011. Addressing longitudinal connectivity in the systematic conservation planning of fresh waters. Freshwater Biology **56**:57–70.

Hill, R. A., E. W. Fox, S. G. Leibowitz, A. R. Olsen, D. J. Thornbrugh, and M. H. Weber. 2017. Predictive mapping of the biotic condition of conterminous US rivers and streams. Ecological Applications **27**:2397-2415.

Homer, C. G., J. A. Dewitz, L. Yang, S. Jin, P. Danielson, G. Xian, J. Coulston, N. D. Herold, J. D. Wickham, and K. Megown. 2015. Completion of the 2011 National Land Cover Database for the conterminous United States - representing a decade of land cover change information. Photogrammetric Engineering and Remote Sensing **81**:345-354.

Jain, T. B., M. A. Battaglia, H. S. Han, R. T. Graham, C. R. Keyes, J. S. Fried, and F. E. Sandquist. 2012. A comprehensive guide to fuel management practices for dry mixed conifer forests in the northwestern United States. U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station, Fort Collins, CO. General Technical Report RMRS-GTR-292.

Kendy, E., and J. D. Bredehoeft. 2006. Transient effects of groundwater pumping and surface-water-irrigation returns on streamflow. Water Resources Research **42**:W08415.

Lake, P. S., N. Bond, and P. Reich. 2007. Linking ecological theory with stream restoration. Freshwater Biology **52**:597–615.

Macdonald, L.A., and S. Smith. 1999. Bridge replacements: an opportunity to improve habitat connectivity. *In:* International Conference on Wildlife Ecology and Transportation, Missoula, MT, Proceedings.

Margoluis, R., C. Stem, N. Salafsky, and M. Brown. 2009. Using conceptual models as a planning and evaluation tool in conservation. Evaluation and Program Planning **32**:138–147.

McEvoy, J., D. J. Bathke, N. Burkardt, A. E. Cravens, T. Haigh, K. R. Hall, M. J. Hayes, T. Jedd, M. Poděbradská, and E. Wickham. 2018. Ecological drought: accounting for the non-human impacts of water shortage in the Upper Missouri Headwaters Basin, Montana, USA. Resources **7**:14.

Meyer, J. L. 1997. Stream health: incorporating the human dimension to advance stream ecology. Journal of the North American Benthological Society **16**:439-447.

Moilanen, A., and H. Kujala. 2006. Zonation spatial conservation planning framework and software v. 1.0, User manual. Edita, Helsinki, Finland.

Moilanen, A., J. Leathwick, and J. Elith. 2008. A method for spatial freshwater conservation prioritization. Freshwater Biology **53**:577–592.

Moilanen, A., F. M. Pouzols, L. Meller, V. Veach, A. Arponen, J. Leppanen, and H. Kujala. 2014. Spatial conservation planning methods and software: Zonation Version 4 User Manual. C_BIG Conservation Biology Informatics Group. Dept. of Biosciences, University of Helsinki, Finland.

Napper, C. 2007. Road decommissioning effectiveness monitoring techniques. *In:* Advancing the Fundamental Sciences: Proceedings of the Forest Service National Earth Sciences Conference, October 18–22, 2004, San Diego, CA. Furniss, M., C. Clifton, and K. Ronnenberg (eds). US Department of Agriculture Forest Service, Pacific Northwest Research Station, Portland, OR. General Technical Report PNW-GTR-689:318–327.

Norris, R. H, and M. C. Thoms. 1999. What is river health? Freshwater Biology **41**:197-209.

Noson, A. C., R. A. Schmitz, and R. F. Miller. 2006. Influence of fire and juniper encroachment on birds in high-elevation sagebrush steppe. Western North American Naturalist **66**:343-353.

NRCS [Natural Resources Conservation Service]. 1996. Conservation crop rotation effects on soil quality. U.S. Department of Agriculture, Technical Note No. 2.

Pervez, M. S., and J. F. Brown. 2010. Mapping irrigated lands at 250-m scale by merging MODIS data and national agricultural statistics. Remote Sensing **2**:2388-2412.

Poff, N. L., J. D. Allan, M. B. Bain, J. R. Karr, K. L. Prestegaard, B. D. Richter, R. E. Sparks, and J. C. Stromberg. 1997. A paradigm for river conservation and restoration. BioScience **47**:769–784.

Pollock, M. M., N. W. Weber, and G. Lewallen. 2015. Beaver dam analogues. *In:* The beaver restoration guidebook: working with beaver to restore streams, wetlands, and floodplains. Pollock, M. M., G. Lewallen, K. Woodruff, C. E. Jordan, and J. M. Castro (Eds). United States Fish and Wildlife Service, Portland, Oregon. pp. 82-96.

Pusey, B. J., and A. H. Arthington. 2003. Importance of the riparian zone to the conservation and management of freshwater fish : a review. Marine And Freshwater Research **54**:1–16.

R Core Team. 2017. R: A language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria. URL https://www.R-project.org/.

Regonda, S. K., B. Rajagopalan, M. Clark, and J. Pitlick. 2005. Seasonal cycle shifts in hydroclimatology over the western United States. Journal of Climate **18**:372–384.

Richardson, E.V., and J. R. Richardson. 1999. Determining contraction scour. *In:* Stream Stability and Scour at Highway Bridges. Richardson, E.V., and P.F. Lagasse (Eds). American Society of Engineers. pp. 483-490.

Roni, P., K. Hanson, and T. Beechie. 2008. Global review of the physical and biological effectiveness of stream habitat rehabilitation techniques. North American Journal of Fisheries Management **28**:856–890.

Ryan, K. C., E. E. Knapp, and J. M. Varner. 2013. Prescribed fire in North American forests and woodlands: history, current practice, and challenges. Frontiers in Ecology and the Environment **11:**s1.

Rybicki, M., C. Winkelmann, C. Hellmann, P. Bartels, and D. Jungmann. 2012. Herbicide indirectly reduces physiological condition of a benthic grazer. Aquatic Biology **17**:153–166.

Stoms, D. M., F. W. Davis, S. J. Andelman, M. H. Carr, S. D. Gaines, B. S. Halpern, R. Hoenicke, S. G. Leibowitz, A. Leydecker, E. M. Madin, and H. Tallis.. 2005. Integrated coastal reserve planning: making the land–sea connection. Frontiers in Ecology and the Environment **3**:429–436.

Suurkuukka, H., R. Virtanen, V. Suorsa, J. Soininen, L. Paasivirta, and T. Muotka. 2014. Woodland key habitats and stream biodiversity: does small-scale terrestrial conservation enhance the protection of stream biota? Biological Conservation **170**:10–19.

Switalski, T., J. Bissonette, T. DeLuca, C. Luce, and M. Madej. 2004. Benefits and impacts of road removal. Frontiers in Ecology and the Environment **2**:21-28.

Symstad, A.J., and S. A. Leis. 2017. Woody encroachment in Northern Great Plains grasslands: perceptions, actions, and needs. Natural Areas Journal **37**:118-127.

Tallis, H. T., T. Ricketts, A. D. Guerry, E. Nelson, D. Ennaanay, S. Wolny, N. Olwero, K. Vigerstol, D. Pennington, G. Mendoza, and J. Aukema. 2011. InVEST 2.1 beta User's Guide. The Nature Capital Project.

Taylor, P. D., L. Fahrig, K. Henein, and G. Merriam. 1993. Connectivity is a vital element of landscape structure. Oikos **68**:571–573.

Terrado, M., S. Sabater, B. Chaplin-Kramer, L. Mandle, G. Ziv, and V. Acuna. 2015. Model development for the assessment of terrestrial and aquatic habitat quality in conservation planning. Science of the Total Environment **540**:63–70.

Theobald, D. M. 2013. A general model to quantify ecological integrity for landscape assessments and US application. Landscape Ecology **28**:1859–1874.

Theobald, D. M., D. M. Merritt, and J. B. Norman III. 2010. Assessment of threats to riparian ecosystems in the western US: A report presented to The Western Environmental Threats Assessment Center. USDA Stream Systems Technology Center, Prineville, OR, and Colorado State University, Fort Collins, CO.

Theobald, D.M., S. E. Reed, K. Fields, and M. Soule. 2012. Connecting natural landscapes using a landscape permeability model to prioritize conservation activities in the United States. Conservation Letters **5**:123-133.

Undersander, D. J., B. Albert, D. Cosgrove, D. Johnson, and P. Peterson. 2002. Pastures for profit: A guide to rotational grazing. Cooperative Extension Publications, University of Wisconsin-Extension. R-10-02-5.5M-500.

Van Auken, O. W. 2009. Causes and consequences of woody plant encroachment into western North American grasslands. Journal of Environmental Management **90**:2931-2942.

Van der Maarel, E., ed. 2005. Vegetation ecology. Blackwell Publishing, Malden, MA.

Watts, M. E., I. R. Ball, R. S. Stewart, C. J. Klein, K. Wilson, C. Steinback, R. Lourival, L. Kircher, and H. P. Possingham. 2009. Marxan with Zones: software for optimal conservation based land-and sea- use zoning. Environmental Modelling & Software **24**:1513–1521.

Wenger, S. J., C. H. Luce, A. F. Hamlet, D. J. Isaak, and H. M. Neville. 2010. Macroscale hydrologic modeling of ecologically relevant flow metrics. Water Resources Research **46**:W09513.

Williams, R. E., B. A. Roundy, A. Hulet, R. F. Miller, R. J. Tausch, J. C. Chambers, J. Matthews, R. Schooley, and D. Eggett. 2017. Pretreatment tree dominance and conifer removal treatments affect plant succession in sagebrush communities. Rangeland Ecology & Management **70**:759-773.

Woods, B. A., J. L. Rachlow, S. C. Bunting, T. R. Johnson, and K. Bocking. 2013. Managing high-elevation sagebrush steppe: do conifer encroachment and prescribed fire affect habitat for pygmy rabbits? Rangeland Ecology and Management **66**:462-471.

Yochum, S. E. 2017. Guidance for Stream Restoration. U.S. Department of Agriculture, Forest Service, National Stream & Aquatic Ecology Center, Fort Collins, CO. Technical Note TN-102.3.

Appendix A: Spatial Data Sources

We relied on a variety of publicly available spatial datasets (Table A1) to determine locations where actions could be implemented, the magnitude and extent of threats, and the current or projected future condition of conservation targets. Most of the datasets used in this analysis are available from the original source at a West-wide or national exent and could be used in similar analyses for other geographic regions.

Table A1. Spatial data sources used in development of prioritization tool.

Dataset	Source	Description	Data format	Original spatial resolution	Original spatial extent
Biome-specific connectivity flowlines	Theobald, D. Unpublished data. Conservation Science Partners, Truckee, CA. (See Theobald et al. 2012 for methodology)	Estimated connectivity among core areas of grassland, shrubland, and forest as a function of landscape permeability. The model used to generate the dataset was based on the assumption that areas that are less modified by humans (i.e., more "natural") are more likely to allow for animal movement and other ecological flows. Least-cost paths were calculated across the landscape with movement resistance values directly related to the degree of human modification, and network centrality metric was used to quantify the relative importance of each landscape cell to the broader landscape configuration. Connectivity routes with high centrality ("flowlines") were identified and indicate highly permeable connections between core areas.	Vector	NA	Rocky Mountains region
Biotic condition of streams and rivers	U.S. Environmental Protection Agency (Hill et al. 2017)	Estimated biological condition of stream segments based on a multimetric index of benthic invertebrate assemblages. Data were produced using a random forest model that predicts the probable condition of streams based on nearby and upstream landscape features, including human-related alterations to watersheds. Data can be interpreted as the predicted probability of a stream being in good condition, given upstream and nearby landscape settings.	Vector	NA	conterminous United States
BLM grazing allotments	Bureau of Land Management	Boundaries of BLM grazing allotments.	Vector	NA	United States
DNRC grazing lands	Montana Department of Natural Resources and Conservation	Boundaries of grazing agreements on state trust lands. Includes agreements classified as "Grazing Lease", "Grazing Competitive Bid", "Ag & Grazing Lease", "Ag & Grazing Competitive Bid", or "Forest Grazing License."	Vector	NA	Montana

Human Modification Index	Theobald, D. Conservation Science Partners (Theobald 2013)	Overall level of human modification of the landscape as a function of multiple anthropogenic stressors (e.g., residential and commercial development, transportation infrastructure, pollution, invasive species, energy development, mining). The model uses a fuzzy sum approach that assumes the contribution of a given threat decreases as values from other threats overlap.	Raster	90 m	North America
Irrigated lands	U.S. Geological Survey (Pervez and Brown 2010)	Irrigated agricultural lands mapped using a geospatial modeling approach implemented for three time periods (2002, 2007 and 2012). Model inputs included the National Land Cover Dataset, USDA Census of Agriculture irrigated area statistics, and annual maximum vegetation index calculated from NASA Moderate Resolution Imaging Spectroradiometer imagery.	Raster	250 m	conterminous United States
Montana conservation easements	Montana State Library	Private lands parcels on which a public agency or qualified Land Trust has placed a Conservation Easement in cooperation with the land owner. This dataset was derived from the Montana Cadastral parcel layer.	Vector	NA	Montana
National Bridge Inventory	Department of Homeland Security	Inventory of over 600,000 bridges located on public roads, including Interstate Highways, U.S. highways, state and county roads, and publicly-accessible bridges on Federal lands.	Vector	NA	United States
National Hydrography Dataset Plus Version 2.1	U.S. Environmental Protection Agency and U.S. Geological Survey	Naturally occurring and constructed bodies of surface water (lakes, ponds, and reservoirs), paths through which water flows (canals, ditches, streams, and rivers), and related entities such as point features (springs, wells, stream gages, and dams).	Vector	NA	conterminous United States
National Land Cover Database 2011	U.S. Geological Survey (Homer et al. 2015)	Descriptive spatial data for characteristics of the land surface including thematic class (e.g., urban, agriculture, forest). NLCD 2011 was based primarily on a decision-tree classification of Landsat satellite data from approximately 2011.	Raster	30 m	United States
Private conservation lands	Montana State Library	Parcels owned by land trusts and other private conservation organizations (i.e., already managed for conservation).	Vector	NA	Montana
Public lands	Montana State Library	Public administered lands that are recorded in the Montana Department of Revenue's tax appraisal database. This dataset was derived from the statewide Montana Cadastral Parcel layer.	Vector	NA	Montana
Stream flow metrics	U.S. Forest Service Rocky Mountain Research Station (Wenger et al. 2010)	Estimated historical (1915-2006) and projected future (2030-2059 or 2070-2099) stream flow metrics for stream segments based on daily runoff and baseflow from the Variable Infiltration Capacity (VIC) macroscale hydrologic model. Projections were based on an ensemble of ten global climate models from CMIP3 using the A1B emissions scenario. The dataset includes the following variables: mean annual flow, mean summer	Vector	NA	western United States

		flow (June 1-Sept. 30), mean August flow, number of daily winter flows exceeding the 95th or 99th percentile of daily flows across the entire year, 1.5 year flood, and center of flow mass.			
Stream sinuosity	National Water-Quality Assessment - Hydrologic Systems Team	Sinuosity of catchment reaches compiled for both individual catchments and reach catchments accumulated upstream through the river network (i.e., watersheds) from NHDPlus Version 2 data. Sinuosity was calculated as the curvilinear length of the mainstem streamline divided by the straight-line distance between the endpoints of the line.	Vector	NA	conterminous United States
TIGER/Line roads	U.S. Census Bureau	Primary, secondary, local neighborhood, and rural roads, city streets, vehicular trails (4wd), ramps, service drives, alleys, parking lot roads, private roads for service vehicles (logging, oil fields, ranches, etc.), bike paths or trails, bridle/horse paths, walkways/pedestrian trails, and stairways.	Vector	NA	United States
USFS grazing allotments	U.S. Forest Service	Boundaries of U.S. Forest Service grazing allotments.	Vector	NA	United States
Valley bottoms	Conservation Science Partners (Harrison-Atlas et al. 2017)	Modeled extent of valley bottoms estimated based on topographic characteristics using USGS National Elevation Data and National Hydrography Dataset flowlines.	Raster	10 m	western United States
Wildfire hazard potential	U.S. Forest Service and Fire Modeling Institute (Dillon et al. 2015)	Estimated relative potential for wildfire that would be difficult for suppression resources to contain ("wildlife hazard potential"). Model inputs included wildfire likelihood and intensity generated in 2014 with the Large Fire Simulation system, spatial fuels and vegetation data from LANDFIRE 2010, and point locations of fire occurrence.	Raster	270 m	conterminous United States

Appendix B: Zonation Parameterization

Zonation algorithm

Zonation ranks landscape units by iteratively removing them from the landscape. Units may be composed of single cells or groups of cells, if planning units are identified (see below). The first unit removed (i.e., the least important to retain) receives the lowest prioritization rank; the last unit remaining (i.e., the most important to retain) receives the highest rank. Units are selected for removal by determining which unit when removed results in the smallest 'marginal loss' of conservation value in the remaining units - in other words, the total loss of value across all targets when that unit is removed.

Loss of conservation value is quantified in a way that integrates several key ideas. First, it accounts for complementarity of the remaining units - their collective representation of all conservation targets of interest. Choice of a unit removal rule (see below) allows us to define what we consider optimal complementarity; for example, one rule favors maintaining representation of rarer targets, while another aims to benefit the highest total number of targets, even if some rare targets aren't well-represented.

Second, loss of conservation value is influenced by the spatial arrangement of the remaining units. Zonation aims to prioritize aggregated areas with good representation of conservation targets where possible, rather than individual units that may be scattered throughout the landscape, which could result in highly fragmented focal conservation areas. Aggregated priorities are in part promoted by only considering units on the edge of the remaining set of units for removal. However, the way in which remaining units are considered aggregated or connected can also be controlled. For example, applying a penalty for greater fragmentation among priority units can encourage selection of larger core areas as priorities. Alternatively, considering directed connectivity along stream networks (see below) can help prioritize units with high potential for benefits to downstream targets.

Planning units

We treated subwatershed units (HUC12) as our unit of analysis in the MHB prioritization tool. This means that all raster cells composing a HUC12 unit were removed and ranked as a group during the prioritization process rather than being ranked individually. Prioritizing subwatershed units rather than individual raster cells was necessary for several reasons. First, it allowed us to appropriately quantify target condition in the context of an action that may apply to a different footprint within a subwatershed (e.g., irrigation adjustment is *applied* to irrigated agricultural lands, but *affects* flow regime of adjacent streams). It also allowed us to consider directed connectivity along stream networks, as upstream/downstream relationships are readily defined among subwatershed units but not within them. Finally, prioritization of units larger than individual cells greatly increases processing speed.

Unit removal rule

We used the additive benefit function as the unit removal rule in the MHB prioritization tool. With this function, the loss of conservation value when a given unit is removed is simply a sum of target-specific losses. While other removal rules focus on maintaining the single rarest remaining target and ultimately prioritize units with the highest rarity-weighted richness of targets, the additive benefit function accounts for proportions of *all* targets contained within a given unit and prioritizes units that provide the greatest total benefits to the greatest total number of targets. We selected this rule because it was the most consistent with the primary goal of the tool - to maximize conservation benefits to multiple terrestrial and freshwater targets.

Directed connectivity

In freshwater systems, connectivity among units is strictly directed - water flows from upstream units to downstream units, so a downstream target may be strongly influenced by the condition of the unit upstream (or even geographically distant headwaters), but not vice versa. This makes prioritization more complex. However, Zonation offers a directed connectivity option, in which upstream/downstream relationships among units can be specified and the impact of conservation or restoration action in a given unit on targets in downstream units can be accounted for. Results of prioritization using directed connectivity tend to rank high-value upstream units with potential for negative downstream impacts if removed more highly than results that do not account for directed connectivity. They may also favor prioritization of connected units along river or stream reaches rather than unit scattered throughout the area of interest (Moilanen et al. 2007). Note that although downstream connectivity relationships can be defined in Zonation as well (e.g., connections between focal units and downstream habitat for anadromous fish), we did not have reason to consider them here.

We defined directed connectivity relationships among subwatershed units using information included in the NHD Watershed Boundary Dataset, which, for each subwatershed unit, gives the identity of the subwatershed immediately downstream. Zonation uses this information to define a ‘tree hierarchy’ among units, which is then treated as the ‘neighborhood’ of units influencing a given focal unit. When calculating loss of conservation value resulting from removal of a focal unit, the loss associated with the unit itself is considered, as well as the loss associated with all units comprising the upstream neighborhood. In the case of conservation actions, a complete loss of 'Target Opportunity Value' in all upstream units means that these units no longer have conservation value for a given target - in other words, the target has been heavily degraded - with negative impacts on the conservation value of the downstream focal unit. It therefore makes sense to focus conservation actions on these upstream units in order to conserve their value while also preventing negative impacts downstream.

In the case of restoration actions, interpreting the impact of loss of the upstream neighborhood is highly counterintuitive. Remember that the target value layers used in the MHB prioritization tool quantify 'Target Opportunity Value'. For restoration actions, this means that units in poor ecological condition have high 'opportunity' value. Thus, a complete loss of 'opportunity' value in all upstream units means that these units no longer have restoration value - in other words, they have been *restored to pristine condition* - with 'negative' impacts on the value of restoring the downstream focal unit. The downstream focal unit now has decreased 'opportunity' value, meaning that the unit's ecological condition has *improved* with 'loss' (restoration) of upstream units. It therefore makes sense to focus restoration actions on upstream units in order to restore them while also promoting downstream declines in restoration opportunity, which are actually positive impacts in terms of ecological condition.

We can make these upstream/downstream relationships more realistic (albeit more complex) by defining the degree to which 'loss' of upstream units affects a downstream focal unit. Zonation integrates a user-defined response curve that describes the proportion of a target's value in the focal unit that is expected to be lost with the proportion of upstream unit area lost (Fig. B1). For example, perhaps the value of the target in the focal unit is expected to decline by 25% if half the upstream units are removed, and by 50% if all upstream units are removed. The response curve describing this relationship would look like the 'moderate benefits' curve below (Fig. B1). The steeper the decline in the response curve, the stronger the effect of considering directed connectivity in the prioritization outcome. A flat curve, in which there is no loss of value in the focal unit with loss of the upstream neighborhood ('no benefits' curve, Fig. B1) is the equivalent of *not* considering directed connectivity in the prioritization process.

We include directed connectivity options in the MHB prioritization tool for stream targets (i.e., 'stream health', 'normative flow regime'). We do not include directed connectivity options for land-based targets (e.g., 'shrub connectivity', 'upland vegetation') because we could not identify direct connections of any appreciable magnitude between actions taken to benefit these targets in upstream units and impacts on the target in downstream units. For stream targets, we have no empirical basis for defining the shape or magnitude of response curves describing the extent to which conservation or restoration actions applied to upstream units positively impact downstream units. We therefore define three generic response curves that span what we deemed to be a reasonable range of possible outcomes (Fig. B1). We encourage users interested in stream targets to explore differences in prioritization outcomes using at least two curve options in order to better understand the implications of this setting for priority selection.

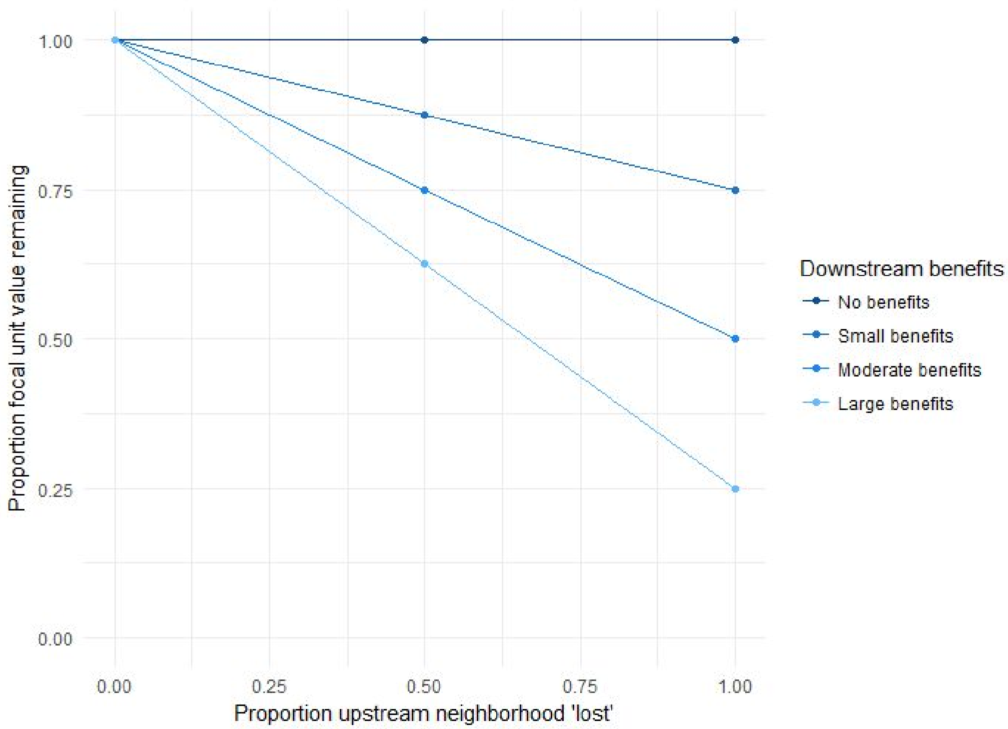

Figure B1. Options for directed connectivity response curves provided in the MHB prioritization tool.