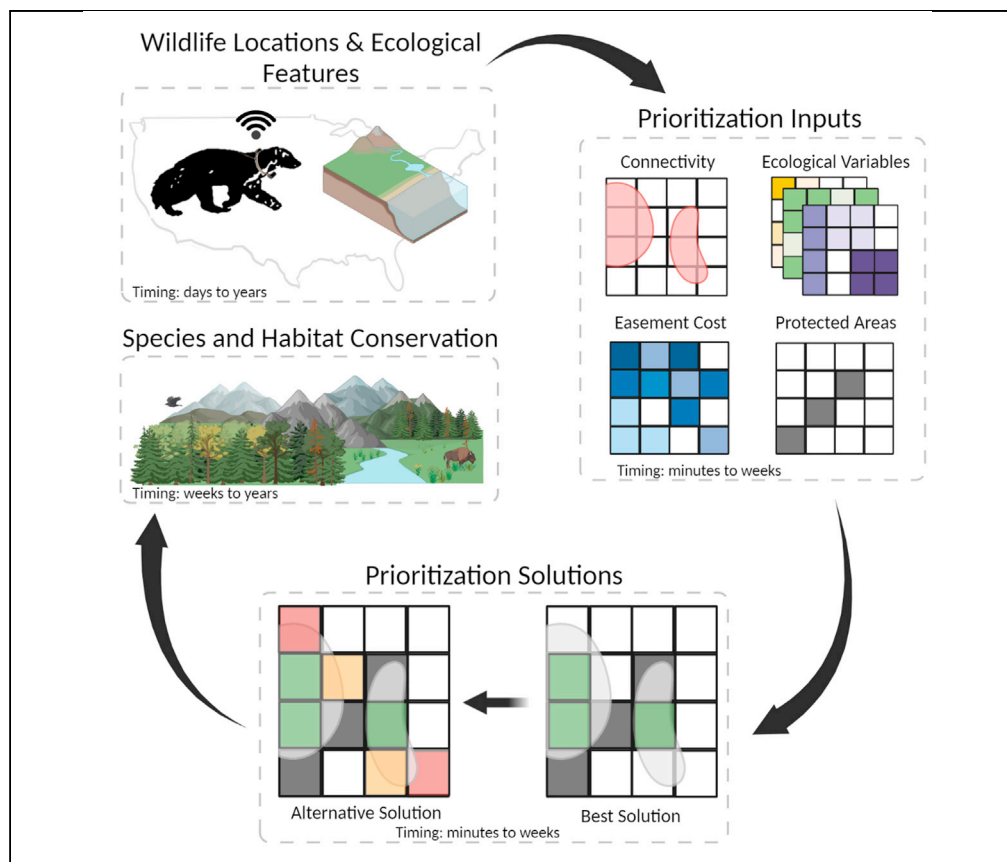


Protocol

Systematic prioritization protocol applied to wolverine habitat connectivity



Kathleen Anne Carroll

kcarroll7@wisc.edu

Highlights
Prioritization for future wolverine habitat connectivity conservation

Uses integer linear programming (ILP)

Details all steps from data acquisition to implementation

I describe a prioritization protocol for future wolverine habitat connectivity conservation using integer linear programming. Conservation prioritization has broad applications across scales, systems, and species. However, the process of preparing, generating, and analyzing the necessary data can be complex. Thus, this protocol details the process from data acquisition to implementation.

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Protocol

Systematic prioritization protocol applied to wolverine habitat connectivity

Kathleen Anne Carroll^{1,2,3,4,*}¹Montana State University, Ecology Department, Montana State University, P.O. Box 173460, Bozeman, MT 59717, USA²Present address: University of Wisconsin-Madison, Department of Forest and Wildlife Ecology, 1630 Linden Dr, Madison, WI 53706, USA³Technical contact⁴Lead contact*Correspondence: kcarroll7@wisc.edu<https://doi.org/10.1016/j.xpro.2021.100882>

SUMMARY

I describe a prioritization protocol for future wolverine habitat connectivity conservation using integer linear programming. Conservation prioritization has broad applications across scales, systems, and species. However, the process of preparing, generating, and analyzing the necessary data can be complex. Thus, this protocol details the process from data acquisition to implementation. For complete details on the use and execution of this protocol, please refer to Carroll et al. (2020) and Carroll et al. (2021).

BEFORE YOU BEGIN

The prioritization protocol below describes the specific steps for prioritizing future wolverine connectivity on private land in western Montana. The prioritization methods have broad applications, including single-species, multi-species, and biodiversity questions (Tack et al., 2019; Scriven et al., 2020; Delso et al., 2021; Hanson et al., 2021) and are not limited to terrestrial systems (Pinsky et al., 2020; Magris et al., 2021). This protocol has resulted in an ongoing collaboration between managers and willing private landowners in Montana, which is unique given historical challenges in science-management-stakeholder partnerships. There are many necessary steps to generate the spatial data layer inputs before prioritizing connectivity (Figure 1). While I outline most steps for data preparation here, there is additional information in both Inman et al. (2012) and Carroll et al. (2020). It is also important to note that the timing of each step is highly dependent on data quantity and quality, study system, study organism(s), availability of ecological datasets, and proficiency with the software. I conducted this work as part of a doctoral dissertation, and thus there was a steep learning curve for many steps; this is reflected in the highly variable timing provided.

Steps to obtain wolverine location data

⌚ Timing: 8 years (varies by species abundance, life history, and necessary sample size for questions of interest)

1. Live wildlife captures are typically necessary to place radio-transmitters on individuals for location data. The steps detailed below were collected for previous work and later applied to the prioritization framework (Inman et al., 2012, 2013).
 - a. Develop a framework for wildlife capture and handling based on species behavior and habitat use (e.g., for wolverines, seek animals in high elevation public land in the western United States).



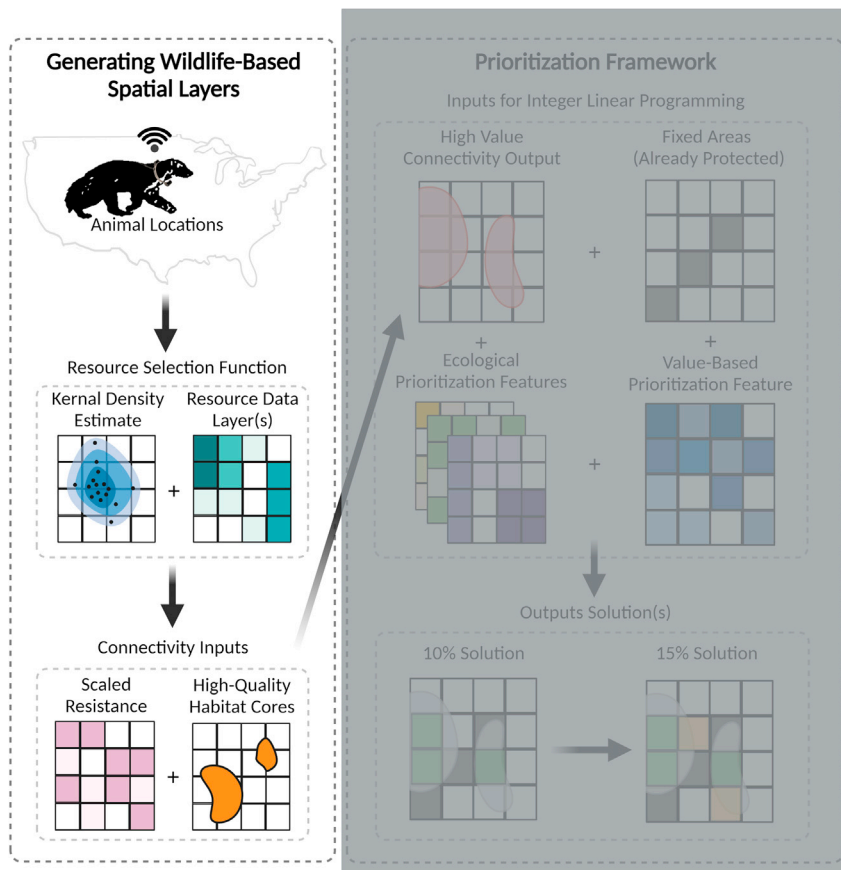


Figure 1. The three steps in the “before you begin” section detail how to generate the spatial layers based on wildlife locations.

- b. Trap design and animal handling must follow sampling protocols and procedures approved by the Animal Care and Use Committees associated with the researchers’ institution.
- c. These wolverines were captured using box traps during the winters of 2001–2010.
- d. All box traps had trap-transmitters (Telonics, TBT-500, Mesa, AZ) to minimize the time between capture and handling.
2. Fit individuals with transmitters
 - a. All individual wolverines were sedated for transmitter implants.
 - b. Each of the 38 individuals (23F, 15M) was fitted with an intra-peritoneal very high frequency (VHF) radio transmitter (Advanced Telemetry Systems M1245, M1250, M1255, Isanti, MN; Telonics Imp400L, Imp300L).
 - c. Eighteen (11F, 7M) individuals were also fitted with global positioning system (GPS) collars (Televilt POSREC 300, Telemetry Solutions, Concord, CA; Lotek Wireless Inc. 3300SL, Newmarket, Ontario, Canada). These collars weighed approximately 300 g and had a drop-off mechanism.
 - d. Individual Attribute Collection
 - i. Identification Number: each animal was given a unique identification number.
 - ii. Age class: individuals were classified as either juvenile, subadult, or adult.
 - Age was estimated based on the first detection date, whether or not they had descended testes, amount of toothwear, and cementum annuli (Inman et al., 2012).
 - Juveniles were classified as < 1 year old, subadults as 1–2 years old, and adults as ≥ 3 years old.
 - iii. Sex: individuals were identified as male or female.

3. Monitoring
 - a. VHF telemetry points were collected from the air at approximately 10-day intervals (Inman et al., 2013).

Note: For this dataset, 24 individuals were monitored for over 1 year, 12 for over 3 years, and 6 for over 5 years (Inman et al., 2012).

- b. GPS collars collected locations at 2-h intervals for approximately 3 months.
 - i. Most GPS data were collected during February and March.
4. Post-processing
 - a. Status
 - i. Data on age class and sex were added to each location point for each individual based on their ID.
 - ii. Individuals were also identified as residents with established home ranges or dispersing individuals (Inman et al., 2012, 2013).
 - b. 2257 VHF radio telemetry locations were collected for resident individuals across four mountain ranges.
 - c. 2835 GPS collar locations were collected for resident individuals in the same ranges.
 - d. 365 additional VHF and GPS locations from 5 individuals were collected from a disparate mountain range.
 - e. Data from dispersing individuals (n = 1165 from both VHF and GPS) were kept but not used in subsequent habitat selection models.
 - f. Some points were excluded due to post-handling movements or other errors.
 - g. Data Issues
 - i. Approximately 50% of GPS collar locations were not received, likely due to habitat features (Inman et al., 2013).

Resource selection function (RSF) and data preparation for connectivity analysis

⌚ Timing: Days to Weeks

5. Collection or acquisition of ecological data
 - a. Relevant biotic and abiotic spatial data can be collected, acquired from external sources, or leveraged from remotely sensed images as explanatory variables for RSF models (Inman et al., 2013; Carroll et al., 2020). In both Carroll et al. (2020) and (Carroll et al., 2021), I used pre-existing data layers.
 - i. I used 2040 to 2069 RCP 8.5 snow water equivalent (SWE) projections at a 5-km resolution to generate future connectivity across international borders (US-Canada) as the single explanatory variable (Carroll et al., 2021).
6. Logistic regression model (RSF Model)
 - a. I used logistic regression in R Statistical Software 3.6.5, comparing predictors at “use” locations (n = 5439) to “available” or pseudo-absence points (herein available points; Carroll et al., 2020).
 - i. Available points were located within a kernel density estimate to ensure that these points were within available habitat (Inman et al., 2013; Carroll et al., 2020).

Note: I used the `ade4` and `adehabitatHR` packages – see cran.r-project.org for vignettes.

- ii. Available points were also at least 1 km apart (n = 16,317).
 - iii. The model was run on 70% of the use/availability data, and the rest was withheld for model validation.

7. Model validation
 - a. I used a random test dataset of 30% of the use/availability data for model validation.
 - b. The model predicted use and availability of withheld data with 78% accuracy ($\kappa = 32\%$).
8. Results
 - a. Habitat quality was extrapolated from the RSF model output to produce a single raster layer (1-km resolution), representing the relative probability that wolverines could maintain a home range at any given location across the study area (Carroll et al., 2020).
 - i. The habitat quality was then used to generate resistance layers and core layers (see subsequent section).

Modeling connectivity using Circuitscape 4.0

⌚ Timing: Hours to Weeks

9. Circuitscape 4.0 (McRae et al., 2008; McRae and Shah, 2009)
 - a. Circuitscape is a circuit theory model and represents only one approach to connectivity modeling. Alternative software can be more or less effective for modeling connectivity for different species, and different modeling types have different assumptions, limitations, and caveats (McClure et al., 2016). Special care should be given when selecting software. Additionally, memory limitations and computation limits exist for Circuitscape; see McRae et al. (2008).
10. Data Inputs for Circuitscape 4.0: Circuitscape requires inputs of “core” habitat patches and a resistance layer representing its permeability to individuals.
 - a. Scaled Resistance
 - i. Using the equation below, I generated a scaled habitat resistance raster from habitat quality, where $c = 8$ and $h =$ habitat quality matrix (Keeley et al., 2017; Carroll et al., 2020). This scaling represented a negative inverse relationship between habitat quality and resistance.

$$100 - 99 * ((1 - \exp(-c * h)) / (1 - \exp(-c))) = \text{Scaled Resistance}$$
 Scaled resistance was used as wolverines have lower habitat quality sensitivity during dispersal than within-home range movements (Carroll et al., 2020). The degree to which the resistance was scaled was based on telemetry location from dispersing individuals in a previous analysis.
 - b. Cores, or the sources and destinations for individuals, were selected using a decision threshold at a sensitivity of 0.95 (correct prediction of use) on withheld data (see Carroll et al., 2020).
11. Modeling Mode
 - a. There are several modeling mode options in Circuitscape. I chose to use a pairwise analysis, connecting eight neighbors with current map outputs. Decisions on mode options should be based on the information in the Circuitscape User Guide. [Troubleshooting 1](#)
12. Connectivity Output(s)
 - a. Circuitscape can generate different output types, but I selected current map outputs. As mentioned in Carroll et al. (2020), current maps represent the pathways animals are likely to use and whether or not alternative pathways exist, resulting in current values used in connectivity analyses.

KEY RESOURCES TABLE

REAGENT or RESOURCE	SOURCE	IDENTIFIER
Software and algorithms		
Circuitscape 4.0	McRae et al., 2008; McRae and Shah, 2009	https://circuitscape.org/
R Statistical Software	R Core Team	https://www.r-project.org/

(Continued on next page)

Continued

REAGENT or RESOURCE	SOURCE	IDENTIFIER
PrioritizR	Hanson et al., 2021	https://prioritizr.net/
Gurobi	Gurobi Optimization, LLC	https://www.gurobi.com/
ArcGIS	ESRI	https://www.esri.com/
Deposited data		
Prioritization Shapefiles	Carroll et al., 2021	https://databasin.org/datasets/1276c3bbc0e940ed836dcabdf46dc872/
Wolverine Telemetry Data	Inman et al., 2012	bobinman@mt.gov
Wolverine Occurrence Data	Lukacs et al., 2020	https://doi.org/10.1002/jwmg.21856
Wolverine Connectivity Data	Carroll et al., 2020	https://doi.org/10.1016/j.gecco.2020.e01125
Wolverine Core Habitat Data	Carroll et al., 2020	https://doi.org/10.1016/j.gecco.2020.e01125
Snow Water Equivalent	Integrated Scenarios Group	https://climate.northwestknowledge.net/IntegratedScenarios/
Human Modification	Theobald, 2013	https://databasin.org/datasets/110a8b7e238444e2ad95b7c17e889b66/
Cadastral Data	Montana Cadastral	http://svc.mt.gov/msl/mtcadastral

STEP-BY-STEP METHOD DETAILS

Acquiring input data layers for prioritization

⌚ Timing: minutes to weeks

Several input data layers are needed to solve a systematic conservation planning problem successfully. This step details how I acquired spatial data layers for my wolverine conservation planning problem (Figure 2).

1. Study Area

- a. I selected areas with the highest connectivity value (20%) from the previous Circuitscape analysis (Carroll et al., 2021) in western Montana. This boundary defined areas in which I conducted all other analyses. For this analysis, having a smaller study area helped limit the prioritization analysis to the region of highest interest to collaborators and reduced computation time.

2. Ecological Features

- a. I included four input features to prioritize in the planning problem: current female presence, core size, human modification, and habitat core centrality. I selected these variables based on evidence in the literature and their importance for dispersal and population growth (Carroll et al., 2021).
 - i. Of the four input features, three were generated using wolverine camera trap data from Lukacs et al. (2020) and a “core” habitat shapefile generated in Carroll et al. (2021).

3. Planning Unit Cost

- a. Using Montana cadastral data (www.cdastral.mt.gov), I generated a parcel-level estimate of easement costs. The cadastral data provided a unique tax-assessed property value for each parcel. Easement values were calculated by taking 50% of property value and adding \$5000 (Ferraro, 2003).

4. Protected Areas

- a. I downloaded shapefiles of protected areas from the Protected Areas Database of the US (PAD-US 2.0) at usgs.gov (U.S. Geological Survey (USGS) Gap Analysis Project (GAP), 2018).

Note: There is a newer version (2.1) of the PAD-US dataset available.

- b. A spatial layer or column in a spatial layer can be used to identify whether parcels are already “locked-in.” A locked-in parcel can also be referred to as a “fixed” parcel or protected area. I designated conservation easements, state lands, and federal lands as fixed areas.

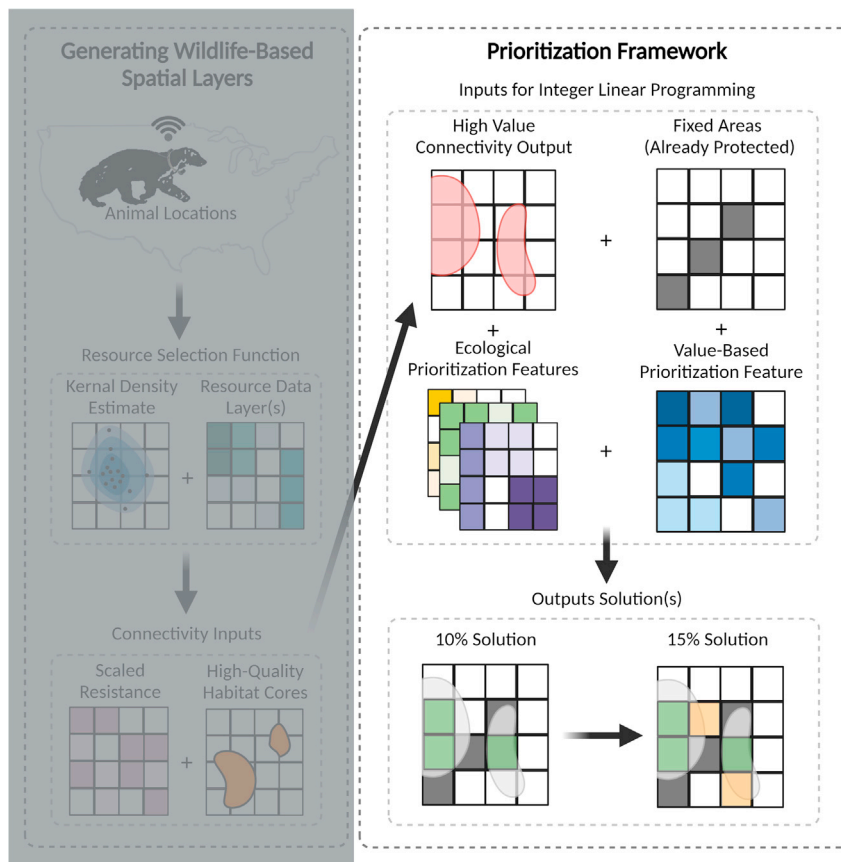


Figure 2. The steps of the prioritization framework needed to generate conservation planning solutions

- c. It should be noted that the activities permitted on protected lands vary greatly, and research goals should determine whether to treat a parcel as fixed or not. I treated all land with any degree of protection as fixed because the goal in this study was to find private land where willing landowners would consider easements.

△ **CRITICAL:** Spatial analysis is a growing field in ecology that requires understanding how any given feature was generated. All input feature layers should be thoroughly reviewed based on their conservation relevance, resolution, and accuracy to ensure the success of later steps.

Integer linear programming with *prioritizr* and a gurobi optimization solver

⌚ Timing: minutes to weeks

I recommend prior experience or practice with R Statistical Software for this section. For additional examples, see prioritizr.net and [Gurobi.com](https://gurobi.com).

5. Install Gurobi
 - a. Gurobi is a commercial computer program and a powerful and fast solver that works well with *prioritizr*. There are several steps to use this software:
 - i. Obtain a license from the Gurobi website. This license is free with an academic affiliation, otherwise, it has an associated cost. Save the license number obtained from the webpage.

- ii. Download the software. [Troubleshooting 2](#)
- iii. Activate and verify the license.

Note: R Statistical Software ([r-project.org](https://www.r-project.org)) is required for the following steps; RStudio is highly recommended as a user-friendly interface ([rstudio.com](https://www.rstudio.com)). Both are free software.

6. Load necessary R Statistical Software Packages. [Troubleshooting 3](#)
 - a. Using the library function in R, call the following packages: `priorizr`, `sp`, `sf`, `raster`, and `rgdal`.
7. Import all data layers into R Statistical Software.
 - a. All of the layers detailed above must be imported into R Statistical software or RStudio (recommended). Shapefiles can be imported using `readOGR` and rasters using the `raster` function.
8. Create one or more planning problems using the example code provided at priorizr.net.
 - a. I created four planning problems.
 - i. Each of the problems I created had a unique relative target. The targets I set were 0.10, 0.15, 0.20, and 0.50. These values (ranging from 0 to 1) tell the planning problem the maximum level of representation I wanted for each feature within the study area.
 - ii. I included a minimum set objective in all problems to minimize the cost of my solutions.
 - iii. I added binary decisions so that each parcel was either prioritized or not (e.g., a binary solution for each problem).
 - iv. I added the Gurobi solver to ensure the code called the Gurobi software for the problem.
 - v. I added my fixed or already protected parcels.

Optional: There are many additional options in the `priorizr` R package suite, including the addition of boundary penalties to reduce fragmentation and contiguity constraints to bolster connectivity. There is also an option to rank the irreplaceability of solutions. I chose not to implement these given my study area's interspersion of private and public land ([Figure 3](#)).

9. Evaluate Prioritization Performance
 - a. The performance of the solution can be evaluated by printing the solution cost summary as illustrated on priorizr.net.
 - b. Solutions should be visually inspected before being exported or mapped using the `spplot` function in R.

EXPECTED OUTCOMES

The anticipated outcome of a planning problem is a mappable data layer. After solving my four planning problems, I exported all solutions (data layers) out of R using the `> writeOGR` function with an ESRI Shapefile driver and brought them into ArcMap for final mapping. After importing files into ArcGIS ([Figure 3](#)), final products can be shared with managers and used for conservation planning. I exported each solution as a Layer File (.lyr) to upload them to DataBasin – see [key resources table](#).

Note: ArcMap is not free, but maps can be made in R Statistical Software, QGIS, or other programs.

LIMITATIONS

I designed this specific protocol for single-species future connectivity conservation, so alternative applications require modifications. Further, Montana has some of the most accurate and freely available cadastral data in the United States, so other cost-layer options may need to be considered in different regions.

TROUBLESHOOTING

Problem 1

Before you begin step 11: Determining which Circuitscape download to use.

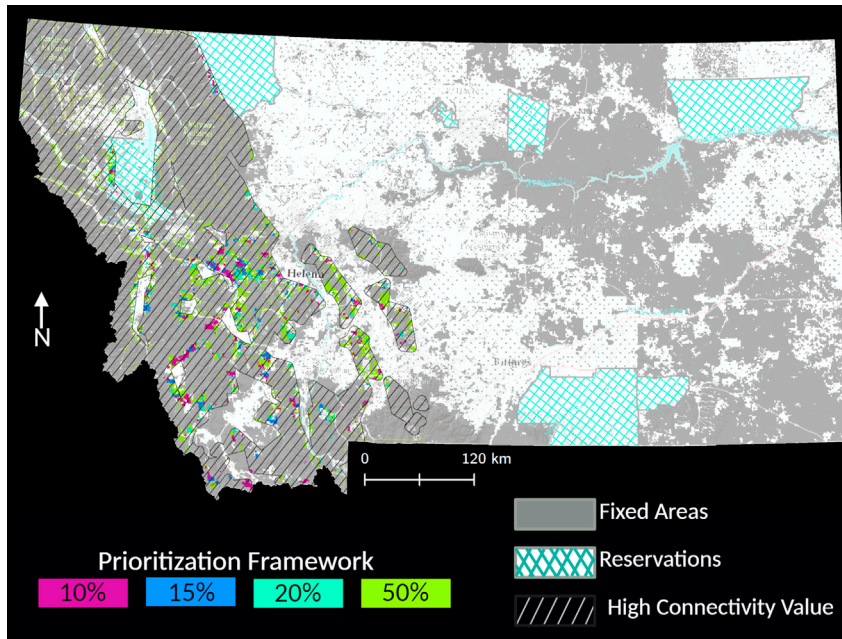


Figure 3. Example of final prioritization map

Potential solution

Circuitscape is not run in R, but instead can be downloaded as an executable file (.exe), run as an ArcGIS toolbox, or coded in Python or Julia (<https://julia-lang.org/>). For this work, I used the ArcGIS toolbox version, which uses drop-down functions. The selected functions are detailed in the protocol.

Problem 2

Step 5: Gurobi installation and activation differ by operating systems.

Potential solution

See https://prioritizr.net/articles/gurobi_installation.html for additional help.

Problem 3

Step 6: Warning or error messages reading: "there is no package called 'package name' "

Potential solution

Use `>install.packages("package name")` before calling package with `library()`. R provides error messages for each error, and solutions are often available within the online R community.

RESOURCE AVAILABILITY

Lead contact

Further information and requests should be directed to and fulfilled by the lead contact, Dr. Kathleen Carroll (kcarroll7@wisc.edu).

Materials availability

The shapefiles generated in Carroll et al. (2021) have been deposited to Data Basin (<https://databasin.org/datasets/1276c3bbc0e940ed836dcabdf46dc872/>).

Data and code availability

Restrictions apply to the availability of the wolverine data, which were used under contract for this study. Requests to access the dataset should be directed to Dr. Bob Inman, bobinman@mt.gov.

The code from this paper is available at https://github.com/KCarrollEcology/StarProtocols2021_Wolverine. However, this paper does not report original code; see (<https://prioritizr.net/>) for R Statistical Software vignette on prioritization.

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AUTHOR CONTRIBUTIONS

Conceptualization, K.A.C.; methodology, K.A.C.; formal analysis, K.A.C.; data curation, K.A.C.; writing, K.A.C.; visualization, K.A.C.; project administration, K.A.C.

DECLARATION OF INTERESTS

The author declares no competing interests.

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