Applications of Graph Theory to Optimize Wildlife Corridor Systems for Multiple Species:

Grizzly Bear and Wolverines in the Northern Rockies

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USFS Rocky Mountain Research Station

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Key causes of biodiversity loss:

Habitat Loss and Fragmentation

urbanization

deforestation

agriculture

Protect a ~~collection~~ of habitat areas

a **network** of habitat areas

Landscape connectivity

Beyond reserve site selection

BENEFITS:

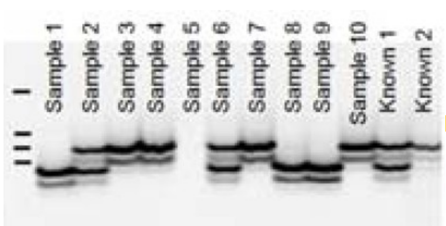
- *Enhanced immigration (*gene flow, genetic diversity, re-colonization of extinct patches, overall meta-population survival)
- The opportunity for some species to *avoid predation*.
- Accommodation of *range shifts* due to climate change.
- Provision of a *fire escape* function.
- Maintenance of *ecological process* connectivity.

- **A wildlife corridor** serves as a linkage between habitat/natural areas, and is **meant to facilitate movement between these natural areas**

Measure Landscape Connectivity

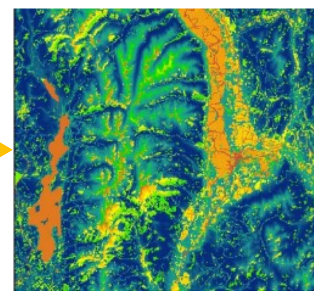
Large-scale geographical data:

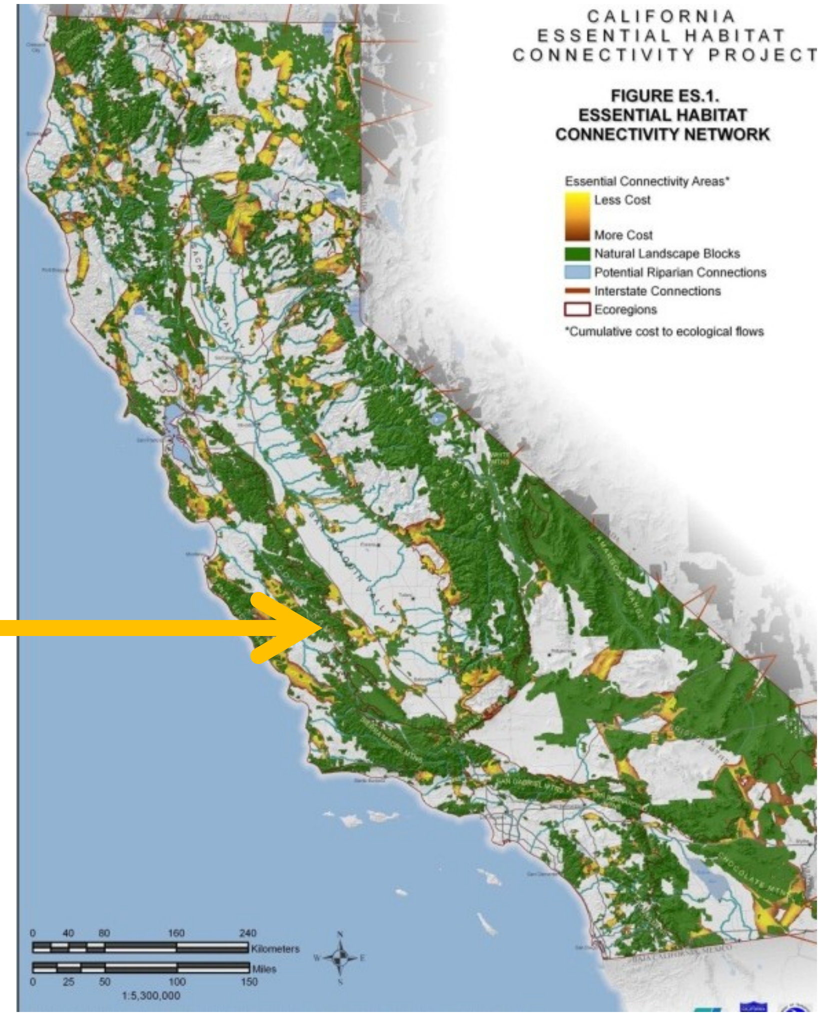
density
d cover
Elevation
Roads
Slope



inference

Resistance to Movement



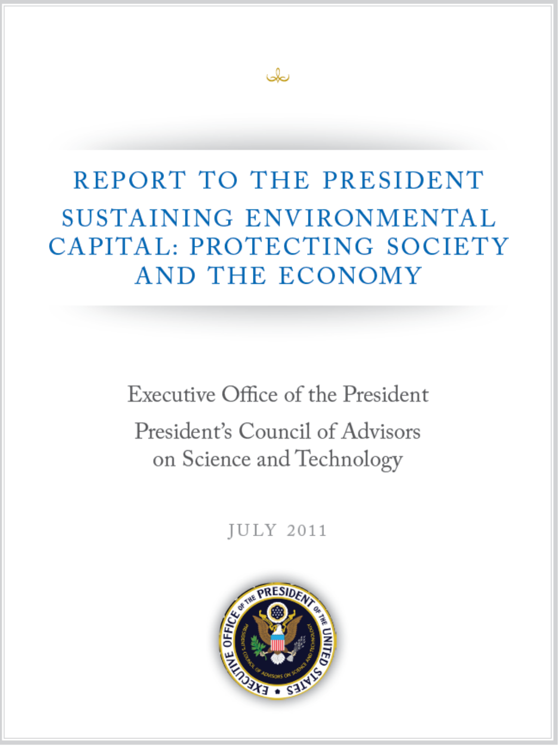


Spatial Species Data:
DNA samples (hair traps)
Telemetry (GPS collars)

Identify most likely movement routes & use for conservation prioritization

Cost-effective conservation

- In 2011 The President’s Council of Advisors on Science and Technology recommended
  - “federal agencies that implement biodiversity and ecosystem conservation programs should prioritize expenditures based on their cost-effectiveness.”
  - “Significant improvements in the conservation impact of these programs can be achieved by including an explicit consideration of the cost-effectiveness in the initial determination of priorities“


REPORT TO THE PRESIDENT
SUSTAINING ENVIRONMENTAL CAPITAL: PROTECTING SOCIETY AND THE ECONOMY

Executive Office of the President
President’s Council of Advisors on Science and Technology

JULY 2011

Cost-effective Corridor Design

- ‘Connectivity Plans’: Conservation priorities set considering only ecological benefits
  - One end of the spectrum (Best Linkages)
- Minimum Cost Corridors (ignore resistances)
  - The other end of the spectrum (Cheapest Linkages)
  - Spend the least possible to make sure core areas are connected
- Limited economic resources have to be used in the most effective way possible
  - Systematic budget-constrained conservation planning
  - Multiple species considered together
  - Reserve Site Selection: Zonation, Marxan, etc.
- Underlying computational challenges:
  - Discrete Optimization
  - Network Design

Contribution

- We develop a methodology for multispecies corridor conservation such that ecological benefits are maximized subject to a budget constraint and explicit species tradeoffs can be incorporated
- ***A strategic and systematic approach to <u>corridor</u> conservation planning that supports finding cost-efficient and conservation-effective plans.***

Budget-constrained Corridor Design

Given:

- landscape of cells/parcels
- landscape resistance of land cells
- Pairs of core areas to connect
- Conservation costs of land cells
- Budget

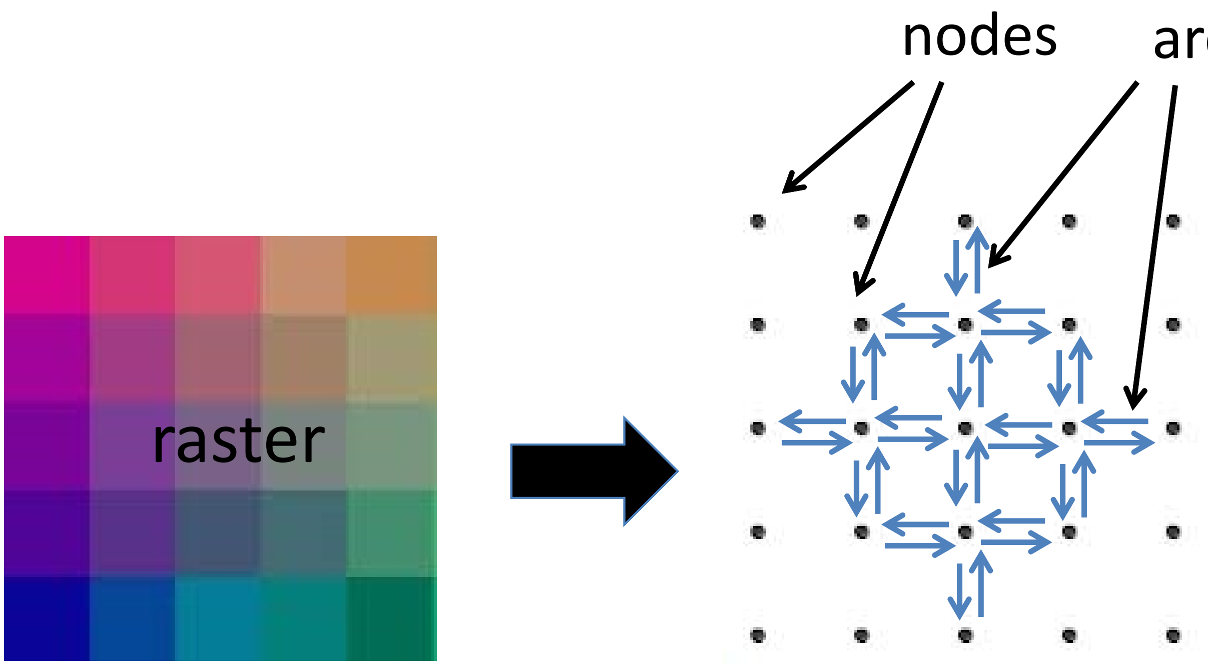
Find:

- A set of parcels to protect such that
- a path of protected cells connects each pair of core areas
- Total cost < Budget
- **Minimized resistance along chosen paths**

Graph optimization problem
(generalized version of the Steiner Forest Problem)
solved using multi-commodity mincost flow formulation

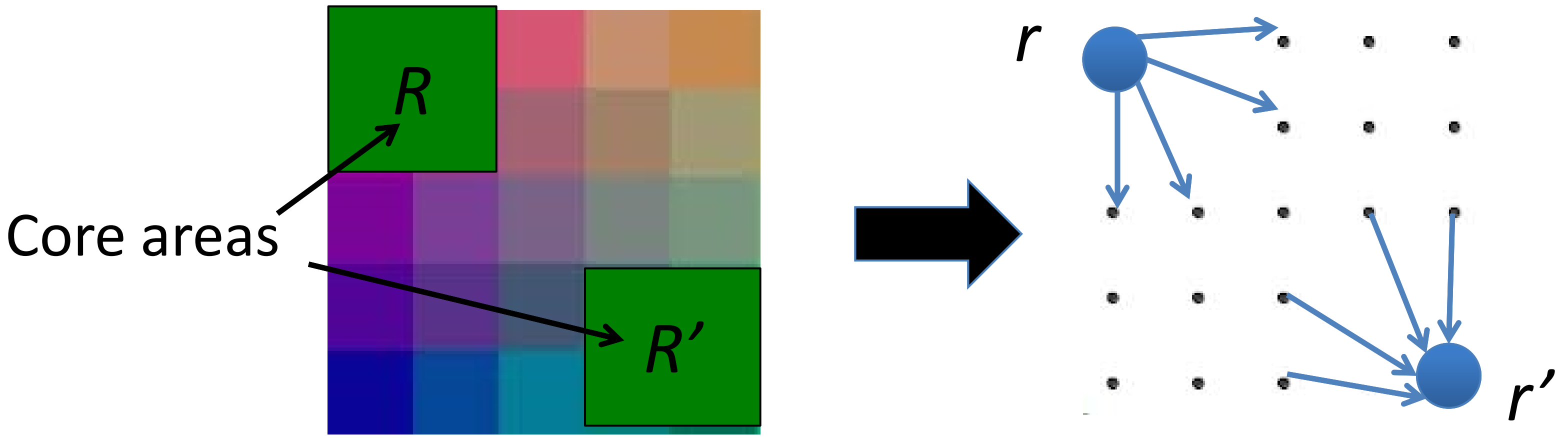
Computational Model

- **Raster Graph: G(V,E)**
  - V: a set of nodes, one for each raster cell
  - E: directed arcs between every pair of adjacent raster cells
- **Raster cell cost:** c(v)
- **Raster cell resistance:** r(v)
- **Budget:** B



Computational Model

- **Core area nodes:**
  - mega nodes A corresponding to core areas; each core area a covers a set of raster cells V_a
- **Core area pairs:** $P \subseteq A \times A$
- **Pair Graph for each pair of reserves: p=(r,r')**
  - outgoing arcs from reserve **r** to all raster cells that are adjacent to the reserve but outside of it
  - incoming arcs to reserve **r'** from all raster cells that are adjacent to the reserve but outside of it



Method: Mixed Integer Programming

- Decision variables: one binary variable x_v for each raster cell v
- Budget constraint: $\sum_{v \in V} c(v) x_v \leq B$
- For each core area pair $p=(s,t)$
  - Encode shortest path as min-cost flow in the pair graph: 1 unit of flow pushed from s to t
    - Continuous variable f_{pe} representing flow on each arc e between raster cells
    - Flow conservation constraint at each raster cell node v
    - Source constraint on s & Sink constraint on t
    - Incoming edges can carry flow only if node is purchased
- Objective:
  - Flow cost on edges: $d(e=(u,v)) = [r(v)+r(u)]/2$
  - Minimize $R = \sum_{p \in P} \sum_{e \in E} d(e) f_{pe}$

A system on linear constraints and a linear objective over binary and continuous variables

Two species corridor design

- The model allows us to find the best resistance corridor designs within a given budget for one species
- What happens when we have two?
- Easy extension!
- Given two species **g** and **w**, with corresponding resistance and core area pairs:
  1. Compute the best solution for **g only** at budget B, and record optimal resistance $\mathbf{R_g(B)}$
  2. Compute the best solution for **w only** at budget B, and record optimal resistance $\mathbf{R_w(B)}$
  3. Optimize for core area pairs of both g and w, minimizing

$$\alpha \frac{R_g}{R_g(B)} + (1-\alpha) \frac{R_w}{R_w(B)}$$

- Vary α to study species tradeoffs

CASE STUDY

Connectivity between populations in protected areas in the Western Montana

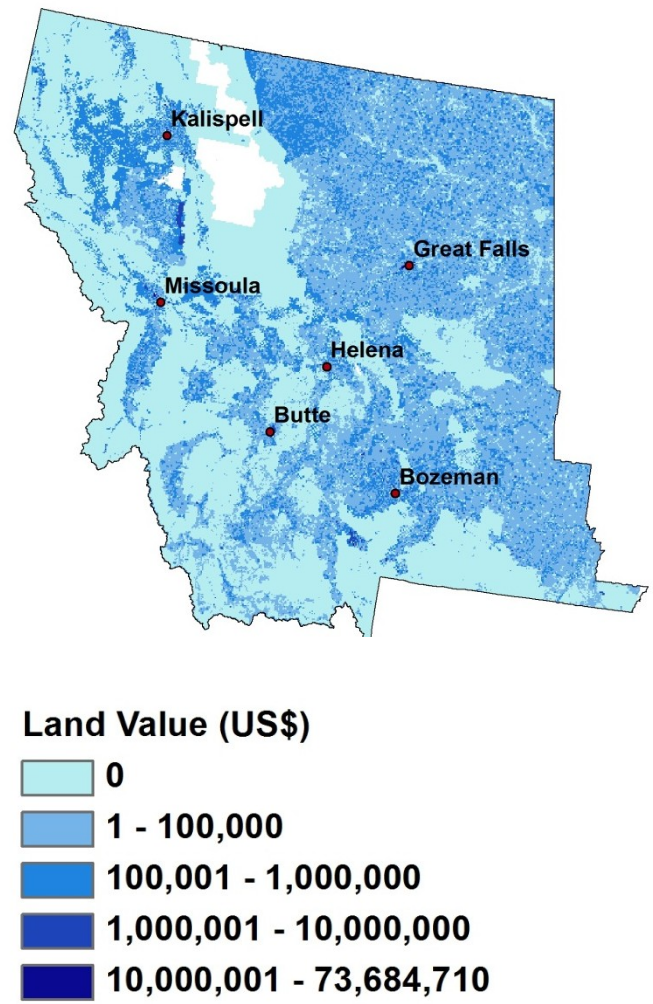
State of Montana expects to allocate money for the purchase of land to establish wildlife corridors for species of concern.

Plum Creek Timber Company, the largest private owner of forest land in Montana, announces tentative plans to sell land in western Montana.

Do we know how to identify which parcels for purchase?

Land Value Data:

- Over 600,000 parcels
- County tax assessed value

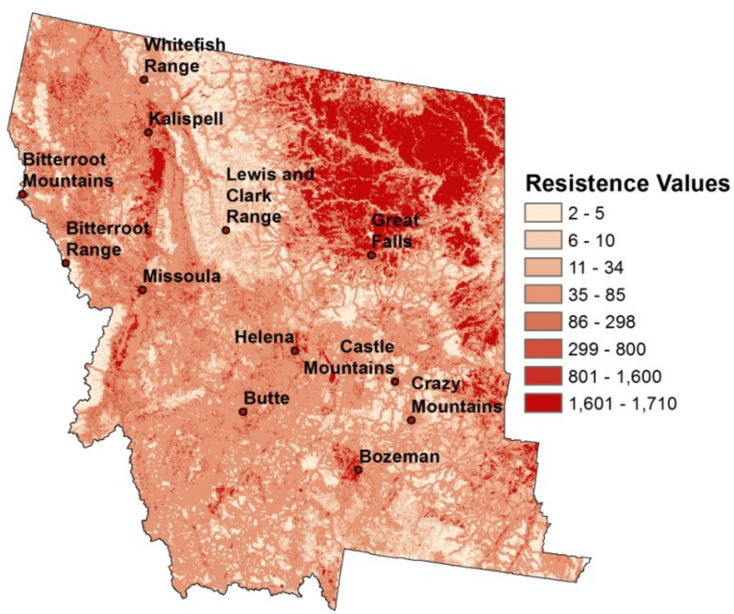


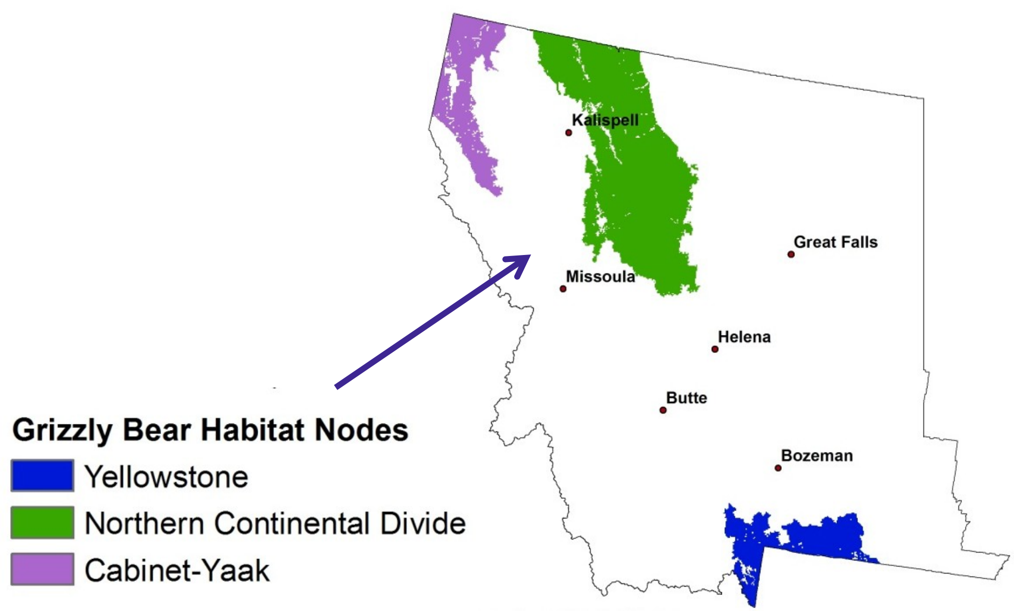
Two Species with Differing Habitat Needs

http://www.defenders.org/grizzly-bear/basic-facts

Grizzly Bear

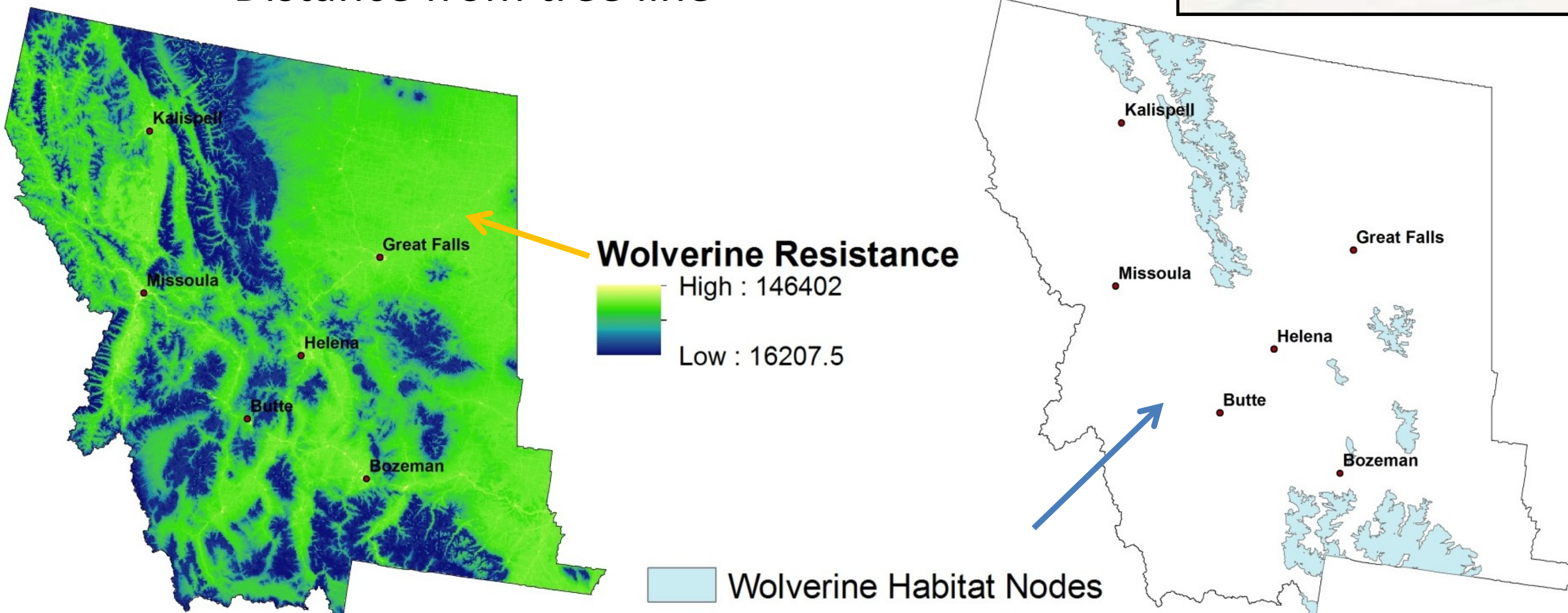
- Core habitat needs and movement
  - Lots of food
  - Minimal human contact





Wolverine

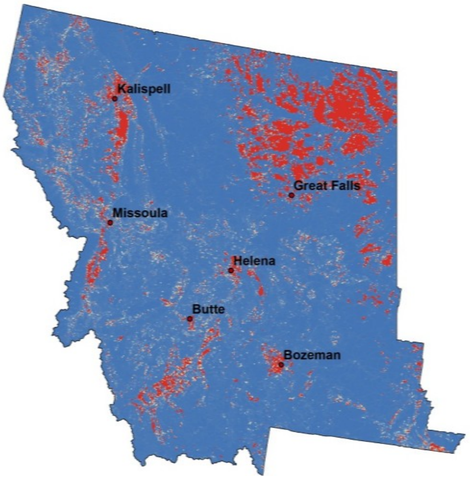
- Core habitat needs
  - Spring snow cover for breeding
- Factors affecting movement:
  - Human population density
  - Road density
  - Forest edge
  - Snow
  - Ruggedness
  - Distance from tree line

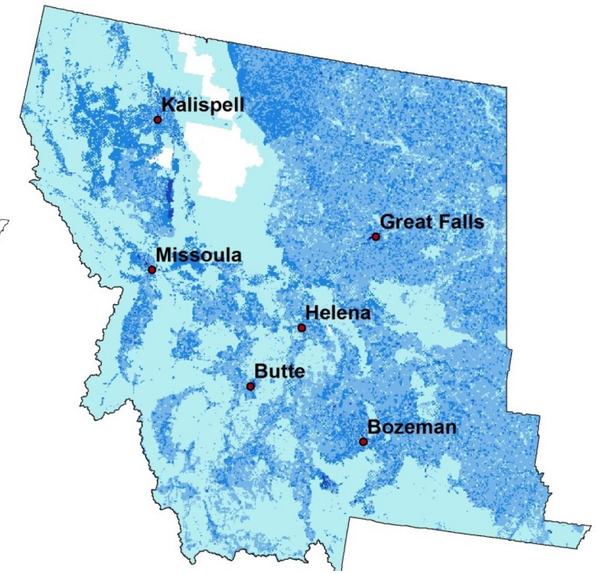


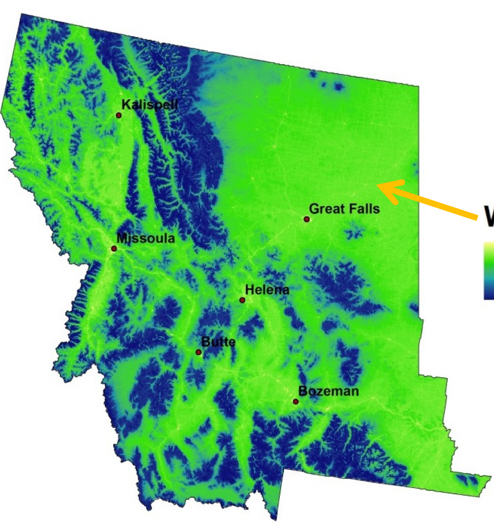
Case study: grizzlies & wolverines in MT

Georgia Tech

Binary Variables: 42,065





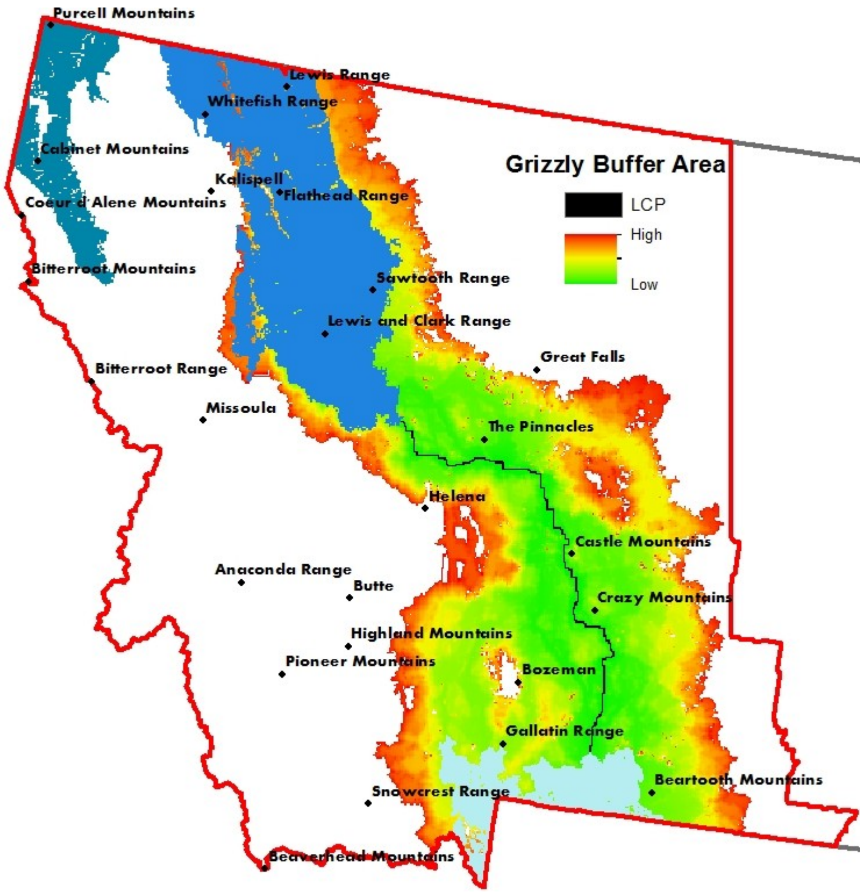


Resistance-only solution: ignore economic costs

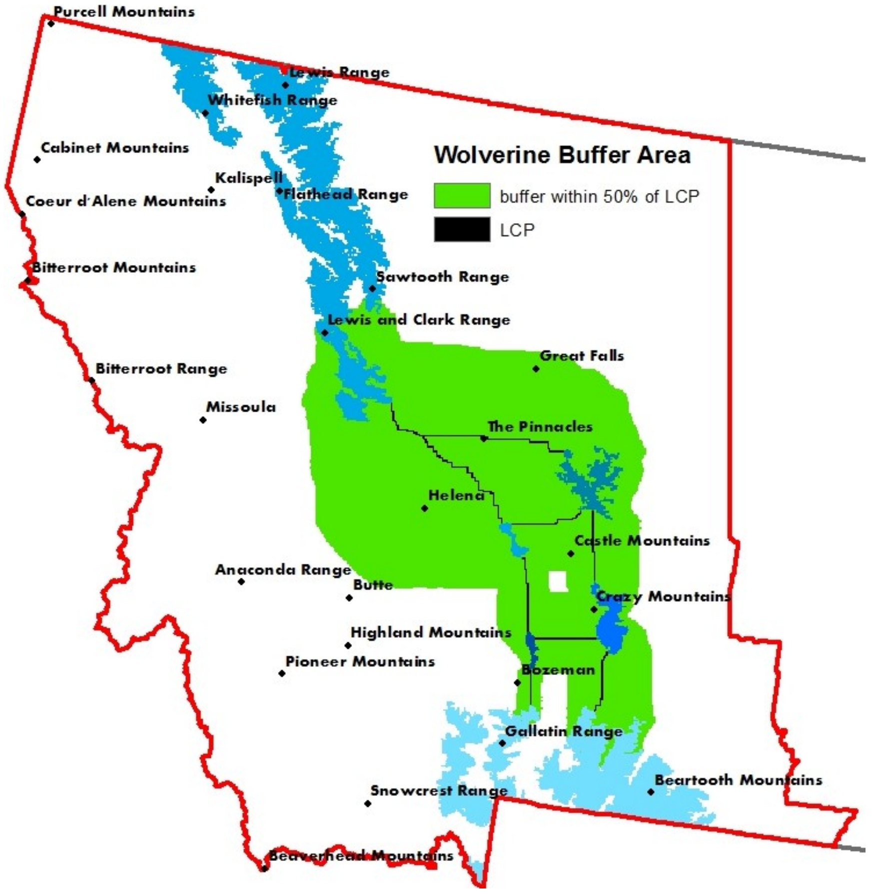
Georgia Tech

Grizzly = 4,521; Wolverines = 20,926,460

joint cost = $31,832,800 (32M)



1 pair



8 pairs

Cost-only solution:
multiple species, ignore resistances

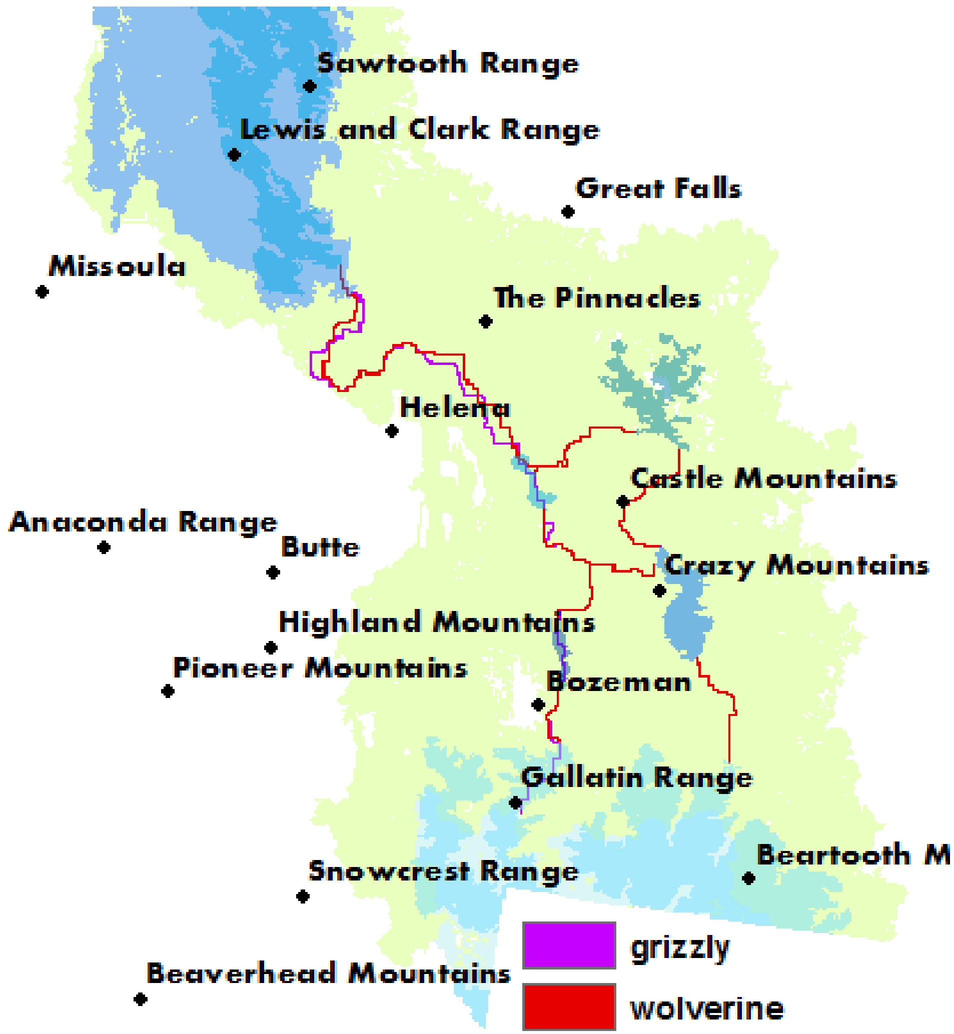
248% worse than 4,521

Grizzly=15,745; Wolverines=35,455,559

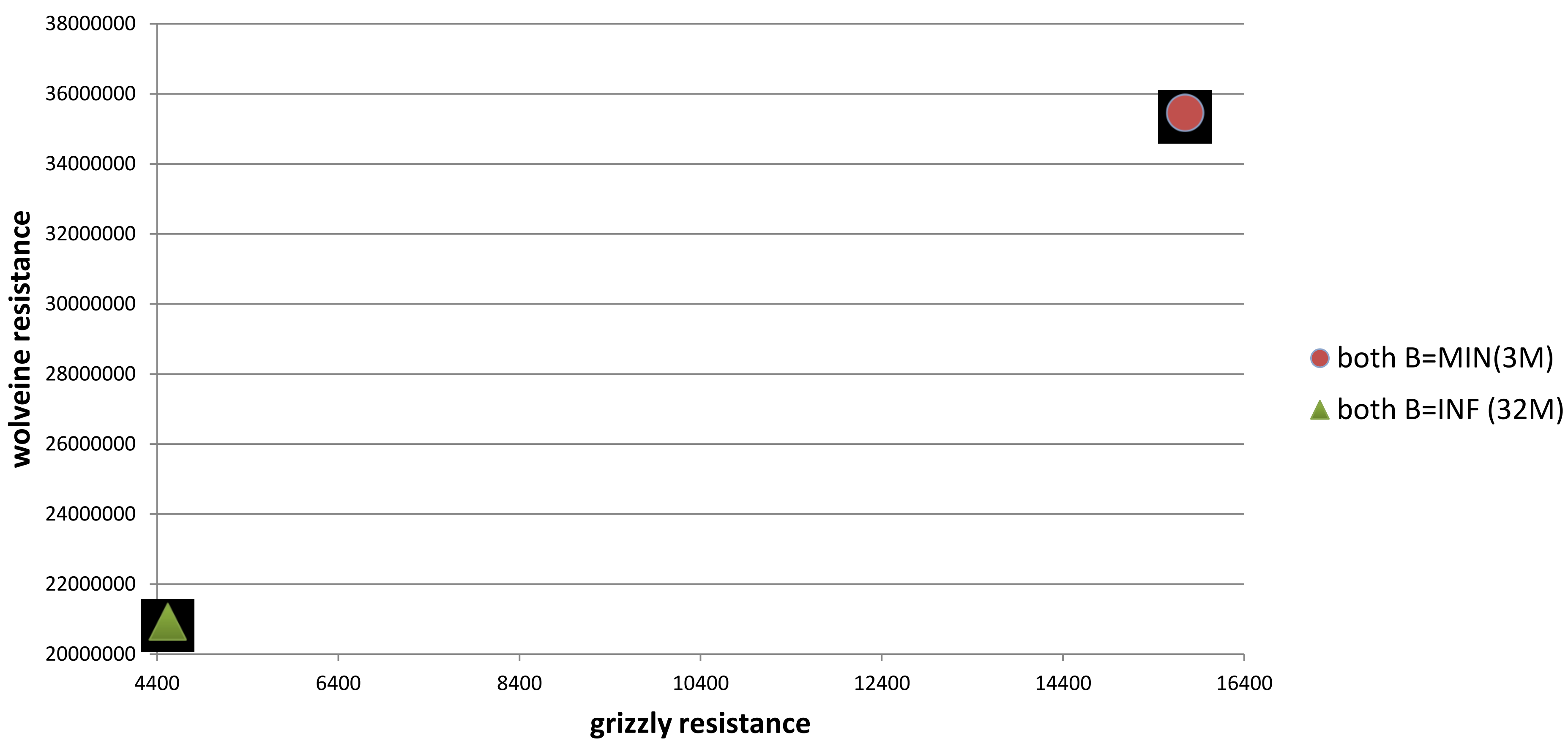
69% worse than 20,926,460

joint cost=$2,952,577 (3M)

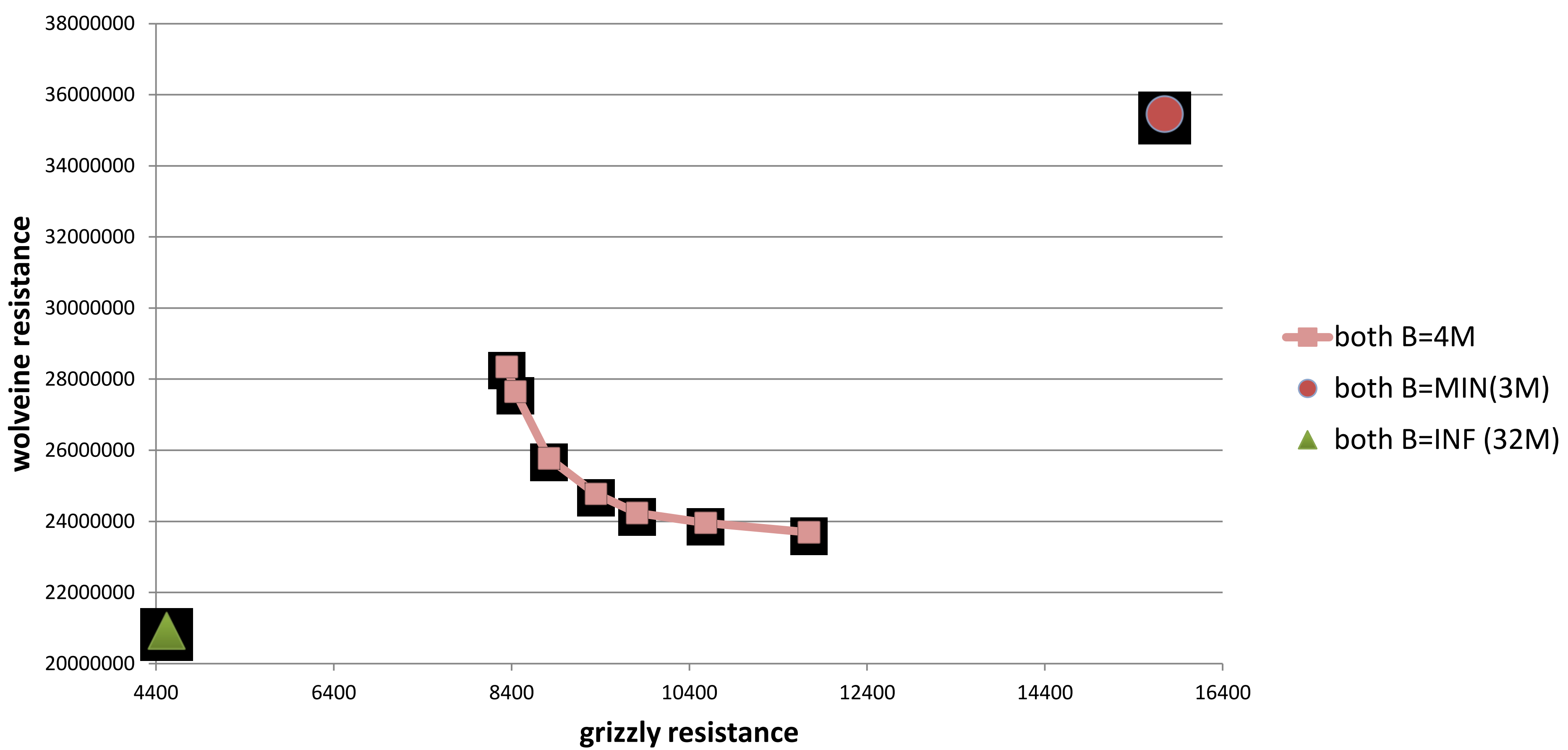
Only 9% of $32M



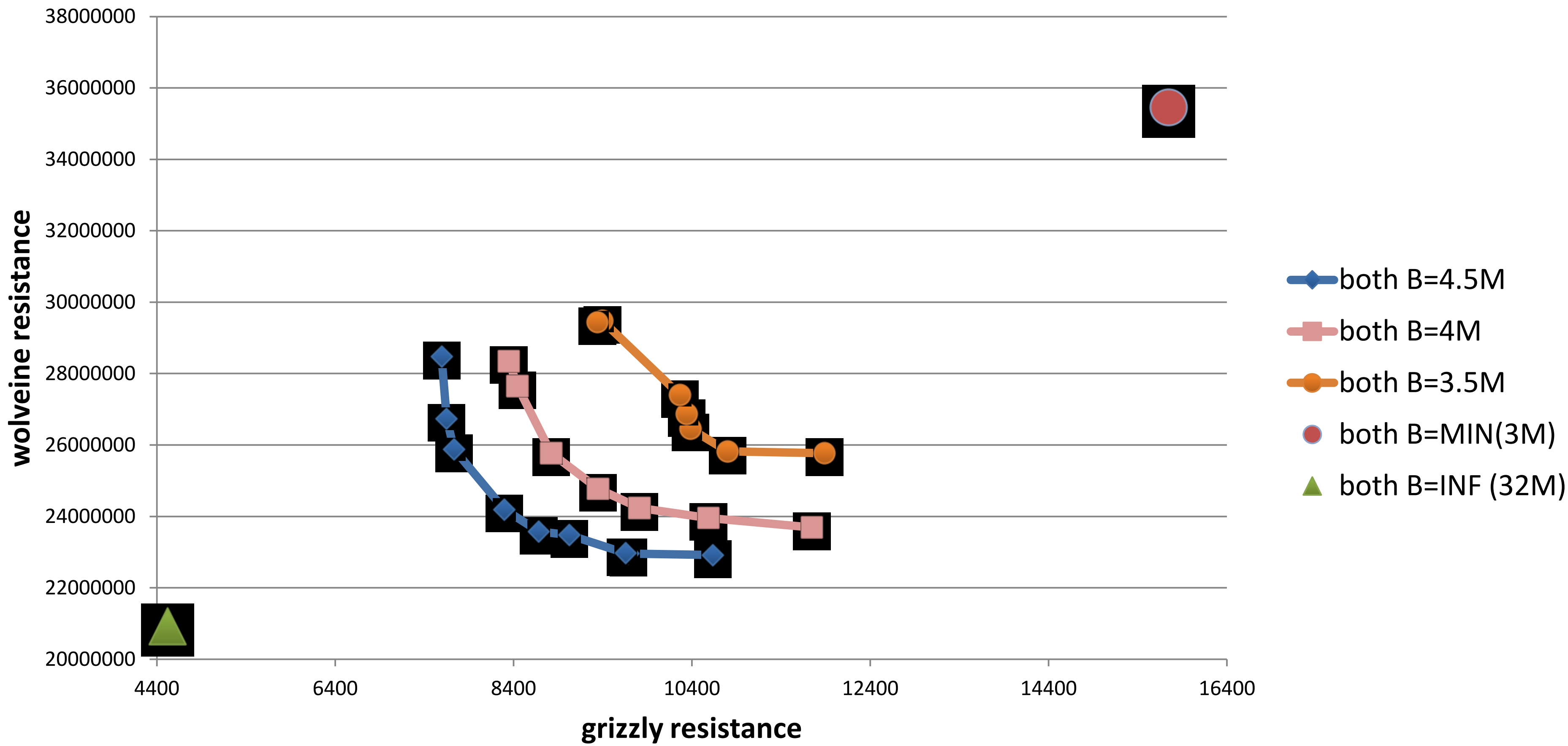
Wolverine vs. Grizzly Tradeoffs



Wolverine vs. Grizzly Tradeoffs



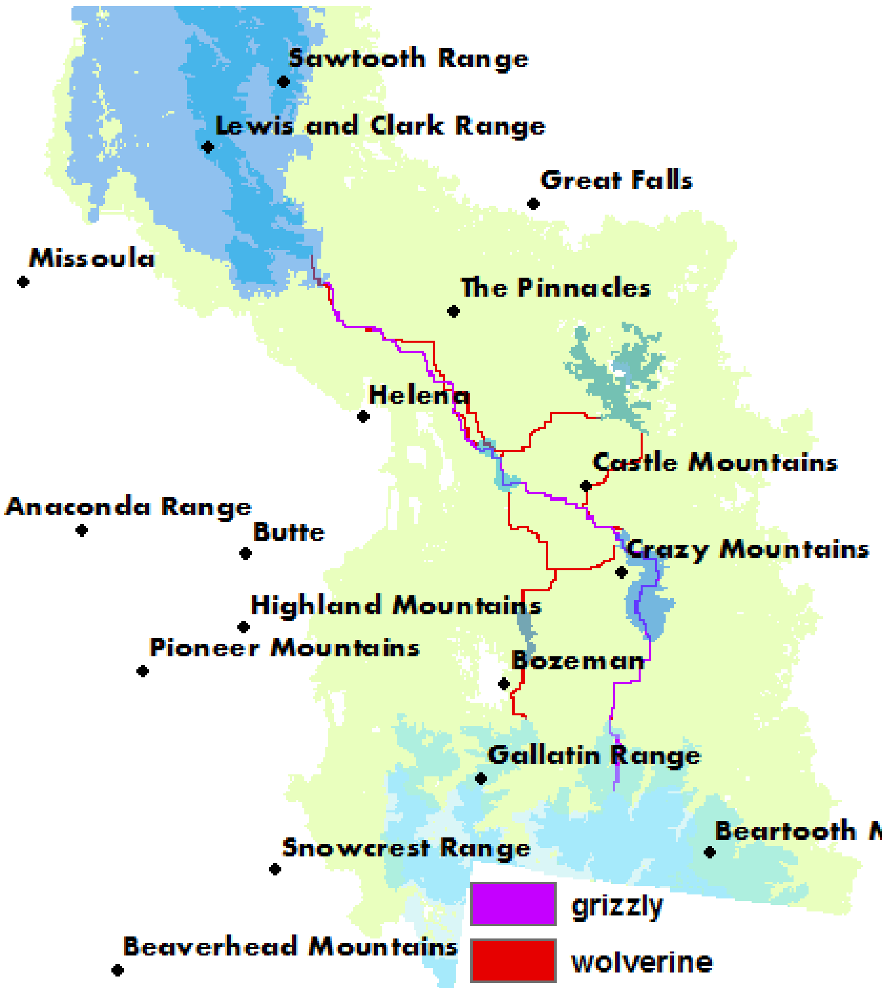
Wolverine vs. Grizzly Tradeoffs



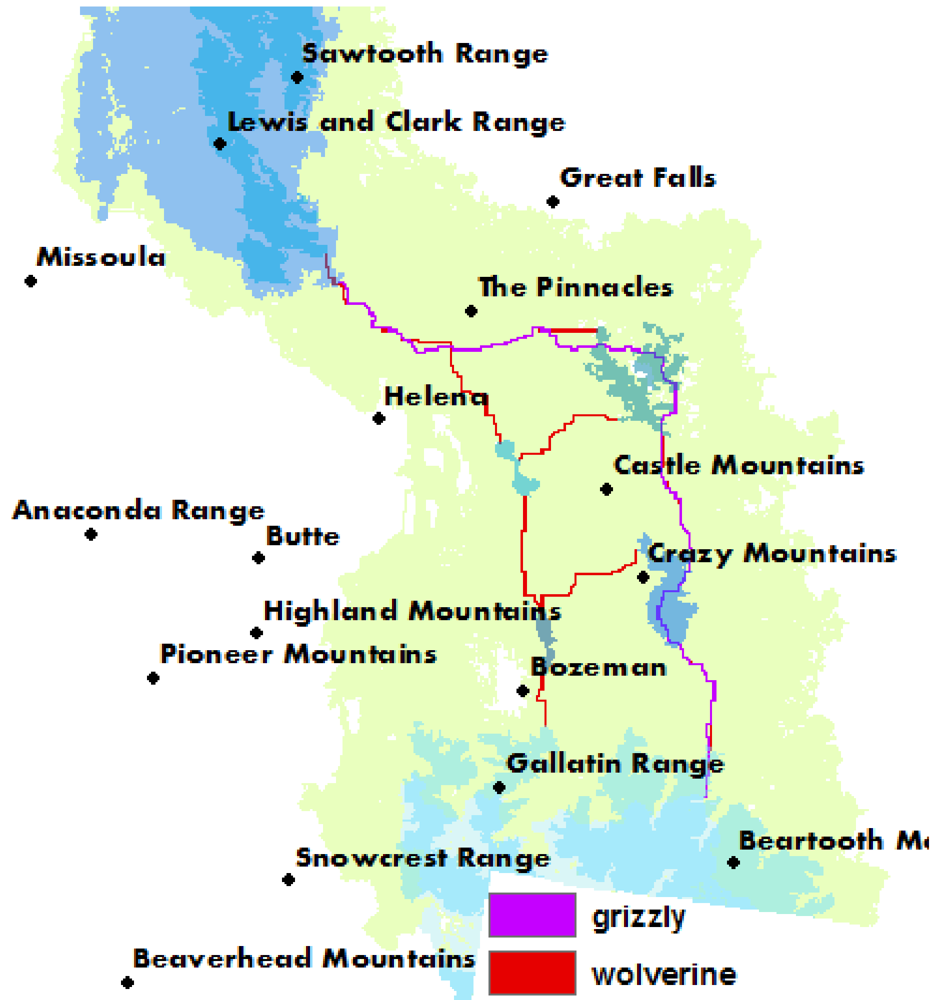
HW: Intel x5690 3.46GHZ, 12 cores, 96GB RAM

Budget = $4,000,000
for multiple species

B=4M Prefer Grizzlies



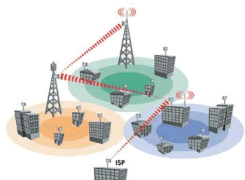
B=4M Prefer Wolverines



Takeaways

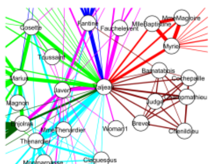
- Setting conservation priorities and plans without economic costs is extremely inefficient ($32M vs $3M)
- Minimizing costs alone is not ecologically effective
- Small increases in overall budget beyond the minimum can have great ecological returns
- Trade offs between species at each budget level are intricate and result in spatially and numerically disparate solutions
- All interacting dimensions should be systematically explored to make justifiable and informed conservation plans

Landscape connectivity vs. Network Design



Sensor Networks

Transportation Networks



Social Networks

Network Design

Steiner tree problem,
Survivable network design,
etc

New general models and methodologies

- Minimum Steiner Multigraph Problem
- Budget-Constrained Steiner Connected Subgraph Problem with Node Profits and Node Costs
- Upgrading Shortest Path
- Minimum Delay Generalized Steiner Network

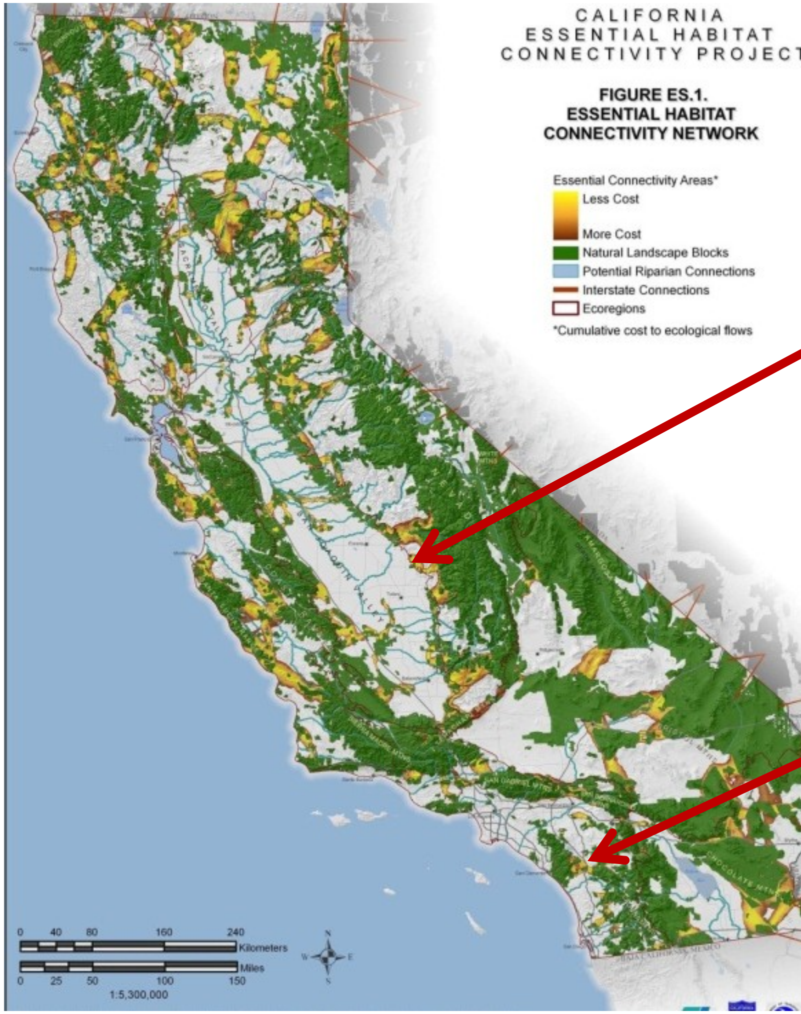
How do we choose which habitats to protect so that landscapes will stay robustly well-connected for wild animal species?

Landscape Connectivity

How do factor in specific features of wildlife conservation, e.g., different species requirements, interactions of species, etc?

THANK YOU!

Upgrading Landscape Connectivity



Conservation restoration opportunities

Prevention of land use change (land acquisition)

Given opportunities for conservation actions with implementation costs and their effect on landscape resistance, design the best budget-constrained strategy

Bistra Dilkina, Katherine Lai, Carla Gomes. CPAIOR 2011