# Computational Advances in Conservation Planning for Landscape Connectivity

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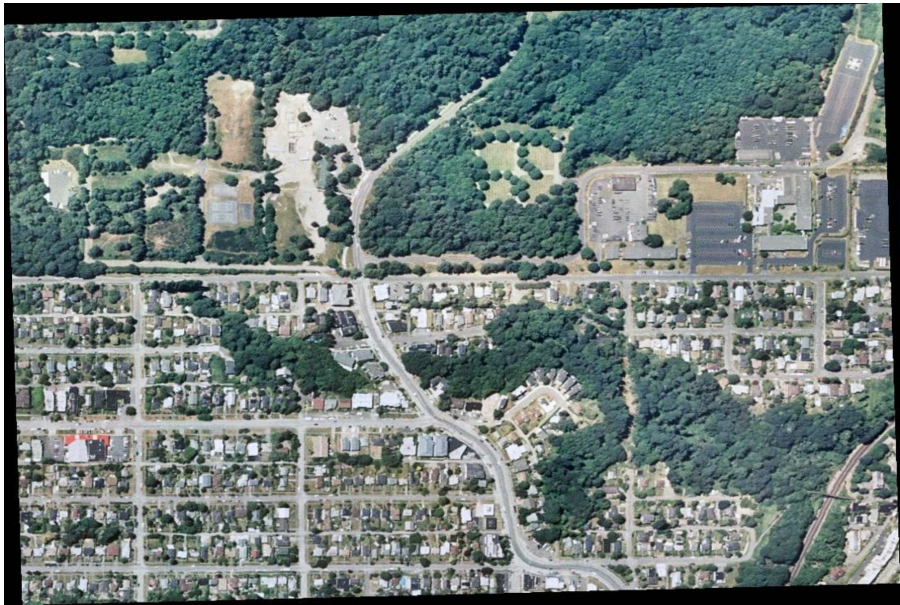
# Landscape configuration

- Habitat loss and fragmentation due to human activities such as forestry and urbanization
- Landscape composition dramatically changes and has major effects on wildlife persistence



# Landscape Connectivity

Definitions of connectivity from ecology:

*Merriam 1984*: The degree to which absolute isolation is prevented by landscape elements which allow organisms to move among patches.

*Taylor et al 1993*: The degree to which the landscape impedes or facilitates movement among resource patches.

*With et al 1997*: The functional relationship among habitat patches owing to the spatial contagion of habitat and the movement responses of organisms to landscape structure.

*Singleton et al 2002*: The quality of a heterogeneous land area to provide for passage of animals (landscape permeability).

# Wildlife corridors for landscape connectivity

- Current definitions emphasize that a wildlife corridor is a **linear landscape element** which serves as a linkage between historically connected habitat/natural areas, and is **meant to facilitate movement between these natural areas** (McEuen, 1993).

**BENEFITS:**

- *Enhanced immigration (*gene flow, genetic diversity, recolonization of extinct patches, overall metapopulation 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.

# Evaluating connectivity

- Most efforts to date by ecologists, biologists and conservationists is to **measure** connectivity and **identify** existing corridors (and not so much to plan or design)
- Methods
  - Patch Metrics
  - Graph Theory
  - Least-cost analysis
  - Circuit Theory
  - Individual-based models

Simple
Few Assumptions
Needs Less Input Info
Structural focus

↕

Complex
Lots of Assumptions
Needs More Input Info
Process focus

# Evaluating Connectivity

- Path Metrics
  - Statistics on size, nearest neighbor distance
  - Structural, not process oriented
- Graph Theory
  - Describes relationships between patches
  - Patches as nodes connected by distance-weighted edges
  - Minimum spanning tree
  - Node centrality
  - No explicit movement paths considered

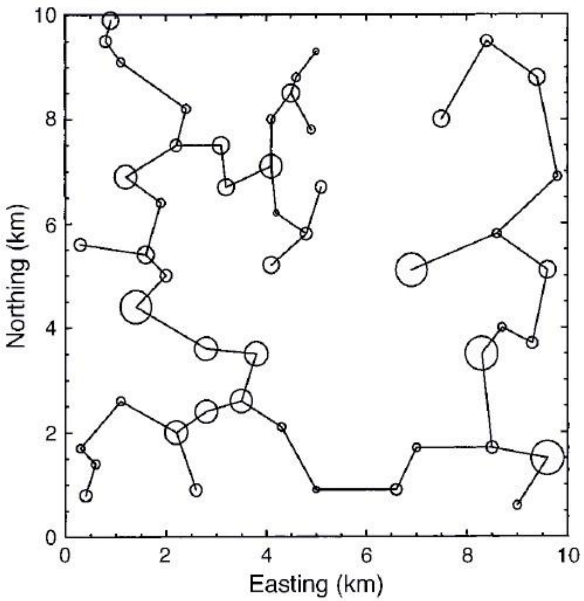



FIG. 2. A hypothetical landscape of 50 circular habitat patches in a 100-km$^2$ landscape. Edges drawn comprise the minimum spanning tree of the graph (based on distance).

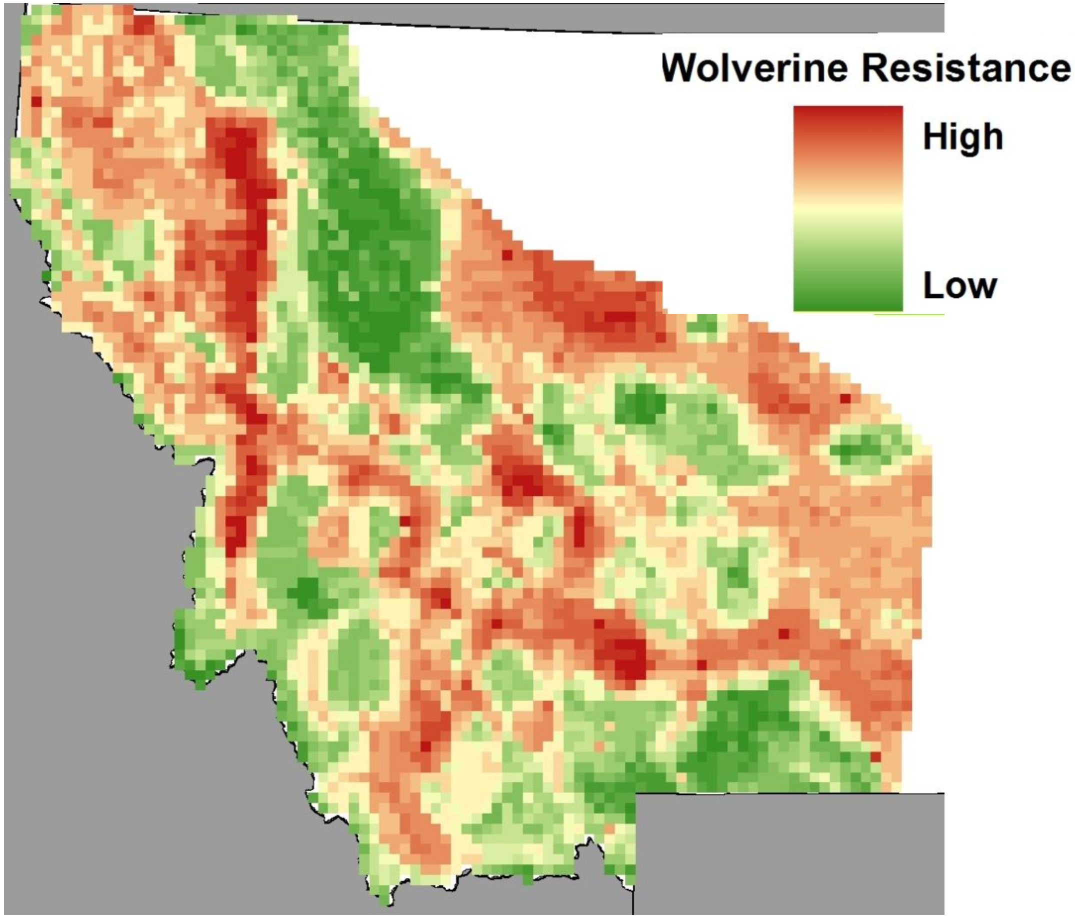
Urban & Keitt 2001

# Least-cost Paths & Circuit Theory: Steps of analysis

- Identify target species
- Habitat modeling – identifying habitat patches or core areas of necessary quality and size
- Resistance modeling – relate landscape features such as land cover, roads, elevation, etc. to species movement or gene flow
- Analyze connectivity between core areas as a function of spatially-explicit landscape resistance

# Spatially-explicit Resistance

- Landscape is a raster of cells with species-specific resistance values
- Connectivity between pairs of locations = length of the *resistance-weighted shortest path*
- Inferring resistance layers – regression learning task between landscape features and genetic relatedness



# Evaluating connectivity

- Least-cost path modeling
  - Can quantify isolation between patches
  - Spatially explicit – can identify routes and bottlenecks
  - Based on the concept of "movement cost" - each raster cell is associated with species-specific cost of movement
  - For each cell in the landscape compute the shortest resistance-weighted path between core habitat areas it lies on
  - Identify corridors as the cells which belong to paths that are within some threshold of the shortest resistance distance

# Large-scale Corridor Initiatives


CALIFORNIA Essential Habitat Connectivity


Jaguar Corridor Initiative

Using least-cost path analysis

# Motivation

- **Problem:** Habitat fragmentation
  - Biodiversity at risk
- Landscape connectivity is a **key conservation priority**
- **Current approaches only consider ecological benefit**
- **Need computational tools to systematically design strategies** taking into account tradeoffs between ecological benefits and economic costs

# Inspiration: success story for reserve design

- Reserve Design: each parcel contributes a set of biodiversity features and the goal is to select a set of parcels that meets biodiversity targets
- Systematic Planning simultaneously maximizes ecological, societal, and industrial goals: Without increasing land area or timber volume, the strategic approach includes greater portions of key conservation elements
- Computational Models: Minimum Set Cover, Maximum Coverage Problem, Prioritization Algorithms, Simulated Annealing
- Available and widely used Decision Support Tools:

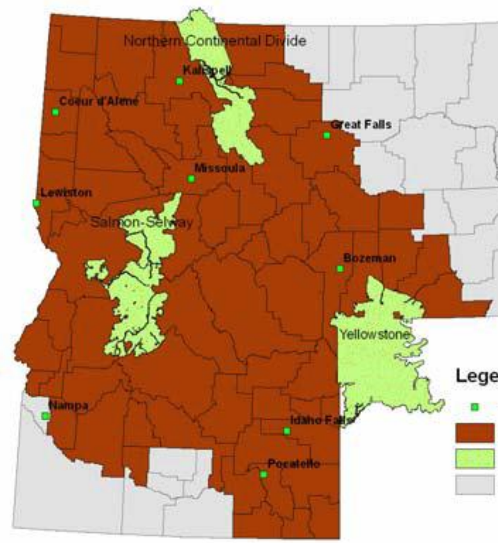
ZONATION
Conservation planning software

Marxan
Informing Conservation Decisions Globally

# Wildlife Corridors

**Wildlife Corridors** Link zones of biological significance (“reserves”) by purchasing continuous protected land parcels

Typically: low budgets to implement corridors.

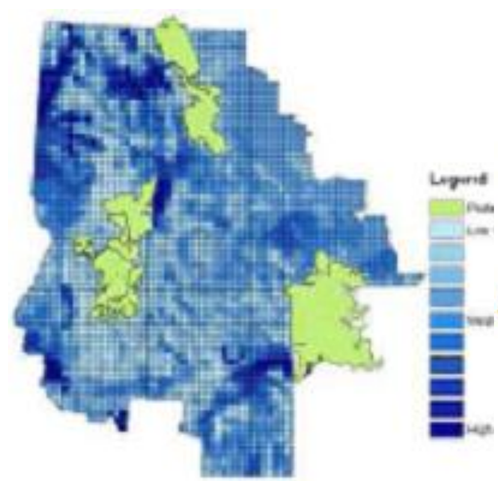



**Example**:

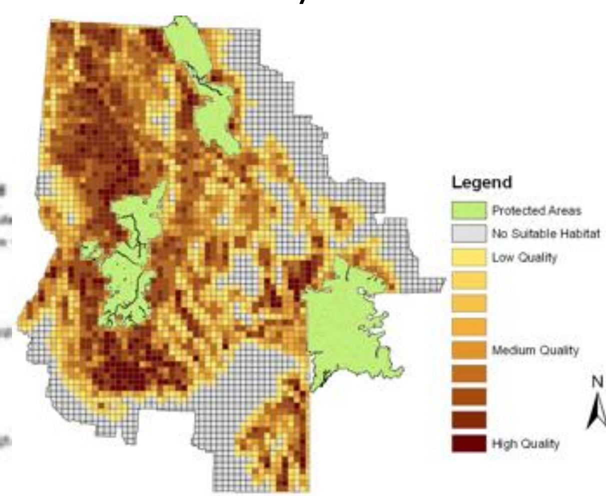
Goal: preserve grizzly bear populations in the Northern Rockies by creating wildlife corridors connecting 3 reserves:

Yellowstone National Park;
Glacier Park and
Salmon-Selway Ecosystem

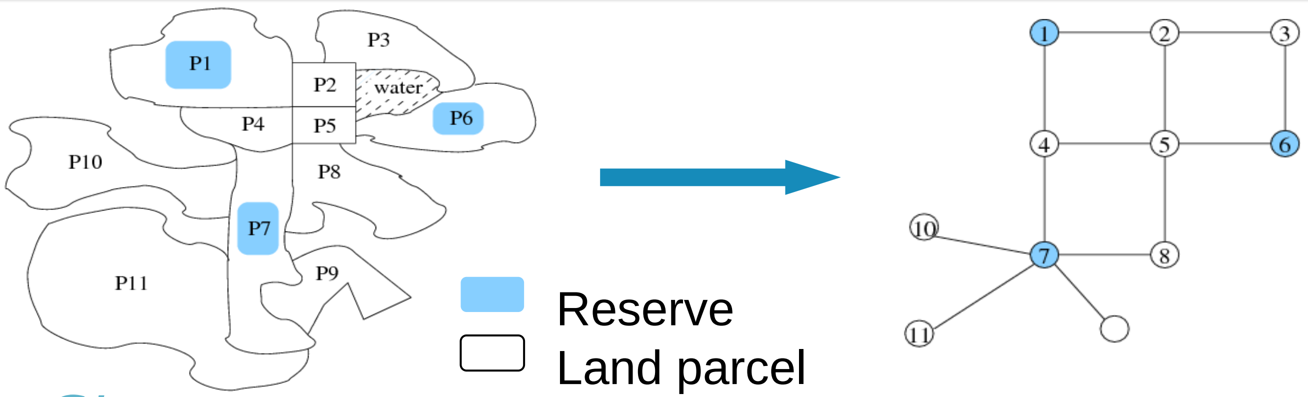
Economic costs



Suitability/resistance



# Connection Subgraph




*Given*

- An undirected graph G = (V,E)
- Terminal vertices T $\subseteq$ V
- Vertex cost function: c(v);   utility function: u(v)

*Is there a subgraph H of G such that*

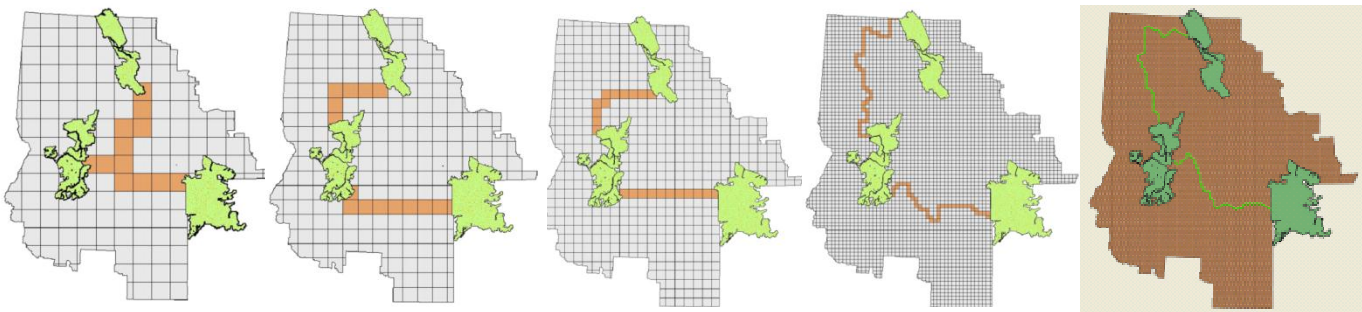
NP-complete

- H is connected and contains T
- cost(H) $\leq$ B;   utility(H) $\geq$ U ?

Also network design, system biology, social networks and facility location planning

# Minimum Cost Corridor

- Ignore utilities → **Min Cost Steiner Tree** Problem
- Fixed parameter tractable – polynomial time solvable for fixed (small) number of terminals or reserves

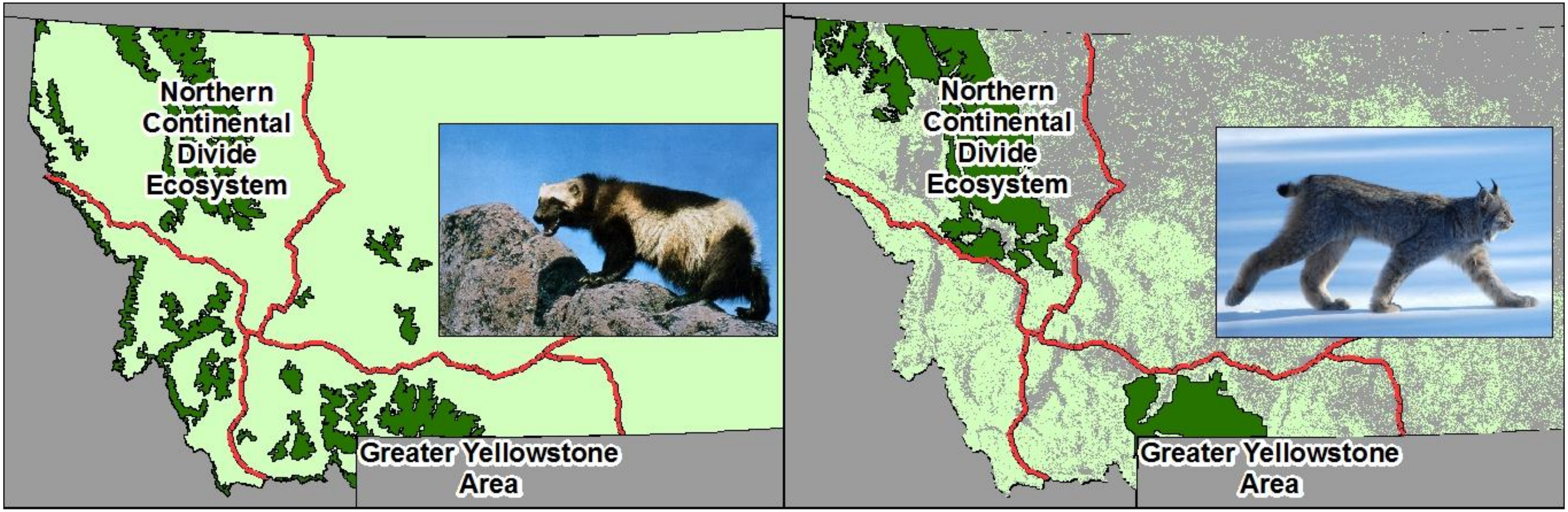


| | | | | |
|---|---|---|---|---|
| 50x50 grid | 40x40 grid | 25x25 grid | 10x10 grid | 25 km² hex |
| 167 Cells | 242 Cells | 570 Cells | 3299 Cells | 1288 Cells |
| $1.3B | $891M | $449M | $99M | $7.3M |
| <1 sec | <1 sec | <1 sec | 10 mins | 2 hrs |

Need to solve problems with large number of cells! →Scalability Issues

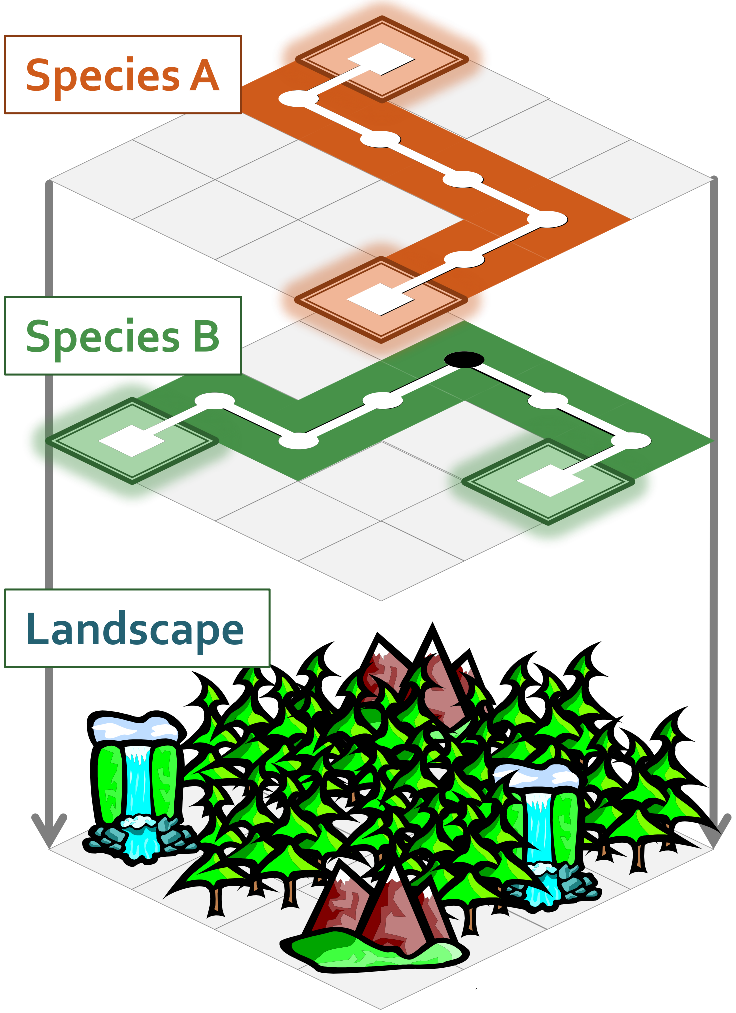
# Case Study: Multi-Species Wildlife Corridor in Montana

**WOLVERINES** **CANADA LYNX**




Species Habitat   Accessible Landscape   Barriers

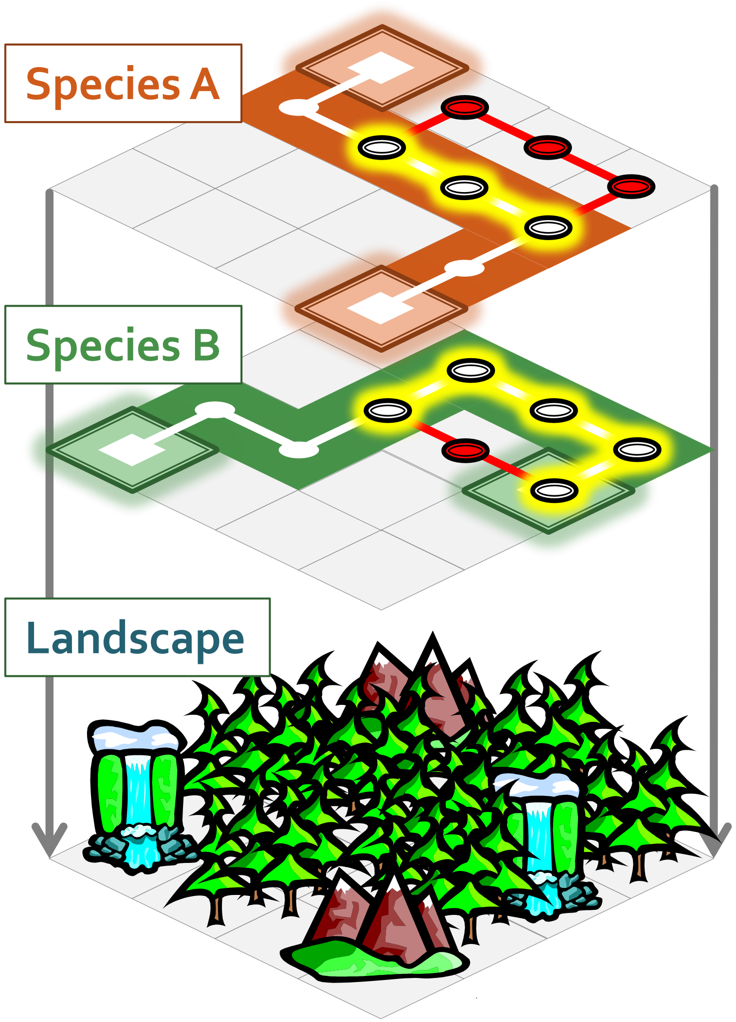
# Finding the Min-Cost Multi-Species Corridor

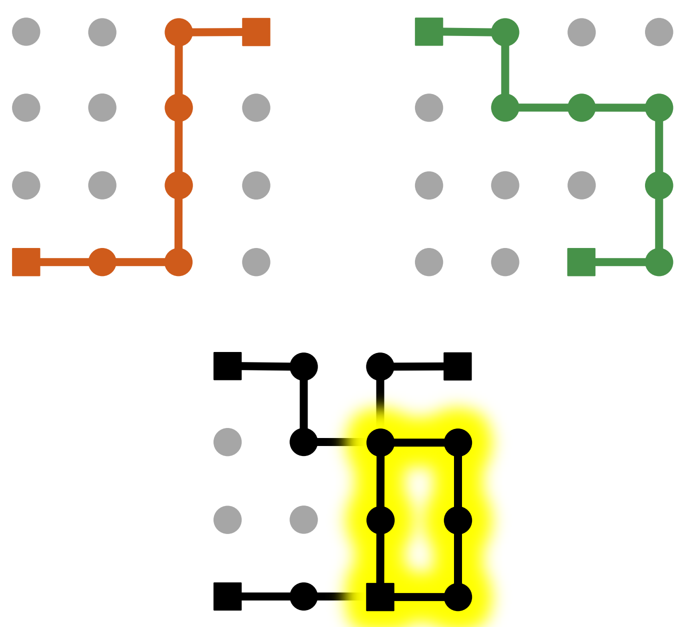



- Species-specific features
  - Barrier
  - Accessible landscape
  - Habitat patch (terminal)
- For each species
  - Model input as a graph
  - Connect **terminals** via **accessible landscape**
- Only feasible solution: **all** the species' nodes

# Steiner Multigraph Problem: Harder than Steiner Tree

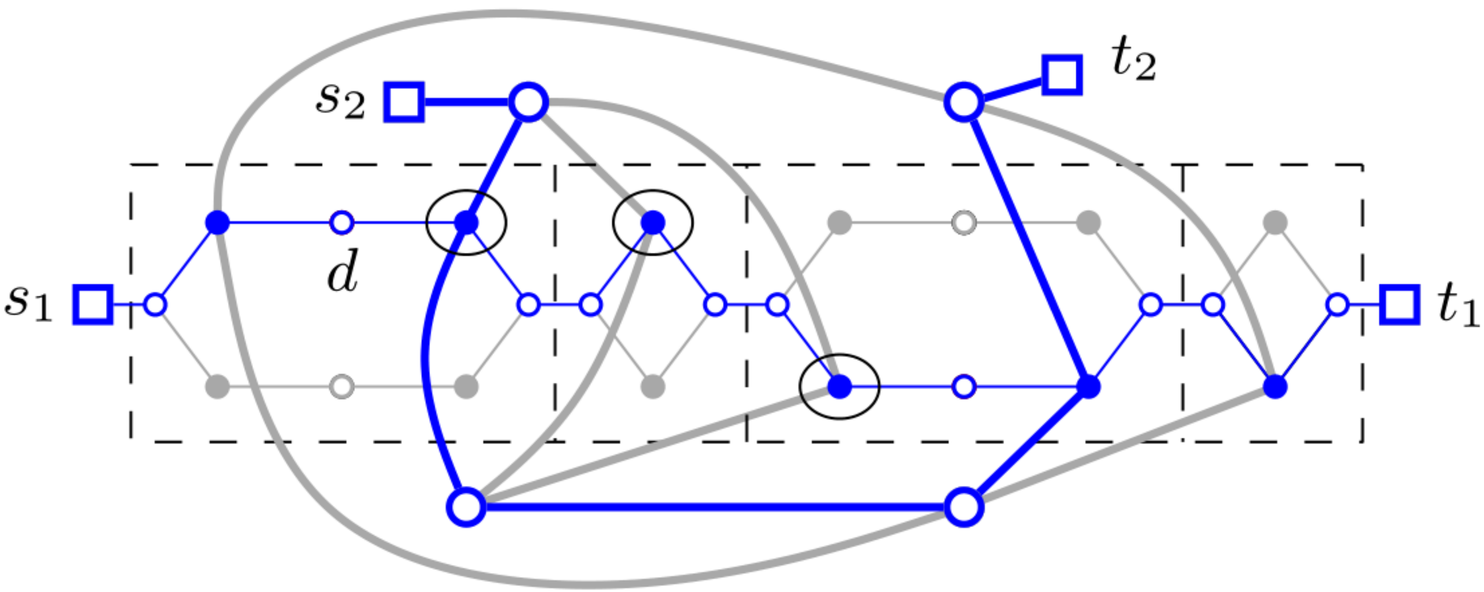
- An optimal solution may contain **cycles**!



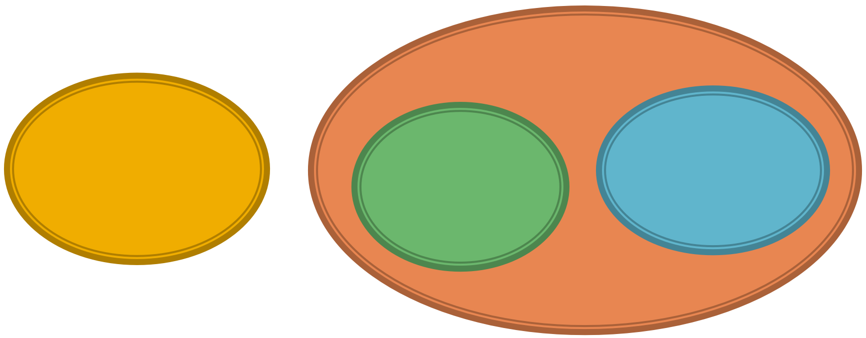
# Steiner Multigraph Problem: 2 Species, 2 Terminals Each

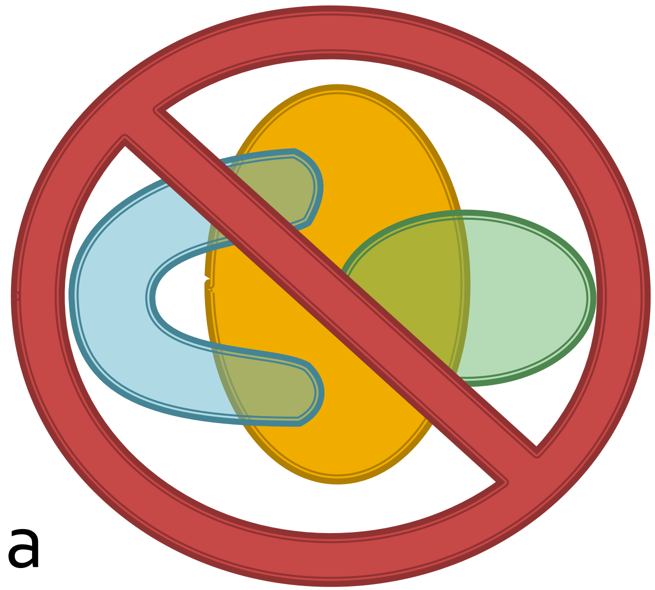
- **Theorem**: Steiner Multigraph is NP-hard for 2 species, 2 terminals each, even for planar graphs.
- Reduction from 3SAT



# Steiner Multigraph Problem: Laminar DP Algorithm

- Special case:
  - "**Laminar**" or modularity property on $V_i$





- **Theorem**: Optimal solution to a **laminar** instance is a **forest**, and laminar Steiner Multigraph is in FPT.
- DP algorithm: exponential in # terminals, poly in # nodes

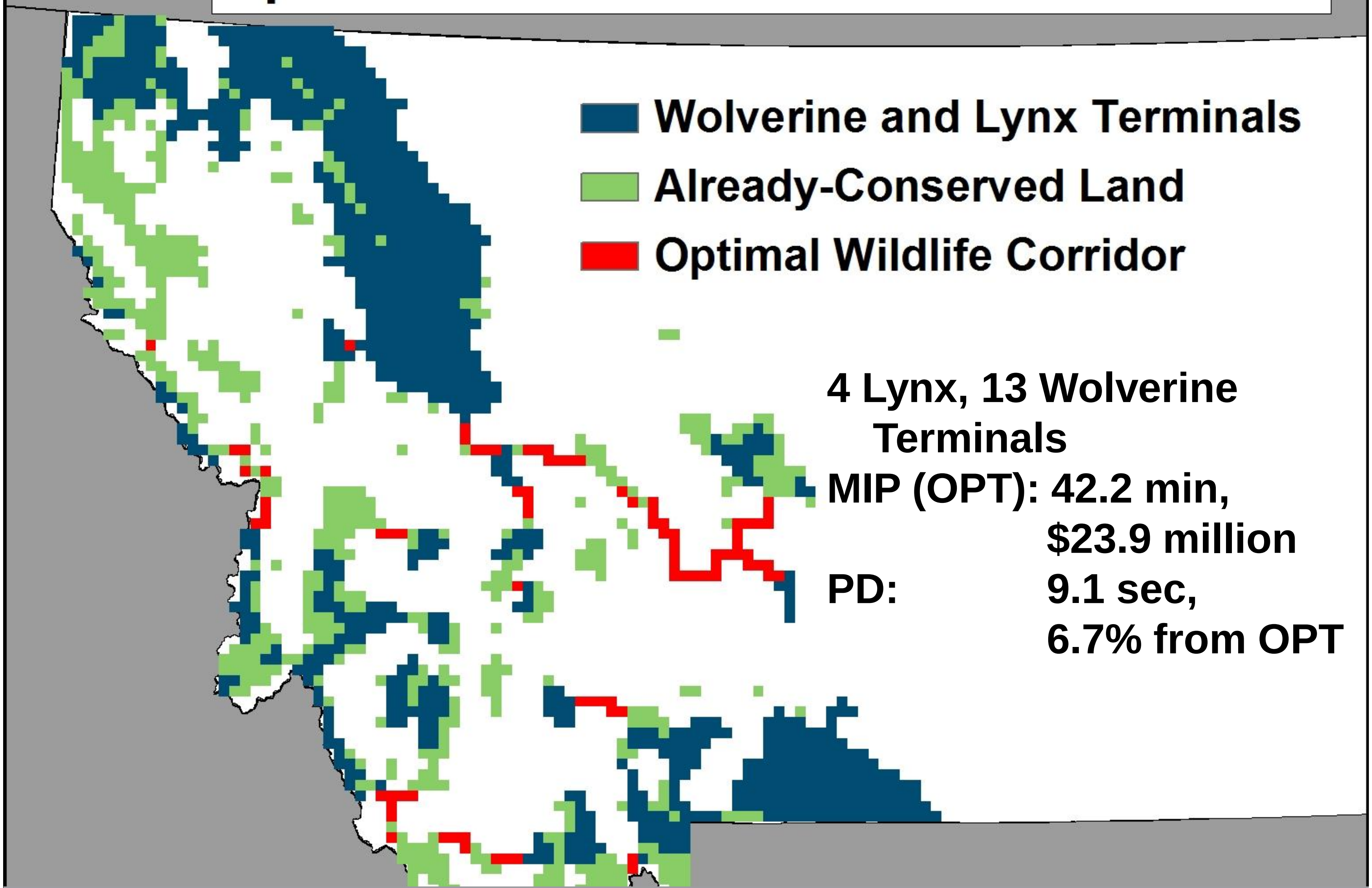
# Steiner Multigraph Problem: Solution Approaches

| Algorithm | Time | Guarantee |
|---|---|---|
| MIP | Exponential | Optimal |
| Laminar DP (laminar only) | Poly for constant # terminals | Optimal |
| Iterative DP | Poly for constant # terminals | # species |
| Primal-Dual | Poly | ∞ |

# Steiner Multigraph Problem: Mixed Integer Program

- Multicommodity flow encoding
- For each species $i \in P$
  - Designate a source terminal $s_i \in T_i$
  - Sink terminals: $T_i' = T_i \setminus \{s_i\}$
  - Require 1 unit of flow from $s_i$ to each $t \in T_i'$
- Global constraint
  - Require a node to be bought before it can be used to carry flow

# Optimal Western Montana Wildife Corridor




4 Lynx, 13 Wolverine Terminals

MIP (OPT): 42.2 min, \$23.9 million

PD: 9.1 sec, 6.7% from OPT

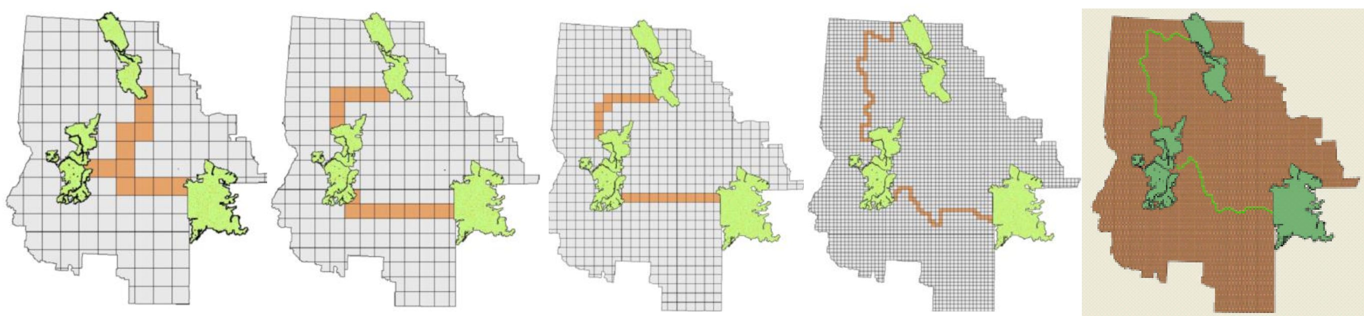

Katherine J. Lai, Carla P. Gomes, Michael K. Schwartz, Kevin S. McKelvey, David E. Calkin, and Claire A. Montgomery



- AAAI, Special Track on Computational Sustainability, August 11, 2011

# Minimum Cost Corridor

- Ignore utilities → **Min Cost Steiner Tree** Problem
- Fixed parameter tractable – polynomial time solvable for fixed (small) number of terminals or reserves



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| <1 sec | <1 sec | <1 sec | 10 mins | 2 hrs |

Need to solve problems with large number of cells! →Scalability Issues

What if we were allowed extra budget?

# Connection Subgraph

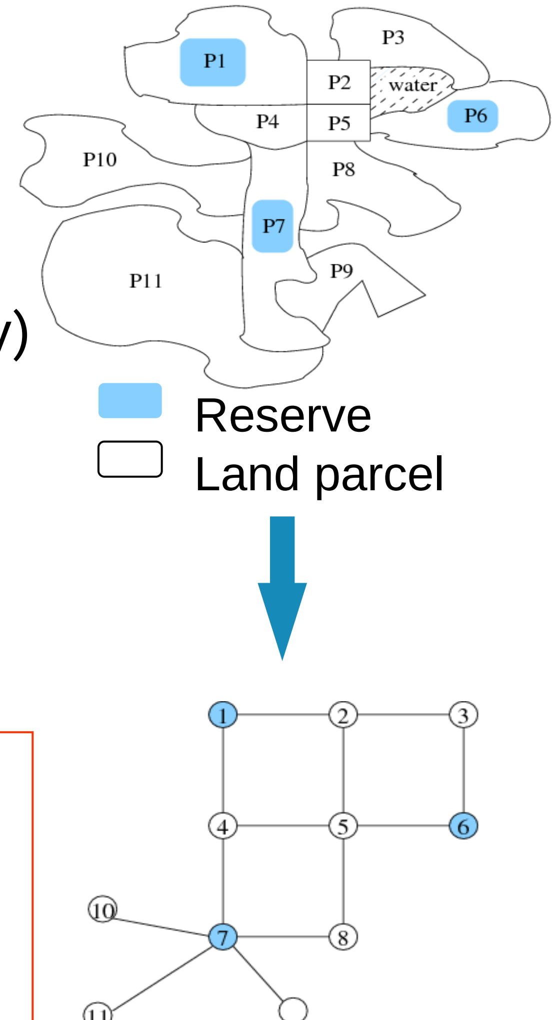
*Given*

- An undirected graph G = (V,E)
- Terminal vertices $T \subseteq V$
- Vertex cost function: c(v); utility function: u(v)

*Is there a subgraph H of G such that*

- H is connected and contains T
- $\mathrm{cost}(H) \leq B$;
- Has maximum utility(H) ?

**NP-hard**




Worst Case Result!
Real-world problems are not necessarily worst case and they possess
hidden sub-structure
that can be exploited allowing scaling up of solutions.

# Encoding: Single Commodity Flow (SCF)

–Variables: $x_i$ , binary variable, for each vertex i ( 1 if included in corridor ; 0 otherwise)

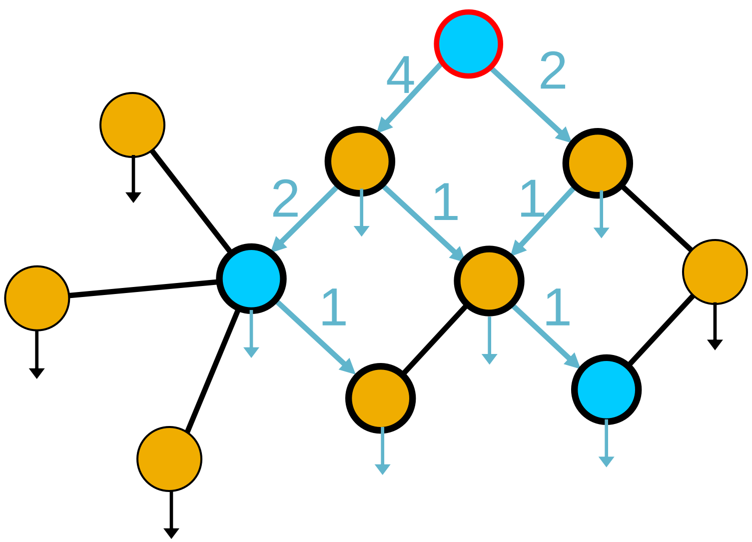
–Cost constraint: $\sum_i c_i x_i \leq C$

–Utility optimization function: maximize $\sum_i u_i x_i$

–Connectedness: use a single commodity flow encoding

– One reserve node designated as root

– One continuous variable for every directed edge $f_e \geq 0$




-- Root is the only source of flow

-- Every node that is selected ($x_i$=1) becomes a sink for 1 unit of flow

-- Flow preservation at every non-root node i:

- Incoming flow = $x_i$ + outgoing flow

-- Non-selected nodes ($x_i$=1) cannot carry flow:

- Incoming flow $\leq N * x_i$

# Solving the connection subgraph problem: Phase I

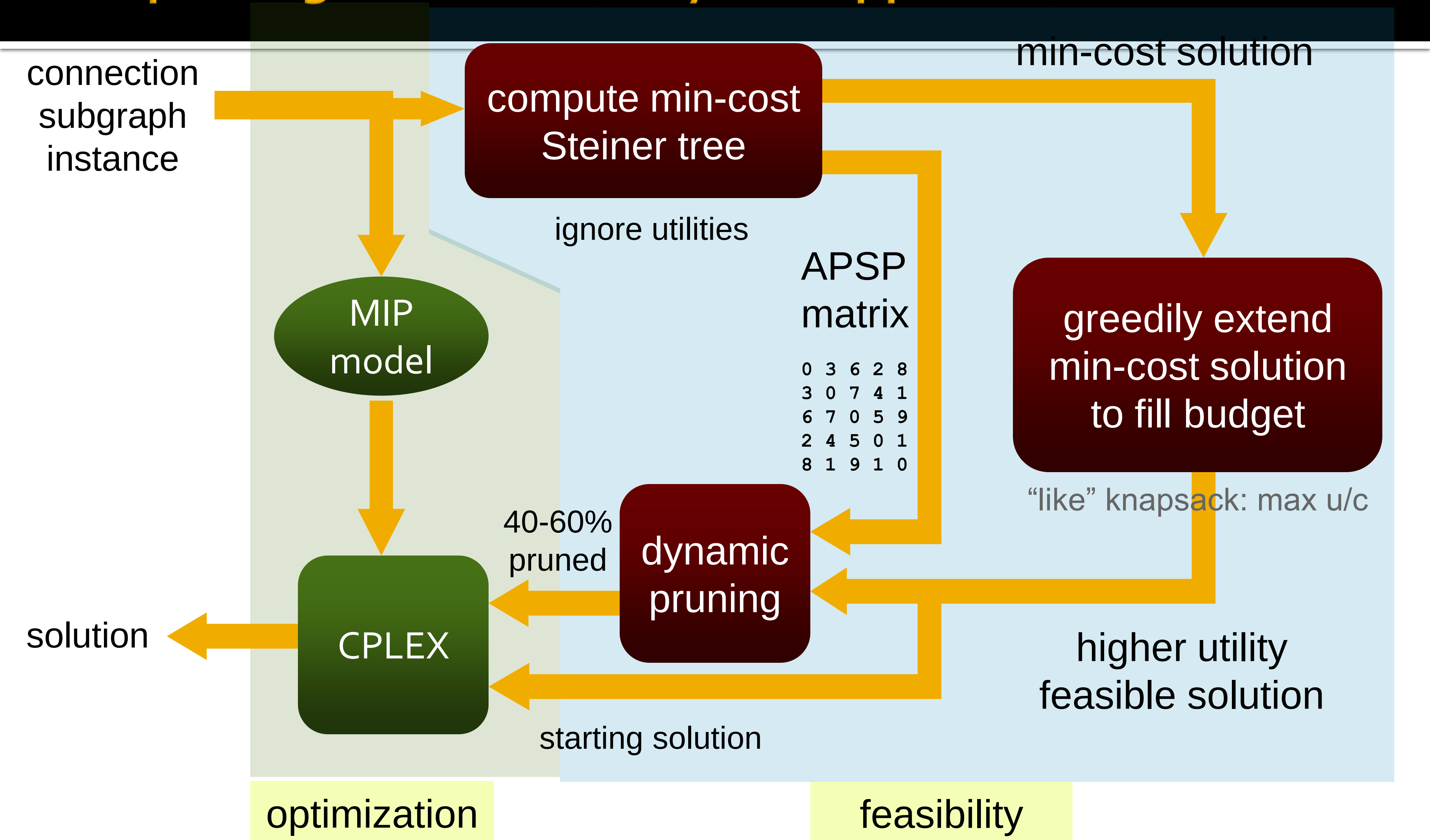
- 1st Phase – compute the minimum Steiner tree
  - Produces the minimum cost solution
  - Produces all-pairs-shortest-paths matrix used for pruning the search space
  - Given a budget:
    - Pruning: nodes for which the cheapest tree including the node and two terminals is beyond the budget can be pruned (uses all-pairs-shortest-paths matrix). This significantly reduces the search space size, often in the range of 40-60% of the nodes.
    - Greedy (often sub-optimal) Solution: use the remaining budget above the minimum cost solution to add more nodes sorted by highest utility/cost ratio

This phase runs in polynomial time for a constant number of terminal nodes.

# Solving the connection subgraph problem: Phase II

- Refines the greedy solution to produce an optimal solution with Cplex
  - Greedy solution is passed to Cplex as the starting solution (Cplex can change it).
  - Computes an optimal solution to the utility-maximization version of the connection subgraph problem.

# Solving the Connection Sub-Graph Problem: Exploiting Structure (A Hybrid Approach)

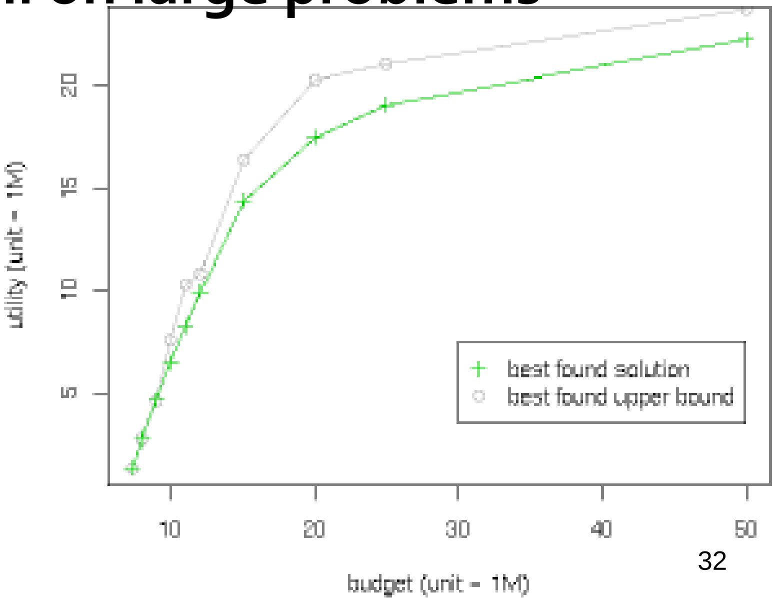



Conrad, G., van Hoeve, Sabharwal, Sutter 2008

# Grizzly bear data: 25hex grid

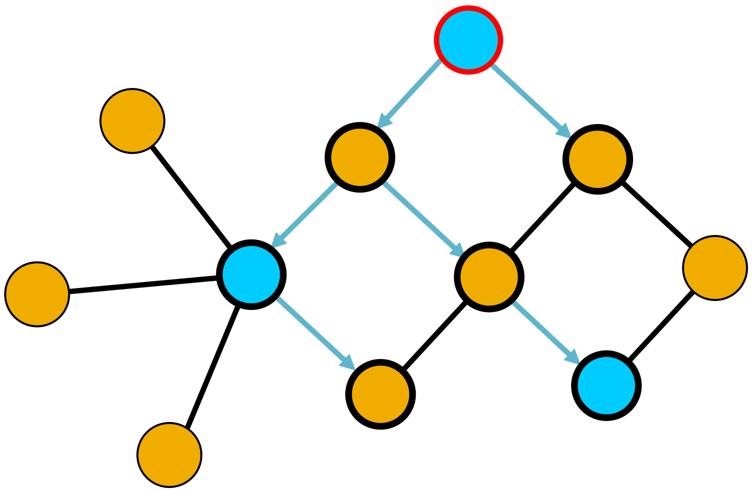
- MIP+CPLEX gives a natural way to model and solve the optimization problem
- Connectivity: Single Flow encoding is natural formulation
  - **But does not perform very well on large problems**
  - **Large optimality gaps after long runtimes**

Grizzly bears 25hex grid: best found solution with upper bound on optimum **AFTER 30 days**



# Encoding: Directed Steiner Tree (DFJ)

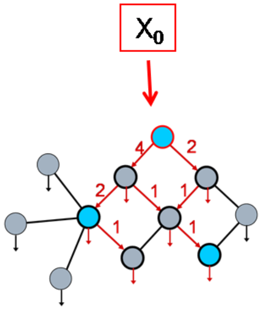
- One binary variable for every node $x_i$ and every directed edge $y_e$
- One reserve node designated as *root*



- A node i is selected if it has an incoming edge
  - Sum incoming edges = $x_i$
- Tree: every node has at most one incoming edge
  - Sum incoming edges $\leq 1$
- Outgoing edges only if selected
  - $y_e \leq x_i$ for e=(i,j)
- Connectedness to root:

$$\sum_{(i,j) \in E' | i \in S, j \in V \setminus S} y_{ij} \geq x_k, \quad \forall S \subset V - r, \forall k \in S$$

# Models Are Important!!!



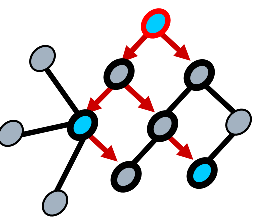

$$
\begin{aligned}
\max & \sum_{i \in V} u_i x_i \\
\text{s.t.} & \sum_{i \in V} c_i x_i \leq C \\
& x_t = 1 \qquad \forall t \in T \\
& x_i \in \{0,1\} \qquad \forall i \in V \\
& \sum_{j \in V-r} x_j = \sum_{i:(r,i) \in E'} y_{ri} \\
& \sum_{i:(i,j) \in E'} y_{ij} = x_j + \sum_{i:(j,i) \in E'} y_{ji} \qquad \forall j \in V \\
& y_{ij} < n x_j \qquad \forall (i,j) \in E' \\
& y_{ij} \geq 0 \qquad \forall (i,j) \in E'
\end{aligned}
$$

## Single Commodity Flow

Quite compact (poly size) ☺

Produces good solutions fast ☺

Takes a long time to prove optimality ☹



$$
\begin{aligned}
\max & \sum_{i \in V} \left( u_i \sum_{j \in \delta(i)} y_{ji} \right) \\
\text{s.t.} & \sum_{i \in V} \left( c_i \sum_{j \in \delta(i)} y_{ji} \right) \leq C \\
& \sum_{j \in \delta(i)} y_{ji} = 1 \qquad \forall i \in T, \\
& \sum_{j \in \delta(i)} y_{ji} \leq 1 \qquad \forall i \in V - T \\
& y_{ij} + y_{ji} \leq 1 \qquad \forall i \in V - T, \forall j \in \delta(i) - r \\
& \sum_{(i,j) \in E' | j \in S, i \in V \setminus S} y_{ij} \geq \sum_{j \in \delta(k)} y_{jk}, \qquad \forall S \subset V - r, \forall k \in S \quad [CUTS] \\
& y_{ij} \in \{0,1\} \qquad \forall (i,j) \in E'
\end{aligned}
$$

## Directed Steiner Tree

Exponential Number of Constraints ☹

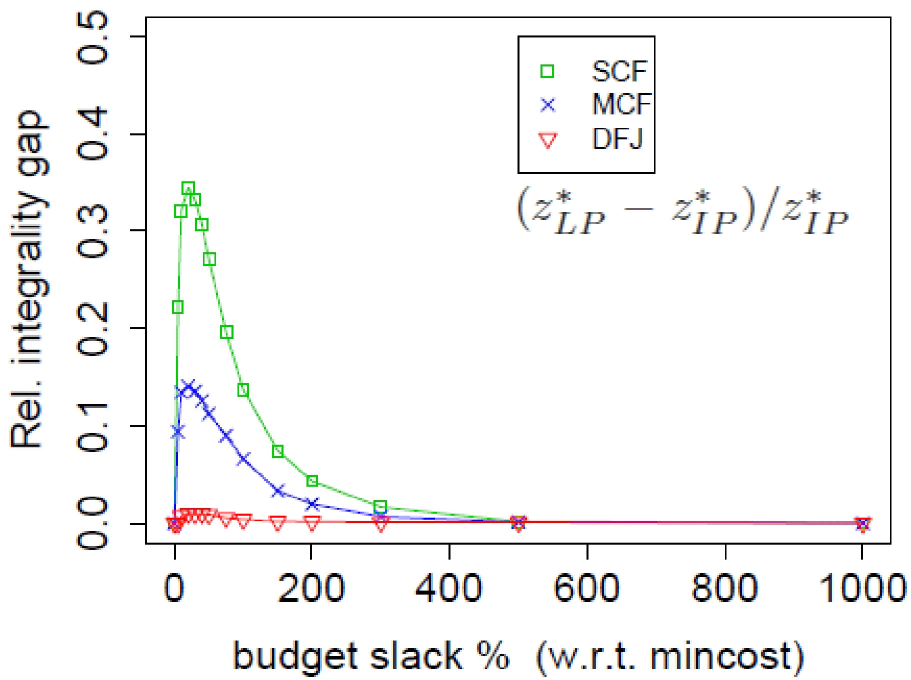
Complex Solution approach ☹

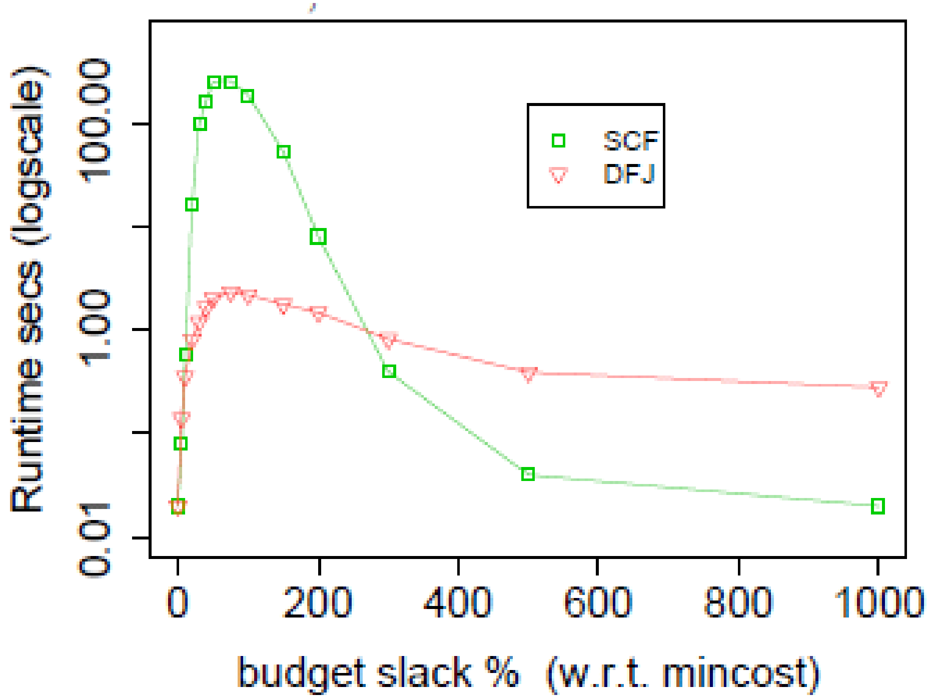
Captures Better the Connectedness Structure ☺

Provides good upper bounds ☺

# Evaluate on Synthetic Instances

synth - 100 cell grid




How tight is the encoding?

Compare UB obtained from LP relaxation to optimum integer soln

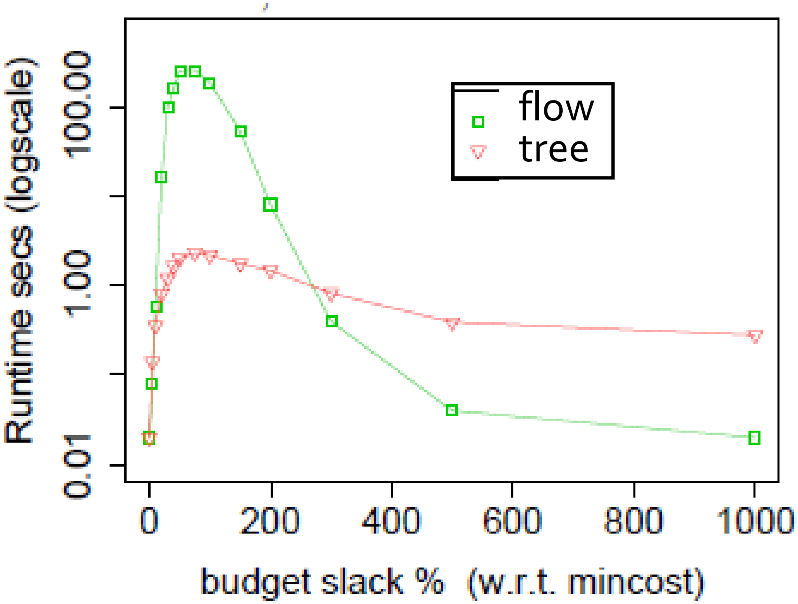
How fast do we find integer solns?

New encoding has greatest impact on the hardest region

# Models Are Important!!!

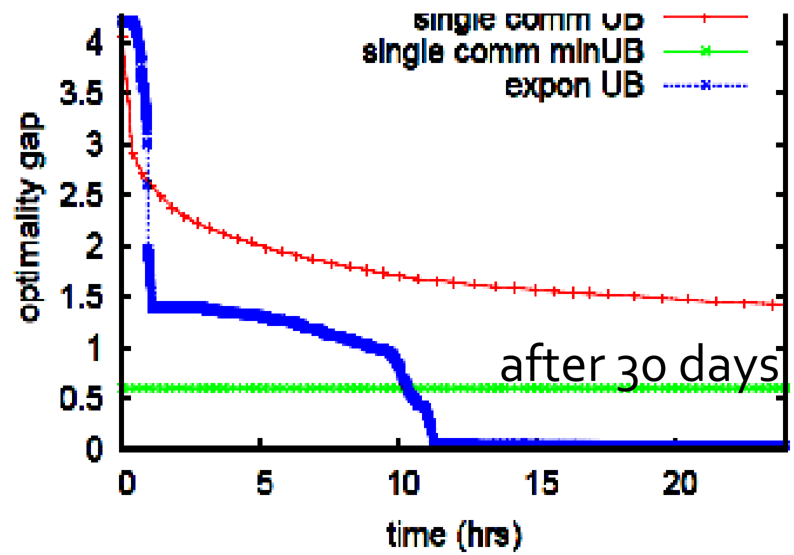
10x10 grid

synth - 100 cell grid




| budget slack | encoding | time | objective | opt. gap |
|---|---|---|---|---|
| 10% | greedy | < 2 mins | 10691163 | NA |
| 109475 | SCF | 8 hrs | 10877799 | 31.15% |
| | DFJ | 25 mins | 12107793 | 0.01% |
| 20% | greedy | < 2 mins | 12497251 | NA |
| 119427 | SCF | 8 hrs | 12911652 | 30.35% |
| | DFJ | 2 hrs 25 mins | 13640629 | 0.01% |
| 30% | greedy | < 2 mins | 13581815 | NA |
| 129379 | SCF | 8 hrs | 13776496 | 28.64% |
| | DFJ | 7 hrs 35 mins | 14703920 | 0.62% |

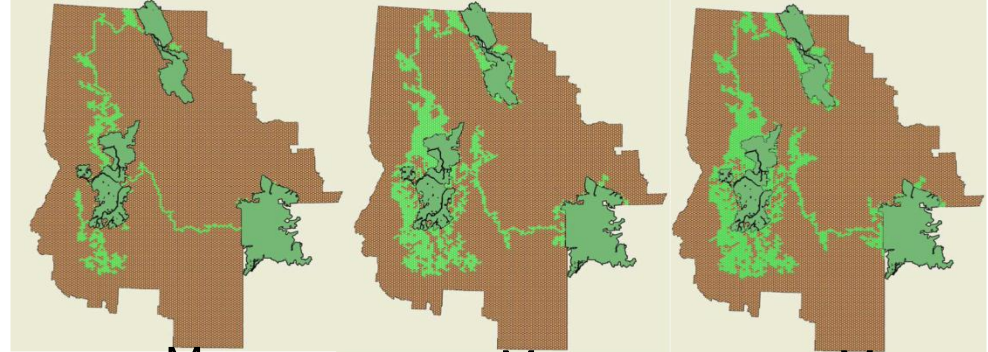
- Flow model good at:
  - finding solutions fast
  - larger budgets
- Tree model good at:
  - critically constrained budgets
  - providing good upper bounds on best possible solut



**Real world instance:**

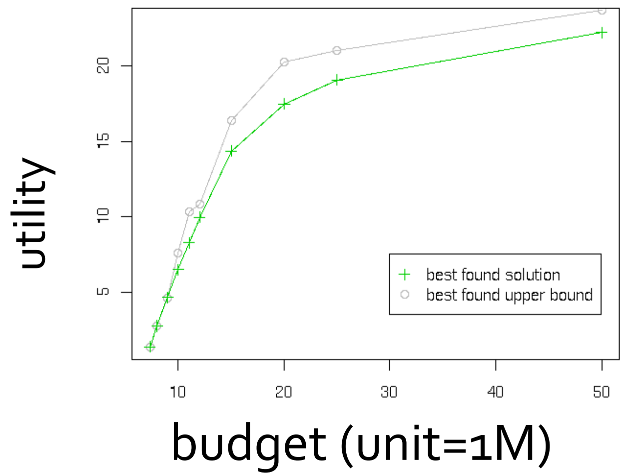
**Corridor for grizzly bears in the Northern Rockies, connecting:**

- **Yellowstone**
- **Salmon-Selway Ecosystem**
- **Glacier Park**



$10M $15M $20M

**Budget-constrained Utility Maximization - very hard in practice**




**Scaling up Solutions by Exploiting Structure:**

- **Identification of Tractable Sub-problems**
- **Typical Case Analysis**
- **Tight encodings**
- **Streamlining for Optimization**
- **Static/Dynamic Pruning**

Our approach allows us to handle large problems
and to find solutions within 1% of optimal for ‘critical’ budgets

Conrad, Dilkina, Gomes, van Hoeve, Sabharwal, Suter 2007-10

# Work in progress

- Additional constraints
  - Minimum and maximum width of corridors
  - Maximum distance between core areas
- Adding robustness to corridor utility measure
  - What if part of the corridor disappears?
  - Multiple disjoint paths within corridor support losing some nodes of the designated corridor
  - We need multiple good (resistance-weighted short) paths

# Protecting landscape connectivity against future degradation

# Different Planning setting

- Implementing whole corridor networks might be economically challenging
- Consider least-cost path corridors in use by species in fragmented and threatened matrix
- Which land parcels to put under conservation management to guard against effects of future degradation  on least-cost path connectivity?

# Problem

- **Land parcels** have (**Nodes** in a graph)
  - **Resistances** (**Delays**)
  - **Conservation measures with costs and conserved resistances** (**Upgrade actions** with upgraded delays)
- **Core habitat areas** (**Terminals**)
- **Goal:** Conserve parcels (upgrade nodes)
  - cost ≤ budget
  - Minimize path lengths
    between pairs of core areas

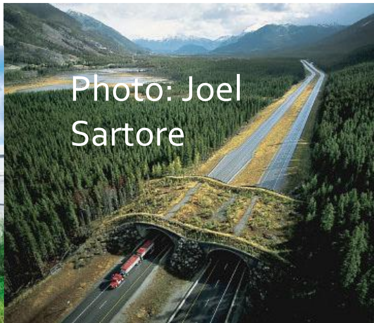


Photo: Joel Sartore

# Model: Upgrading Shortest Paths Problem

- **Given:**
  - **Graph:** $G = (V, E)$
  - **Node delays:** $\mathrm{d}: V \rightarrow \mathbb{R}^+$
  - **Upgrade costs:** $\mathrm{c}: V \rightarrow \mathbb{R}^+$
  - **Upgraded node delays:** $\mathrm{d}': V \rightarrow \mathbb{R}^+$

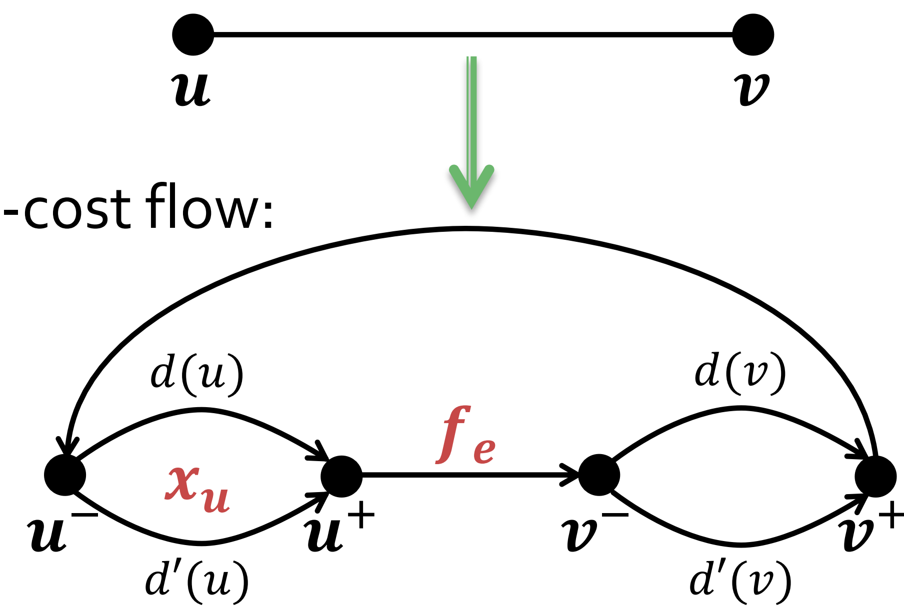
    $(d'(v) \leq d(v), \forall\, v \in V)$
  - **Terminals:** $T \subseteq V$
  - **Terminal pairs:** $P \subseteq T \times T$
  - **Budget:** $B \in \mathbb{R}^+$

**Minimize** avg shortest paths for all terminal pairs $p$ by upgrading nodes costing at most budget $B$

**NP-hard**

# Algorithms: Solve a Mixed Integer Program (MIP)

- Formulate as a Mixed Integer Program:
  - Binary decision variables: nodes to upgrade
  - For each terminal pair (s,t)
    - Construct directed graph with continuous variable for every edge
    - Encode shortest path as min-cost flow:
      1 unit from s to t

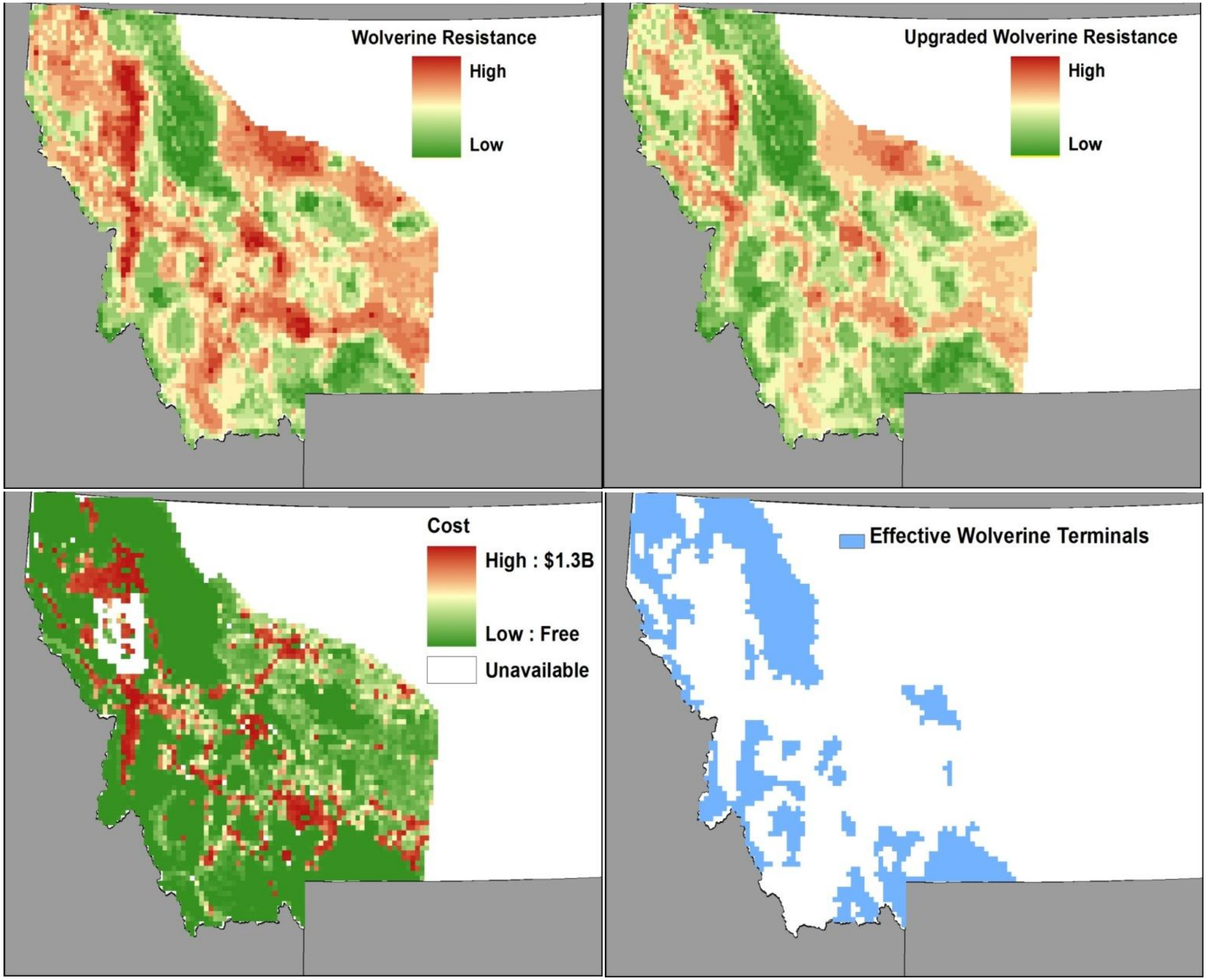


# Algorithms: MIP Flow Encoding

- Global constraint: $\sum_v c_v \, x_v \ \leq B$
- Constraints per **terminal pair** $p = (s, t)$:
  - Pay to upgrade: $f'_{pv} \leq x_v$
  - $flowin_p(s^-) = 0, flowout_p(s^+) = 1$
  - $flowin_p(t^-) = 1, flowout_p(t^+) = 0$
  - Flow conservation for $v \neq s, t$:
    $flowin_p(v^-) = f_{pv} + f'_{pv} = flowout_p(v^+)$
- Objective:
  - $delay_p \qquad = \sum_v [d(v) f_{pv} + d'(v) f'_{pv}]$
  - $\min \frac{1}{|P|} \sum_p delay_p$

# Results:
# Wolverines in West Montana

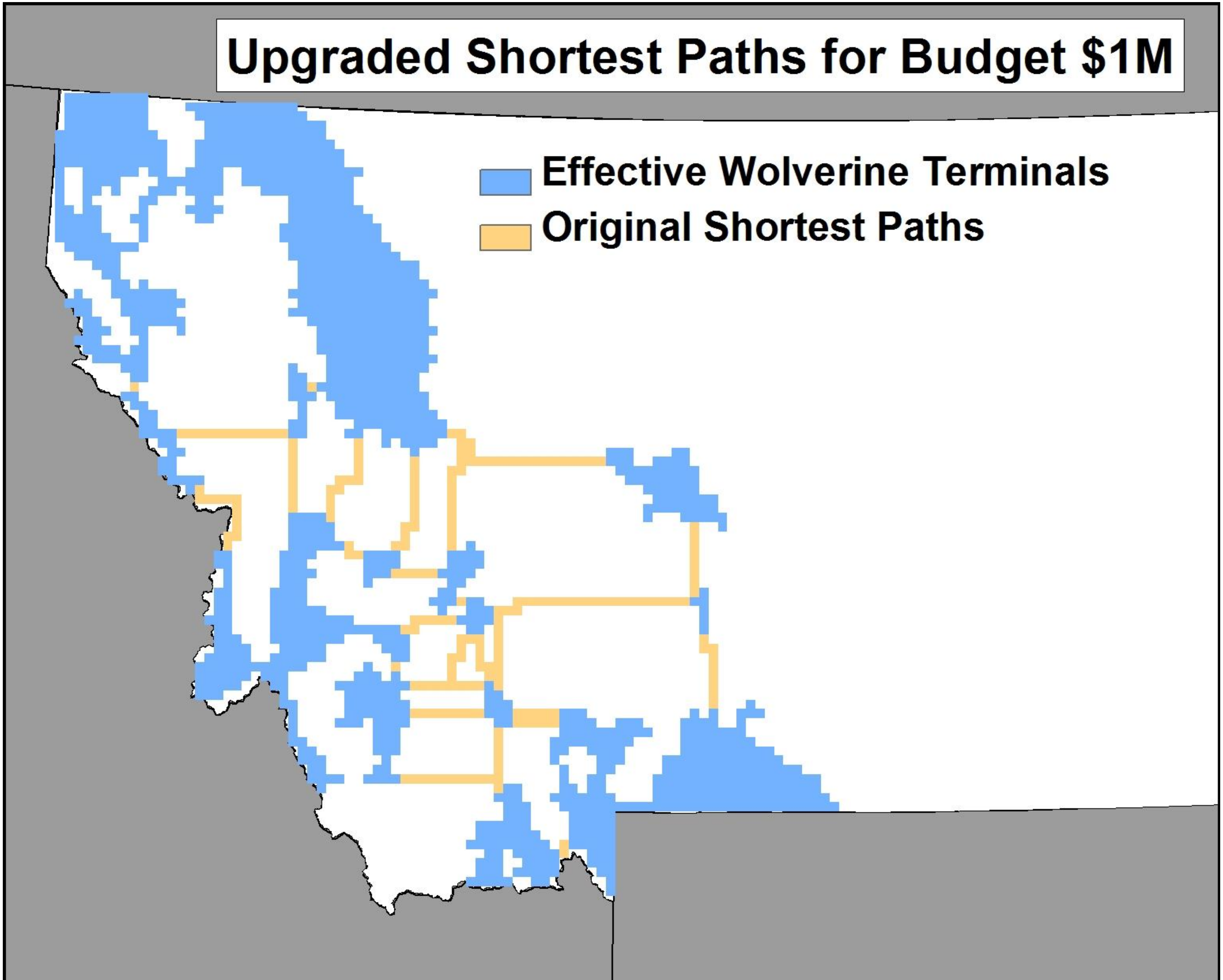
**No** conservation

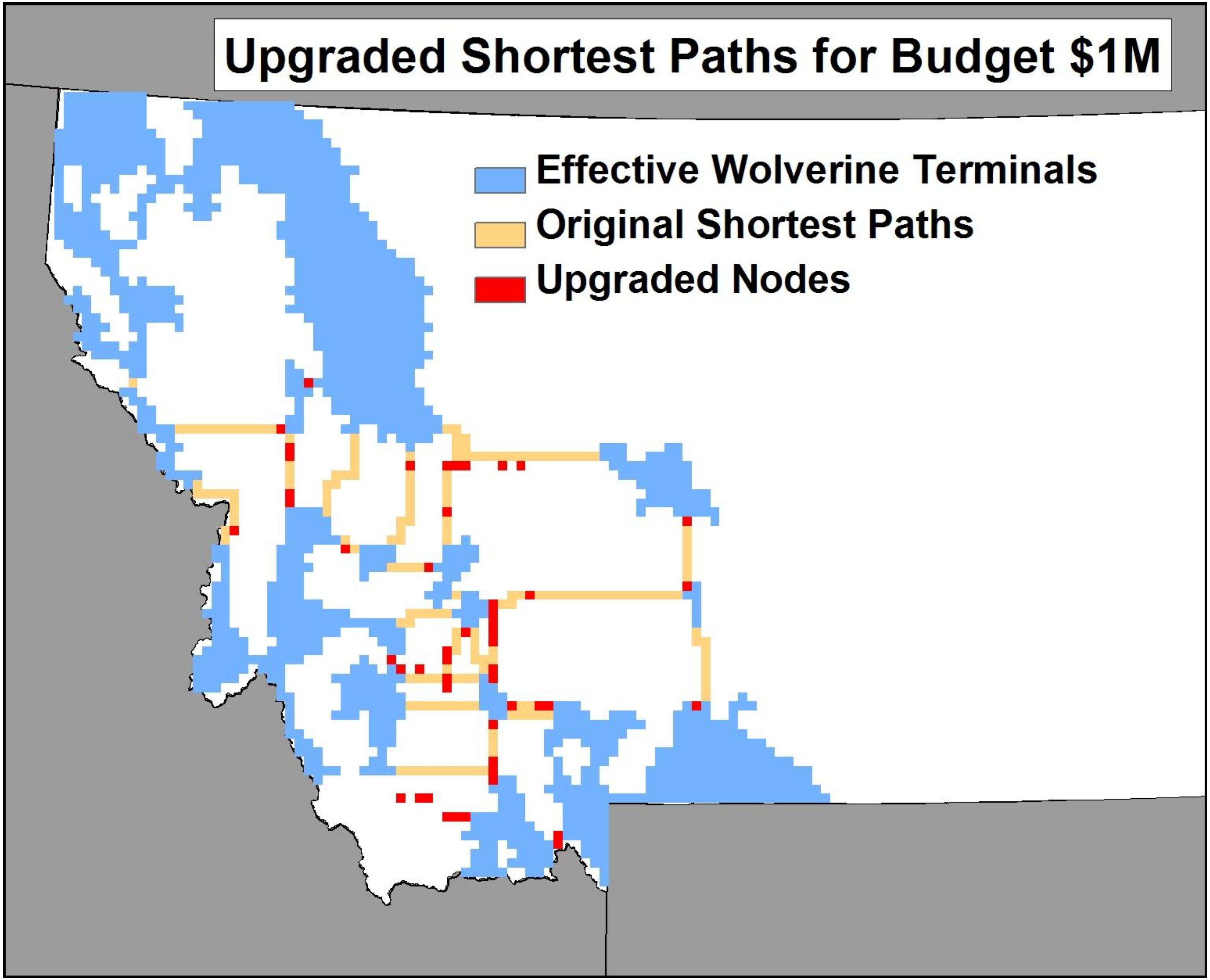



**Under** conservation

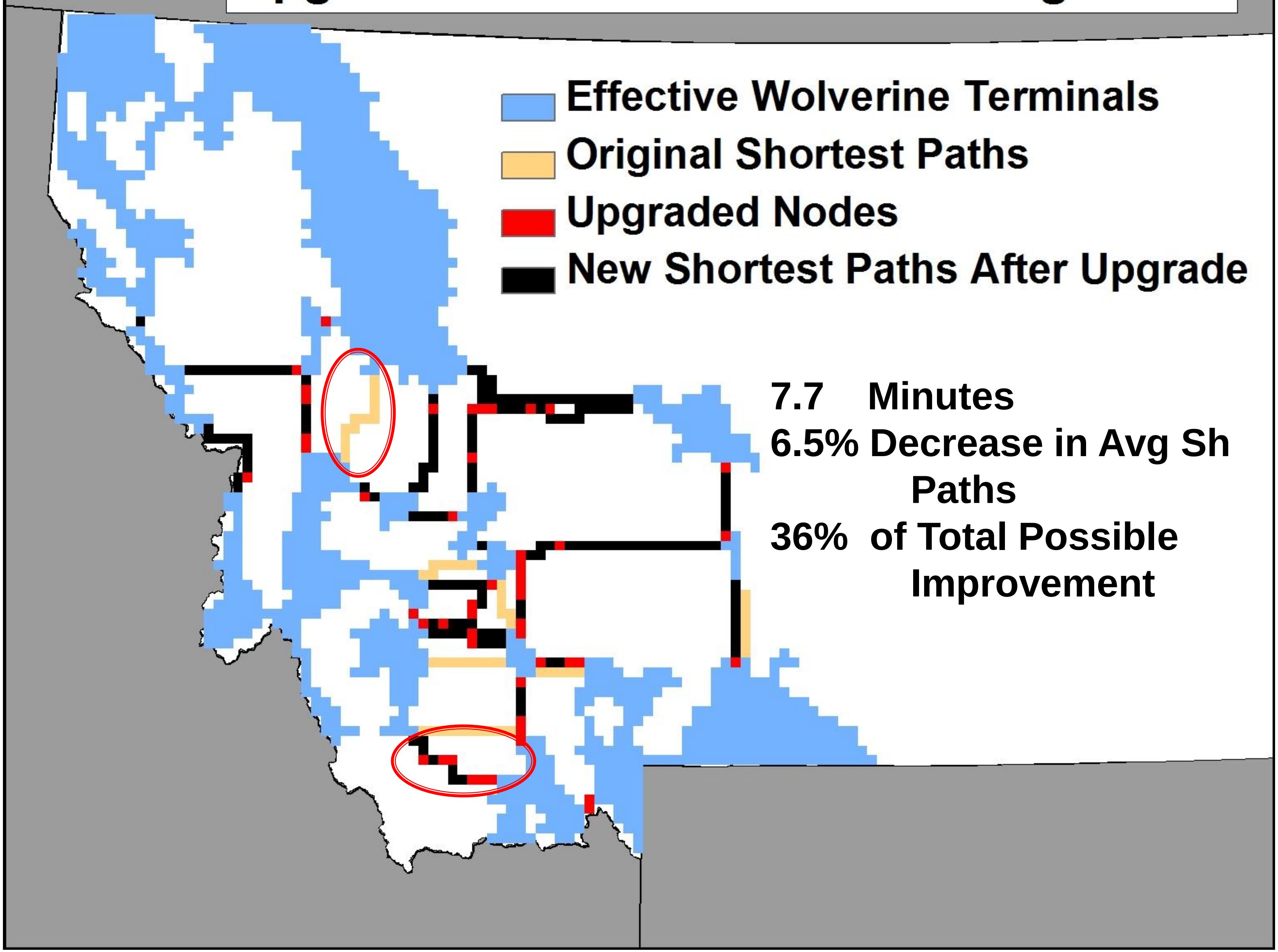
# Results: Wolverines in West Montana

- **Instance**
  - Nodes (6km cells) |V|: 4514
  - Terminals |T|: 13
  - Terminal pairs |P|: 27
  - Costs: 2007 tax data, Estimates for overpasses
  - Delays, Upgraded Delays: Weighted formula
    - Uses land cover, road density, etc.
- **MIP Model**
  - Binary variables: 4514
  - Continuous variables: $|P|(2|E|+2|V|) \approx 1.2M$

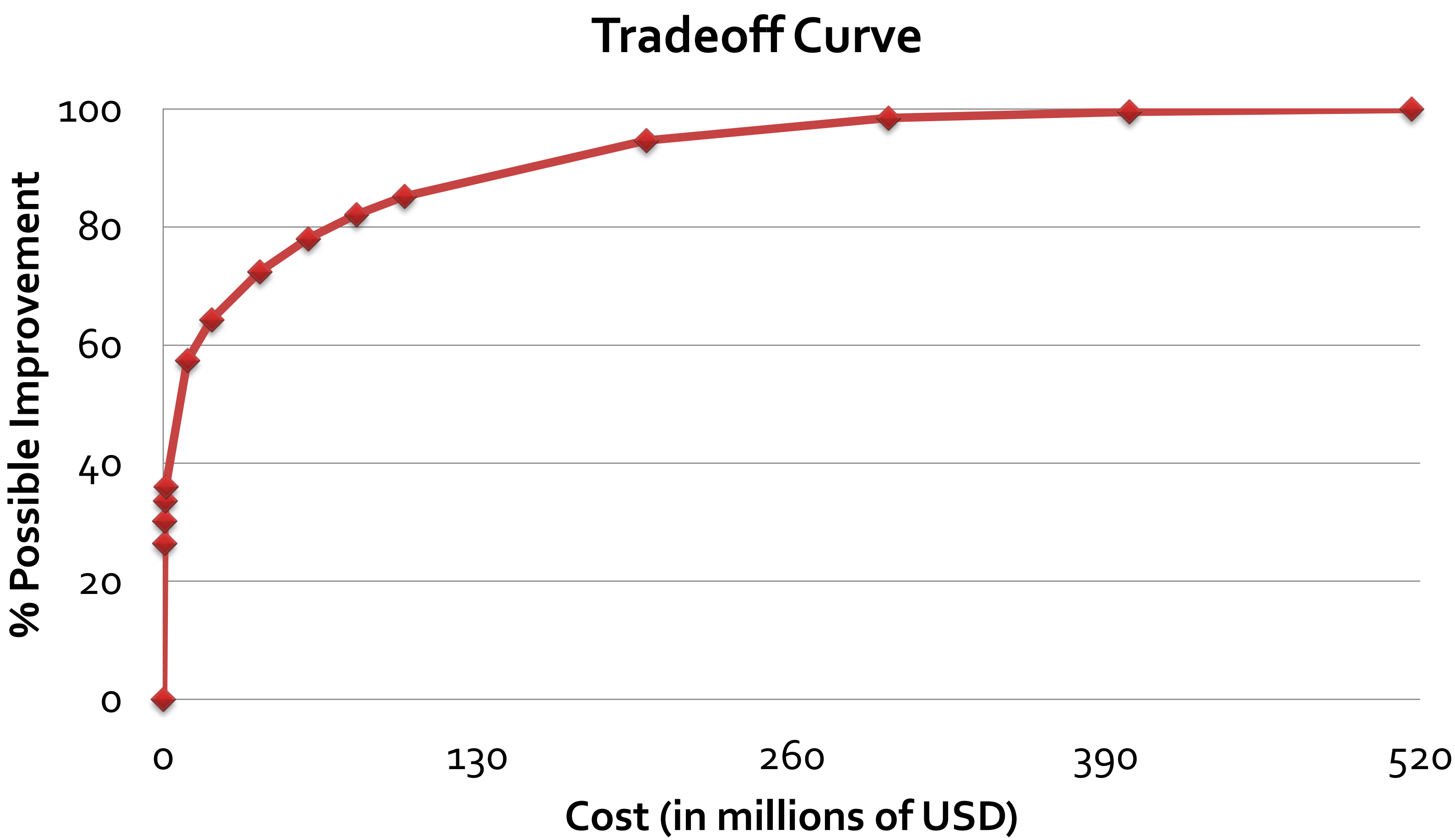

Upgraded Shortest Paths for Budget $1M
Effective Wolverine Terminals
Original Shortest Paths


Upgraded Shortest Paths for Budget $1M
Effective Wolverine Terminals
Original Shortest Paths
Upgraded Nodes

# Upgraded Shortest Paths for Budget $1M



# Results: Wolverines in West Montana



# Work in Progress

- Working with Rocky Mountain Research Station and Oregon State University
  - Mike Schwartz, Kevin McKelvey, Claire Montgomery
  - Apply our model to Western Montana
  - Incorporate models of human density and land use change

- Simultaneously consider multiple species
  - Montana: Wolverine, lynx, grizzly bears

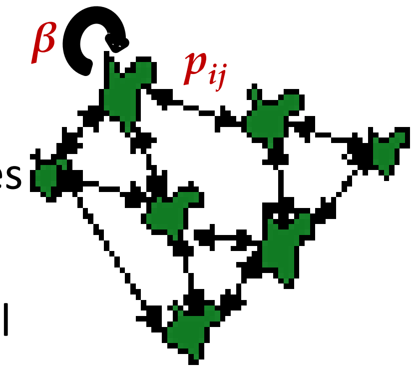
# Summary

- Upgrading Shortest Paths
  - General graph optimization problem
  - Models wildlife conservation application

- In practice, can
  - Solve optimally $\mathbf{1000}$s of nodes in $< \mathbf{30}$ minutes
  - Heuristic even faster, median gap < 8%
- Decision support tool for conservation planners

# Conservation with Stochastic Meta-population Models

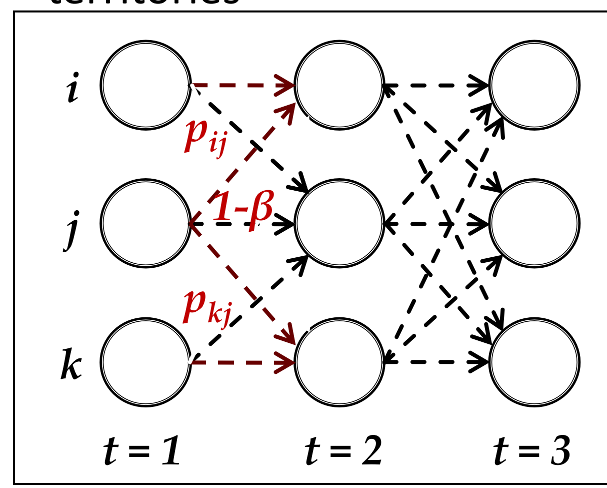
# Conservation with Stochastic Meta-population Models


RCW

Federally-listed endangered species

THE CONSERVATION FUND
America's Partner in Conservation



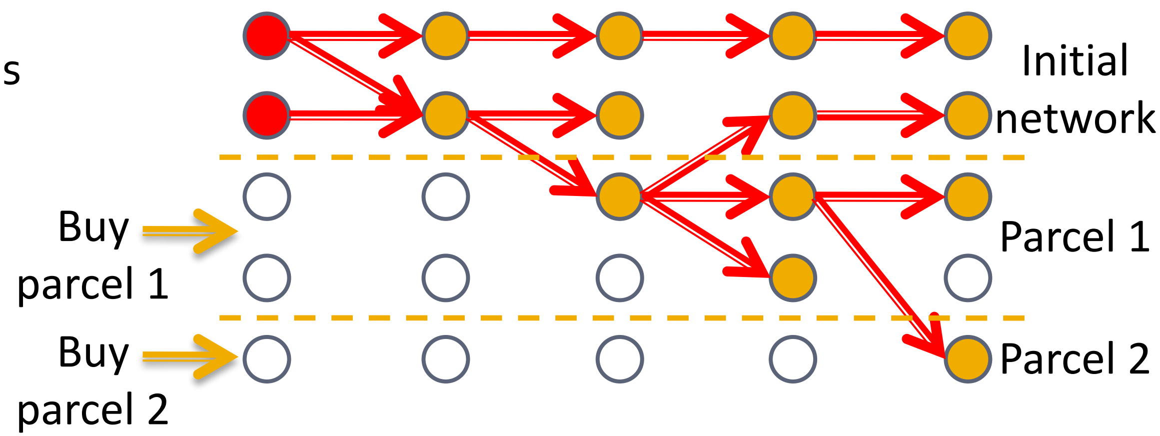

**Given limited budget, what parcels should I conserve to maximize the expected number of occupied territories in 50 years?**

Sheldon, D., Dilkina, B., Ahmadizadeh, K., Elmachtoub, A., Finseth, R., Conrad, J., Gomes, C., Sabharwal, A. Shmoys, D., Amundsen, O., Allen, W., Vaughan, B.; 2009-10

# Cascade Optimization Problem

Given:

- A network with edge probabilities (colonization and extinction)
- Initial network
  - Territories in parcels that are already conserved
- Source nodes
  - Initially occupied territories
- Management actions
  - Parcels (sets of nodes) for purchase and their costs
- Time horizon *T*
- Budget *B*



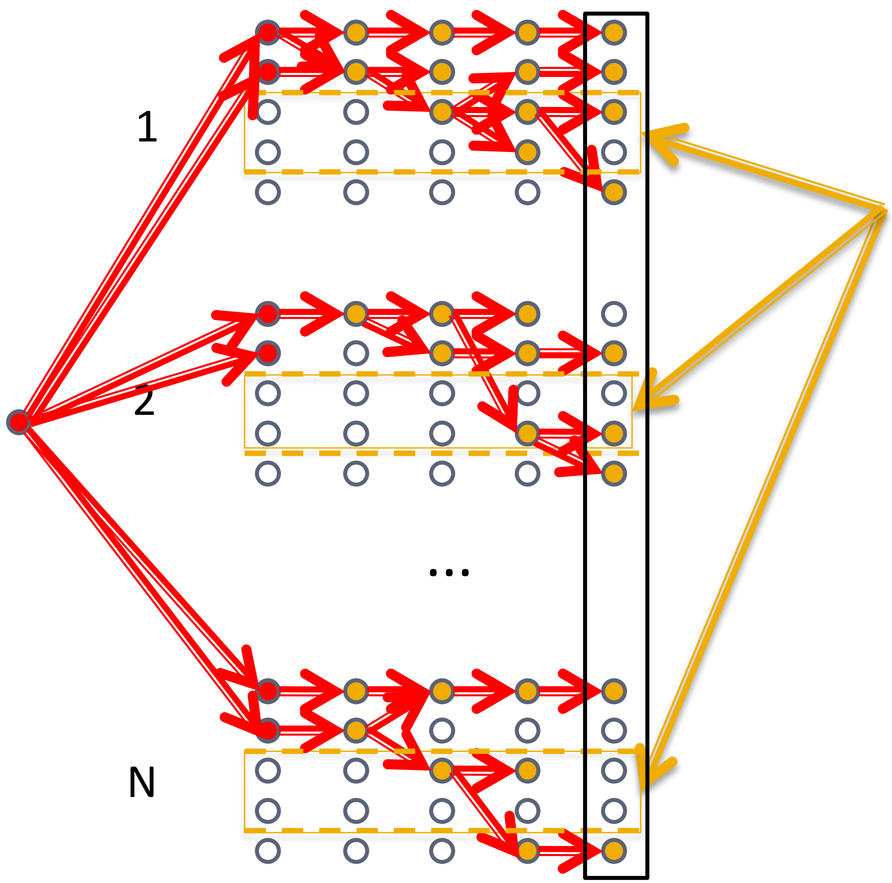

General cascade maximization problem:

- Other management actions such as:
  - increasing edge probabilities
  - buying sources (translocations)

*Find set of actions with total cost at most B that maximizes the* ***expected*** *number of occupied nodes at time T.*

# Sample Average Approximation (SAA)

- Stochastic problem is unwieldy: calculating the objective is #P-hard
- Sample Average Approximation (SAA)

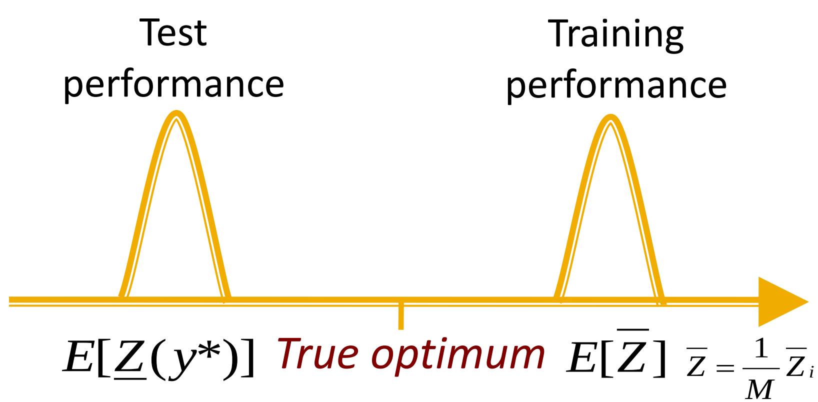



- Sample $N$ *training cascades* by flipping coins for all edges.
- Select single set of management actions that maximized the empirical average over the training cascades.
- A *deterministic network design problem*. Can leverage existing techniques to formulate and solve as mixed integer program (MIP)
- The SAA-MIP approach results in solutions with stochastic optimality guarantees

# Sample Average Approximation (SAA)

- Repeat *M* times for i=1..M
  - Sample *N* *training cascades* by flipping coins for all edges.
  - Solve deterministic optimization problem to obtain buying strategy $y_i$ with optimum *training objective* $Z_i$ (empirical average over the *N* cascades)
  - Evaluate buying strategy an a large sample of *Nvalid validations cascades* and record *validation objective* (empirical average over *Nvalid* cascades)
- Choose the best buying strategy $y^*$ among the *M* proposed strategies according to validation objective
- Evaluate best buying strategy an a large sample of *Ntest test cascades* and record *test objective* $\underline{Z}(y^*)$ (empirical average over *Ntest* cascades)

Stochastic Optimality Bounds




[Norkin et al 1998, Mak et al 1999, Kleywegt et al 2001]

# Deterministic optimization problem: Mixed Integer Program

- Integer variables: $y_l$ = 1 if take action $l$, else 0
- Introduce ***x*** variables to encode reachability, and add constraints to enforce consistency among ***x*** and ***y***

$$
\begin{aligned}
\max_{\mathbf{x},\mathbf{y}} \ & \frac{1}{N}\sum_{k=1}^{N}\sum_{v\in\mathcal{T}} x_v^k \\
\text{s.t.} & \sum_{\ell=1}^{L} c_\ell y_\ell \le B \\
& x_v^k \le \sum_{\ell\in\mathcal{A}(v)} y_\ell, \quad \forall v \notin V_0, \forall k \\
& x_v^k \le \sum_{(u,v)\in E_k} x_u^k, \quad \forall v \notin \mathcal{S}, \forall k \\
& 0 \le x_v^k \le 1, \\
& y_\ell \in \{0,1\}.
\end{aligned}
$$

Must purchase to be reachable

***x*** and ***y*** must be consistent

Only reachable if some predecessor is reachable

# Conservation Strategies

**Greedy:**

Start with empty set

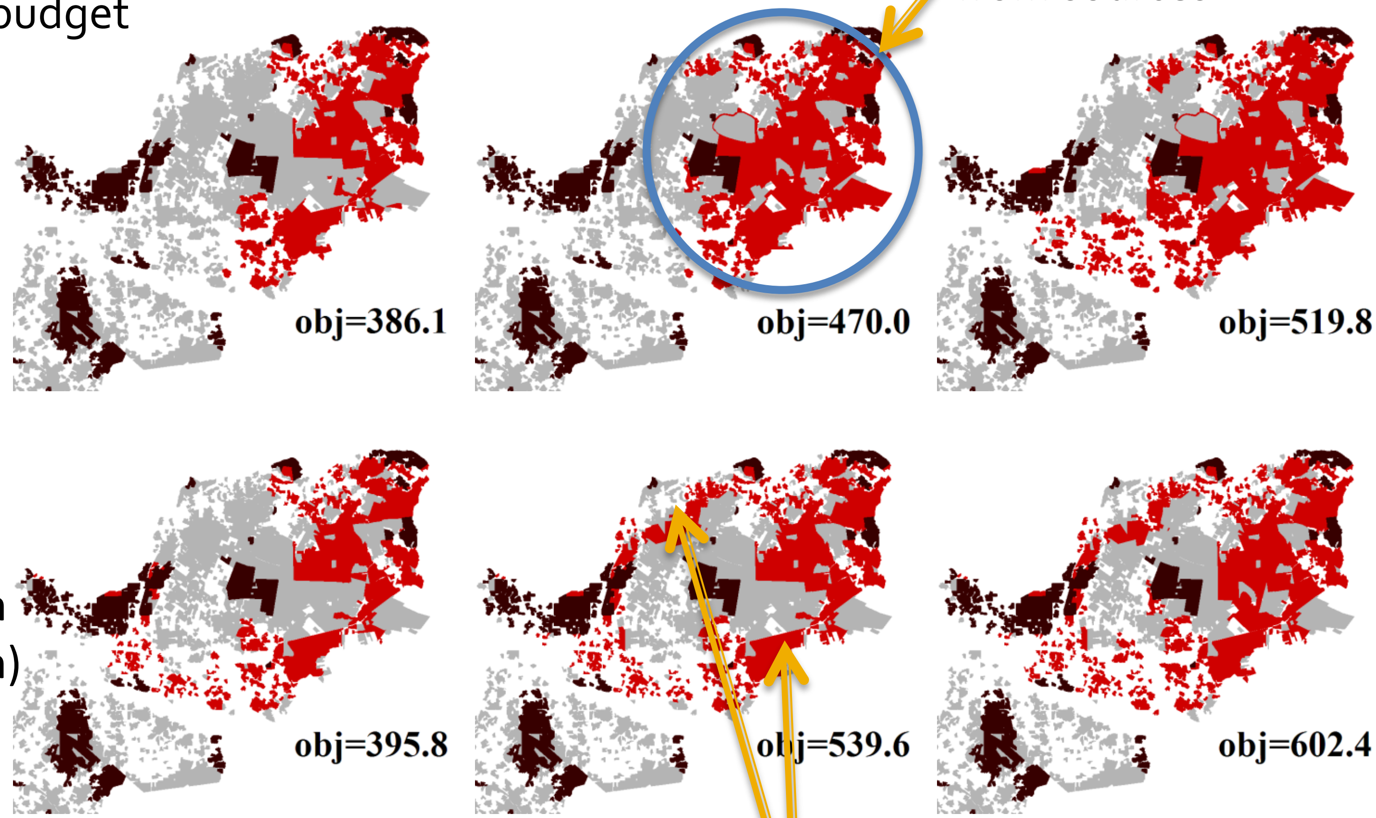
Add actions until exhaust budget

Choose action with best ratio of benefit to cost

Build outward from sources

Greedy Baseline

SAA Optimum (our approach)




$150M

$260M

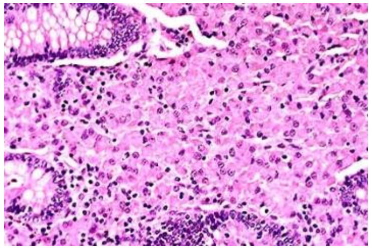
$320M

Path-building (goal-setting)

# Current Work: Minimizing spread

- Invasive species
- Contamination: The spread of toxins / pollutants within water networks.
- Epidemiology: Spread of disease
  - In human networks, or between networks of households, schools, major cities, etc.
  - In agriculture settings.

*Mitigation strategies* can be chosen to minimize the spread of such phenomena.

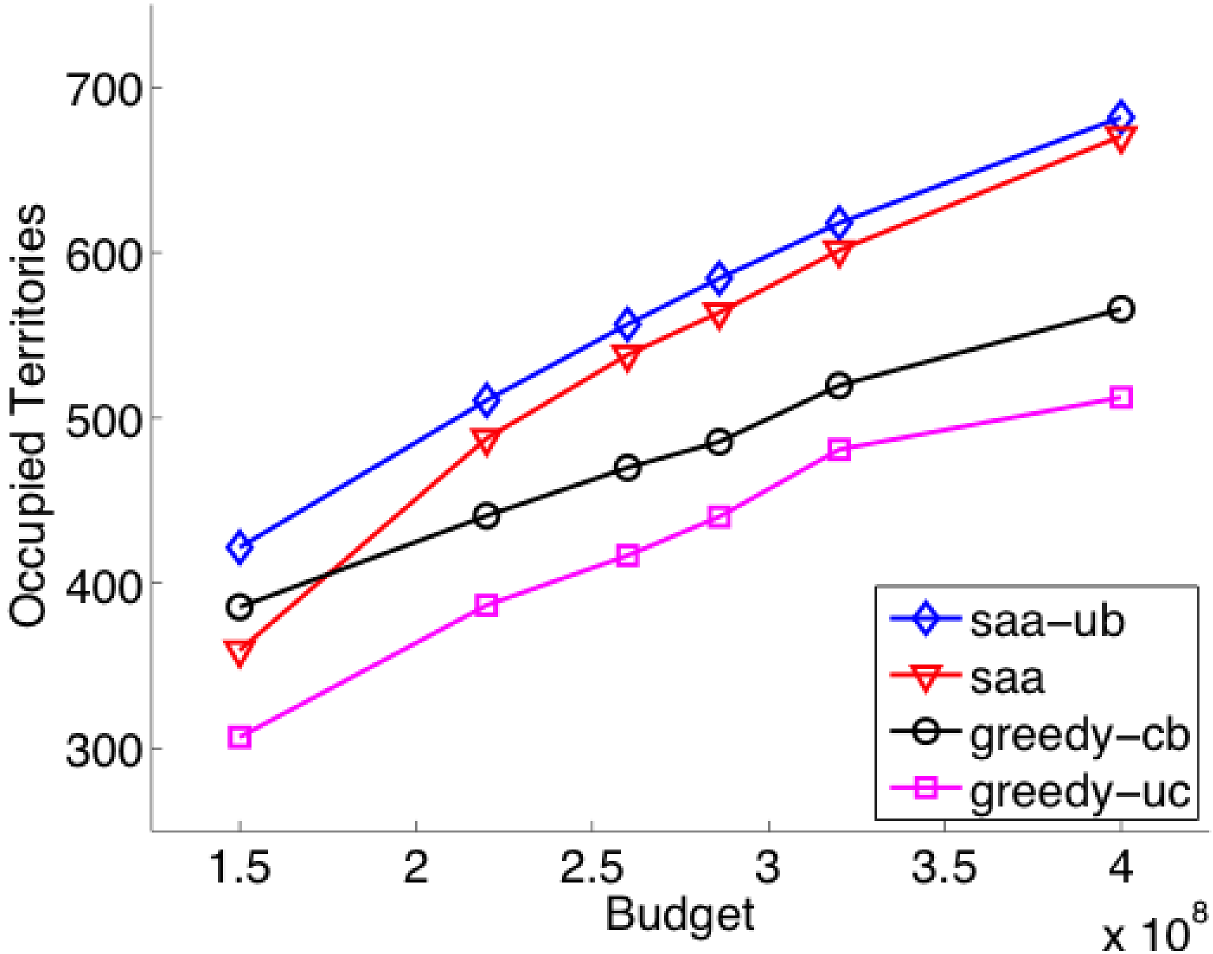


# Summary

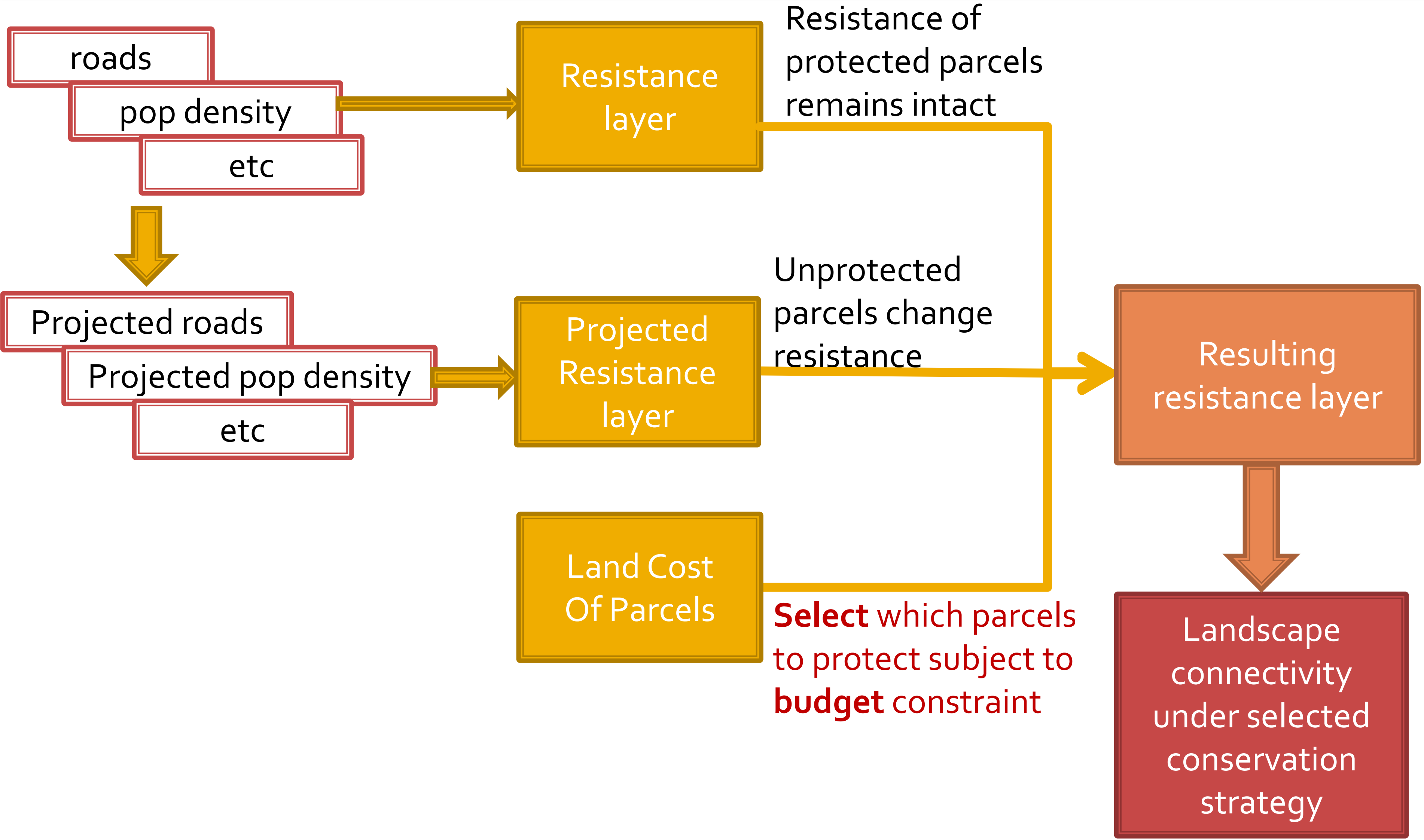
- Planning for landscape connectivity while balancing ecological and economic needs is (worst-case) computationally hard
- Providing good mathematical models and exploiting real-world problem structure allows for solution approaches that scale and have optimality guarantees
- Next: package these methods into freely available Decision Support Tools for ecologists and conservation planners

# Thank you!

# SAA performance



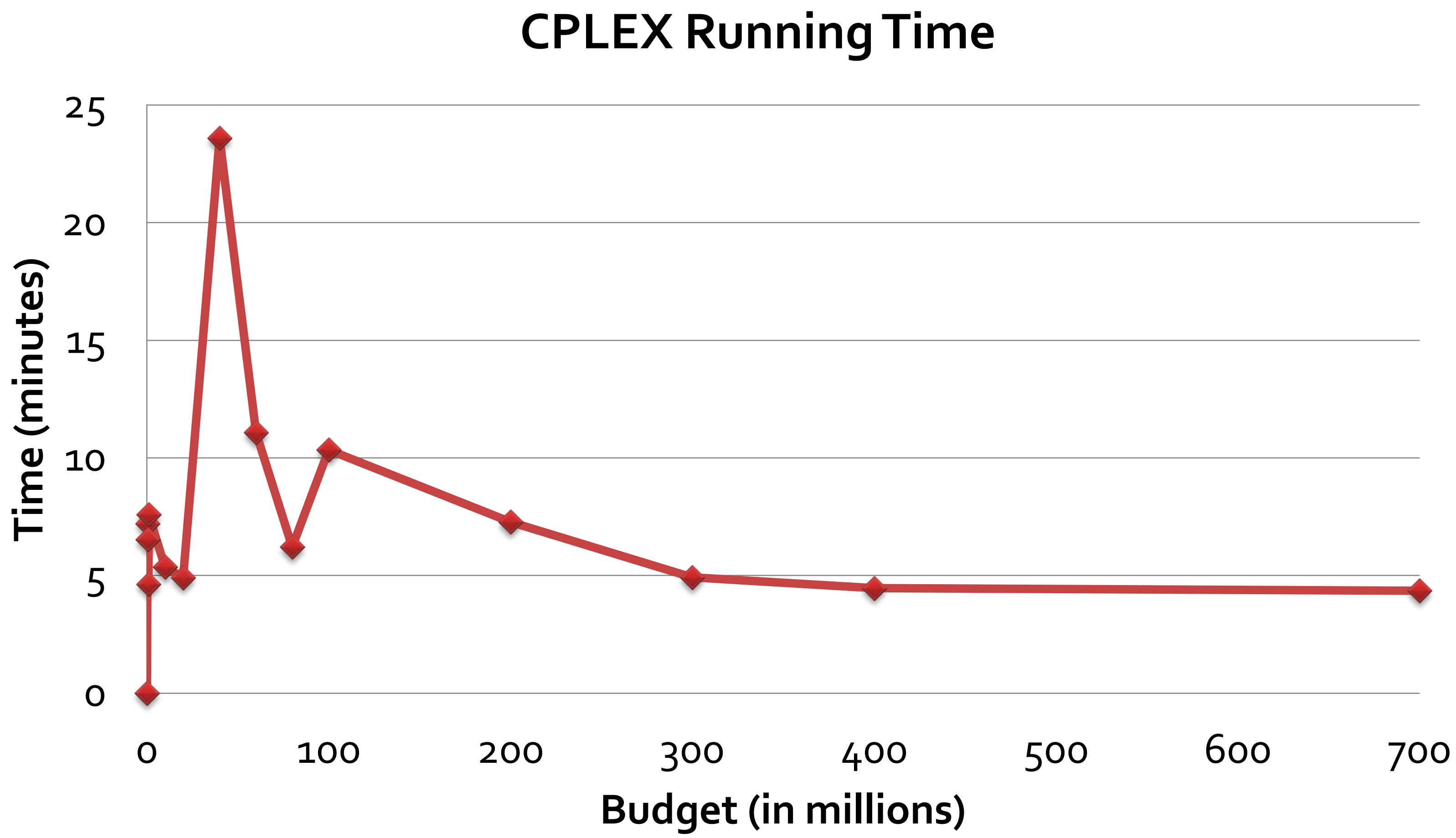
# Overall workflow



# References

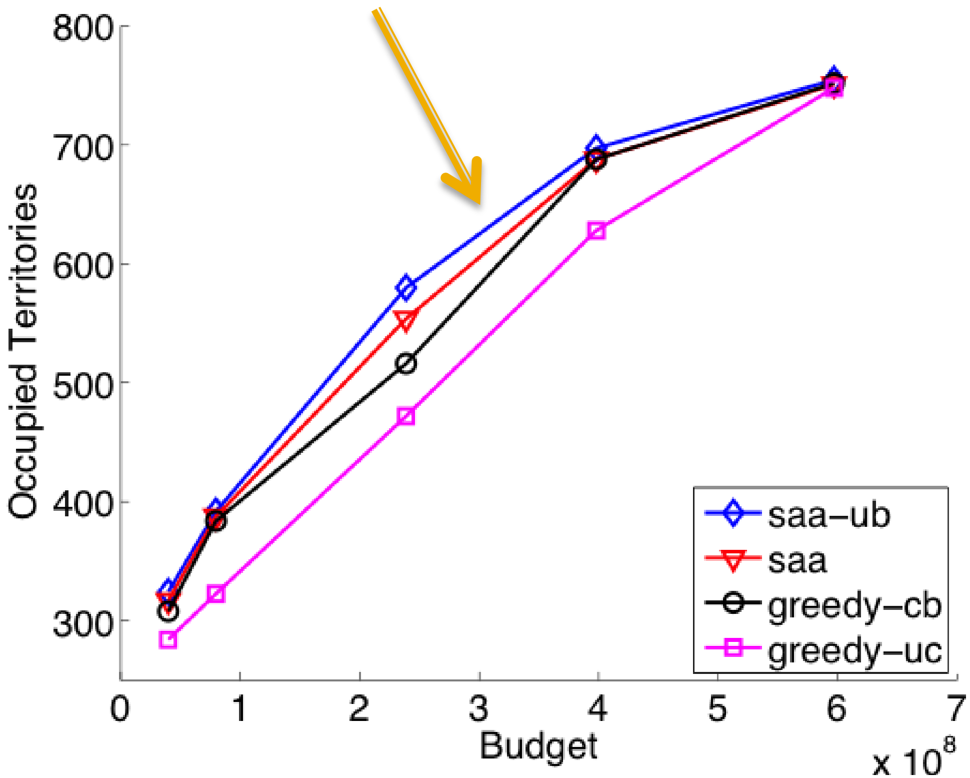
- For wolverine resistance values:
  - Singleton, Peter H.; Gaines, William L.; Lehmkuhl, John F. Landscape permeability for large carnivores in Washington: a geographic information system weighted-distance and least-cost corridor assessment. Res. Pap. PNW-RP-549. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station. 89 p, 2002. Available at http://www.treesearch.fs.fed.us/pubs/5093
- Data sources:
  - Population by census block group: Census 2010, available at http://factfinder2.census.gov
  - Land cover: US Geological Survey, Gap Analysis Program (GAP). February 2010. National Land Cover, Version 1.
  - All other data sources found on Montana's website: http://nris.mt.gov/gis/gisdatalib/gisDataList.aspx

# Results: Wolverines in West Montana



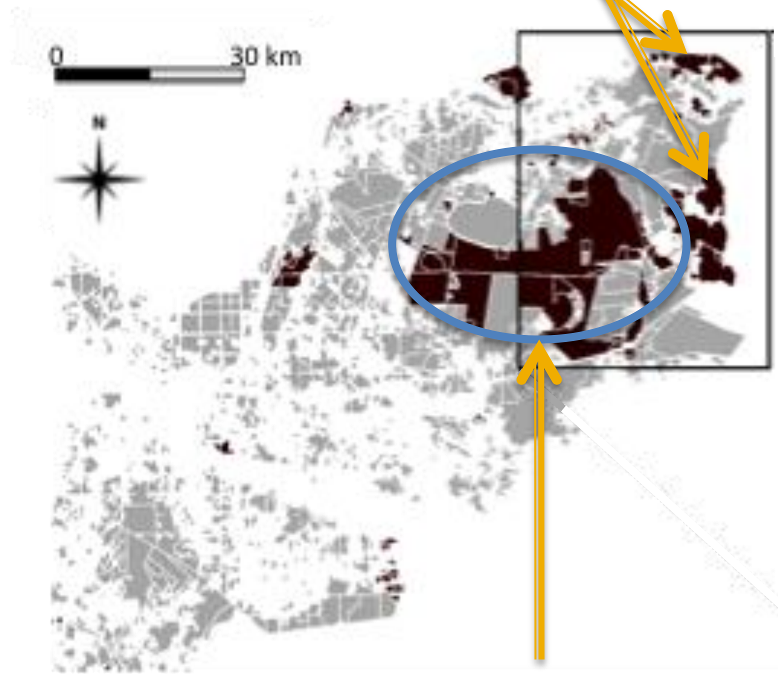
# Results

Upper bound!



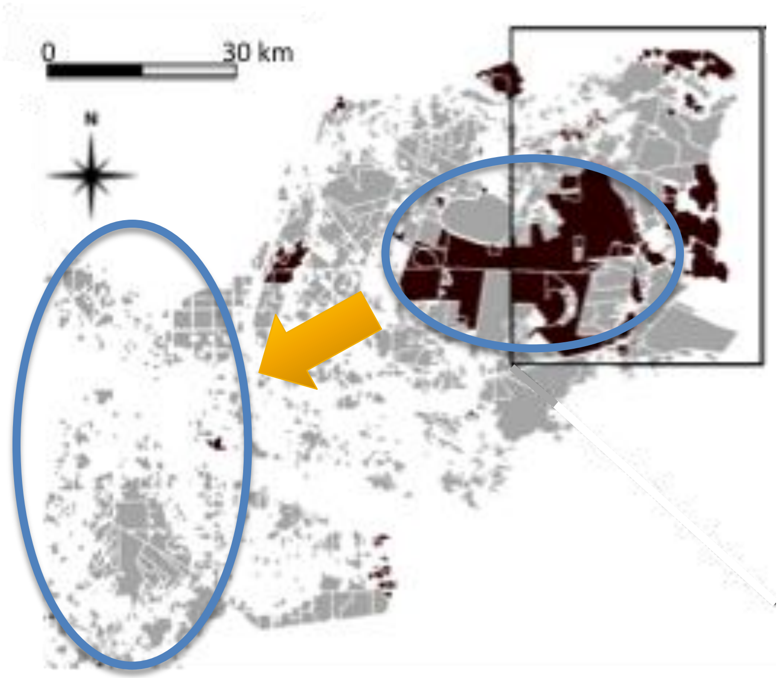

$M = 50$, $N = 10$, $N_{\text{test}} = 500$

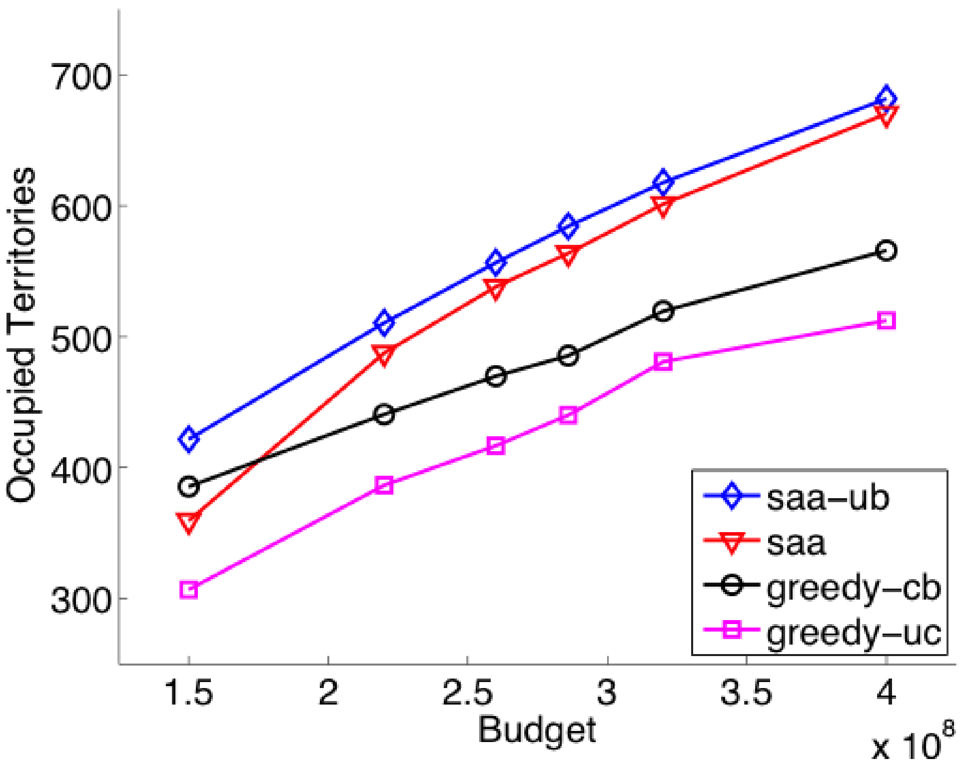
Initial population




Conservation Reservoir

# A Harder Instance




Move the conservation reservoir so it is more remote.