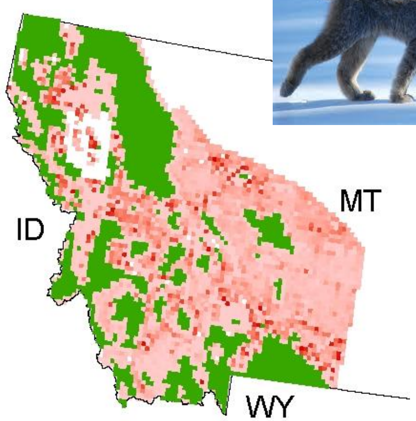
Robust Network Design for Multispecies Conservation



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July 18, 2013 **AAAI'13 - CompSustAI**

Motivation: Biodiversity & Conservation

Key causes of biodiversity loss:

Habitat Loss and Fragmentation

urbanization

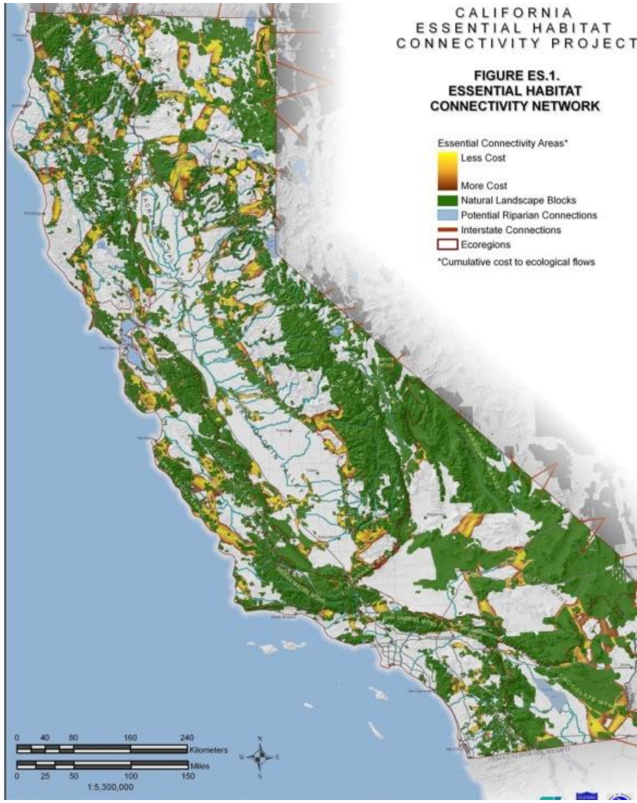
deforestation

agriculture

Maintaining **landscape connectivity** is critical to reduce inbreeding, increase genetic diversity and provide resilience

Motivation: Landscape Connectivity

- Current approaches in conservation biology: measure connectivity and identify likely linkages
- For a given species:
  1. identify core areas
  2. model landscape resistance – landscape is represented as a raster of cells with associated species-specific "movement cost"
  3. connectivity = shortest resistance-weighted path between pairs of core areas



Motivation: Landscape Connectivity

- Cost-effective Conservation Planning
  - Given limited budget, which parcels to buy to
    to ensure a path connecting each pair of core areas
    while minimizing resistance

- Robustness
  - Environmental disasters, wildfires, climate change, etc
  - Need to conserve multiple paths between each pair of core areas

Outline

- Motivation ✔
- Problem Definition
- MIP Formulation
- Local Search Approach
- Experimental Results
- Conclusions and Future work

Problem Definition: Minimum Delay Generalized Steiner Network

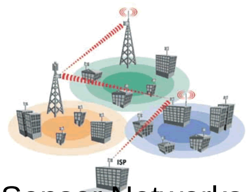
Given:

- Graph $G(V, E)$
- Node costs $c(v)$
- Node delay (or resistance) $d(v)$
- Set of terminals (or core areas) $T \subseteq V$
- Set of terminal pairs $P \subseteq T \times T$
- Budget B
- Connectivity k

Find:

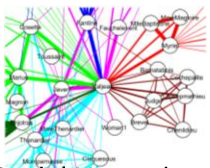
- A subset of nodes V' such that $\sum_{v \in V'} c(v) \le B$
- k vertex-disjoint paths between each pair in P in G(V')
- Minimize the resistance weight of selected paths

Landscape connectivity vs. Network Design



Sensor Networks

Transportation Networks



Social Networks

Steiner tree problem,
Survivable network design,
etc

Network Design

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

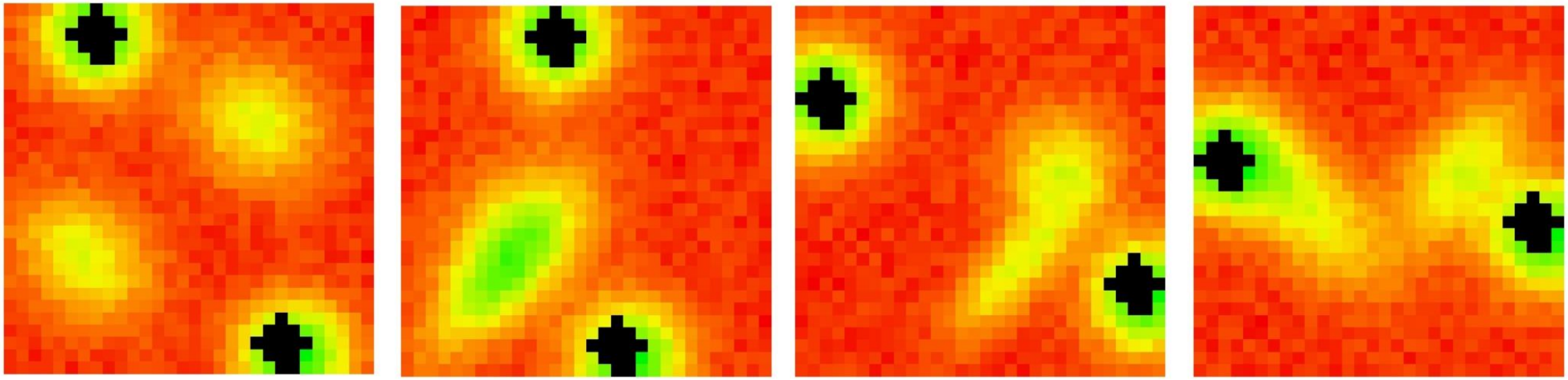
How do factor in specific features of wildlife conservation, e.g., different species requirements, interactions of species, etc?

Multi-commodity flow-based MIP encoding

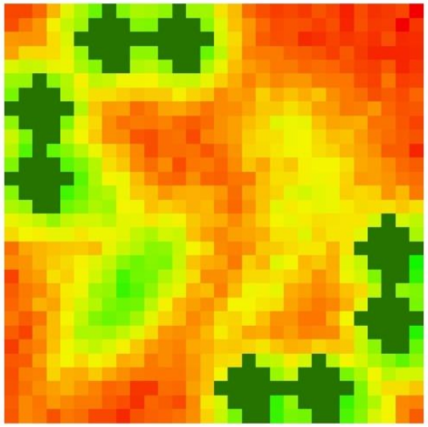
- Variables:
  - x_v – binary variable for each node v; 1 if purchased
  - f_{pe} – flow variable for each pair/commodity p and directed edge e
- Constraints
  - Budget constraint
  - For each commodity / pair p=(s,t):
    - Edges can be used only if both endpoints purchased
    - Make s the source of k units of commodity p, and t the only sink
    - Flow conservation at all nodes but s,t
    - Vertex-disjoint paths: enforce incoming flow in every node except s,t to be at most 1
- Computing the objective:
  - Minimize total resistance using traditional mincost flow formulation
  - Flow cost on edges: $d(e=(u,v)) = \left[d(v) + d(u) \right] / 2$

Synthetic Instances: 4 species on 30x30 grid

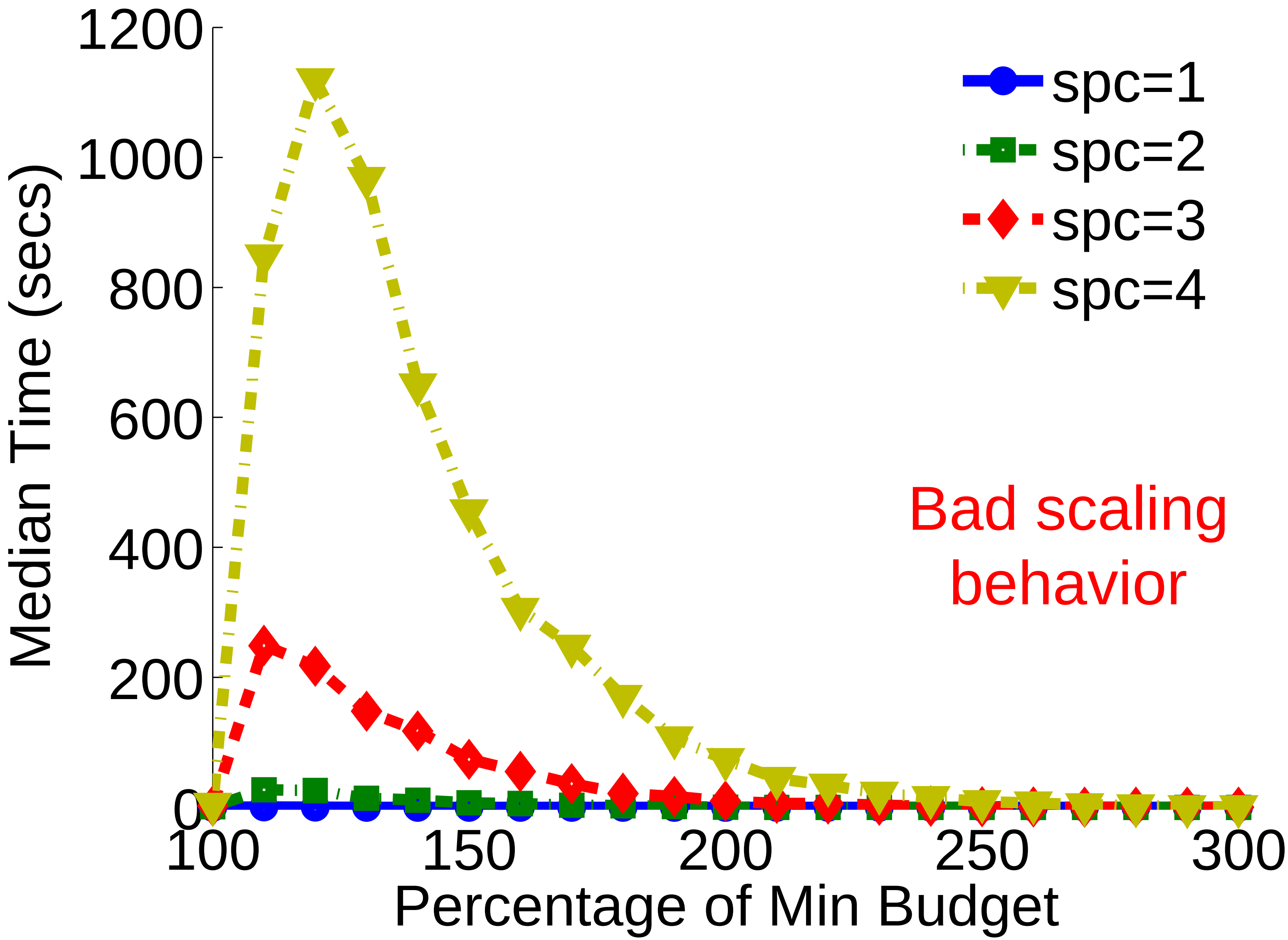
Each species has 2 core areas and specific resistance



Land cost: correlated with resistance, core areas are free



MIP scalability on synthetic benchmark



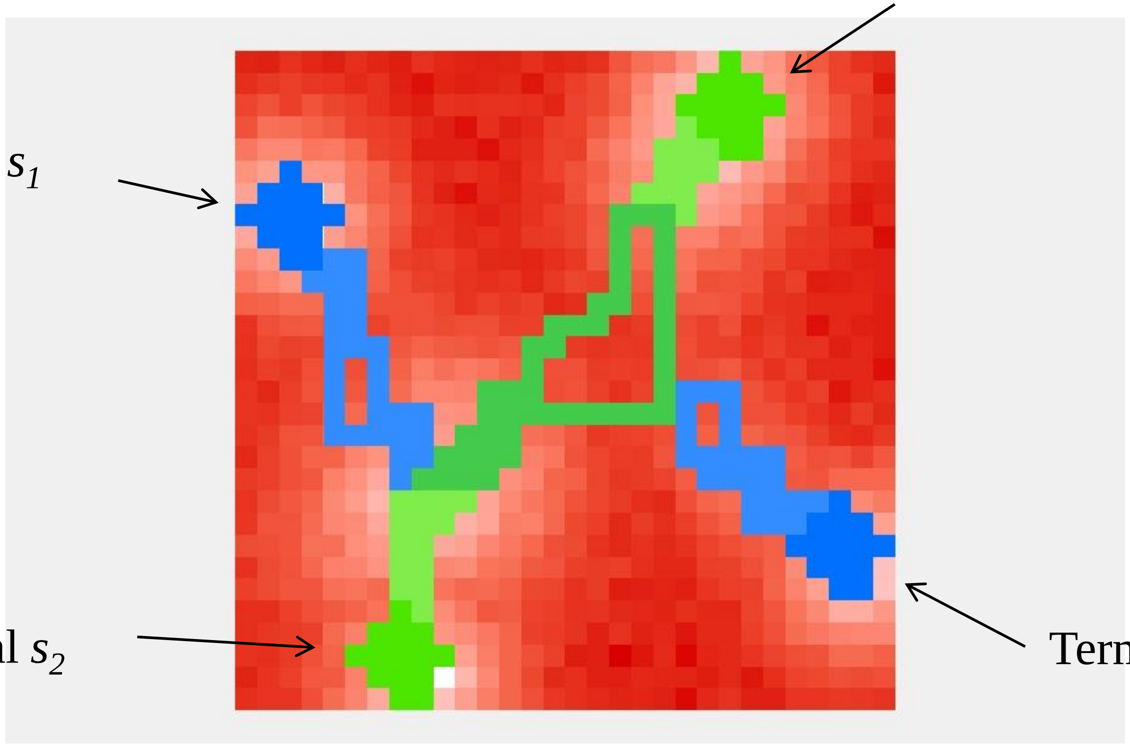
Local Search Approach

- **Challenge**: Intricate **combinatorial structure** (hard constraints for the budget-constrained connectivity requirements) with a complex path-based **optimization** component

- **Proposed Approach**:
  - Find an initial feasible solution (by looking at cost only)
  - Propose moves based on replacing whole parts of the solution but maintaining feasibility (Large-Neighborhood Search)
  - Choose best move available (Hill Climbing)
  - Until no improving move found

  - Two neighborhoods: **HC-SP** and **HC-MIP**

Local Search Approach



Terminal pairs:

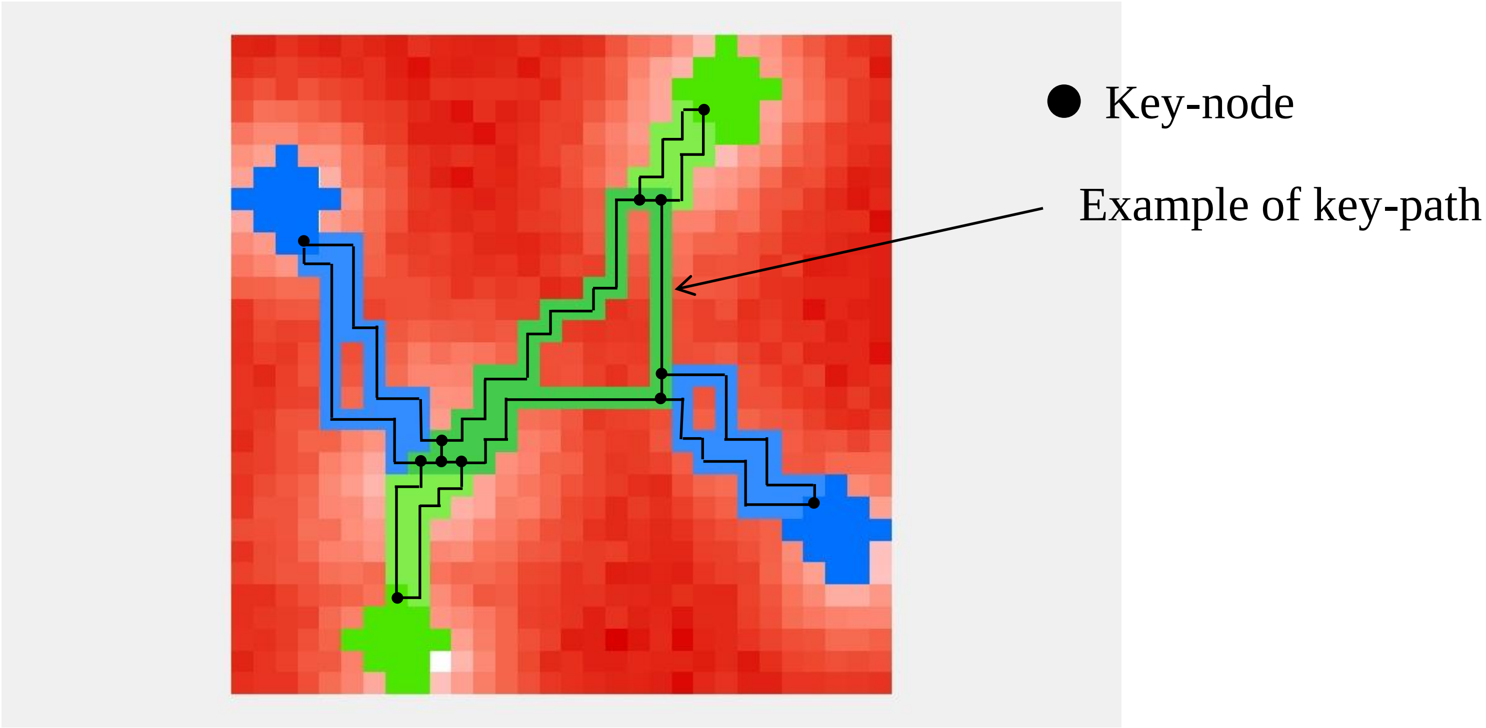
$P=(s_1,t_1), (s_2,t_2)$

Connectivity Req:

k=2

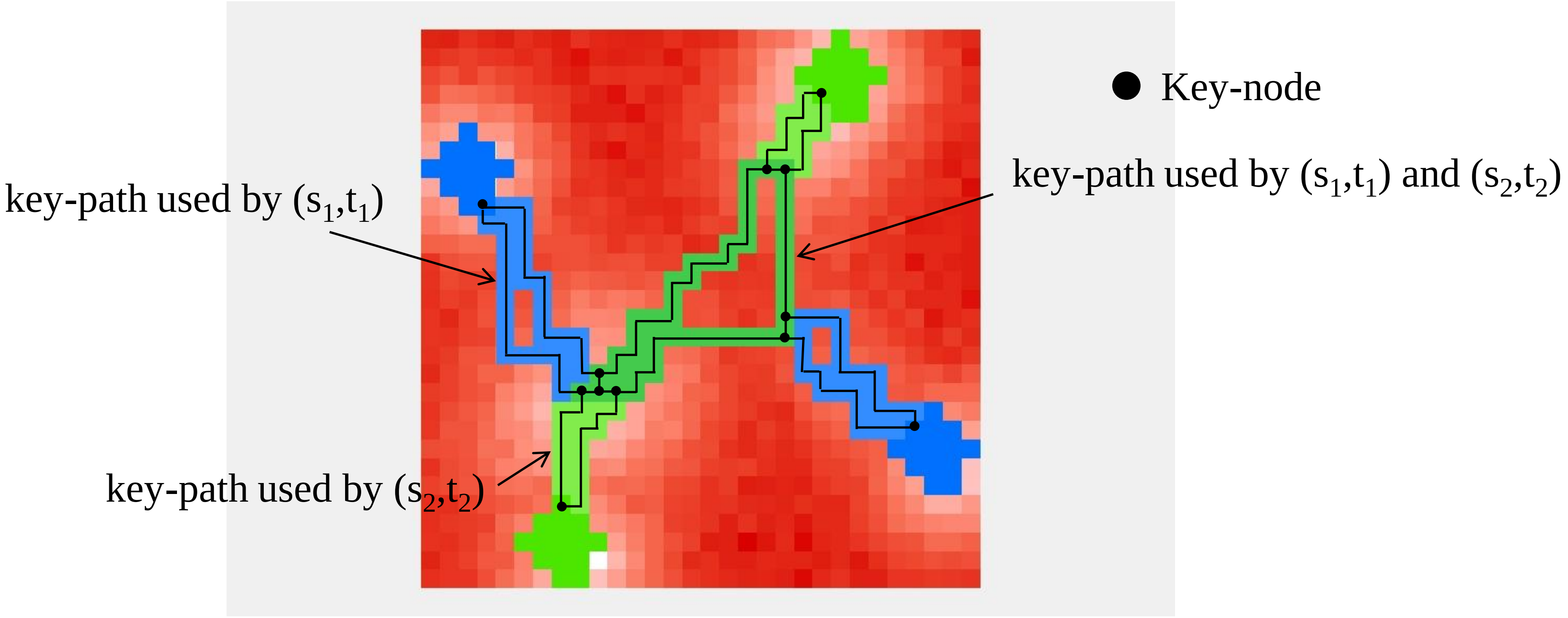
Local Search Approach

- **Definitions:**
  - **Key-node**: A terminal node, or a Steiner node of degree at least 3
  - **Key-path**: A path whose end points are key nodes, and intermediate nodes are not (i.e. Steiner nodes of degree 2).



Local Search Approach

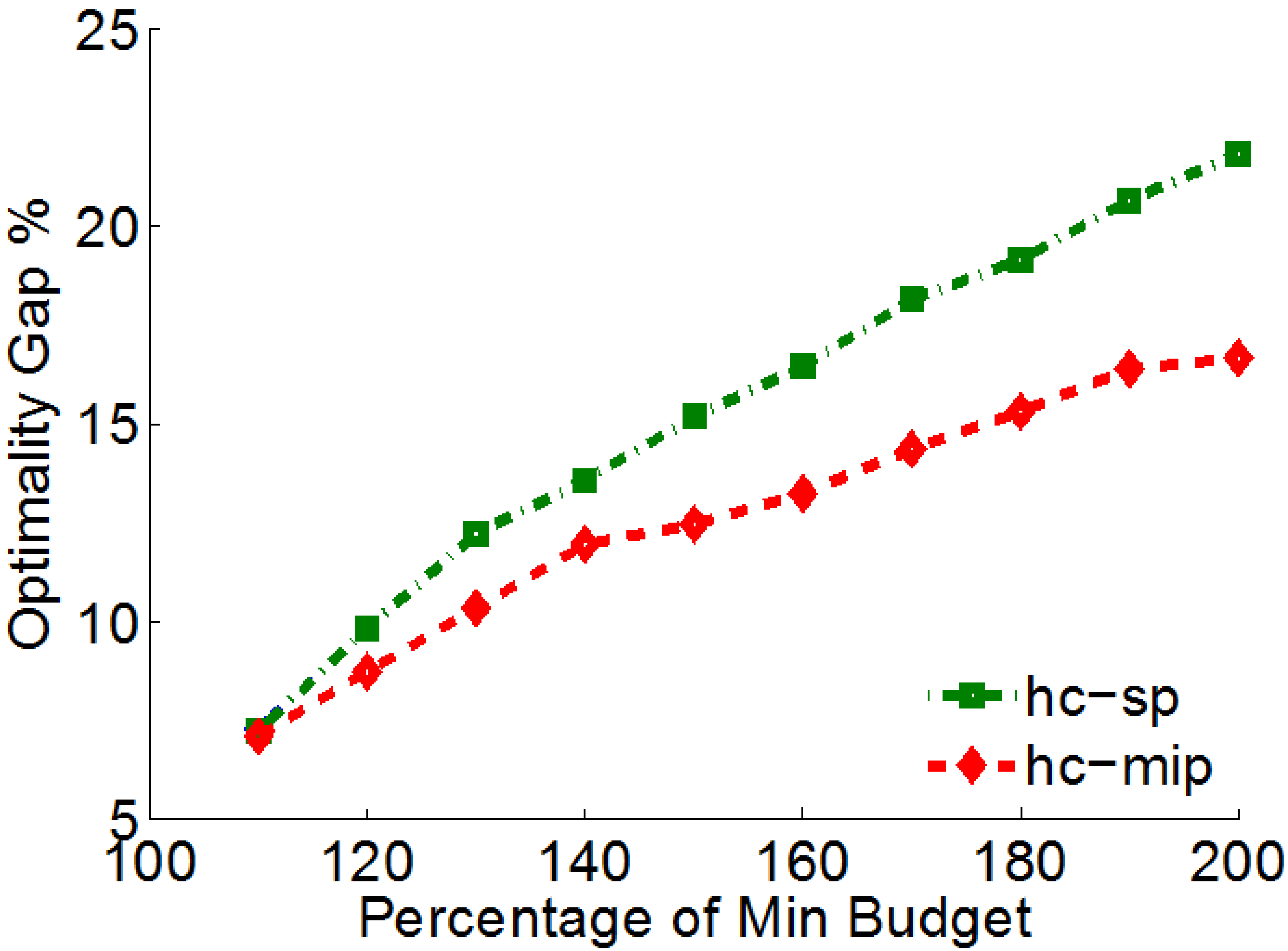
- **Idea**:
  - **All nodes** of a **key-path** p are used by the **same set of commodities**.
  - When **substituting** a key-path p, the new path(s) needs to exclude any node used by other paths of these commodities (keep disjoint).



Local Search Approach

- **Neighborhood**: Given a feasible solution G and a key-path p, a neighbor solution replaces p in G with:
  - **HC-SP**: the delay-aggregated shortest path connecting the end points of p, if its cost does not exceed the remaining budget
  - **HC-MIP**: a set of budget-constrained shortest paths connecting the end points of p
    - HC-MIP involves solving the proposed MIP encoding, but for much smaller subproblems (1 terminal pair, small remaining budget)
    - The neighborhood of HC-MIP contains the one of HC-SP
    - HC-MIP can find best replacement path that is within budget (not shortest)
    - HC-MIP can find replacement involving multiple paths (for separate commodities)

Quality of LS solutions for 4 species

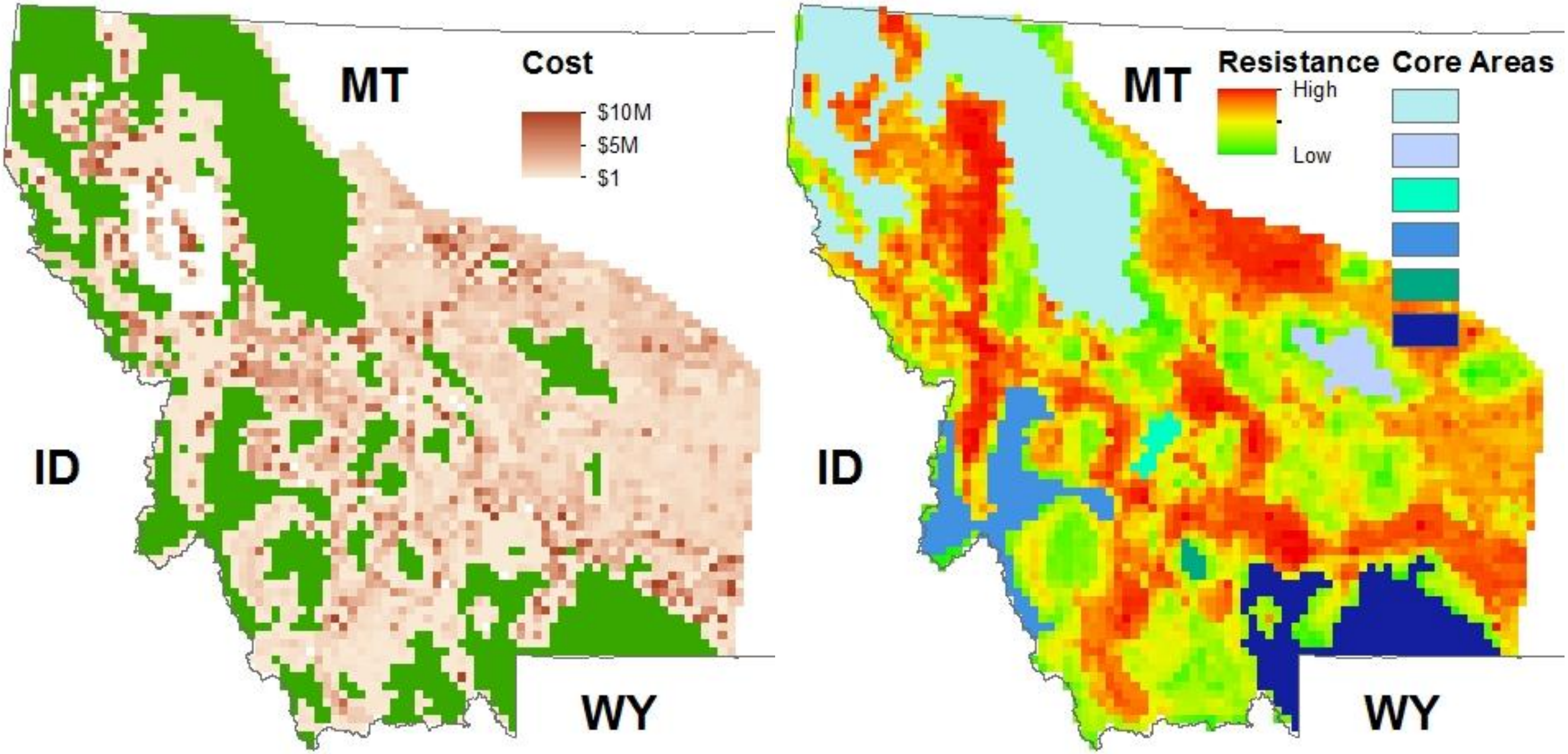


HC-SP
tens of secs

HC-MIP
upto 220 secs

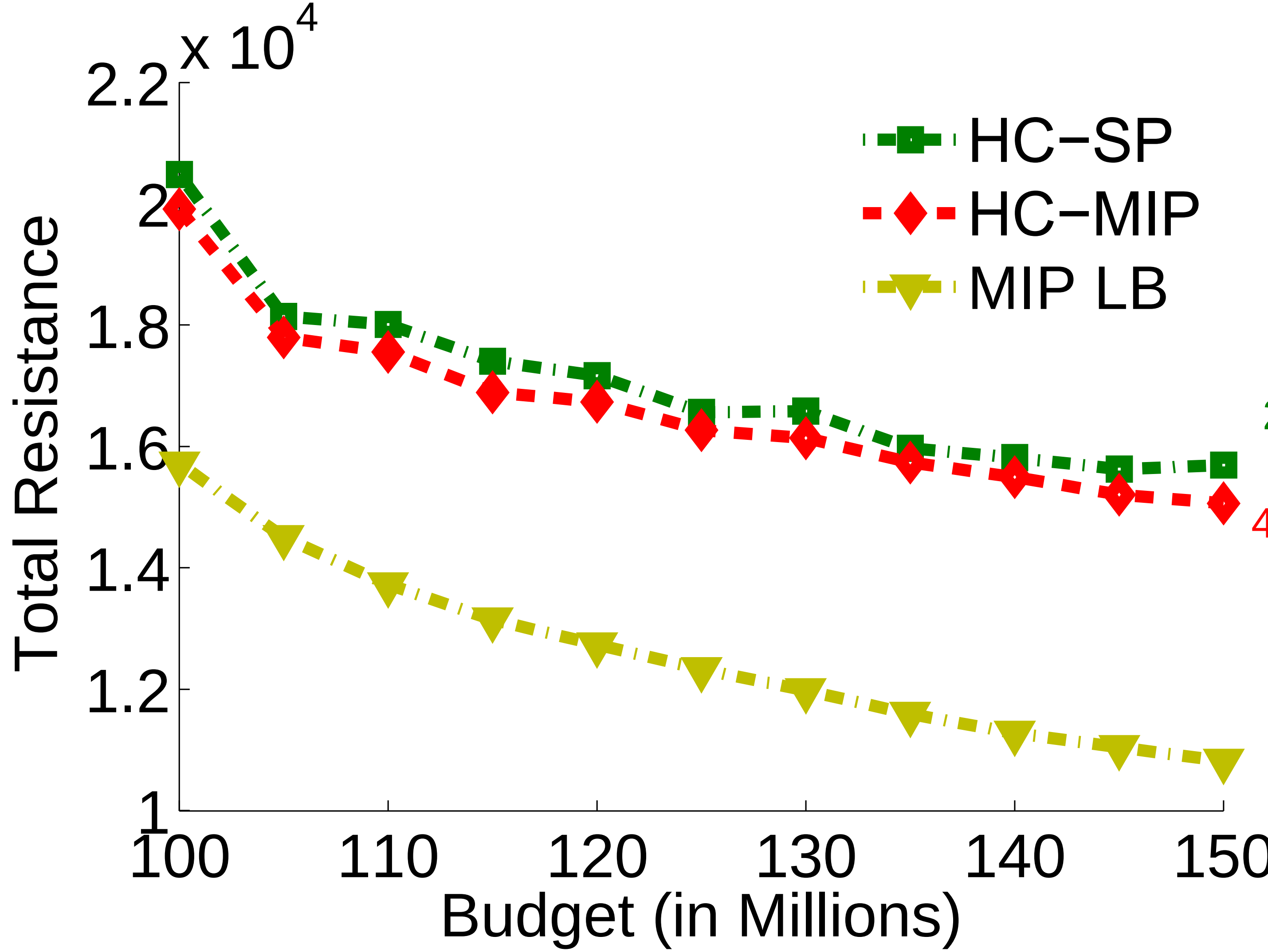
MIP
upto 1119 secs

Real Data: Wolverines in Montana



- Western Montana: 6km grid cells (4514 cells)
- Wolverine: 6 core areas forming **15 pairs**, connectivity k=**4**

Results for wolverines 15 pairs



270 secs per run

4200 secs per run

10 hrs limit

Conclusions & Future Work

- Robust conservation plans for landscape connectivity: problem formulation - Minimum Delay Generalized Steiner Network
- MIP encoding that provides optimal solutions and scales to small number of pairs
- Local Search methods that scale extremely well, but have no guarantees
- Solutions to a large-scale landscape connectivity problem: Wolverine conservation in West Montana
- Minimum Delay Generalized Steiner Network applications in other domains
- Other issues in robustness – climate change

Thank you!

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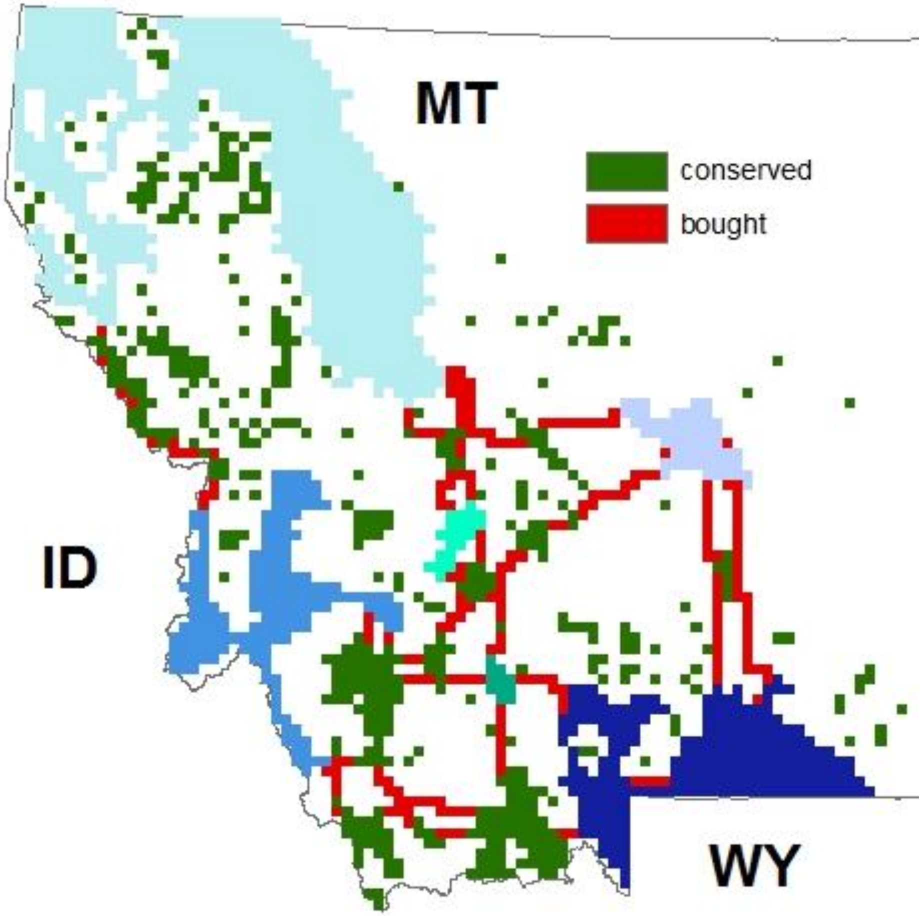
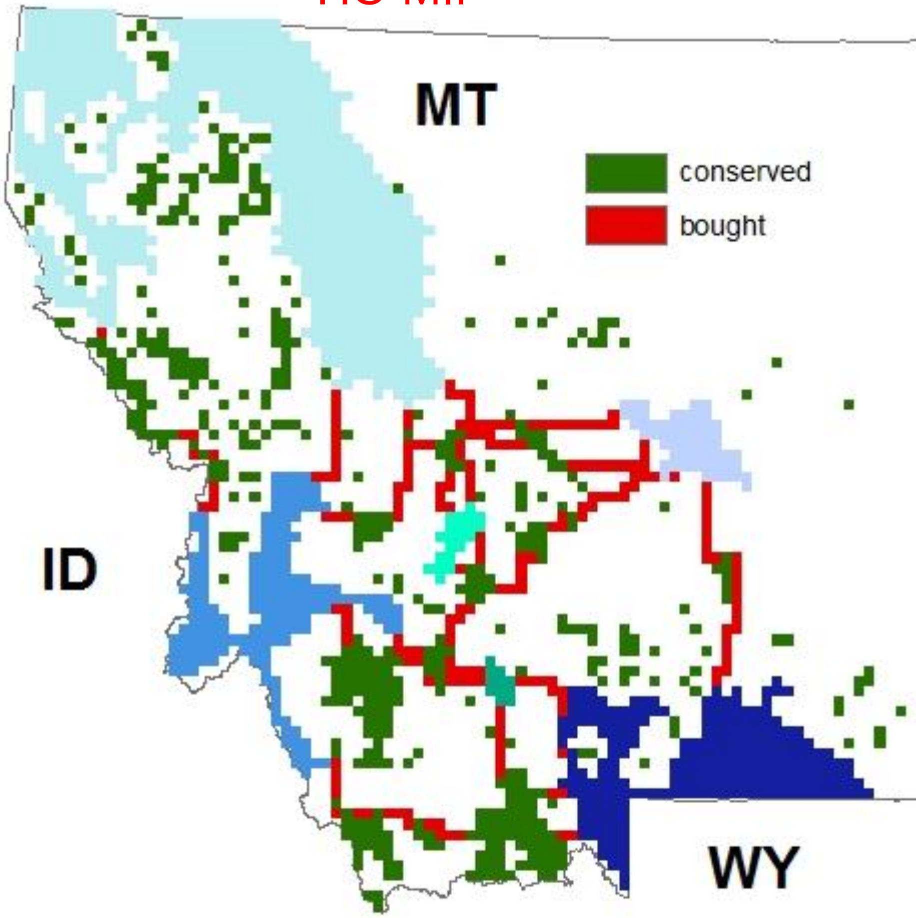
Solutions for B=$115M

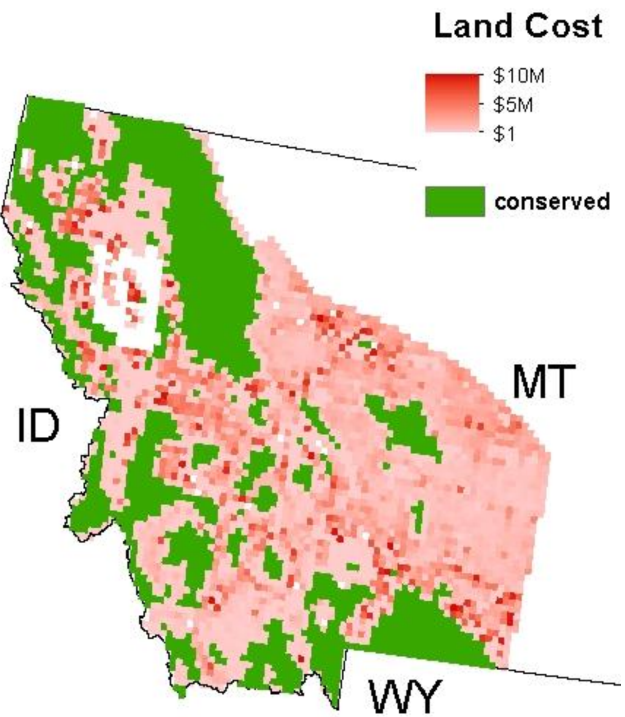
HC-SP

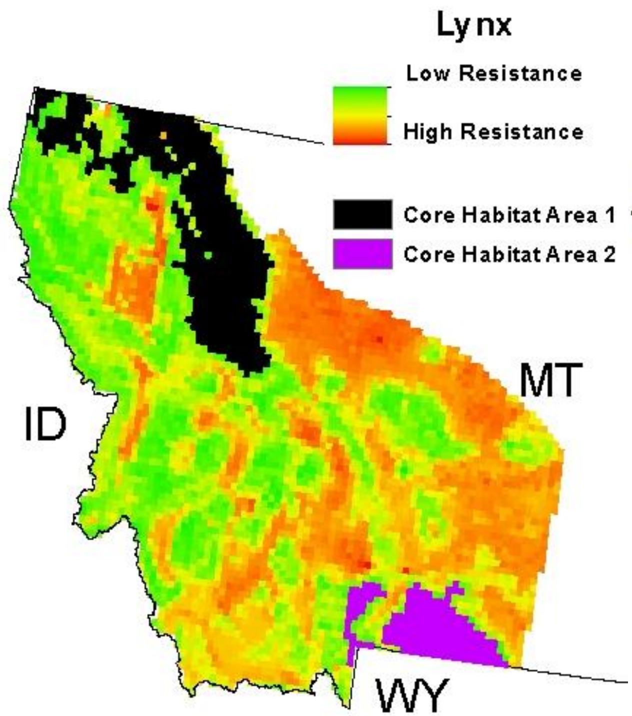


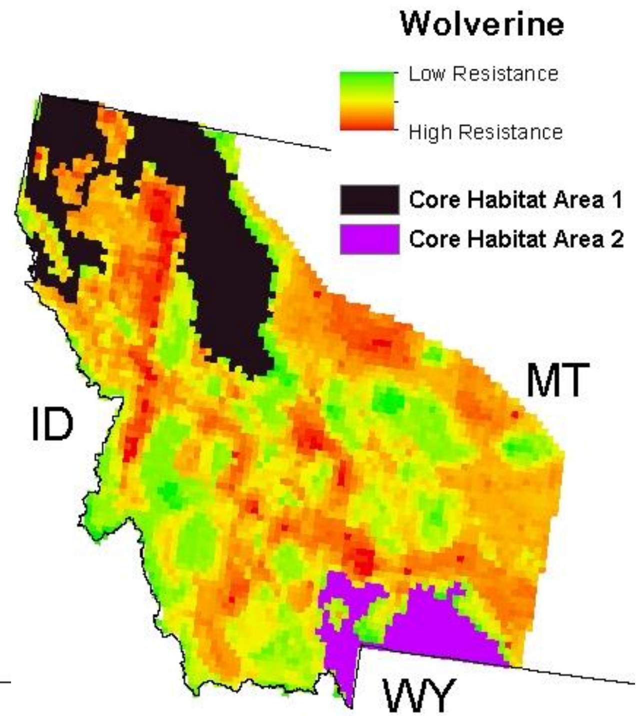
HC-MIP



Real data:
West Montana



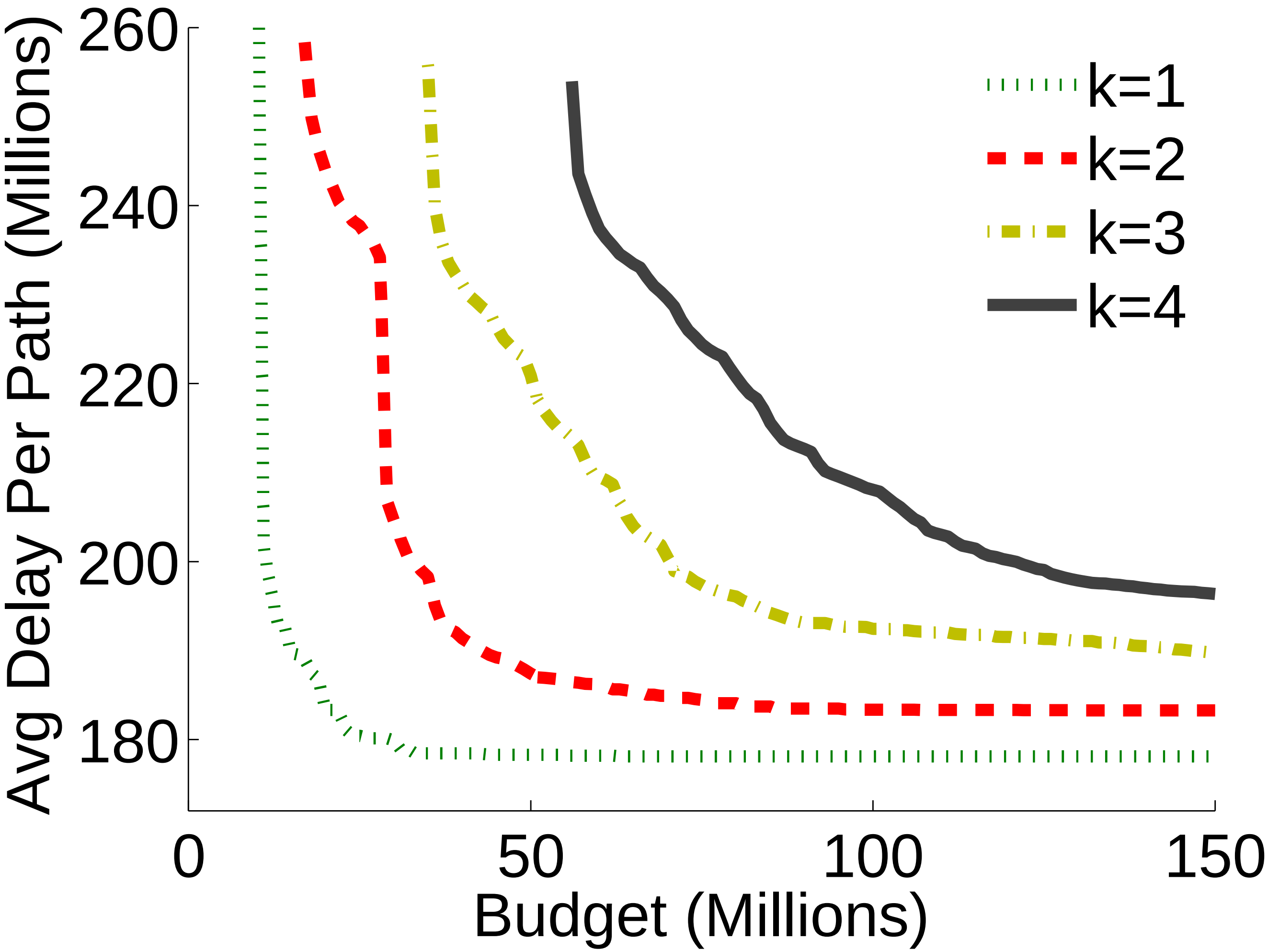




Multi-species

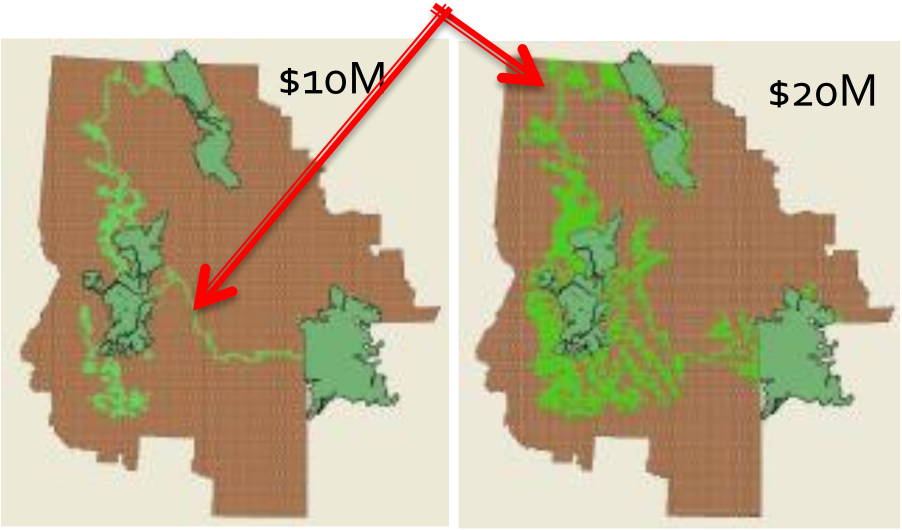
➔ Multigraph GSN

Two species with 1 pair each



Wildlife Corridors

Loss of
a single parcel
will disconnect
corridor



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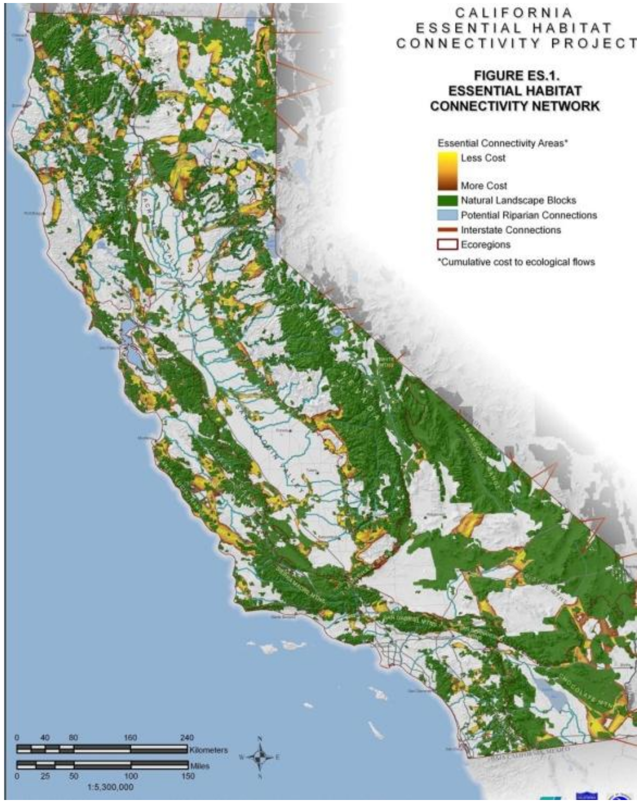

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Multi-commodity flow-based MIP encoding

- For each pair, the existence of k vertex-disjoint paths can be enforced using flow constraints
  - Transform the graph into a directed graph with unit capacities on all edges
  - For each terminal pair p=(s,t) create a separate commodity p
    - Make s the source of k units of commodity p
    - Make t the only sink in the graph for commodity p

- Computing the objective:
  - Minimize total resistance using traditional mincost flow formulation
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Multi-commodity flow-based MIP encoding

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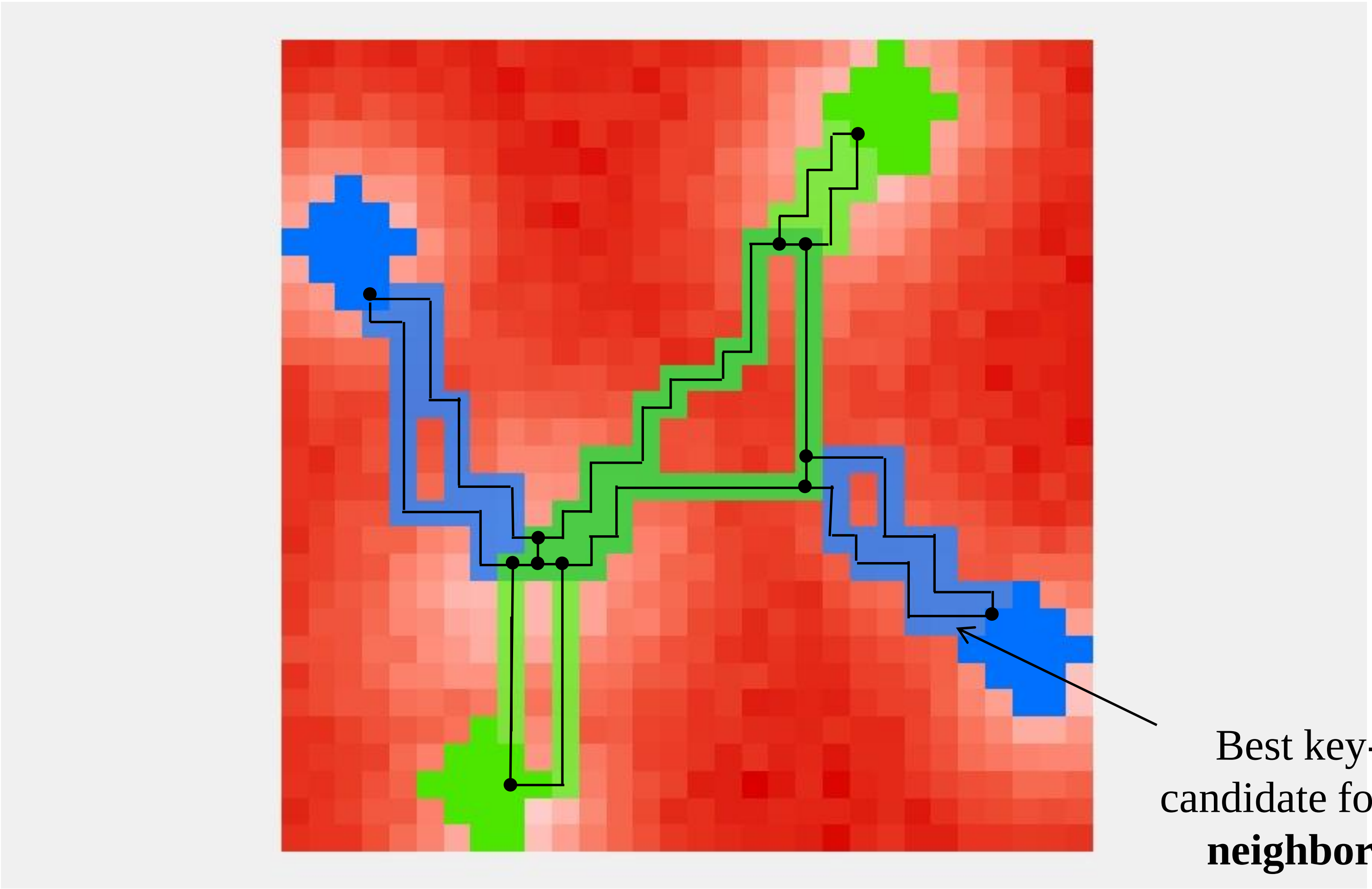
Local Search Approach

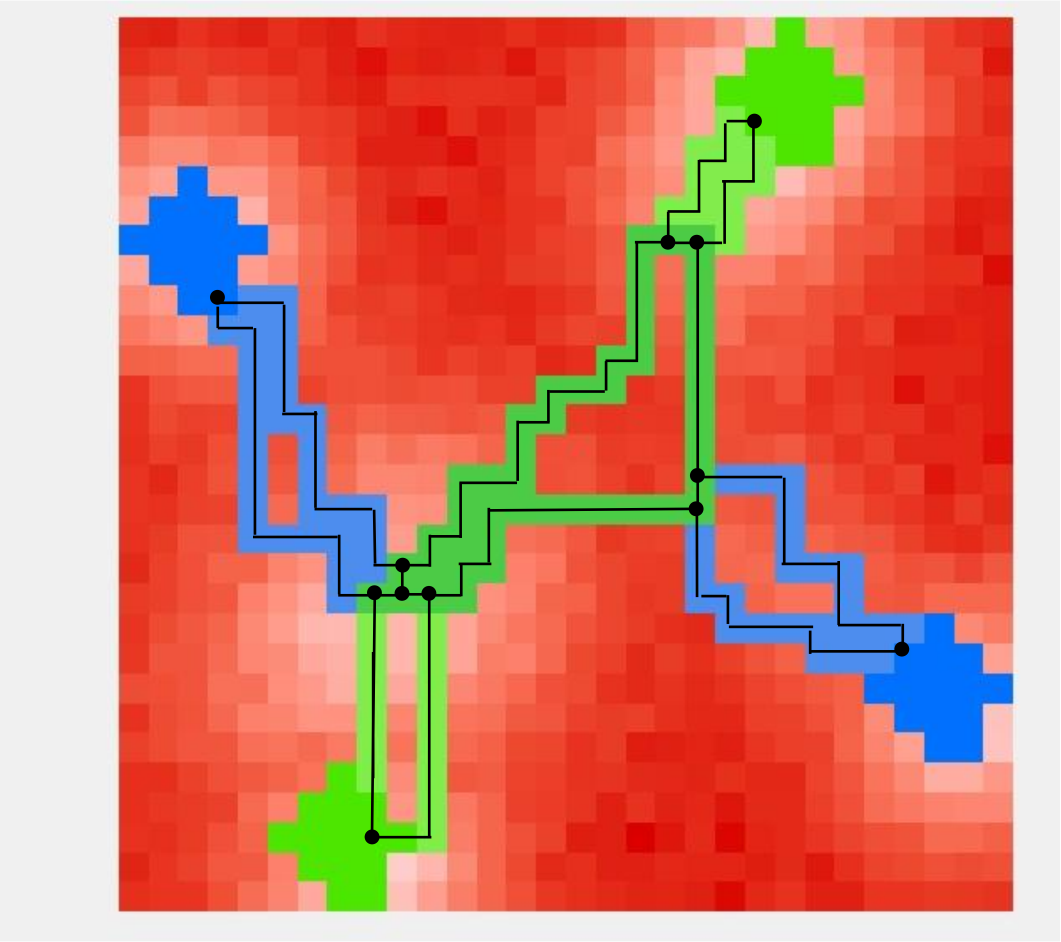
- **Example of HC-SP move:**



Best key-path candidate for the **SP neighborhood**

Local Search Approach

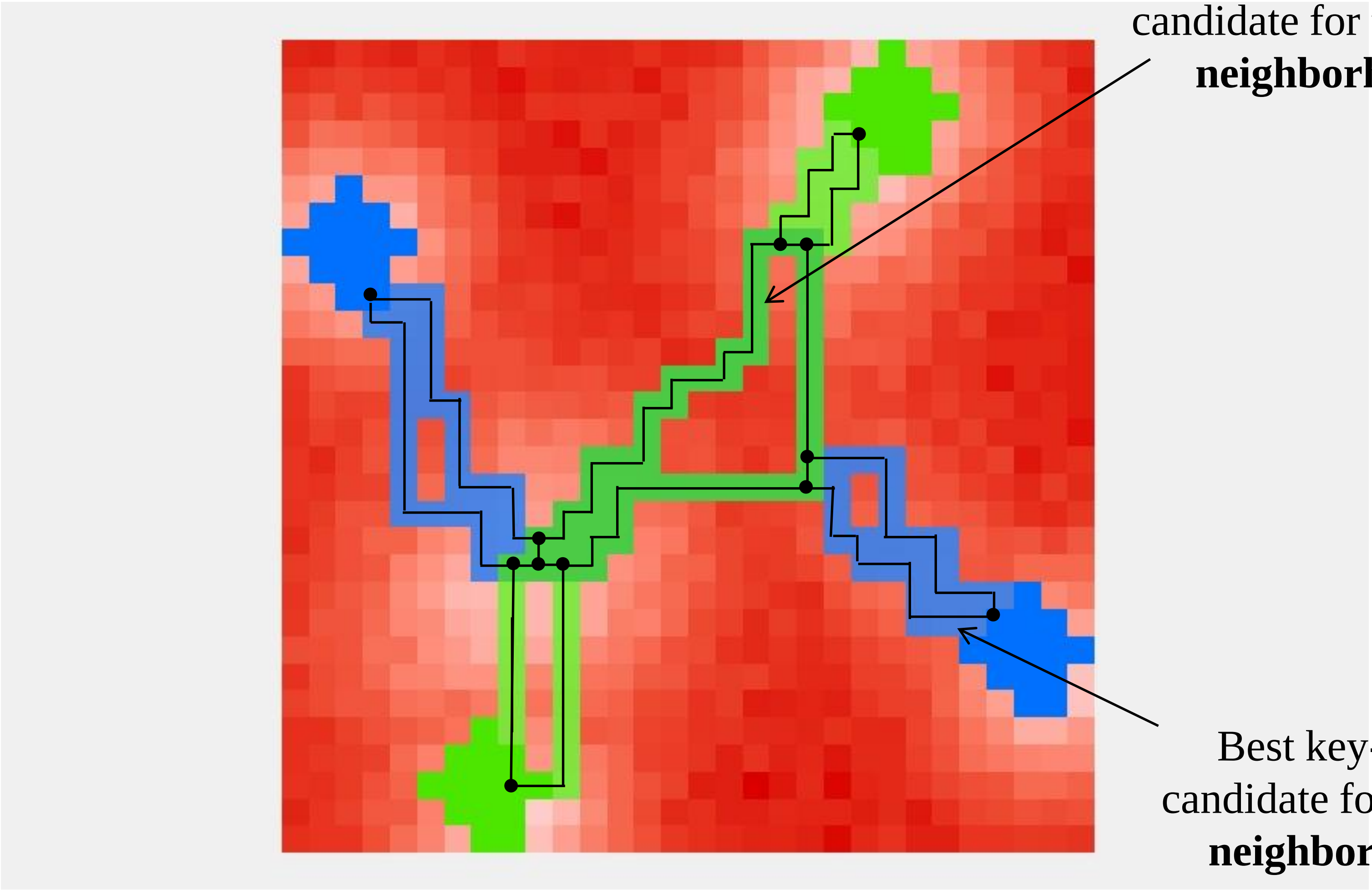
- **Example of HC-SP move:**



Local Search Approach

- **Example of HC-MIP move:**

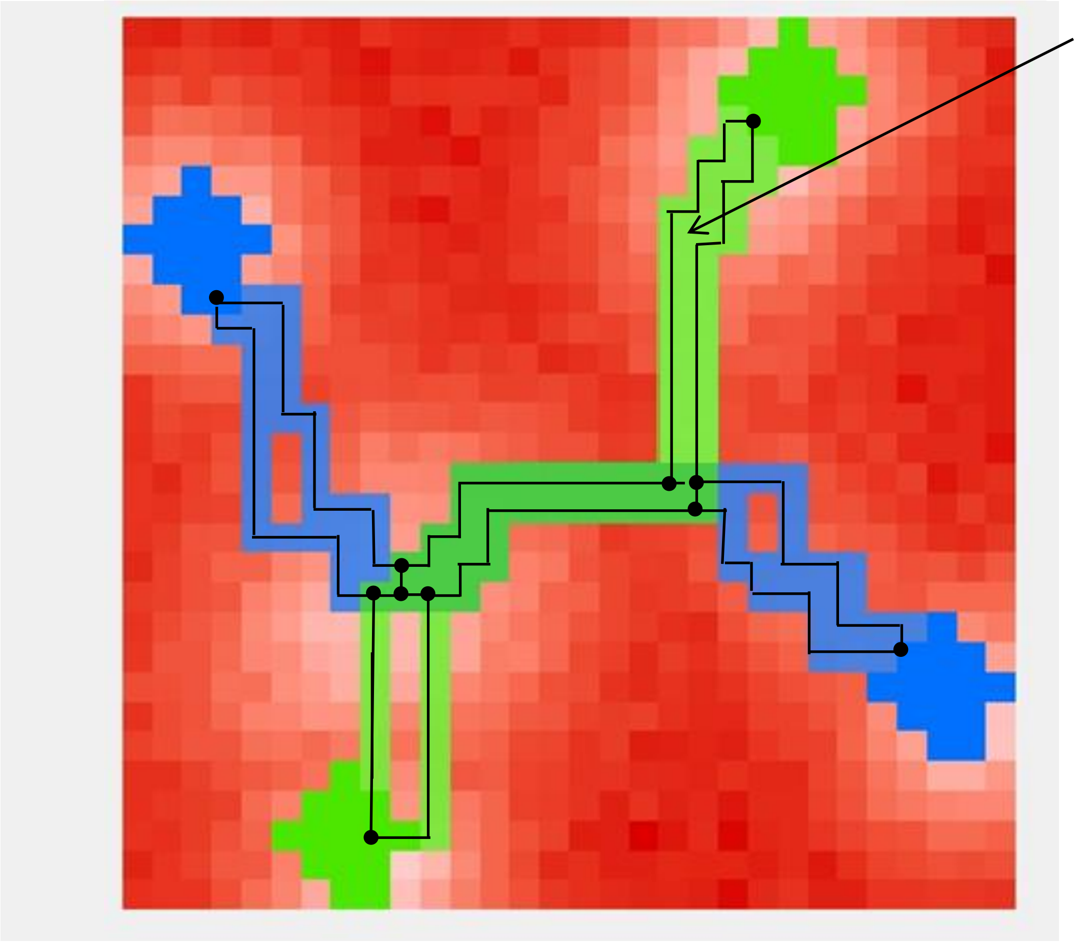
Best key-path candidate for the **MIP neighborhood**



Best key-path candidate for the **SP neighborhood**

Local Search Approach

- **Example of HC-MIP move:**



These nodes are no longer used by the pair (s1,t1). The original key node became a node of degree 2

Local Search Approach

- **Example of HC-SP move:**