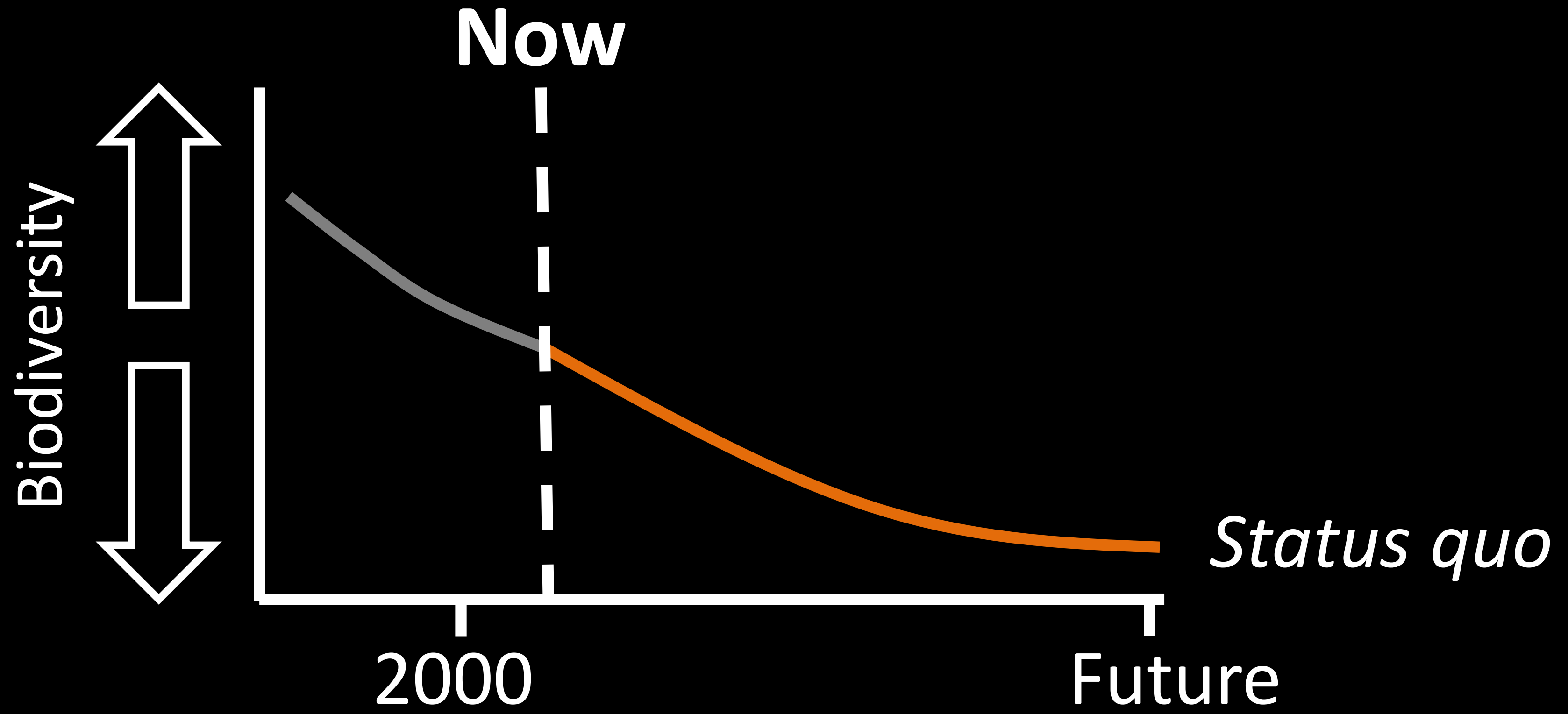
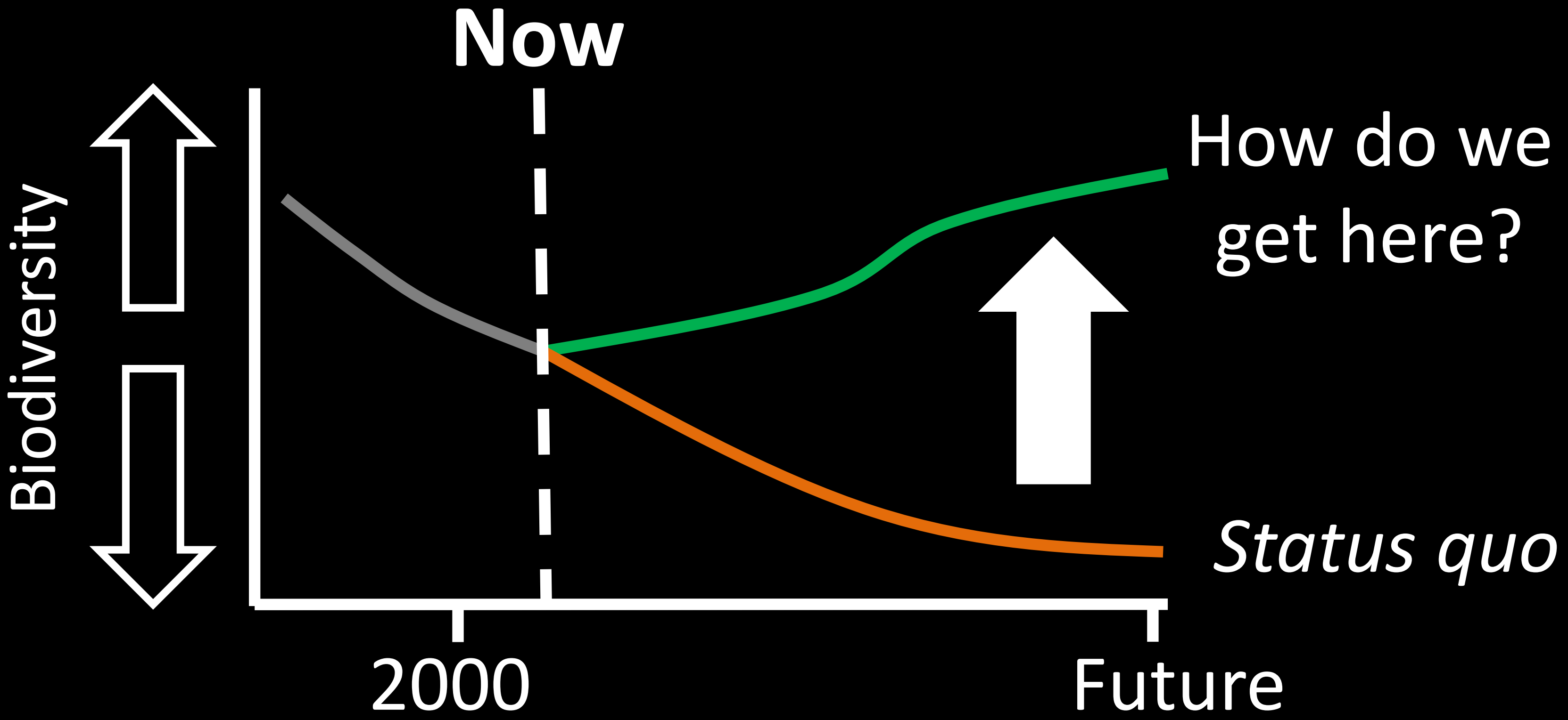
Optimizing to make better conservation decisions

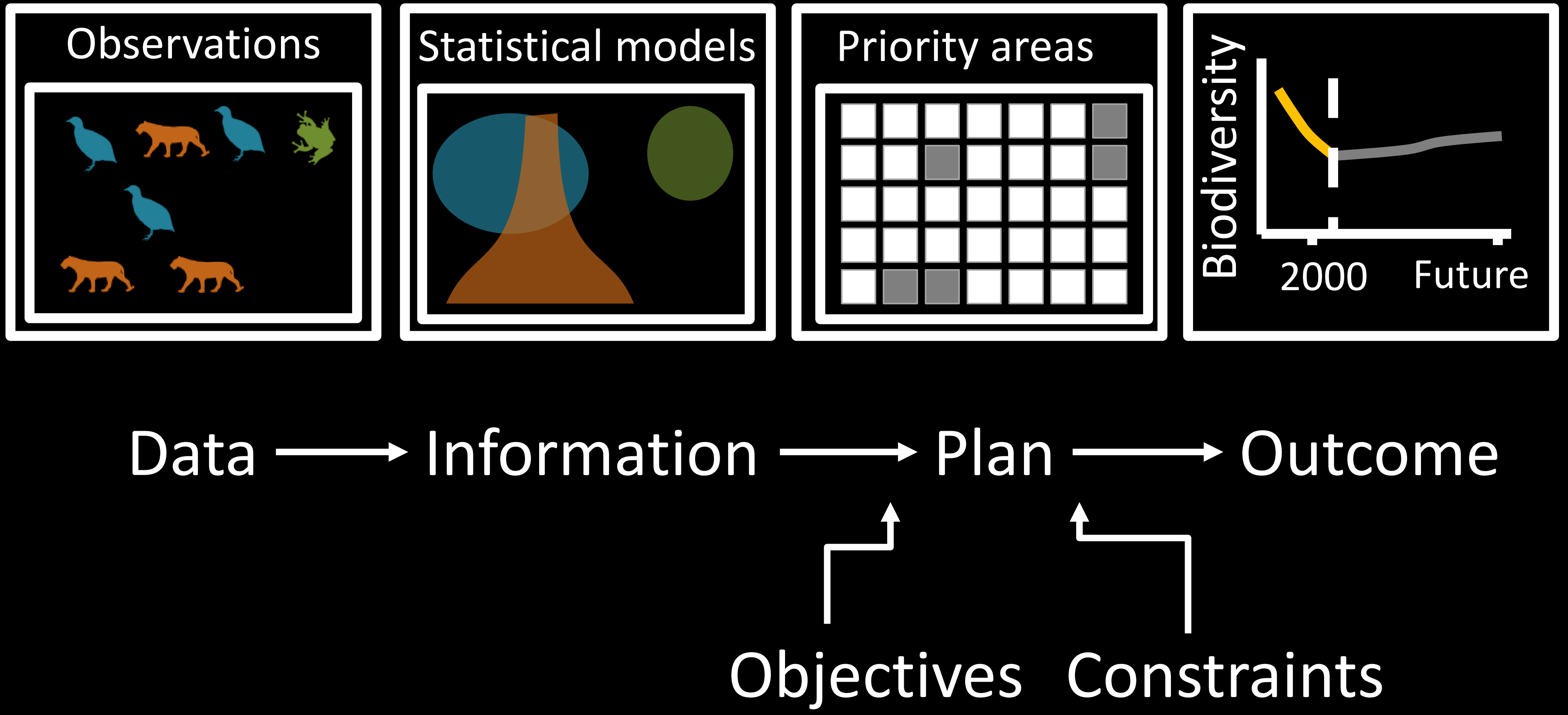
Jeffrey Hanson and Richard Schuster

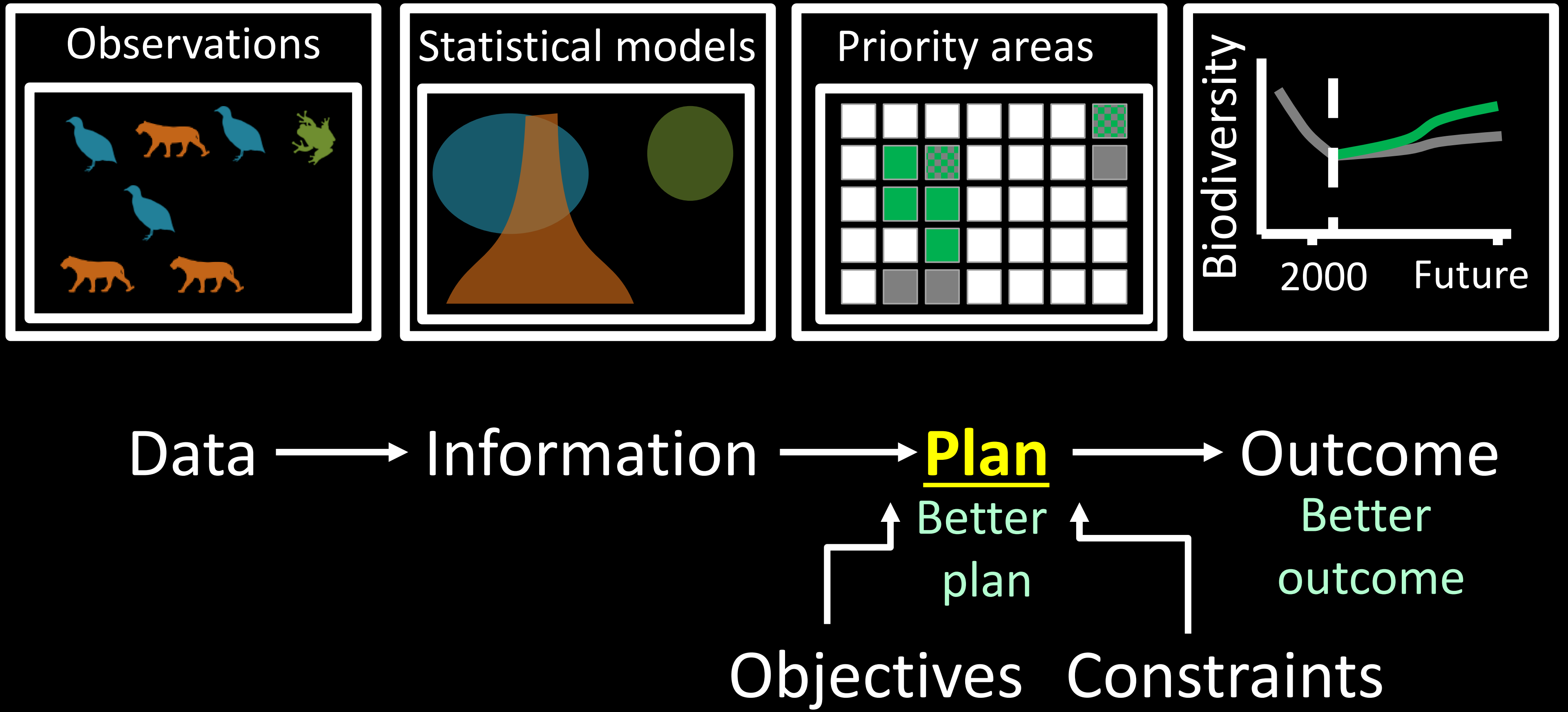
jeffrey.hanson@uqconnect.edu.au

richard.schuster@natureconservancy.ca


Now
Biodiversity
Status quo
2000
Future


Now
Biodiversity
How do we
get here?
Status quo
2000
Future

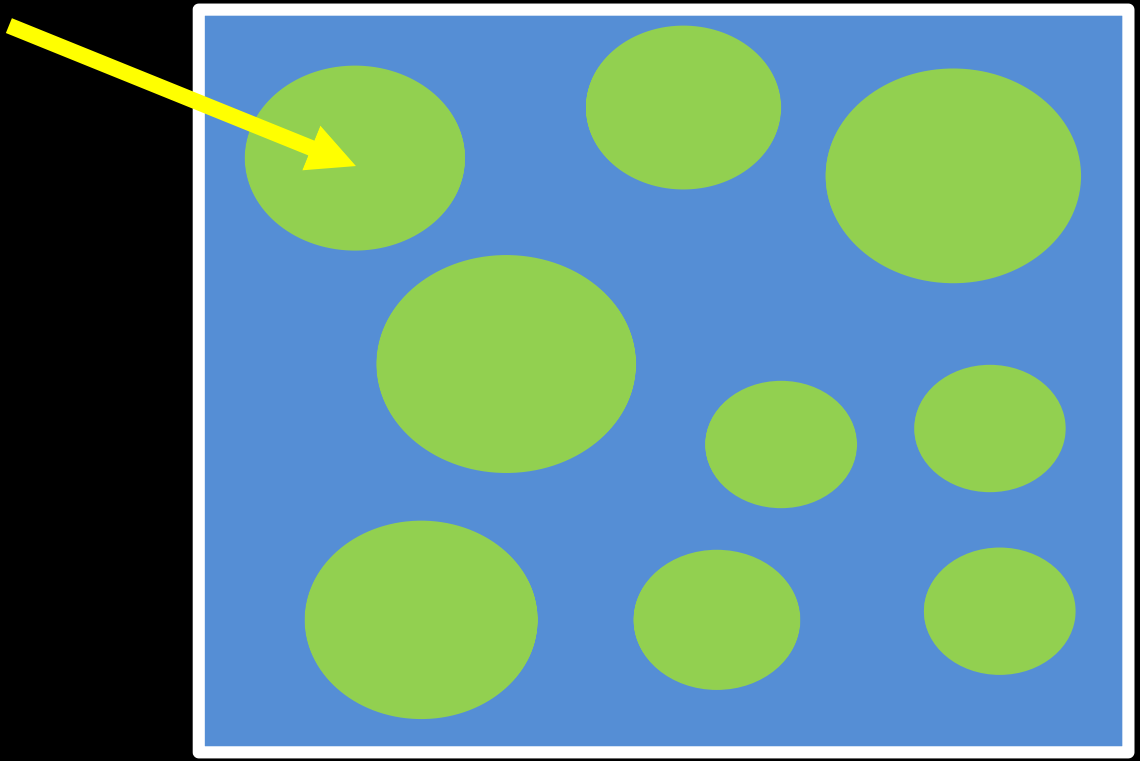

Observations
Statistical models
Priority areas
Biodiversity
2000
Future
Data
Information
Plan
Outcome
Objectives
Constraints


Observations
Statistical models
Priority areas
Biodiversity
2000
Future
Data
Information
Plan
Outcome
Better plan
Better outcome
Objectives
Constraints

Reserve selection

Planning units

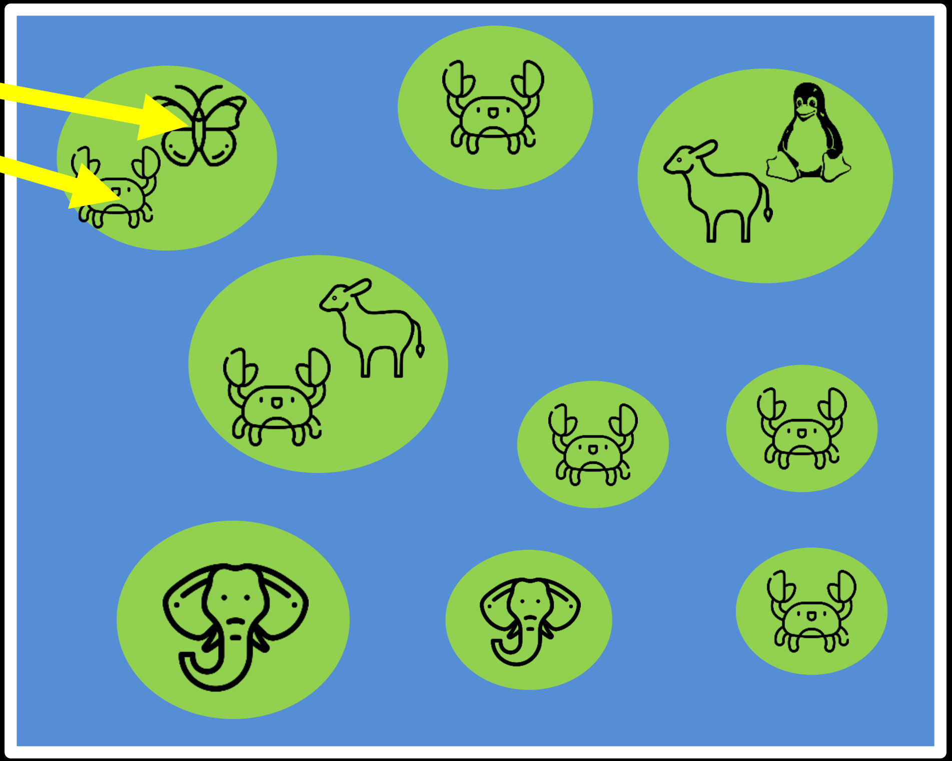
- Discrete places for conservation management
- Each planning unit is managed separately
- Commonly include land parcels, islands, spatial grid cells



Reserve selection

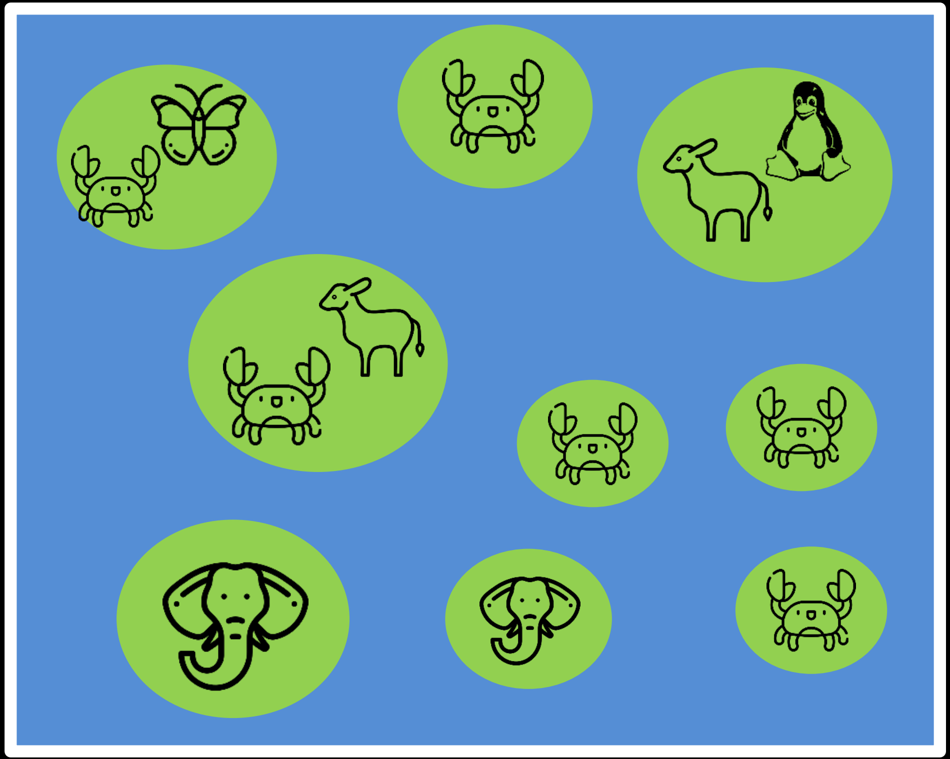
Features

- Stuff that we care about
- Each feature is relatively independent
- Commonly include species, ecosystem types, ecosystem services (e.g., water provisioning, carbon sequestration)



Reserve selection

Which planning units should we manage for conservation?



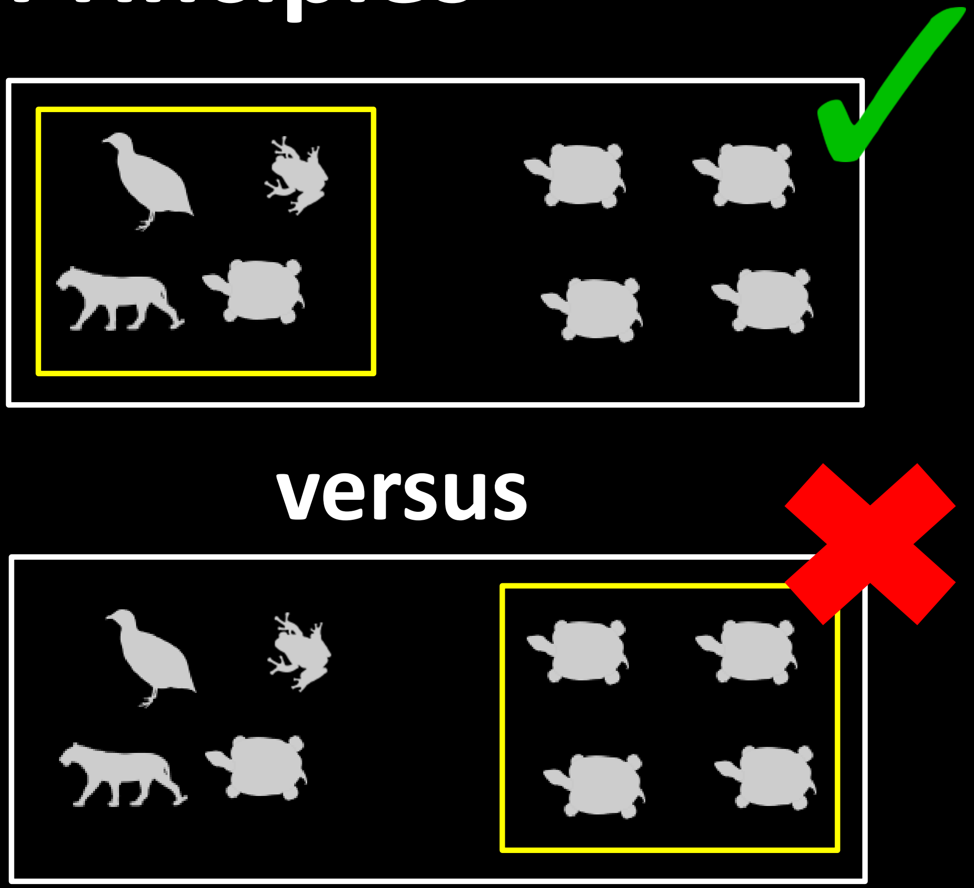
CARE-C Principles

- Comprehensive
- Adequate
- Representative
- Efficient
- Connectivity

Nielsen et al. (2023) Trends Ecol Evol, doi:10.1016/j.tree.2022.09.006

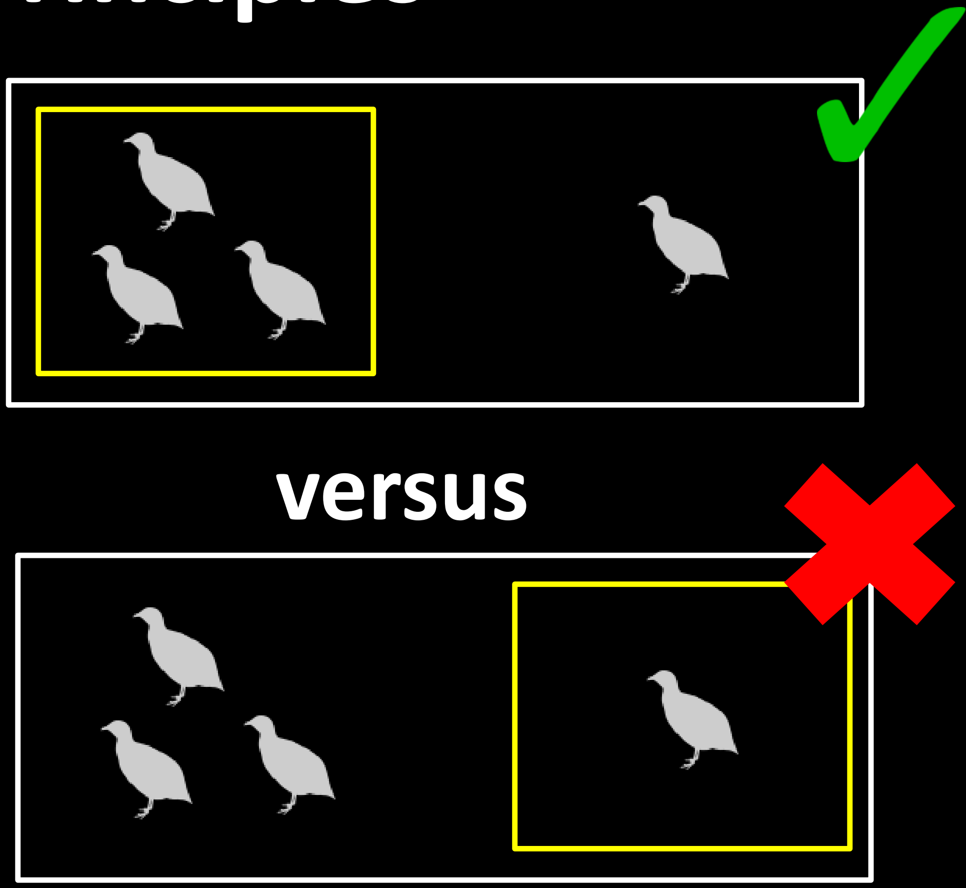
CARE-C Principles

- <u>**Comprehensive**</u>
- Adequate
- Representative
- Efficient
- Connectivity



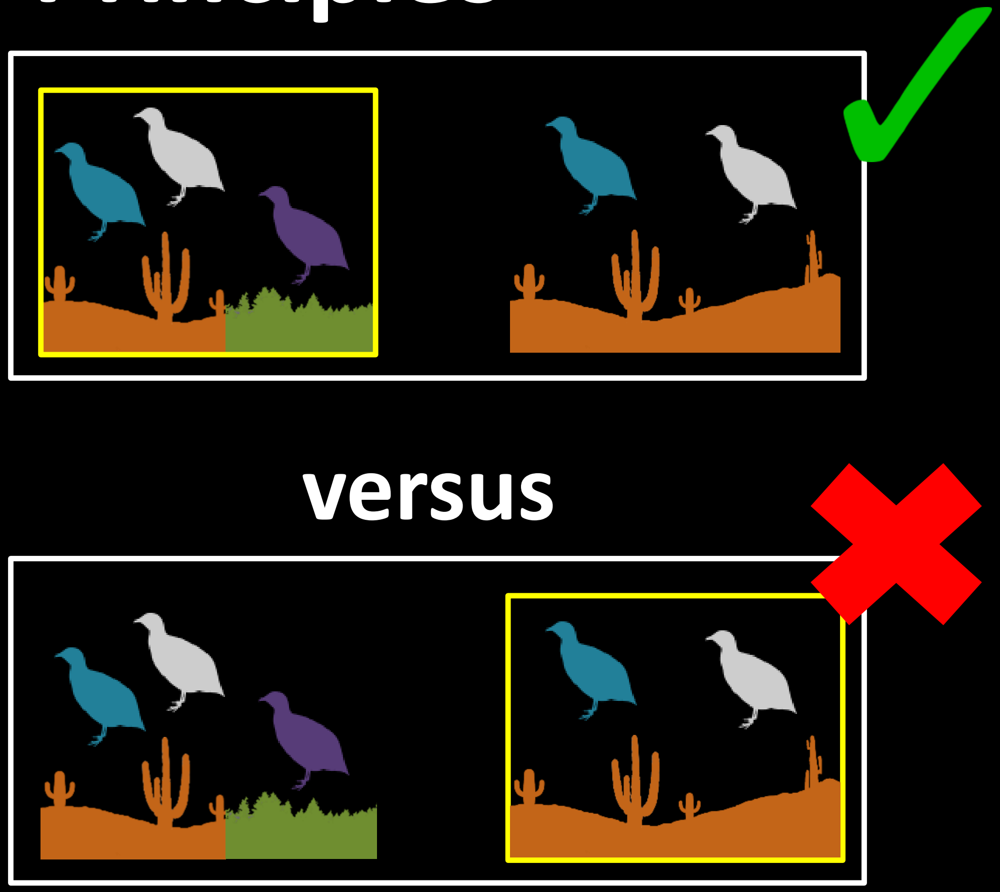
CARE Principles

- Comprehensive
- **<u>Adequate</u>**
- Representative
- Efficient
- Connectivity



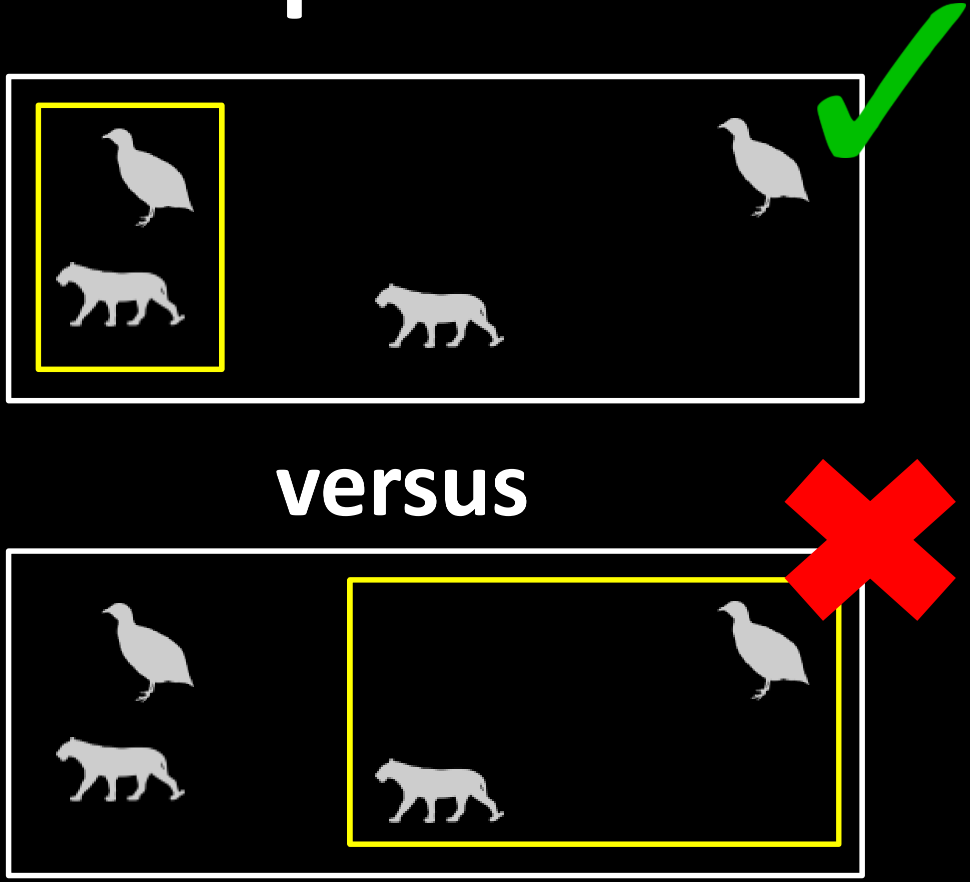
CARE-C Principles

- Comprehensive
- Adequate
- **<u>Representative</u>**
- Efficient
- Connectivity



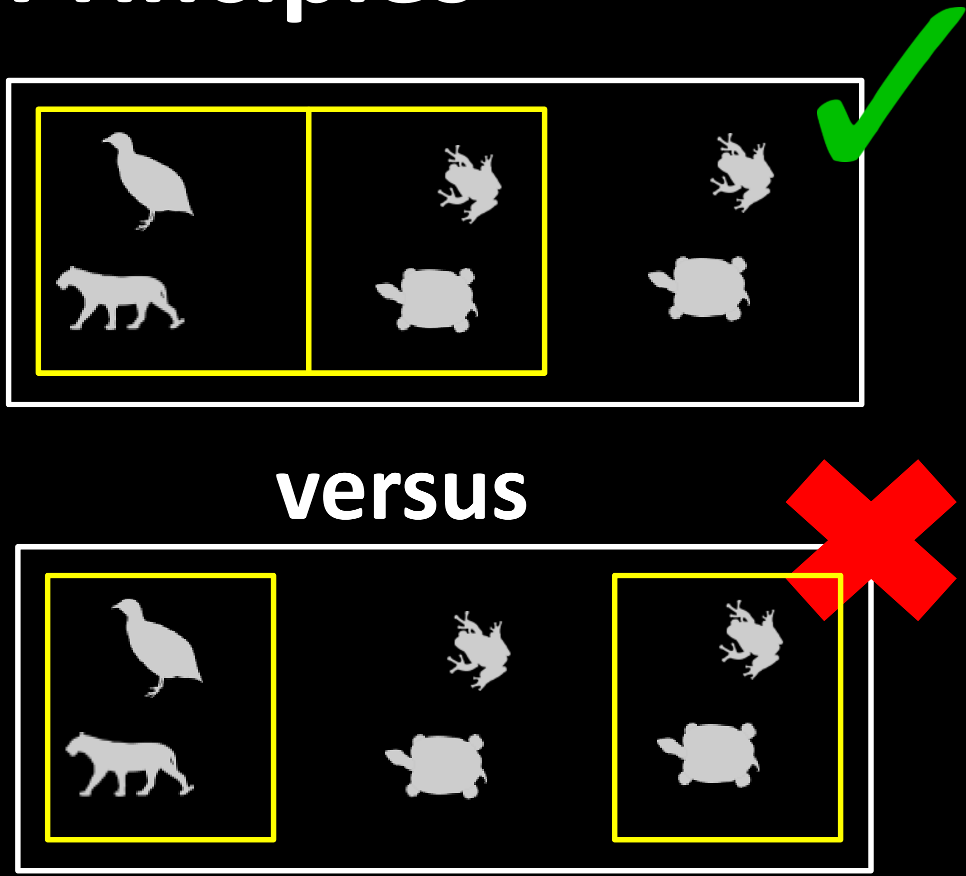
CARE-C Principles

- Comprehensive
- Adequate
- Representative
- <u>**Efficient**</u>
- Connectivity



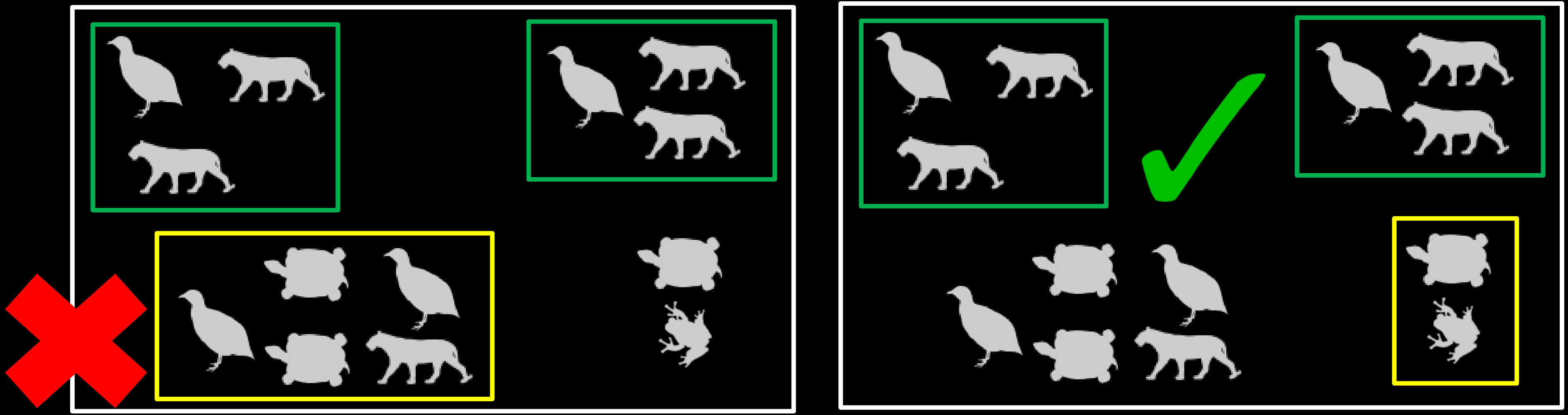
CARE-C Principles

- Comprehensive
- Adequate
- Representative
- Efficient
- **Connectivity**



Principle complementarity

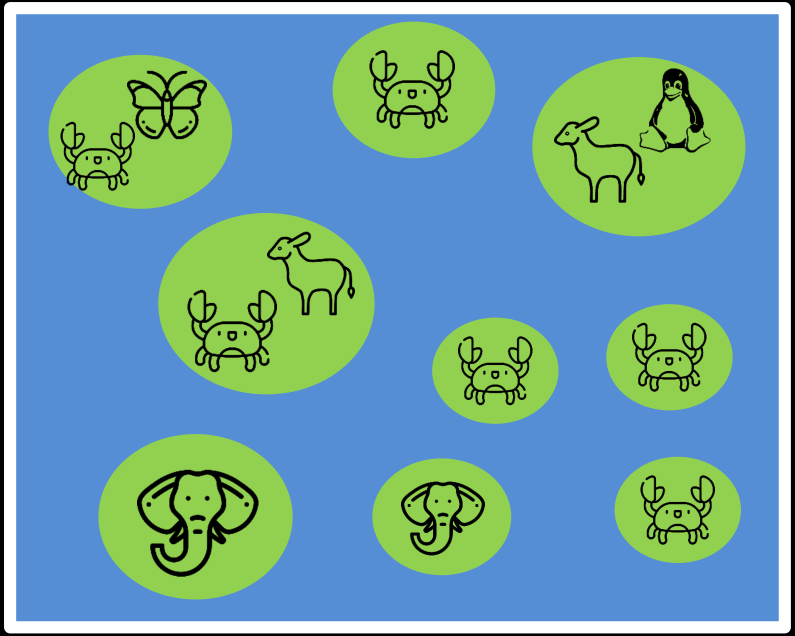
Protected areas should "complement" each other to maximize the performance of the overall protected area network (including. existing protected areas)

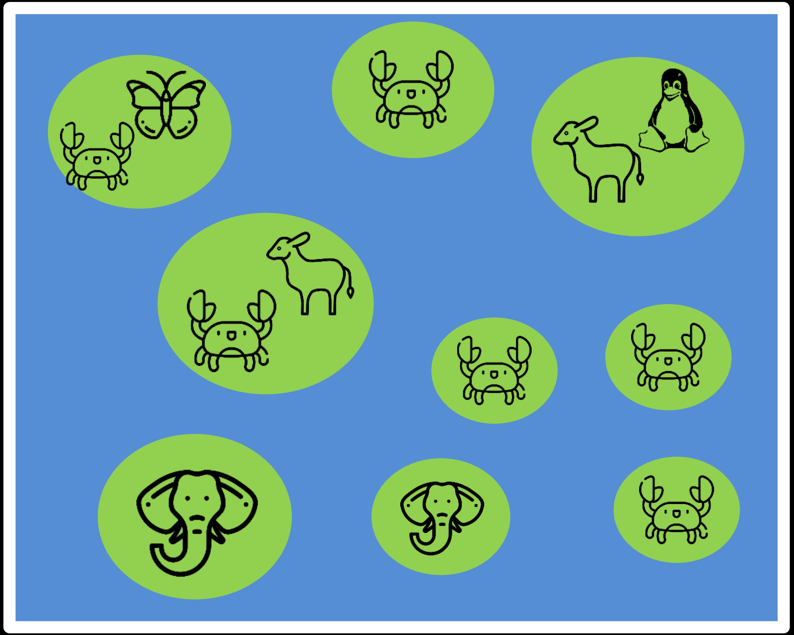


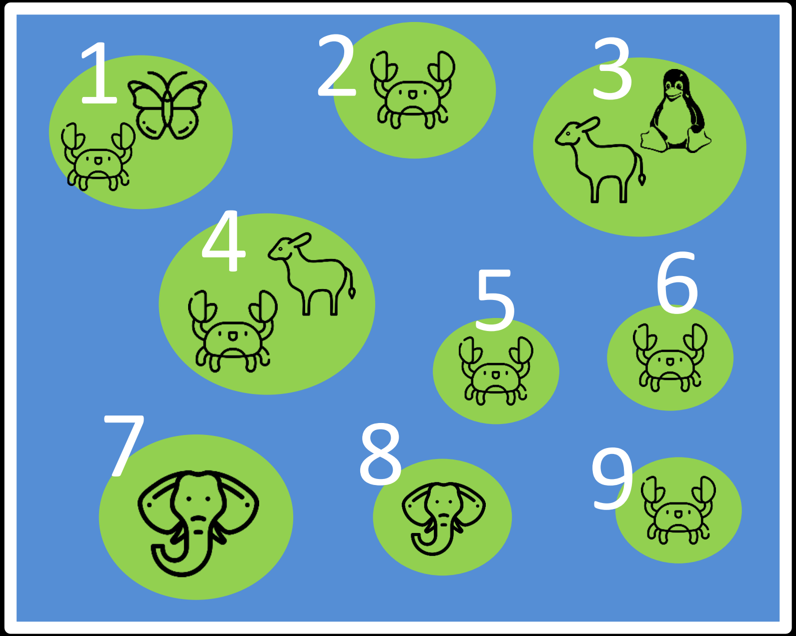
Vane-Wright, et al (1991) Biol Cons, DOI: 10.1016/0006-3207(91)90030-D

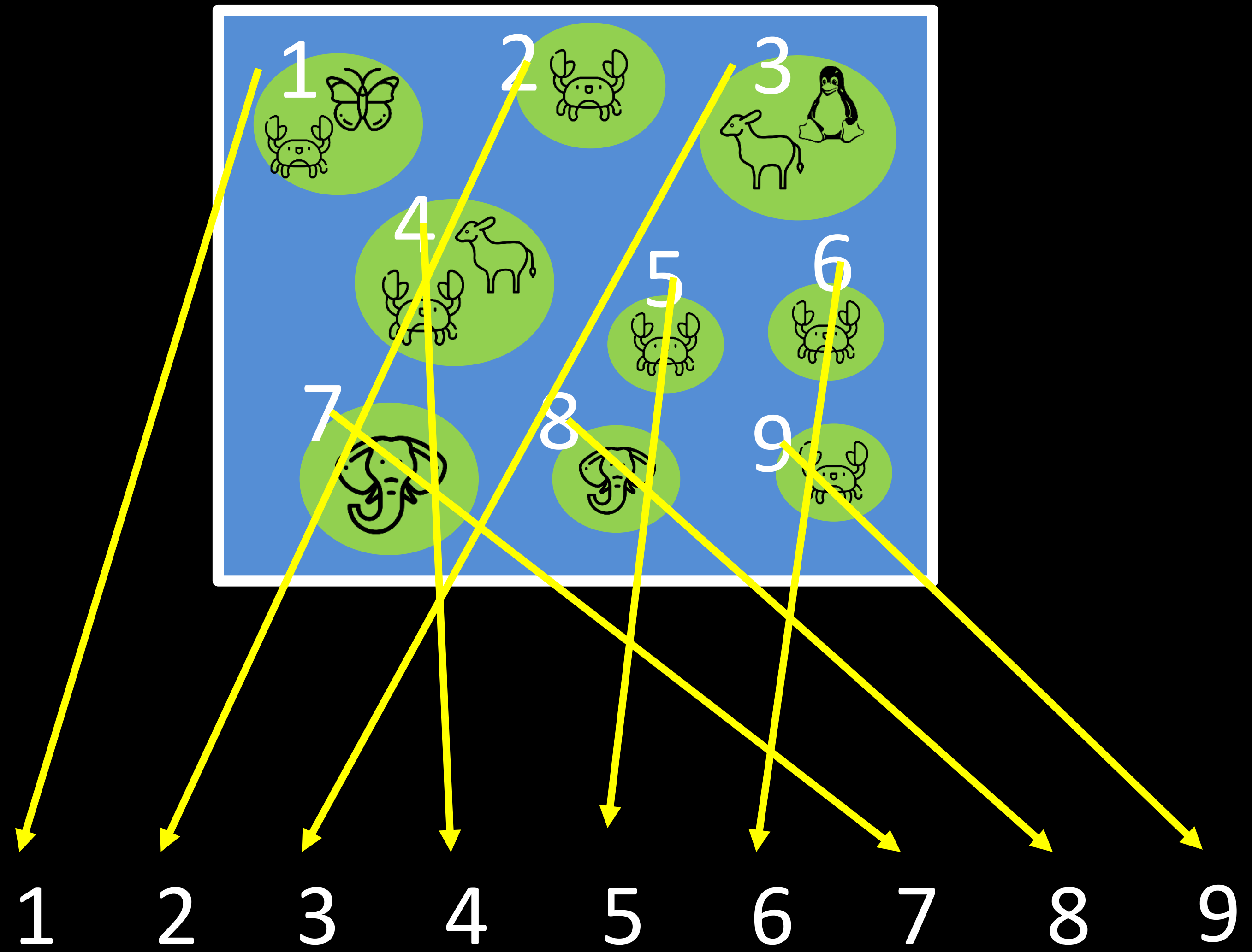
Reserve selection as optimization

- Minimum set formulation
- Objective: min. # of islands
- Constraints: sufficient habitat for each species
- Decisions: create a reserve on an island or not?






1
2
3
4
5
6
7
8
9


1
2
3
4
5
6
7
8
9
1 2 3 4 5 6 7 8 9

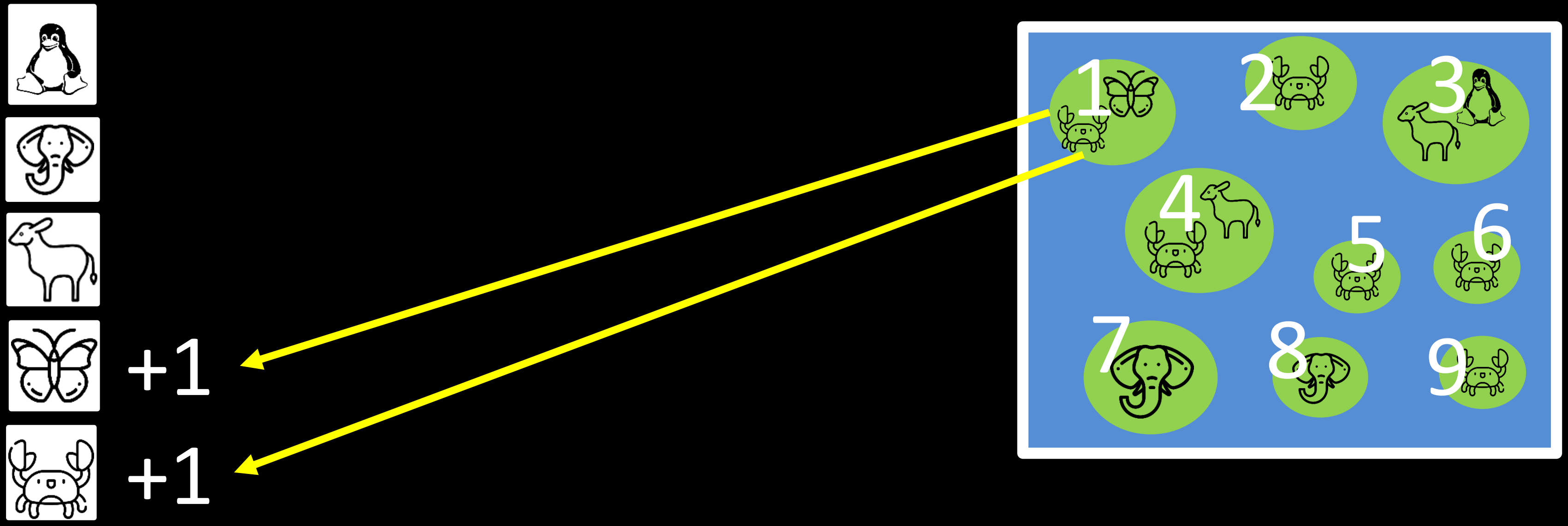
1 2 3 4 5 6 7 8 9

Upper	1	1	1	1	1	1	1	1	1
Lower	0	0	0	0	0	0	0	0	0
V. type	B	B	B	B	B	B	B	B	B
	1	2	3	4	5	6	7	8	9

Min $: +1 +1 +1 +1 +1 +1 +1 +1 +1

Upper	1	1	1	1	1	1	1	1	1
Lower	0	0	0	0	0	0	0	0	0
V. type	B	B	B	B	B	B	B	B	B
	1	2	3	4	5	6	7	8	9

Min $: +1 +1 +1 +1 +1 +1 +1 +1 +1

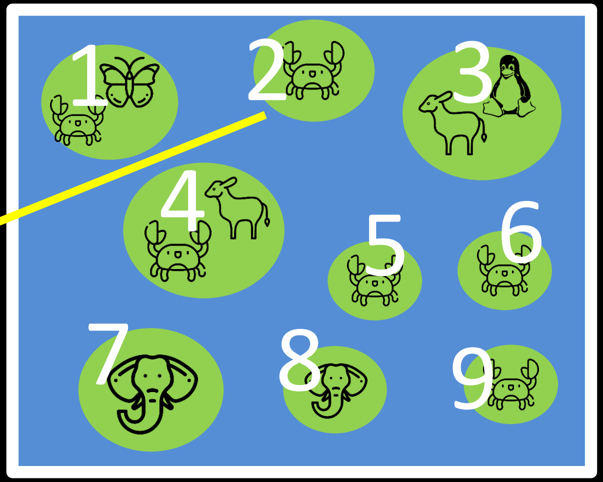


Upper	1	1	1	1	1	1	1	1	1
Lower	0	0	0	0	0	0	0	0	0
V. type	B	B	B	B	B	B	B	B	B
	1	2	3	4	5	6	7	8	9

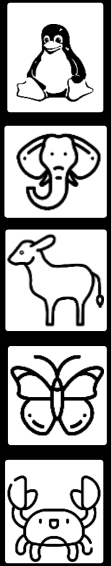
Min $: +1 +1 +1 +1 +1 +1 +1 +1 +1

+1

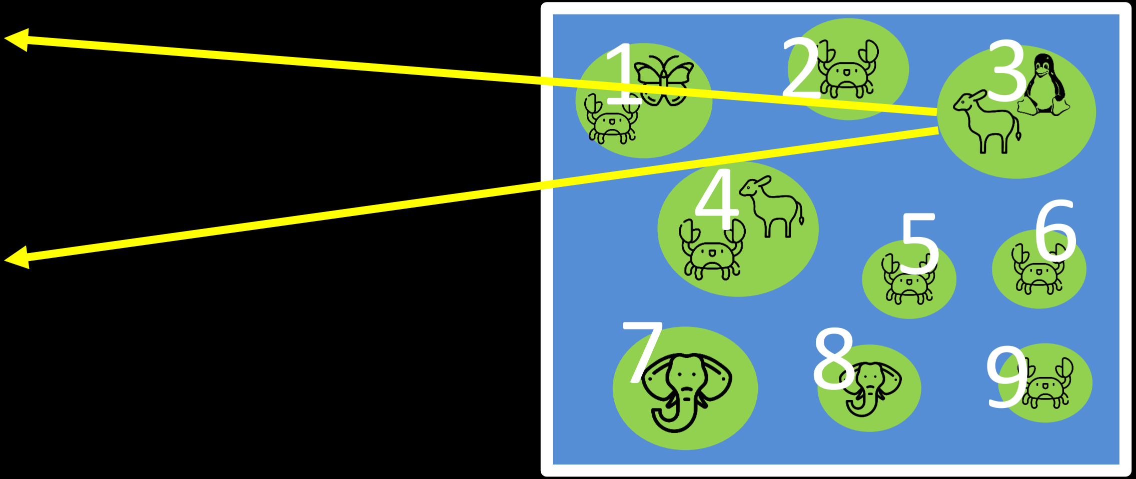
+1 +1



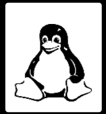
Upper	1	1	1	1	1	1	1	1	1
Lower	0	0	0	0	0	0	0	0	0
V. type	B	B	B	B	B	B	B	B	B
	1	2	3	4	5	6	7	8	9



	1	2	3	4	5	6	7	8	9
Min $:	+1	+1	+1	+1	+1	+1	+1	+1	+1
			+1						
			+1						
	+1								
	+1	+1							
Upper	1	1	1	1	1	1	1	1	1
Lower	0	0	0	0	0	0	0	0	0
V. type	B	B	B	B	B	B	B	B	B



	1	2	3	4	5	6	7	8	9
Min $:	+1	+1	+1	+1	+1	+1	+1	+1	+1
			+1						
							+1	+1	
			+1	+1					
	+1								
	+1	+1		+1	+1	+1			+1
Upper	1	1	1	1	1	1	1	1	1
Lower	0	0	0	0	0	0	0	0	0
V. type	B	B	B	B	B	B	B	B	B

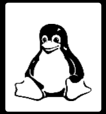
	1	2	3	4	5	6	7	8	9	
Min $:	+1	+1	+1	+1	+1	+1	+1	+1	+1	
			+1							≥ 1
							+1	+1		≥ 1
			+1	+1						≥ 1
	+1									≥ 1
	+1	+1		+1	+1	+1			+1	≥ 1
Upper	1	1	1	1	1	1	1	1	1	
Lower	0	0	0	0	0	0	0	0	0	
V. type	B	B	B	B	B	B	B	B	B	
	1	2	3	4	5	6	7	8	9	

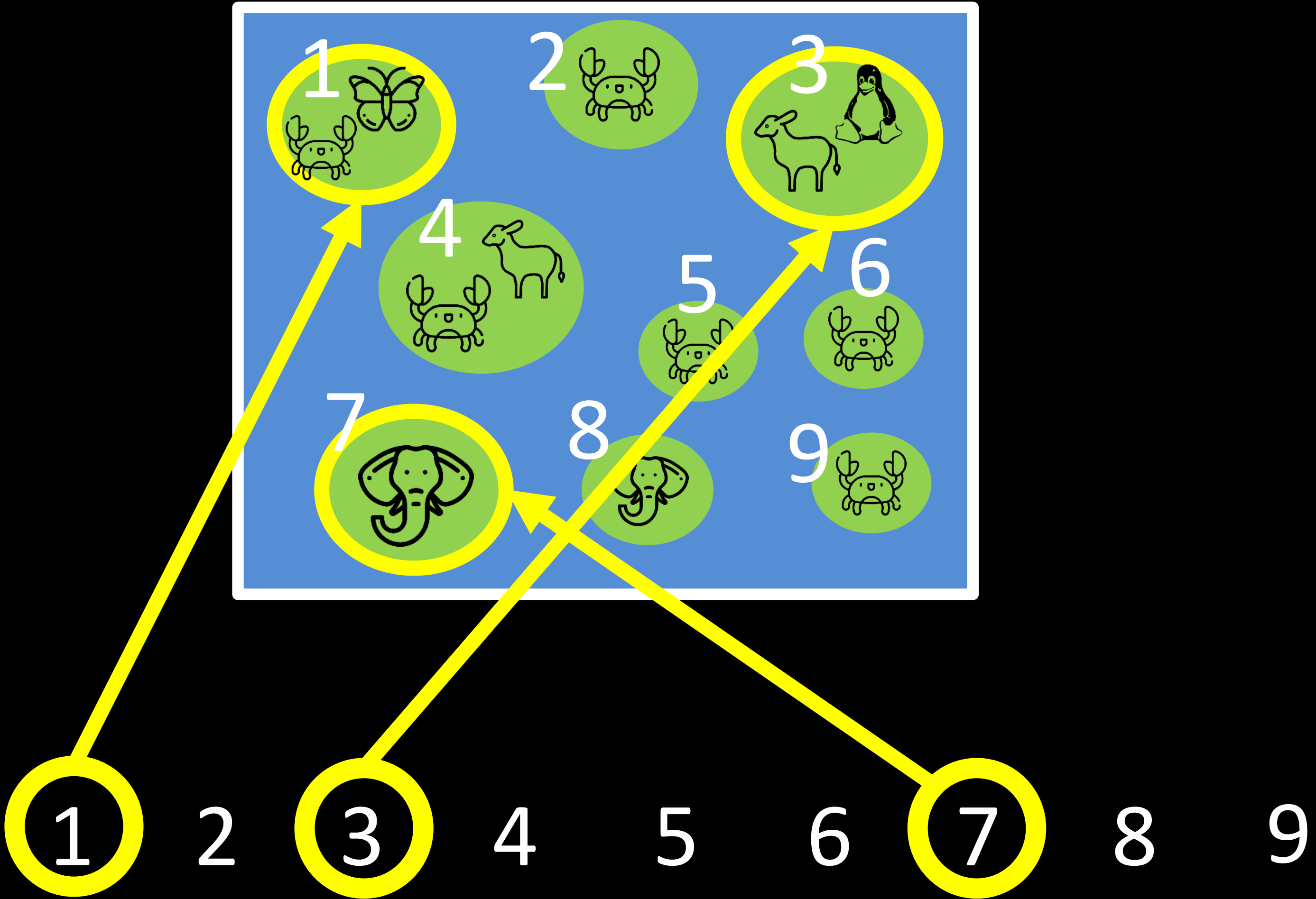
Min $:	+1	+1	+1	+1	+1	+1	+1	+1	+1	
										≥ 1
										≥ 1
										≥ 1
										≥ 1
										≥ 1
Upper										
Lower										
V. type	B	B	B	B	B	B	B	B	B	
	1	2	3	4	5	6	7	8	9	

GUROBI OPTIMIZATION

IBM CPLEX

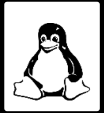
COIN|OR — COMPUTATIONAL INFRASTRUCTURE FOR OPERATIONS RESEARCH

Min $:	+1	+1	+1	+1	+1	+1	+1	+1	+1	
			+1							≥ 1
							+1	+1		≥ 1
			+1	+1						≥ 1
	+1									≥ 1
	+1	+1		+1	+1	+1			+1	≥ 1
Upper	1	1	1	1	1	1	1	1	1	
Lower	0	0	0	0	0	0	0	0	0	
V. type	B	B	B	B	B	B	B	B	B	
	1	2	3	4	5	6	7	8	9	

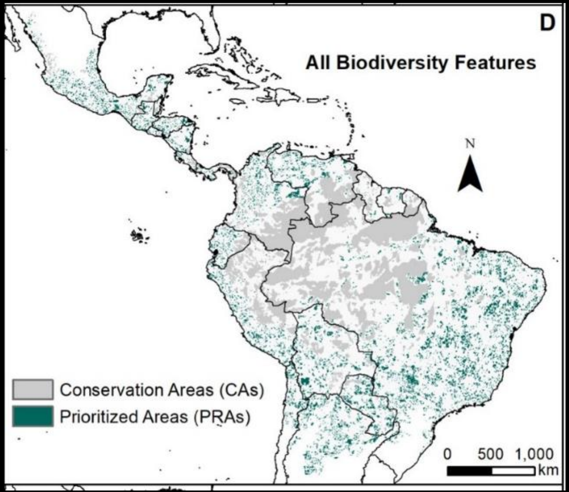

1
2
3
4
5
6
7
8
9
1 2 3 4 5 6 7 8 9

But reality is more complex...

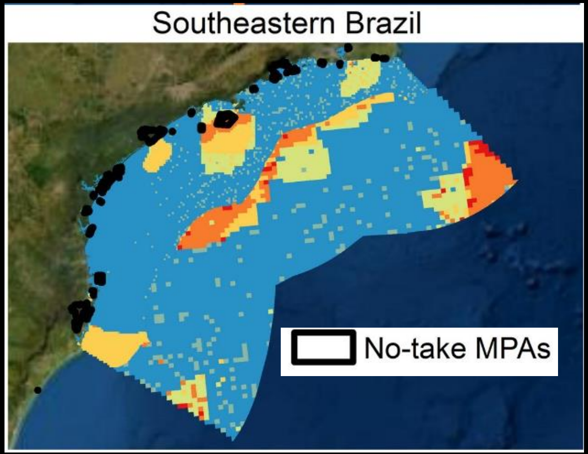
Accounting for existing conservation areas

Min $:	+1	+1	+1	+1	+1	+1	+1	+1	+1	
			+1							≥ 1
							+1	+1		≥ 1
			+1	+1						≥ 1
	+1									≥ 1
	+1	+1		+1	+1	+1			+1	≥ 1
Upper	1	1	1	1	1	1	1	1	1	
Lower	0	1	0	0	0	0	1	0	0	
V. type	B	B	B	B	B	B	B	B	B	
	1	2	3	4	5	6	7	8	9	

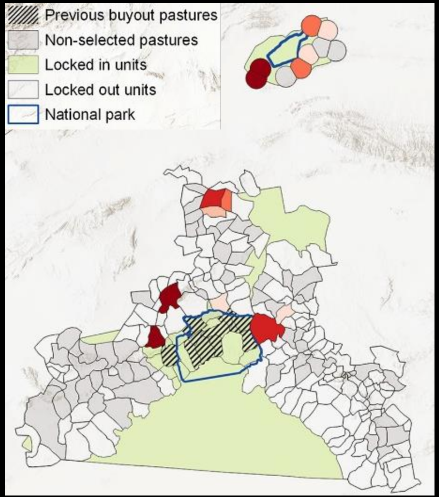
Accounting for existing conservation areas



Protected areas + Indigenous Lands



No-take marine reserves



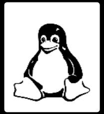
Areas with existing habitat + pastures where grazing rights have already been bought

Burbano-Girón et al. (2022)
DOI:10.1016/j.biocon.2021.109421

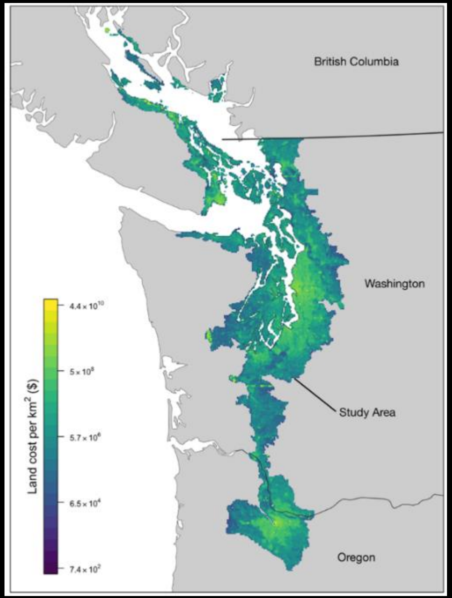
Magris et al. (2020)
DOI:10.1111/ddi.13183

Daberger et al. (2022)
10.1111/csp2.12832

Accounting for **efficiency**

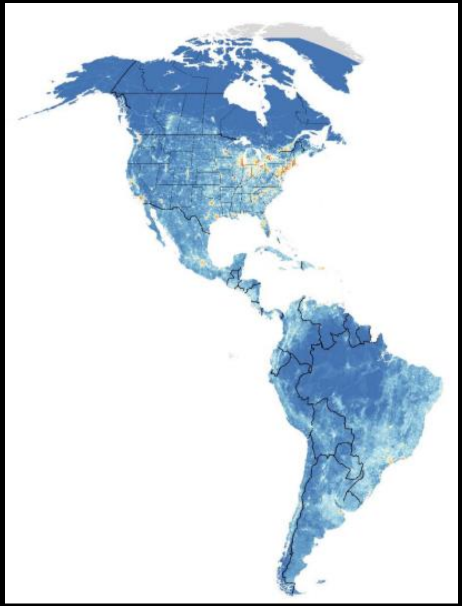
Min $:	+9	+2	+5	+1	+5	+8	+3	+6	+8	
			+1							≥ 1
							+1	+1		≥ 1
			+1	+1						≥ 1
	+1									≥ 1
	+1	+1		+1	+1	+1			+1	≥ 1
Upper	1	1	1	1	1	1	1	1	1	
Lower	0	1	0	0	0	0	1	0	0	
V. type	B	B	B	B	B	B	B	B	B	
	1	2	3	4	5	6	7	8	9	

Accounting for efficiency



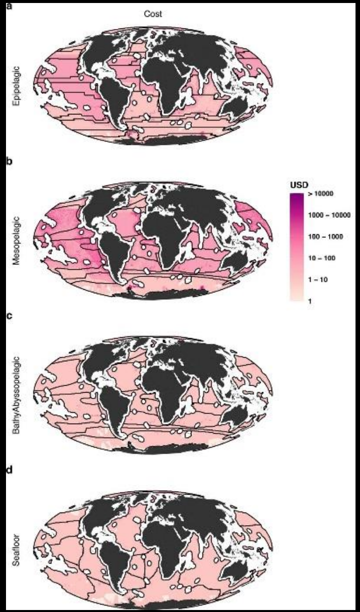
Land value assessments

Rodewald et al. (2019)
DOI:10.1038/s41598-019-52241-2



Human pressure

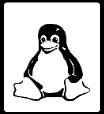
Schuster et al. (2019)
DOI:10.1038/s41467-019-09723-8



Opportunity cost to commercial fisheries

Brito-Morales et al. (2022)
DOI:10.1038/s41558-022-01323-7

Accounting for adequacy, comprehensiveness, and representativeness

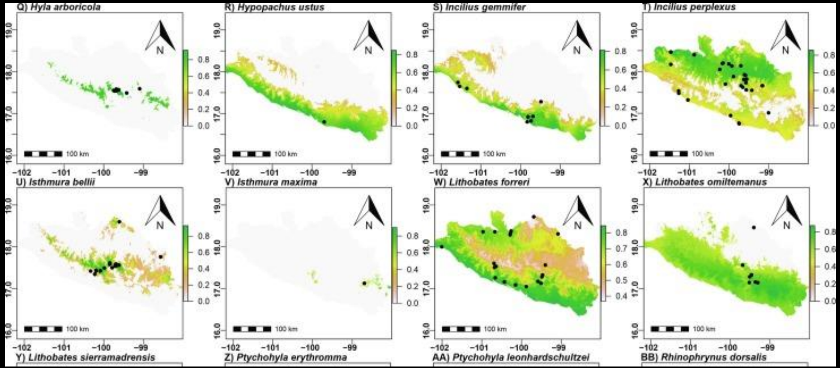
Min $:	+9	+2	+5	+1	+5	+8	+3	+6	+8	
			+10							≥ 10
							+2	+5		≥ 7
			+3	+7						≥ 3
	+1									≥ 1
	+9	+8		+9	+8	+4			+3	≥ 12
Upper	1	1	1	1	1	1	1	1	1	
Lower	0	1	0	0	0	0	1	0	0	
V. type	B	B	B	B	B	B	B	B	B	
	1	2	3	4	5	6	7	8	9	

Accounting for adequacy

Get good data…

High resolution estimates of habitat suitability

Hanson et al. (2022) DOI:10.1038/s41586-020-2138-7



Species distribution models

González-Fernández (2022) DOI:10.1016/j.jnc.2022.126235

and set meaningful targets!

Policy

Southee et al. (2021) DOI: 10.1139/facets-2020-0015

Proctor et al. (2022) DOI: 10.1111/csp2.12771

Expert thresholds

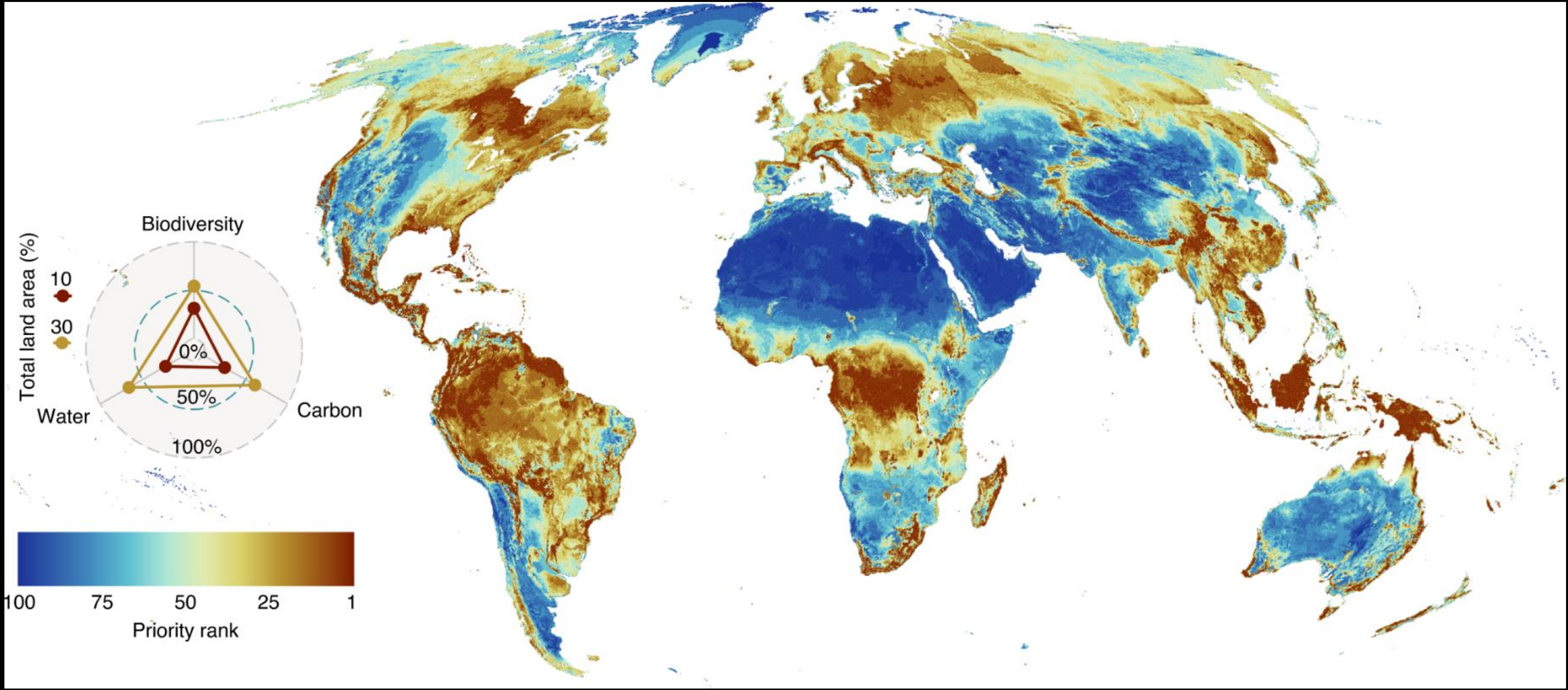
Hanson et al. (2022) DOI: 10.1038/s41586-020-2138-7

Jung et al. 2021 DOI :10.1038/s41559-021-01528-7

Statistical analysis

Taylor et al. (2017) DOI: 10.1371/journal.pone.0169629

Accounting for comprehensiveness

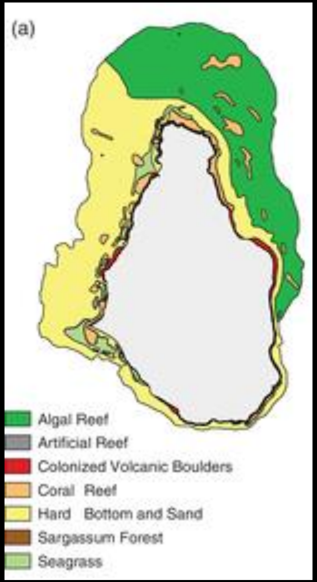


Amphibians, mammals, birds, reptiles, plants, water provisioning, carbon sequestration

Jung et al. 2021 DOI:10.1038/s41559-021-01528-7

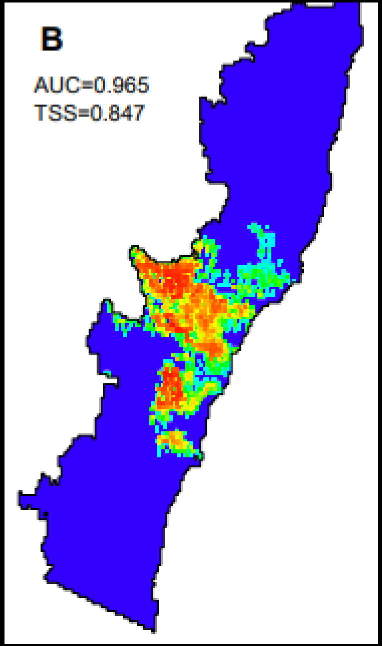
Accounting for representativeness

Ecosystems



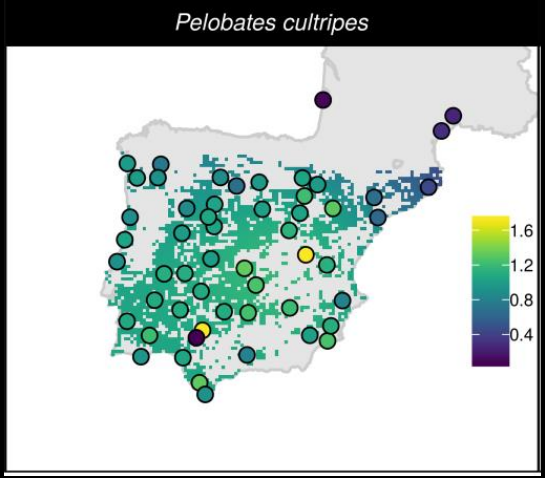
Flower et al. (2010)
DOI: 10.1111/csp2.158

Species



Domisch et al. (2019)
DOI: 10.1111/ddi.12891

Genes



Hanson et al. (2022)
DOI: 10.1111/1365-2664.13718

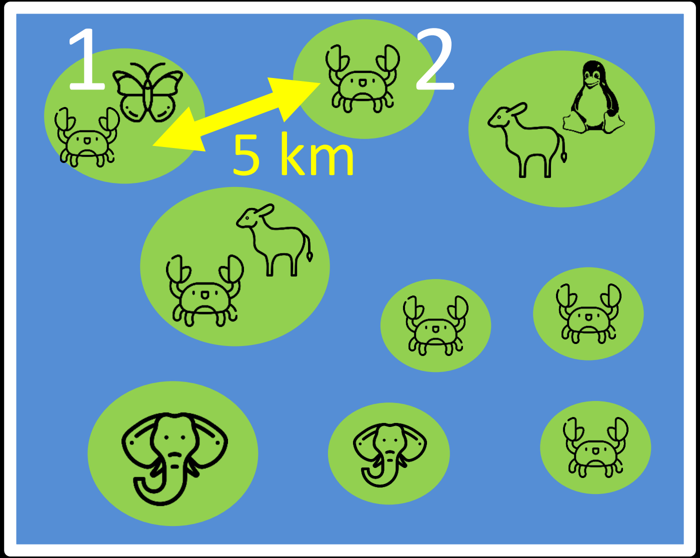
Accounting for connectivity

Min $:	+9	+2	+5	+1	+5	+8	+3	+6	+8	
			+10							≥ 10
							+2	+5		≥ 7
			+3	+7						≥ 3
	+1									≥ 1
	+9	+8		+9	+8	+4			+3	≥ 12
Upper	1	1	1	0	1	1	1	1	0	
Lower	0	1	0	0	0	0	1	0	0	
V. type	B	B	B	B	B	B	B	B	B	
	1	2	3	4	5	6	7	8	9	

What if connectivity = 1/distance?

Min $:	+9	+2	-3*1/5		
	-1		+1	|	≤ 0
		+1	-1	|	≤ 0
	-1	-1	+1	|	≥ -1
Upper	1	1	1		
Lower	0	1	0		
V. type	B	B	B		
	1	2	1&2		

Let's just consider islands 1 and 2



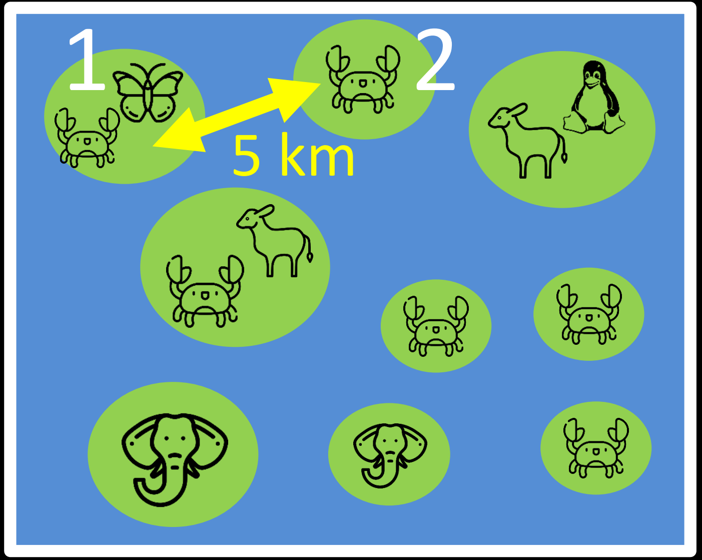
Scaling factor: 3 connectivity units = 1 cost unit

Beyer et al. (2016)
DOI:10.1016/j.ecolmodel.2016.02.005

What if connectivity = 1/distance?

Min $:	+9	+2	-3*1/5	
(1)	-1		+1	≤ 0
(2)		+1	-1	≤ 0
	~~-1~~	~~-1~~	~~+1~~	~~≥ -1~~
Upper	1	1	1	
Lower	0	1	0	
V. type	B	B	B	
	1	2	1&2	

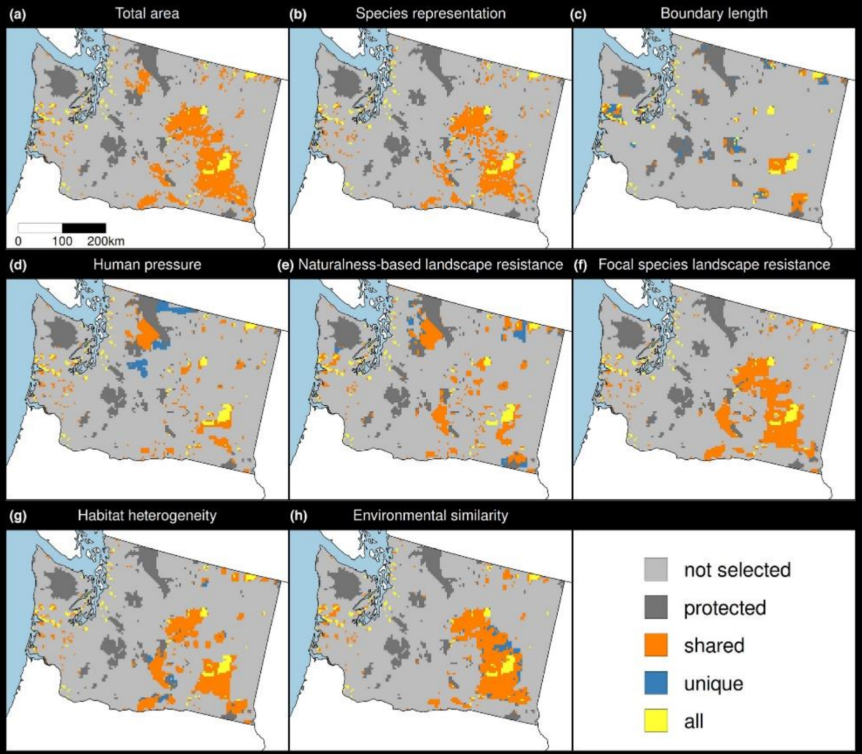
Let's just consider islands 1 and 2



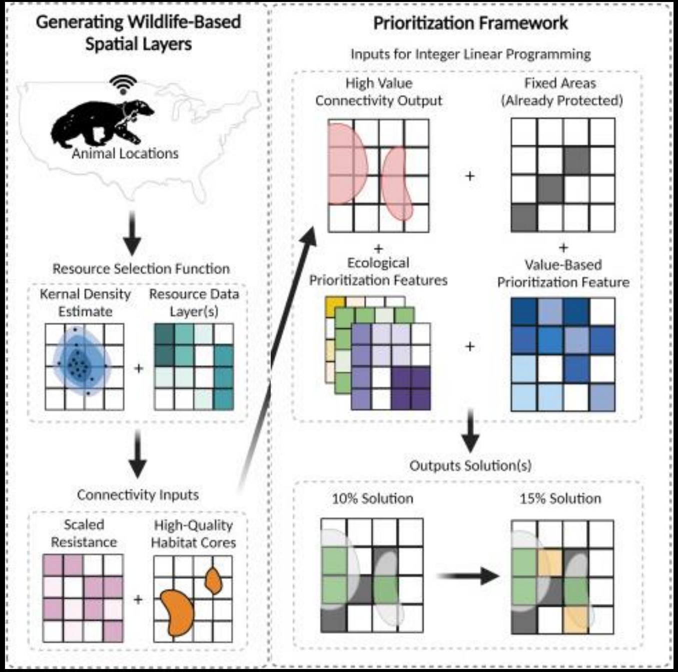
So, +1 variable and +2 constraints per pair of planning units.. increases problem size a lot!

E.g., 1k planning = ~500k extra constraints

Accounting for connectivity

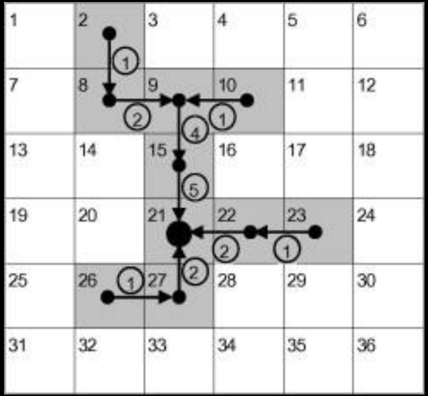


Hanson et al. (2022) DOI:10.1111/1365-2664.14251



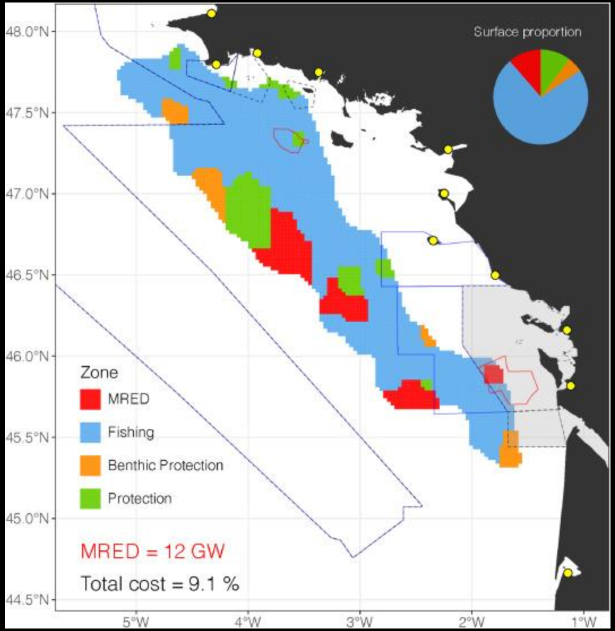
Carroll (2021)
DOI:10.1016/j.xpro.2021.100882

Other stuff too!



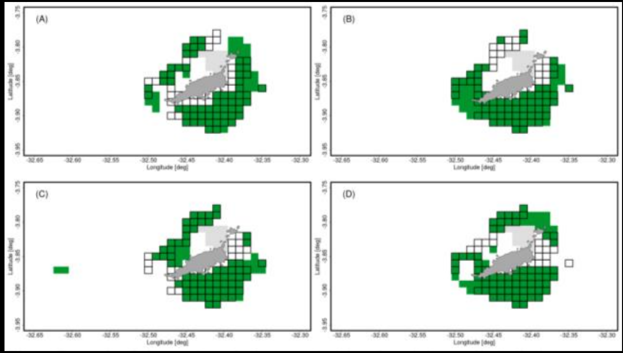
Spatially contiguity

Wang and Önal (2013)
DOI: 10.1016/j.chnaes.2013.07.004



Multiple management zones

Boussarie et al. (2023)
DOI: 10.1016/j.jenvman.2023.117857



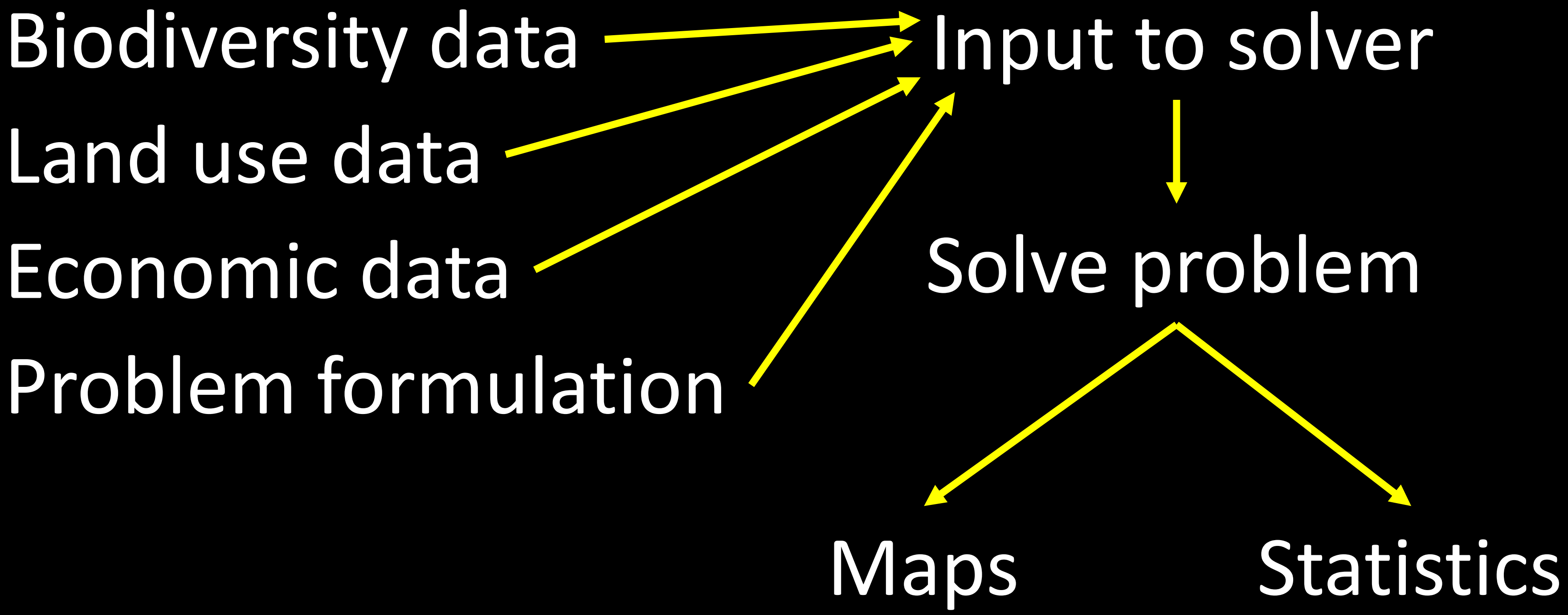
Solution portfolios

Brunel et al. (2022)
DOI: 10.1007/s10666-022-09862-1

prioritizr

- Human readable code
- Design your problem
- Solve it fast!

Package workflow



Package workflow

Biodiversity data

Land use data

Economic data

Problem formulation

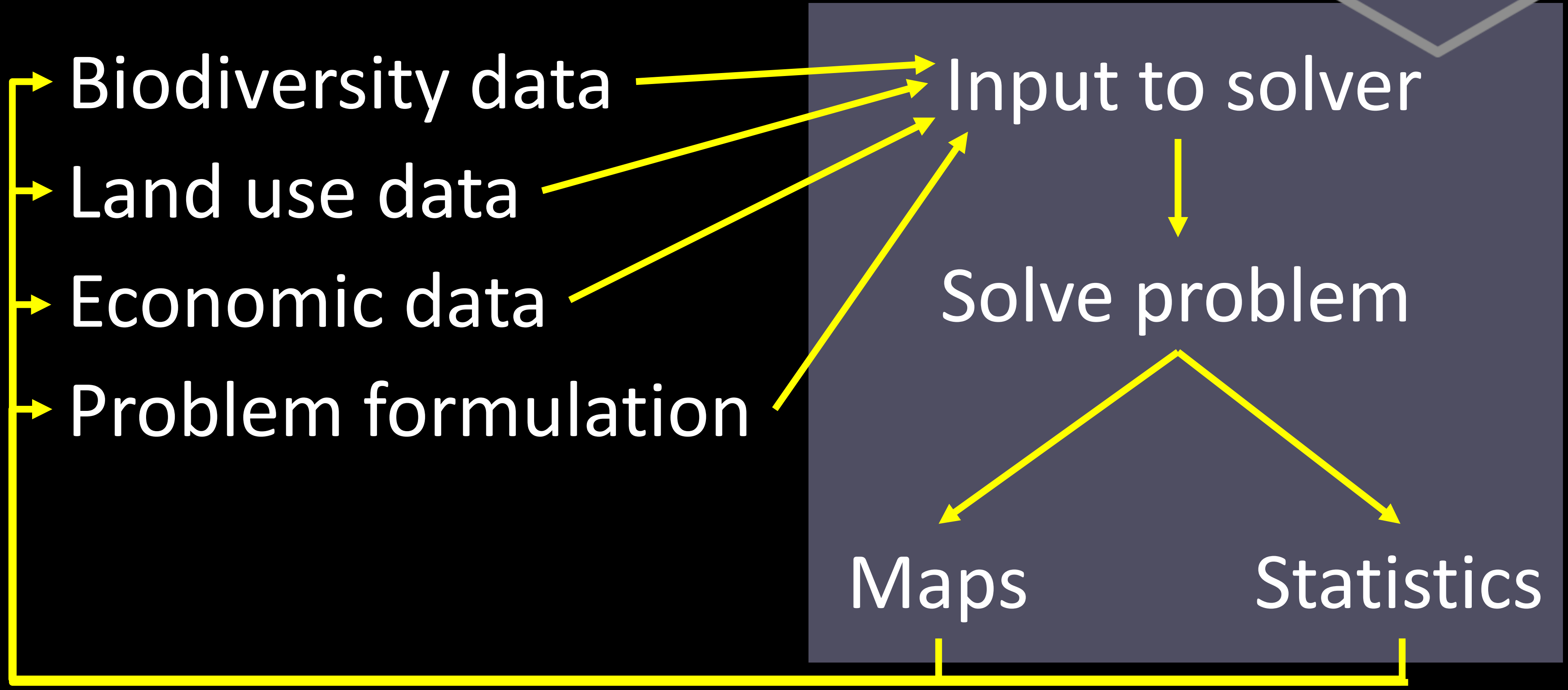
→ Input to solver

→ Solve problem

→ Maps

→ Statistics

Package workflow



Human-readable code

Mental model

```
problem <-
  data +
  objective +
  constraints +
  penalties +
  decision type +
  solver

solution <- solve(problem)
```

Code

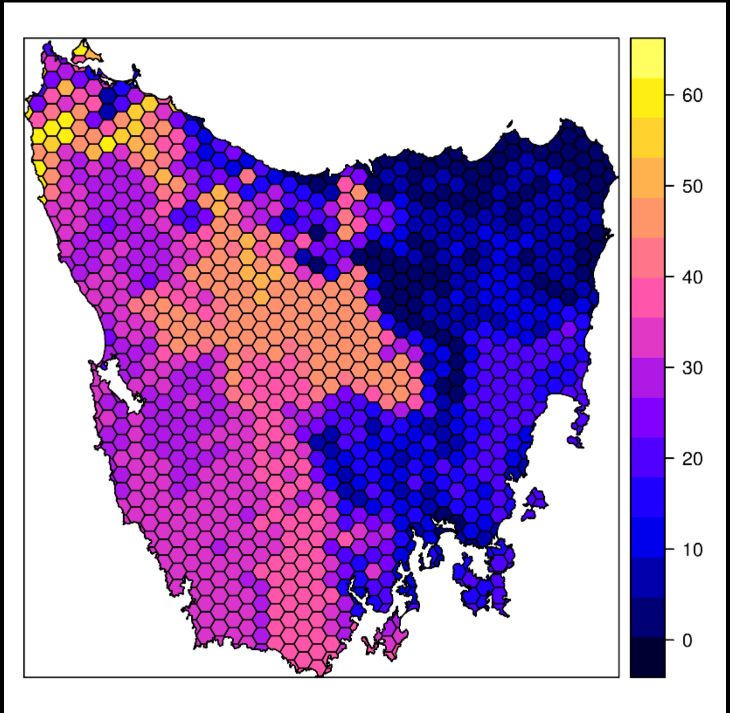
```
p <-
  problem(areas, feats) %>%
  add_min_set_objective() %>%
  add_relative_targets(0.1) %>%
  add_boundary_penalties(5) %>%
  add_binary_decisions() %>%
  add_rsymphony_solver()

solution <- solve(p)
```

Design <u>your</u> problem

Study area: Tasmania, Australia

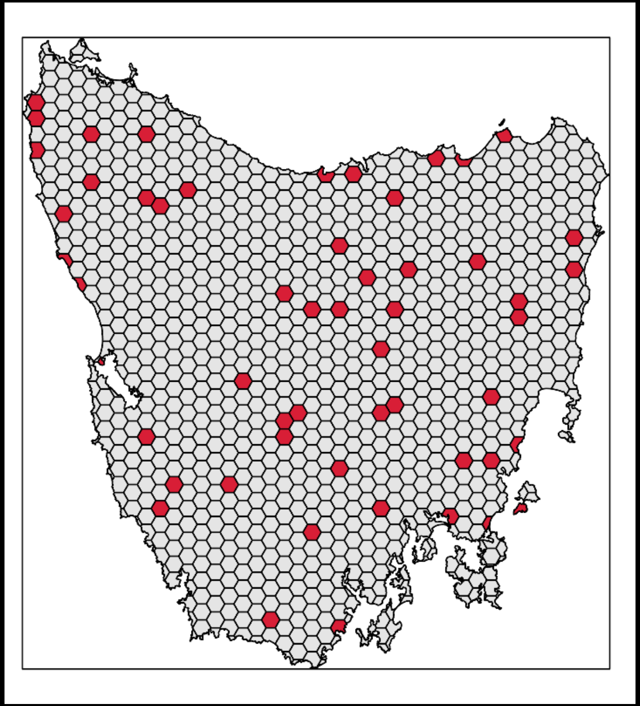
Planning units: 1130 hexagons

Features: 63 vegetation types



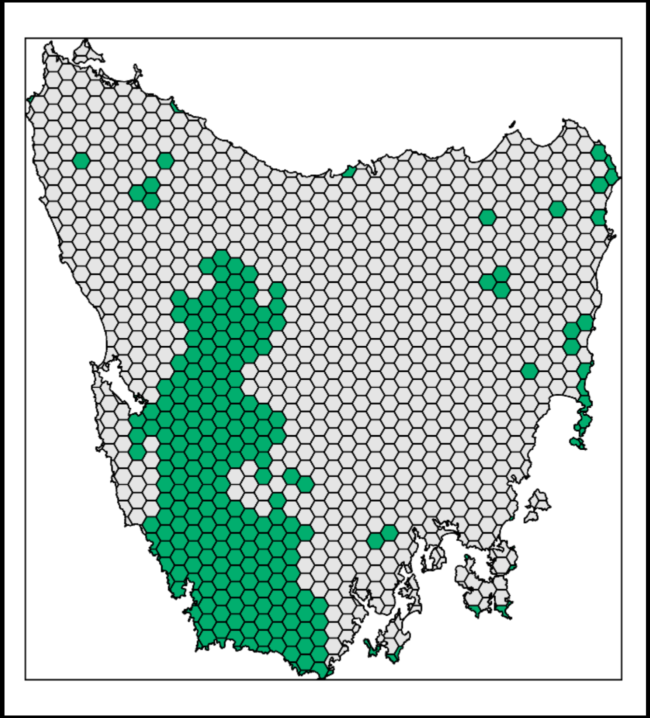
Design your problem

```
problem(tas_pu, tas_features,
        "cost") %>%
add_min_set_objective() %>%
add_relative_targets(0.1) %>%
add_binary_decisions() %>%
add_gurobi_solver(gap = 0) %>%
solve()
```



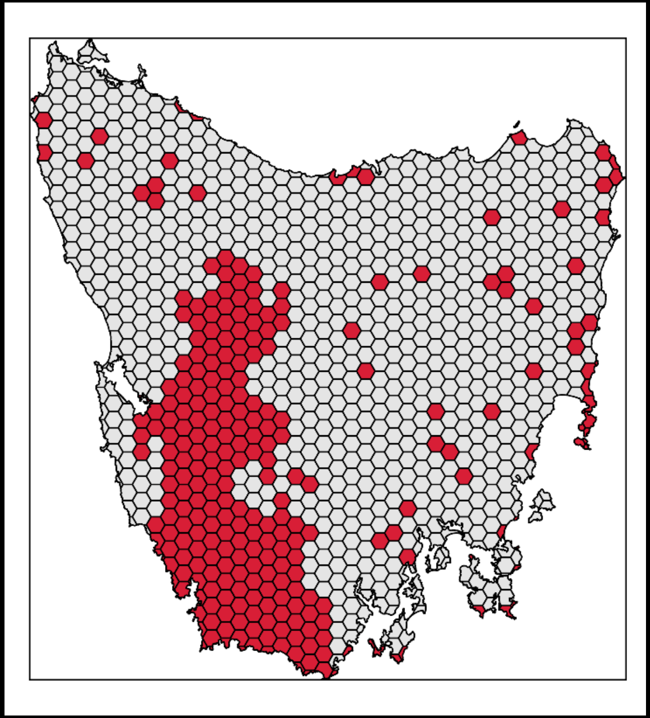
Design your problem

```
problem(tas_pu, tas_features,
        "cost") %>%
add_min_set_objective() %>%
add_relative_targets(0.1) %>%
add_locked_in_constraints("in") %>%
add_binary_decisions() %>%
add_gurobi_solver(gap = 0) %>%
solve()
```



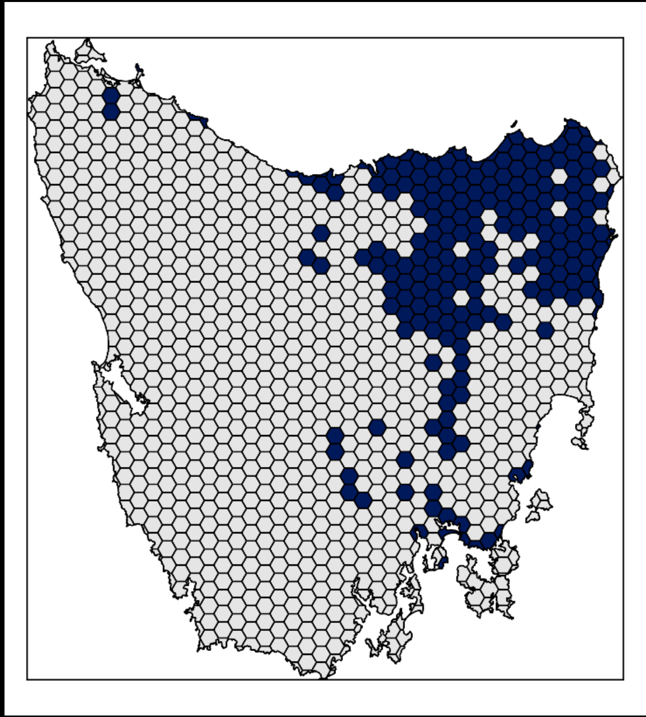
Design your problem

```
problem(tas_pu, tas_features,
        "cost") %>%
add_min_set_objective() %>%
add_relative_targets(0.1) %>%
add_locked_in_constraints("in") %>%
add_binary_decisions() %>%
add_gurobi_solver(gap = 0) %>%
solve()
```



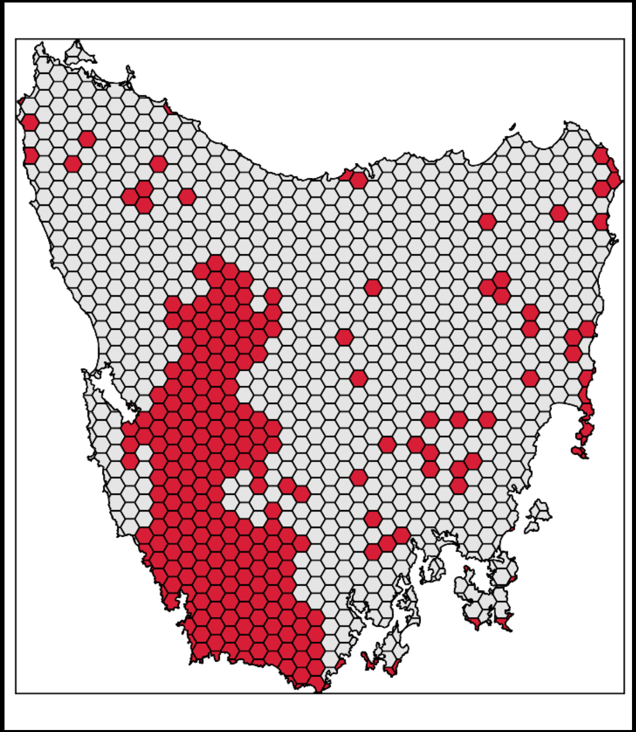
Design *your* problem

```
problem(tas_pu, tas_features,
        "cost") %>%
add_min_set_objective() %>%
add_relative_targets(0.1) %>%
add_locked_in_constraints("in") %>%
add_locked_out_constraints("out") %>%
add_binary_decisions() %>%
add_gurobi_solver(gap = 0) %>%
solve()
```



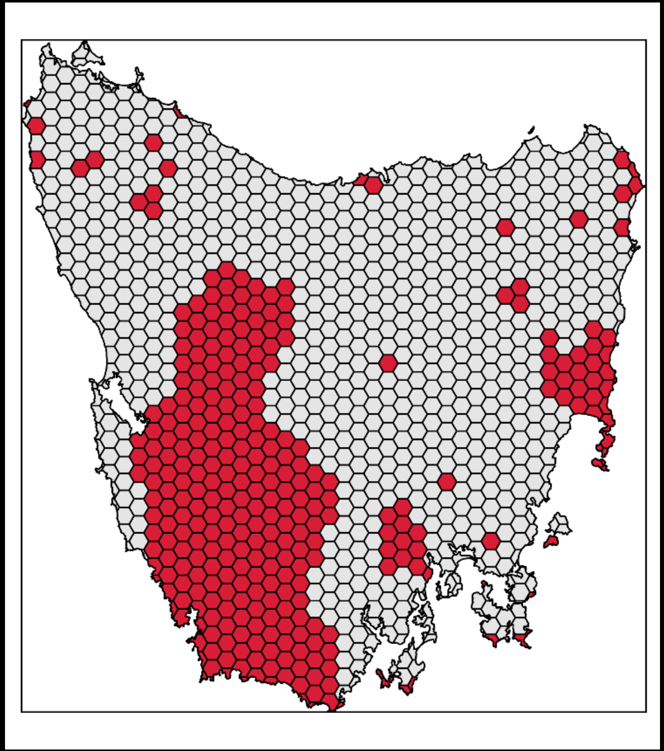
Design your problem

```
problem(tas_pu, tas_features,
        "cost") %>%
add_min_set_objective() %>%
add_relative_targets(0.1) %>%
add_locked_in_constraints("in") %>%
add_locked_out_constraints("out") %>%
add_binary_decisions() %>%
add_gurobi_solver(gap = 0) %>%
solve()
```



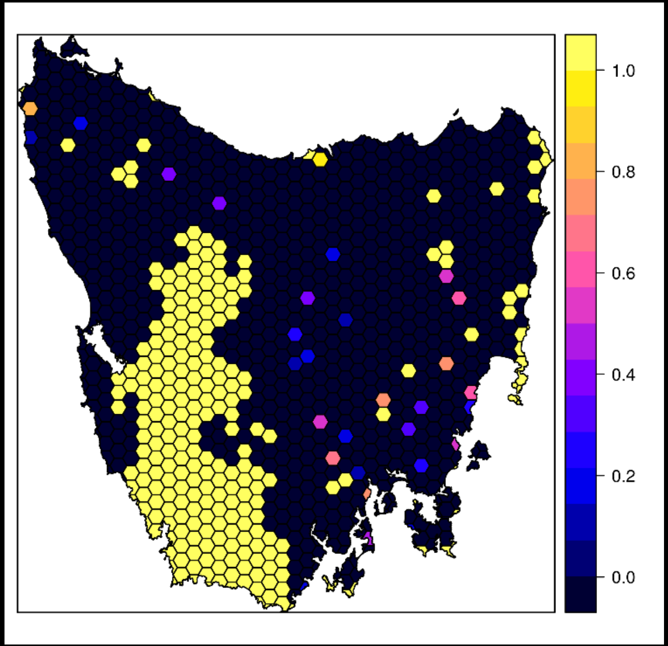
Design your problem

```
problem(tas_pu, tas_features,
        "cost") %>%
add_min_set_objective() %>%
add_relative_targets(0.1) %>%
add_locked_in_constraints("in") %>%
add_locked_out_constraints("out") %>%
add_boundary_penalties(0.01, 0.5) %>%
add_binary_decisions() %>%
add_gurobi_solver(gap = 0) %>%
solve()
```



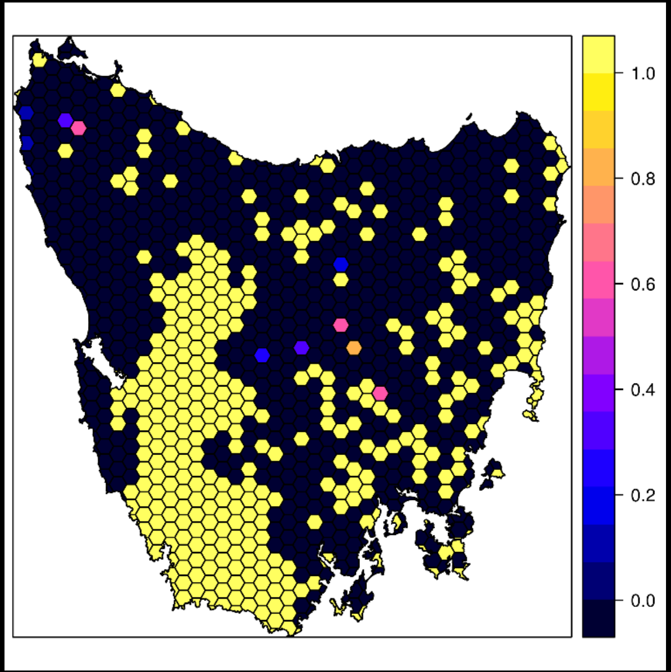
Design <u>your</u> problem

```
problem(tas_pu, tas_features,
        "cost") %>%
add_min_set_objective() %>%
add_relative_targets(0.1) %>%
add_locked_in_constraints("in") %>%
add_locked_out_constraints("out") %>%
add_proportion_decisions() %>%
add_gurobi_solver(gap = 0) %>%
solve()
```

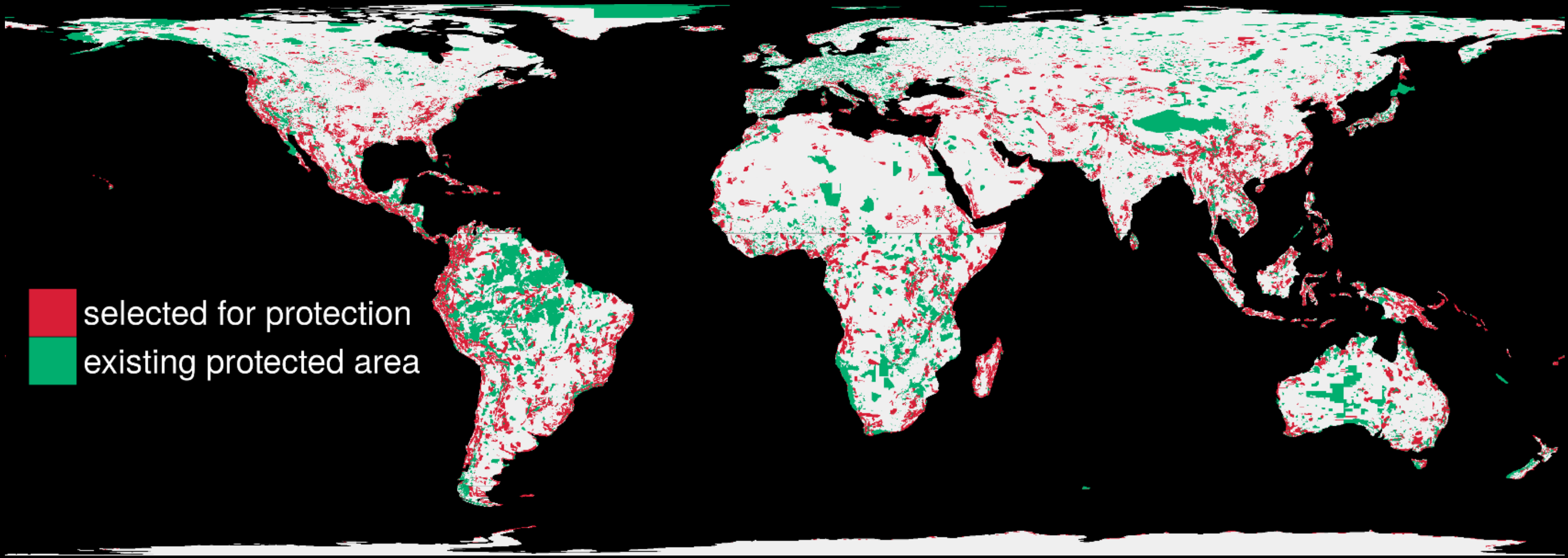


Design your problem

```
problem(tas_pu, tas_features,
        "cost") %>%
add_max_features_objective(budget) %>%
add_relative_targets(0.1) %>%
add_locked_in_constraints("in") %>%
add_locked_out_constraints("out") %>%
add_proportion_decisions() %>%
add_gurobi_solver(gap = 0) %>%
solve()
```



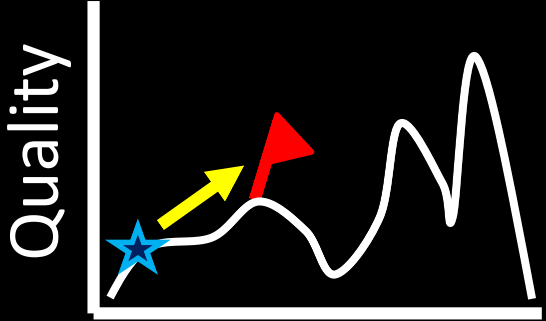
Solve it fast!



1.5 million planning units & 22,644 species: 76 minutes

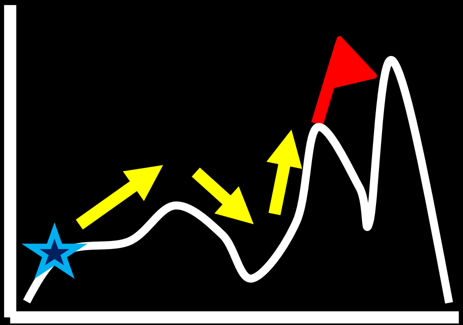
Guaranteed quality

Heuristic algorithms



Different solutions

Meta-heuristic algorithms

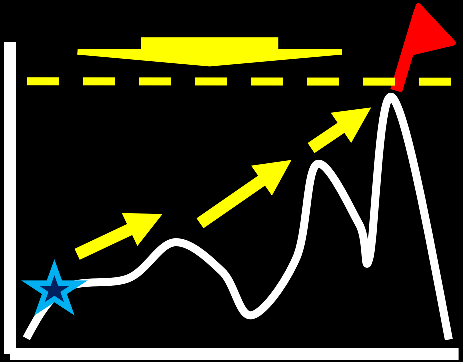


Different solutions

MARXAN
conservation solutions

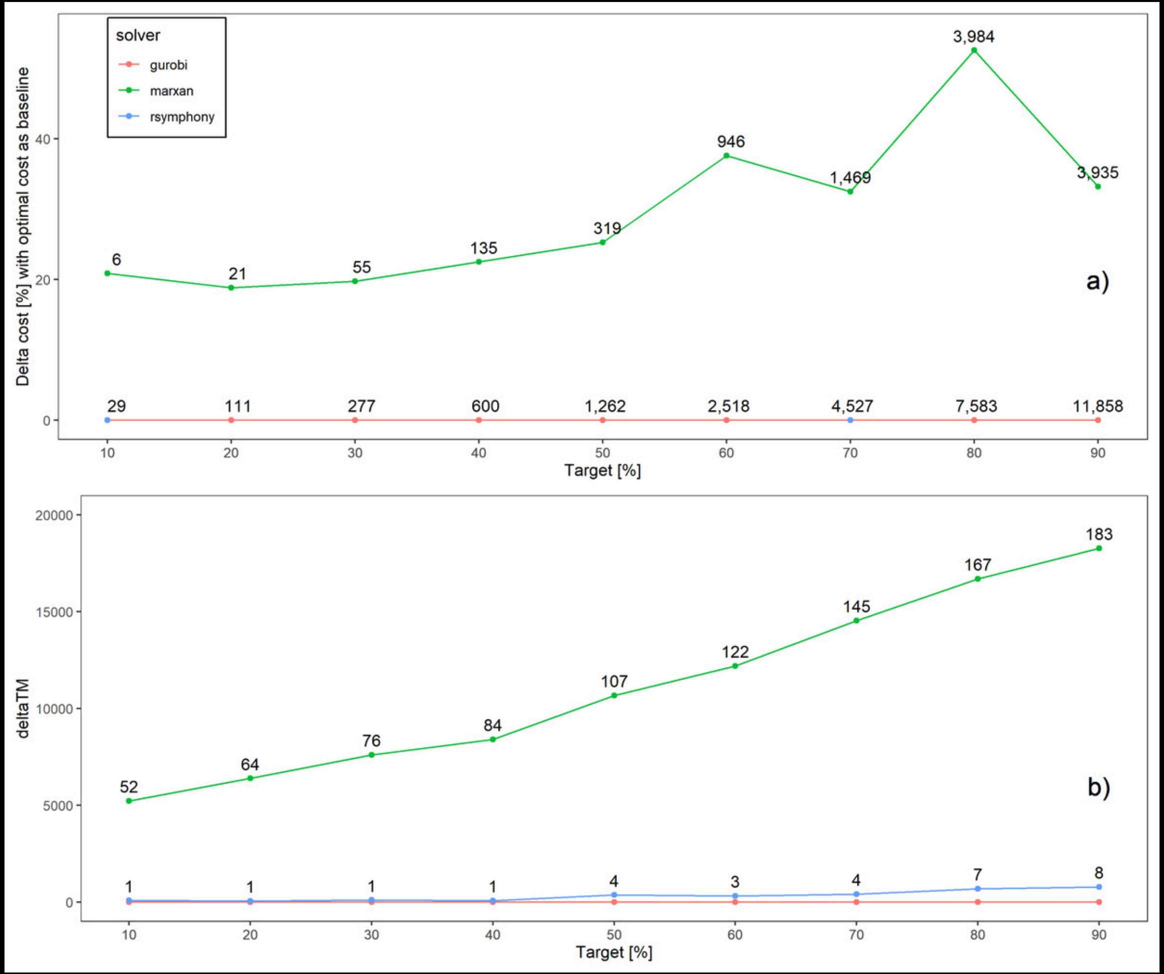
Exact algorithms

Estimate of best solution



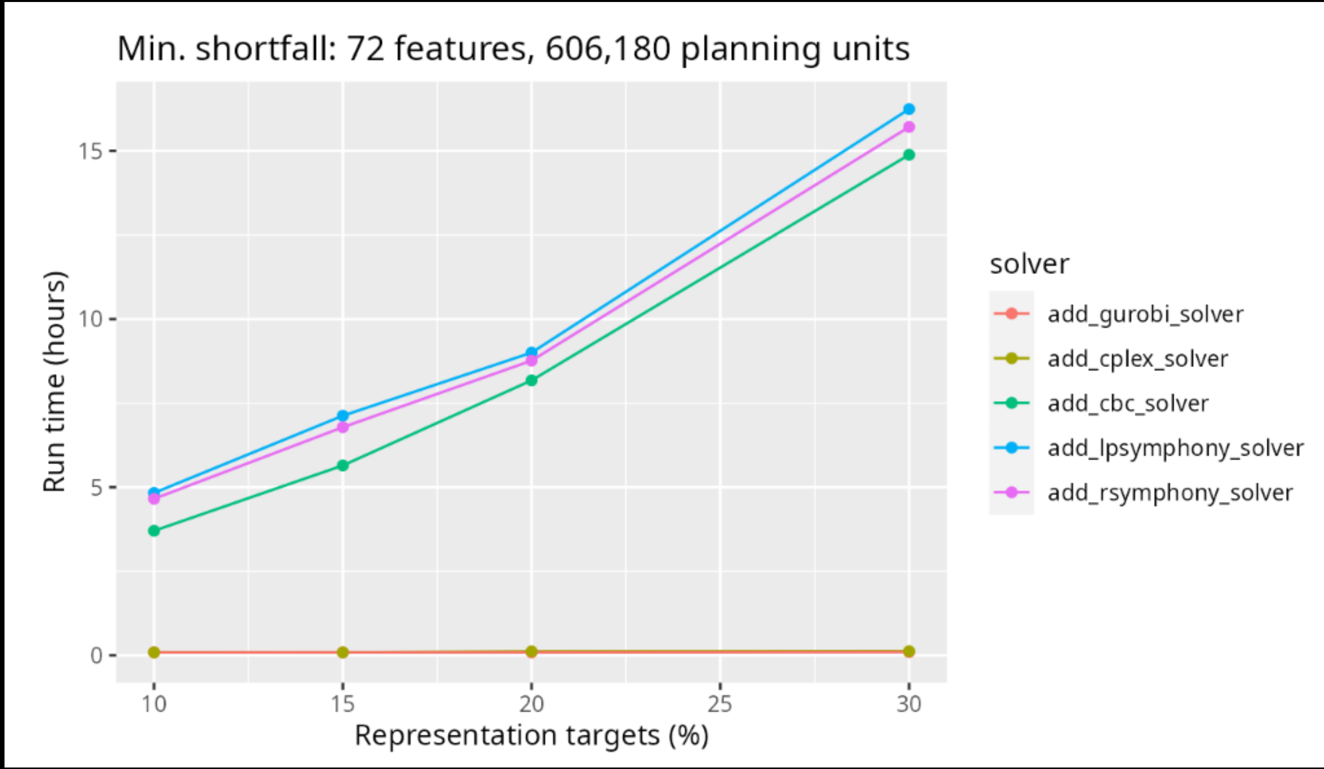
Different solutions

GUROBI
OPTIMIZATION
IBM
CPLEX
COIN|OR



Solve efficiently + fast

Schuster et al. (2020) PeerJ, DOI:10.7717/peerj.9258



The catch: for complex problems, open-source solvers are a lot slower than Gurobi and IBM CPLEX

(https://prioritizr.net/articles/solver_benchmarks.html)

Example

Article | Open Access | Published: 15 April 2019

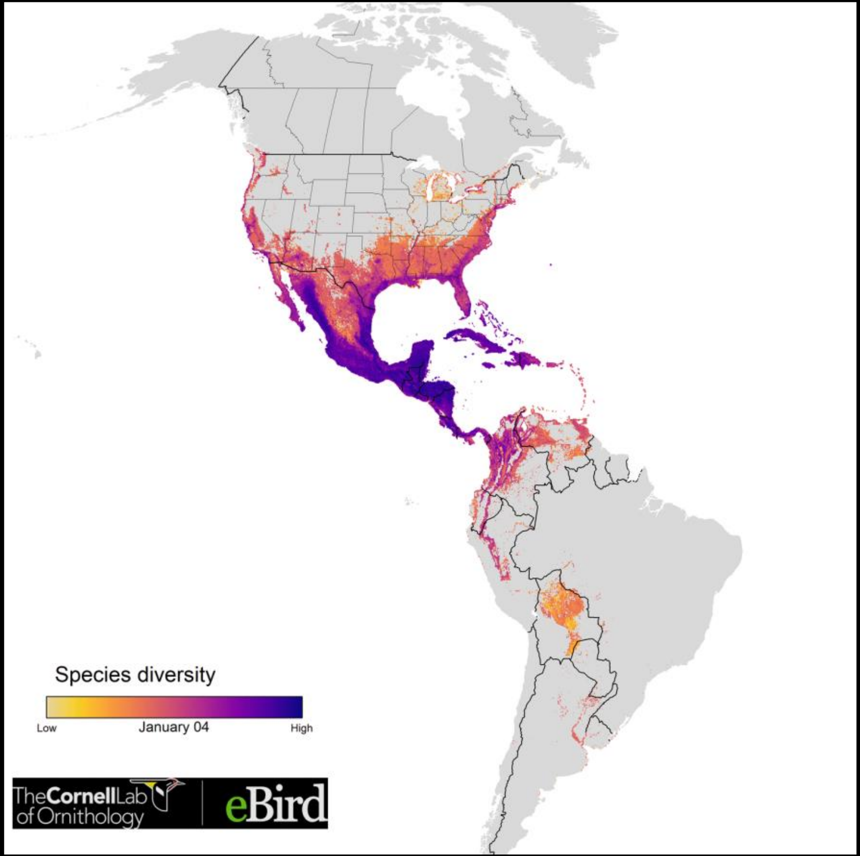
Optimizing the conservation of migratory species over their full annual cycle

Richard Schuster, Scott Wilson, Amanda D. Rodewald, Peter Arcese, Daniel Fink, Tom Auer & Joseph. R. Bennett

Nature Communications **10**, Article number: 1754 (2019) | Cite this article

7249 Accesses | **30** Citations | **130** Altmetric | Metrics

Optimizing the conservation of migratory species over their full annual cycle



117 species
73 million km^2
1.7 million unique locations
14 million checklists

≤ 30,420 features
1.05 million planning units

Analysis powered by:

GUROBI OPTIMIZATION

Schuster et al. (2019) Nature Communications


NATURE
CONSERVANCY
CANADA
Conservation Decision Making
Framework


Resilient Landscapes
Biodiversity
People
Connectivity
Climate
Invasives
Land Use

With CARE, we will identify these priority areas.
What does impact look like?
Conservation of the most important habitats for resilience.
C
CONNECTED
Protected areas are connected so that plants, animals and natural systems are able to survive.
A
ADEQUATE
Protected areas include enough quality habitat to allow a diversity of plants, animals and natural systems to survive.
R
REPRESENTATIVE
Protected areas cover the full range of biodiversity within a region.
E
EFFECTIVE
Protected areas are established and managed effectively to ensure conservation objectives are met.

Where to work?

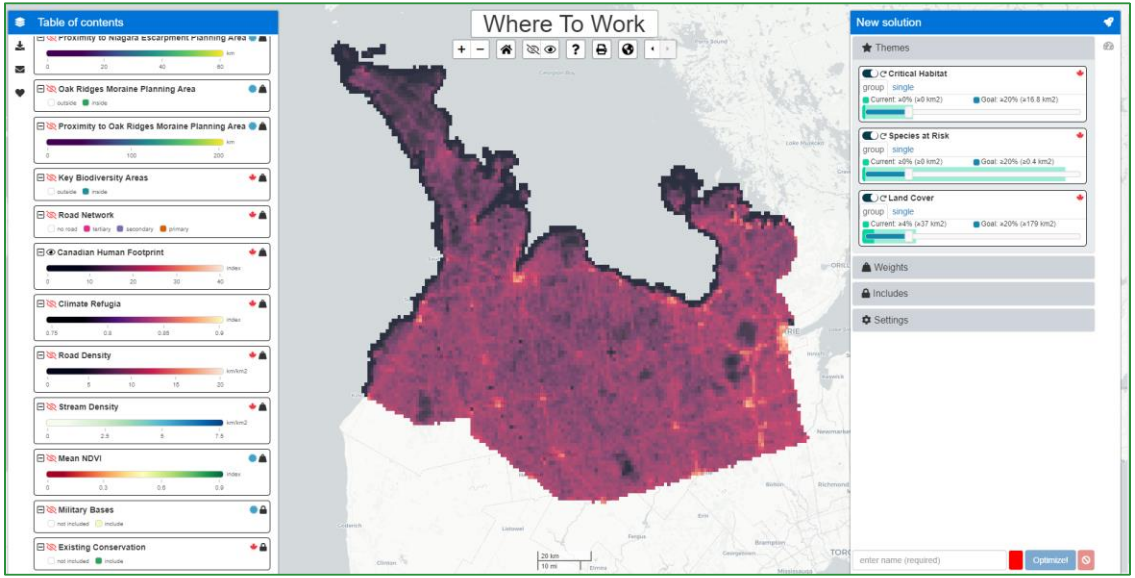
- Resilient landscapes must include:
  - the full range of Biodiveristy,
  - in a sufficiently large area,
  - areas connected to each other
  - protected areas that are effectively managed

- Canada is a big country with a lot of species. Where should we work?

CARE at the Landscape level (Where To Work)

Demo

1. Scalable (Property to Country scale)
2. Seamless (1km grid across Canada)
3. Scientific (best available)



Questions?

jeffrey.hanson@uqconnect.edu.au

richard.schuster@natureconservancy.ca