Systematic Conservation

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RESOURCES FOR THE FUTURE

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Systematic conservation

Spatial optimization of conservation actions

- Reserve site selection (RSS) to determine the optimal spatial configuration of networks of nature reserves
- More general prioritization of conservation activities (spatial and temporal)

Emerged and rapidly developed over the last three decades

- Development of conservation biology as a separate field in the 70s
- First RSS methods to improve expert assessments (early to mid-80s)
- Operations research (late 80s-early 90s)
- Economics (late 90s)

Fast expanding and improving field

- Few hundred papers in the late 90s, recent review identifies closer to 5,000
- Increasingly realistic representations of conservation problems, including ecological processes and spatial and temporal dynamics
- Increasing coverage of species and ecosystems (terrestrial, non-terrestrial)
- Routine application by conservation NGOs and agencies
- More economics and developing country expertise still needed

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Outline

1. Examples of habitat loss
2. Ecological consequences of habitat loss
3. Essential systematic conservation problems
   a) Classical RSS problems: minimal set and maximal coverage
   b) General problem
   c) General problem with exogenous site benefits and costs
4. Important extensions
   a) Multi-objective problems
   b) Spatial ecological processes
   c) Sequential conservation decision problems
   d) Meta-population dynamics
   e) Uncertain species' distributions
   f) Value of information
5. Estimating the cost of conservation
6. Further need for economists' contributions

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Notes and caveats

1. This talk draws from "Conservation prioritization using reserve site selection methods," by Newbold and Siikamäki, forthcoming in "Handbook of the Economics of Natural Resources" (eds. Halvorsen and Layton)

2. My purpose is not to present a comprehensive a review
   a) Comprehensive review out-of-scope
   b) The purpose is to be informative and illustrative
   c) Let me know if I missed your or other essential work

3. I will focus on highlighting contributions by economists
   a) Consistent with the target audience
   b) However, the vast majority of systematic conservation research has taken and will take place outside economics

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Preventing habitat loss is a key goal of systematic conservation

Examples of habitat loss …

Amazon

Source: Landsat, Google Earth Engine

Amazon

Source: Landsat, Google Earth Engine

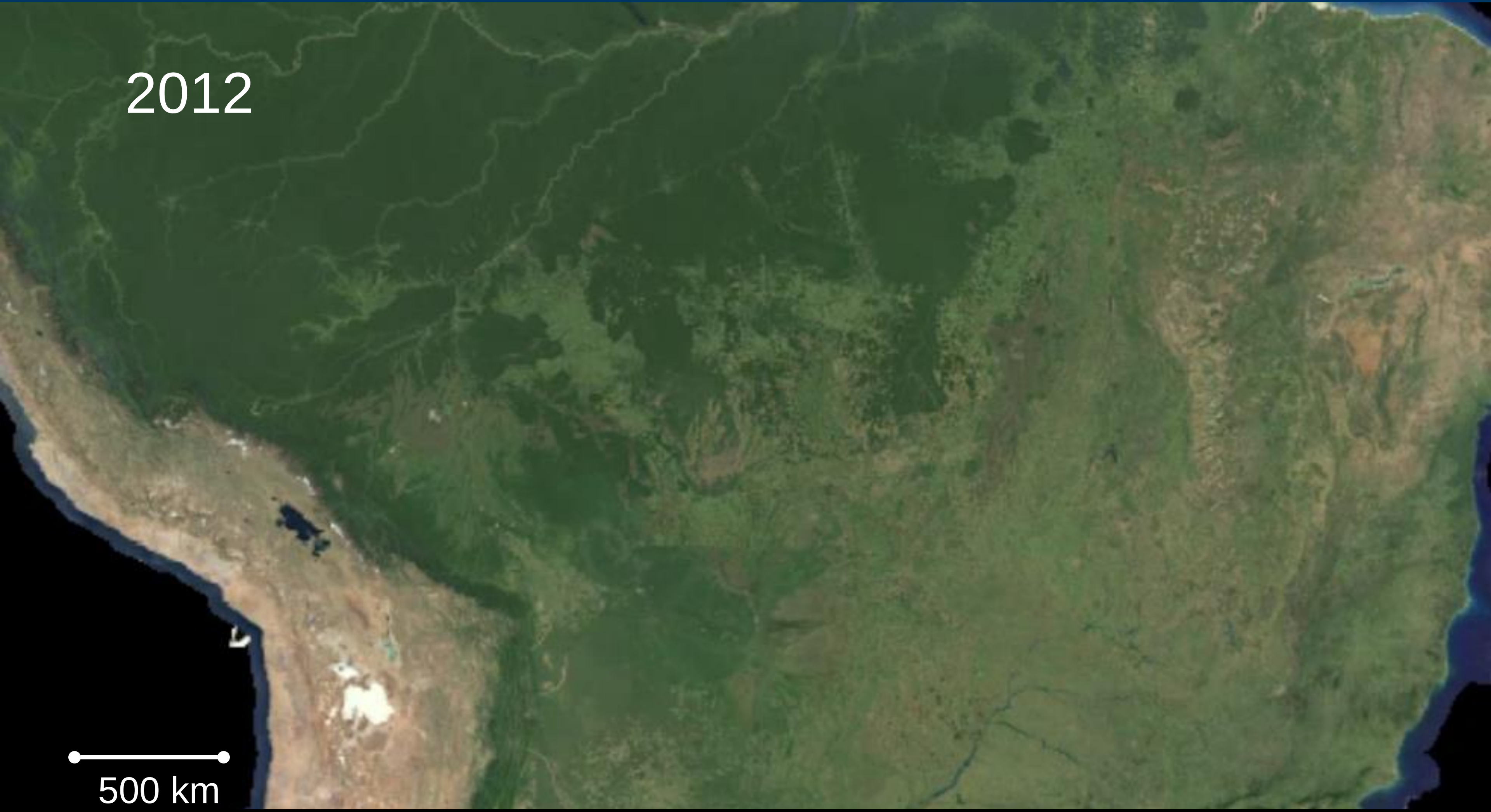
Amazon

Source: Landsat, Google Earth Engine

Amazon

Source: Landsat, Google Earth Engine

Amazon



Source: Landsat, Google Earth Engine

Cancun

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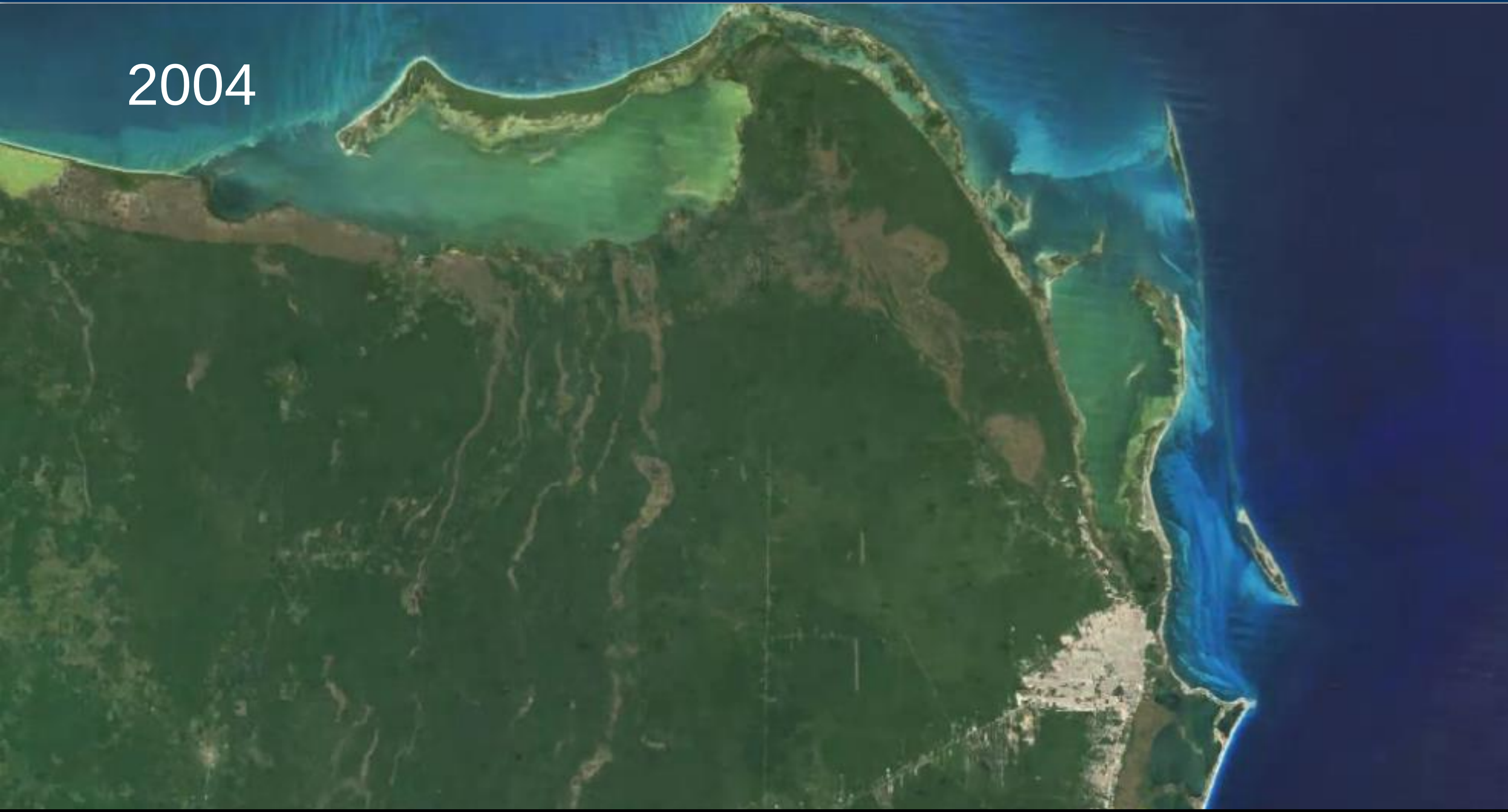
Cancun



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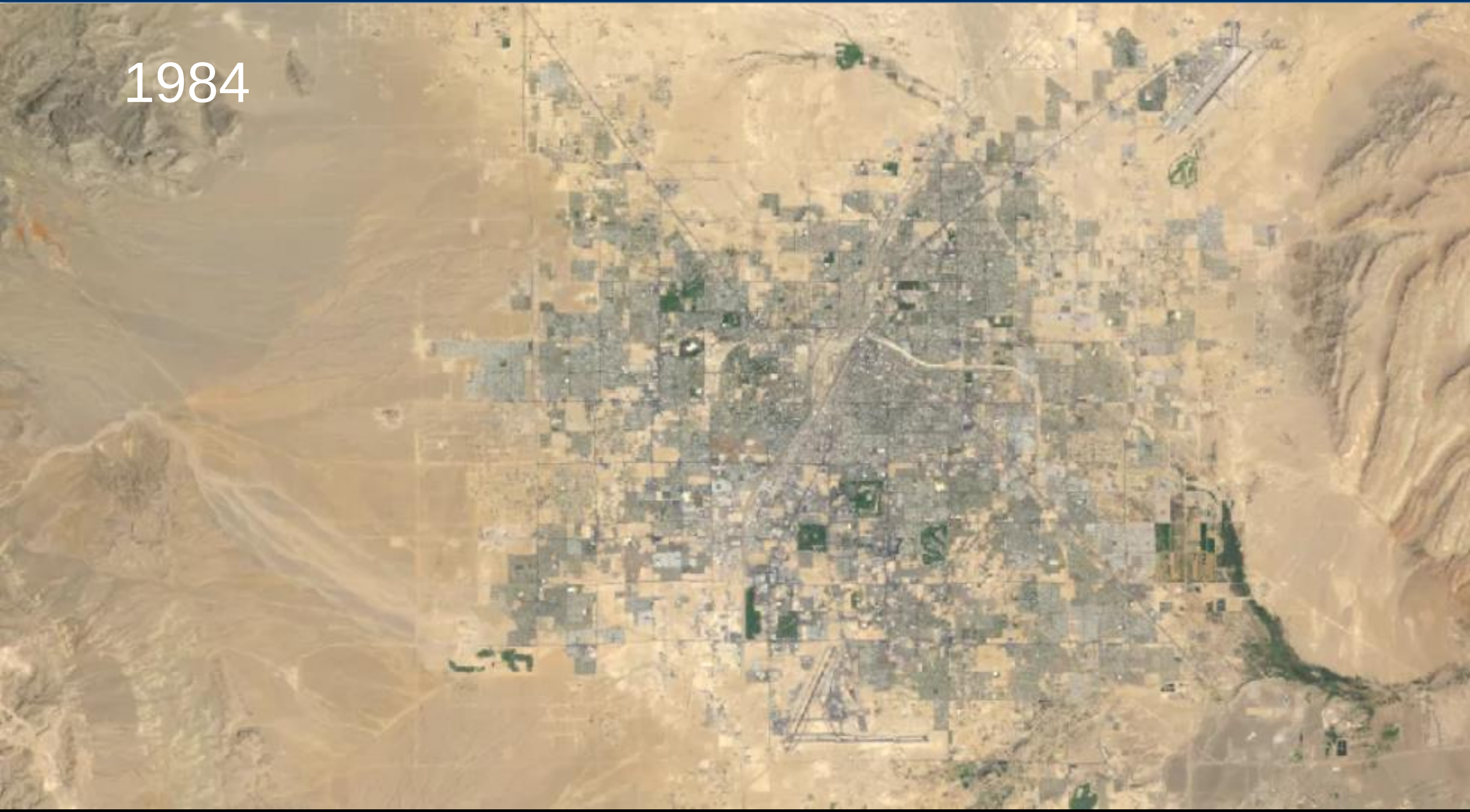
Source: Landsat, Google Earth Engine

Las Vegas



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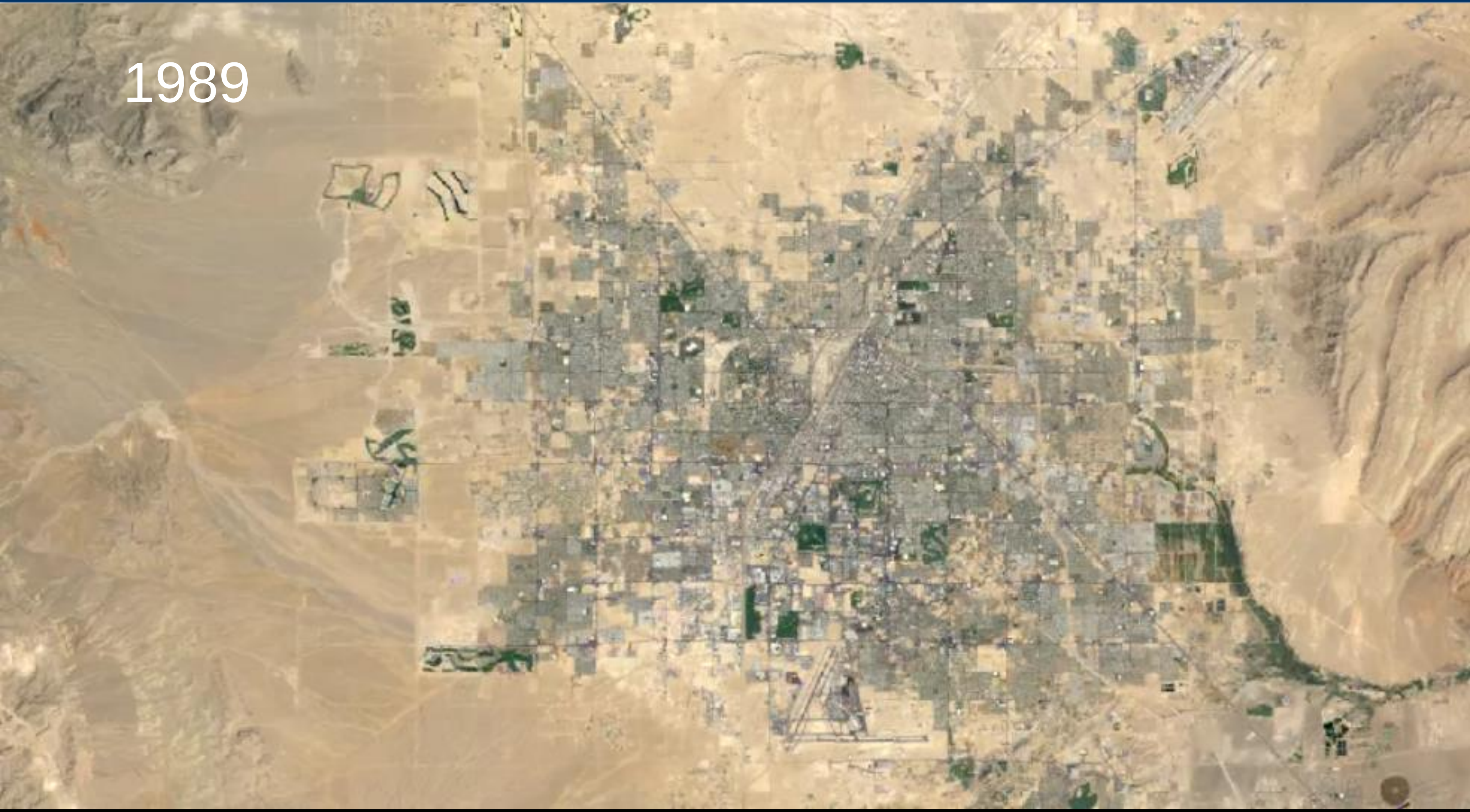
Las Vegas



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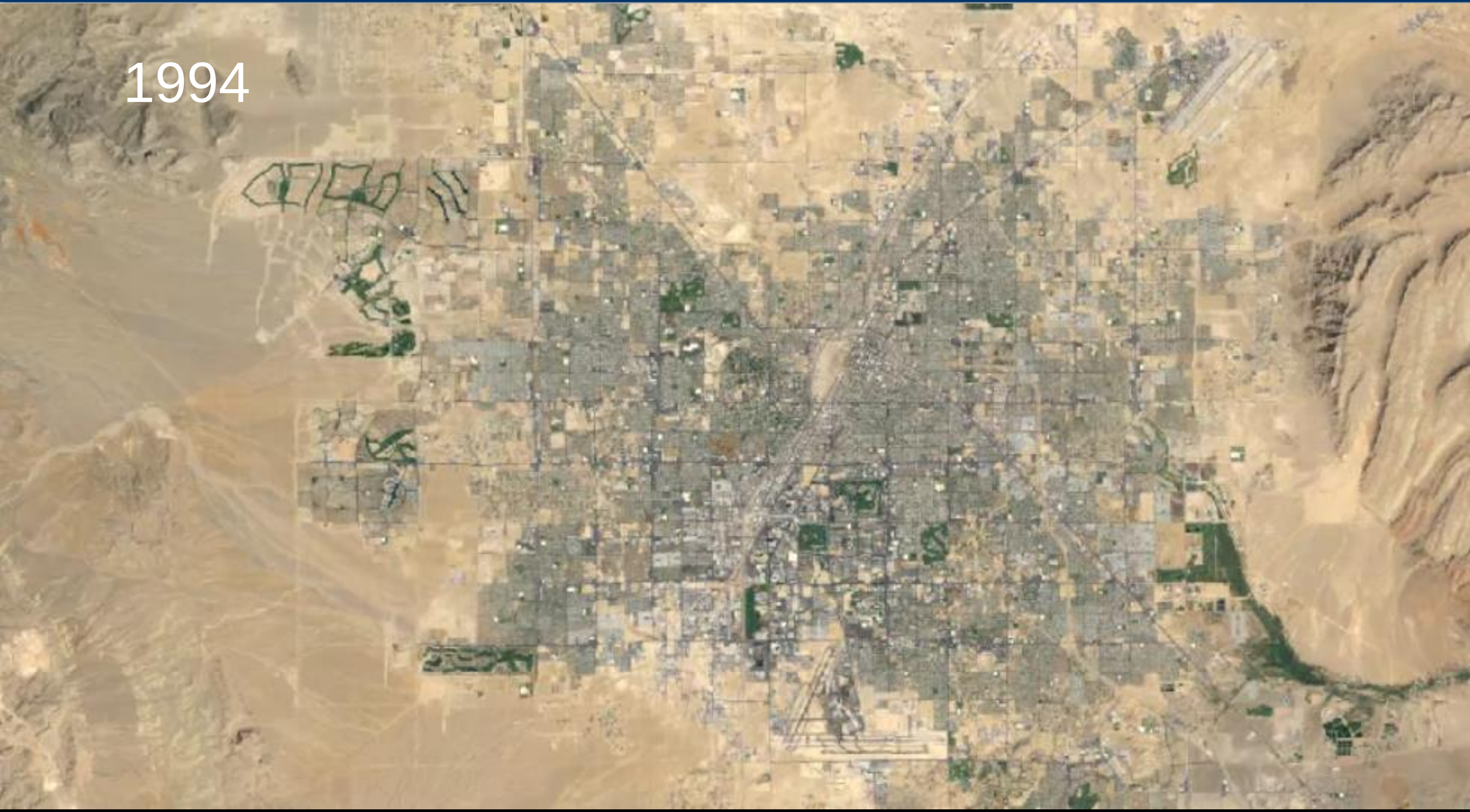
Las Vegas



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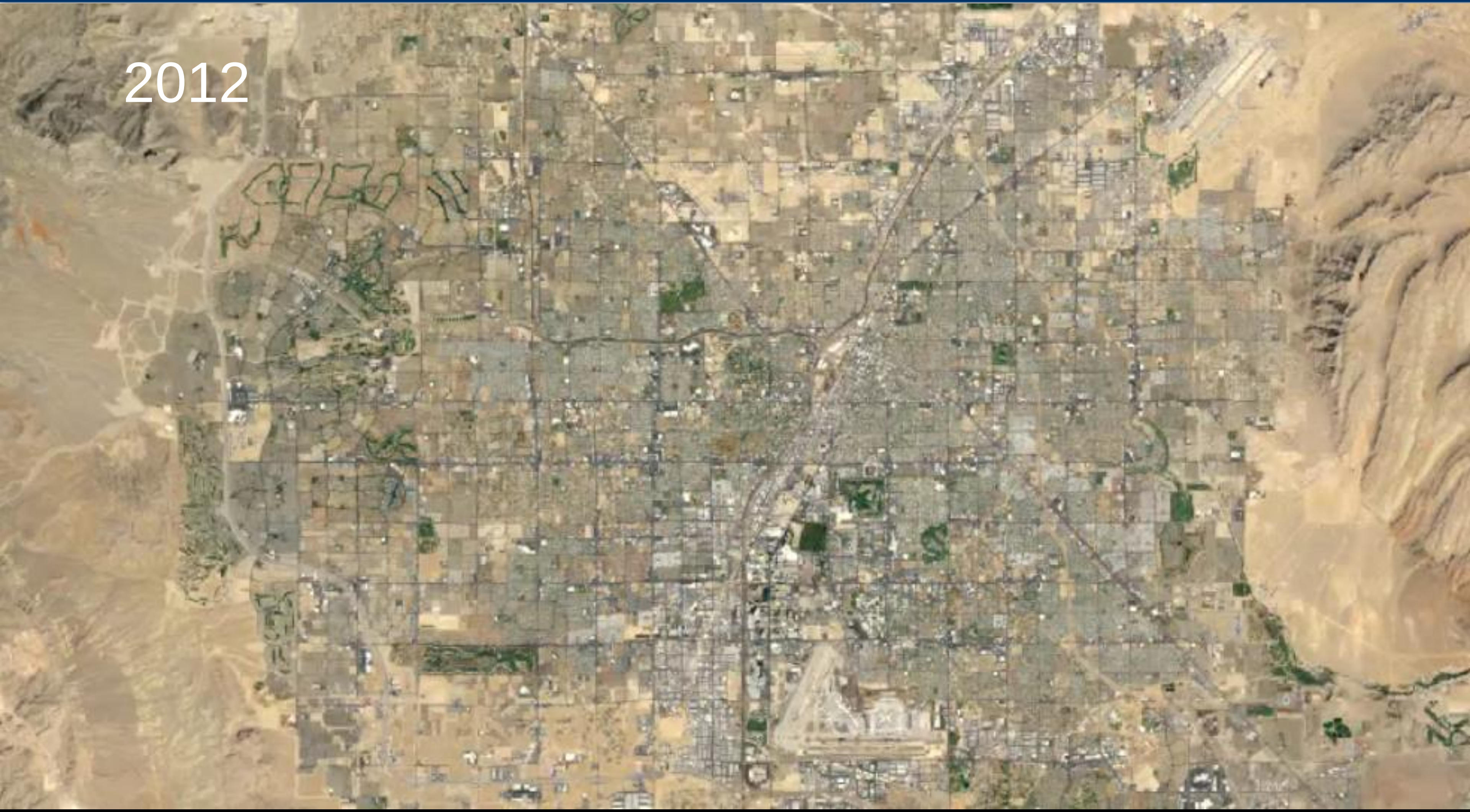

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Ecological consequences of habitat loss

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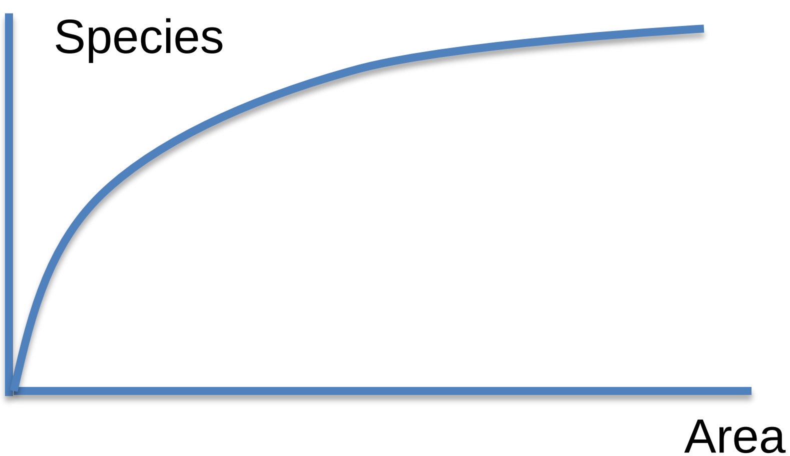
Species Area Relationship

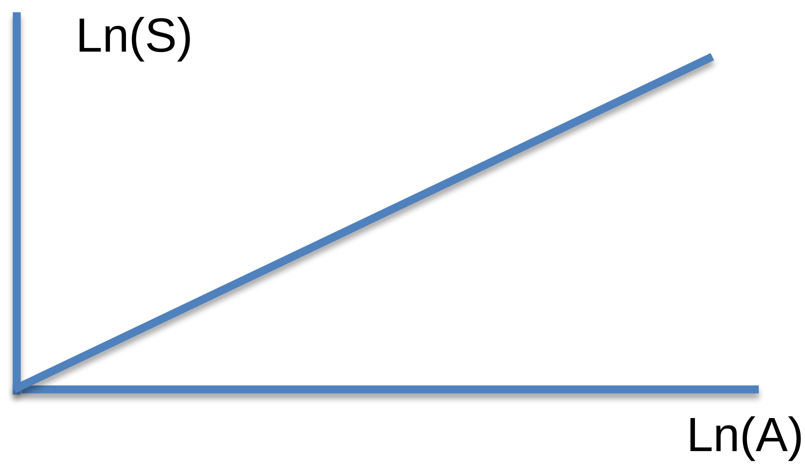
Theory of island biogeography

- Habitats as islands ("islands" generally, not solely as land separated by water)
- Large islands harbor more species
- Darwin, Wallace, MacArthur, Wilson, May, Preston, Simberloff, many others

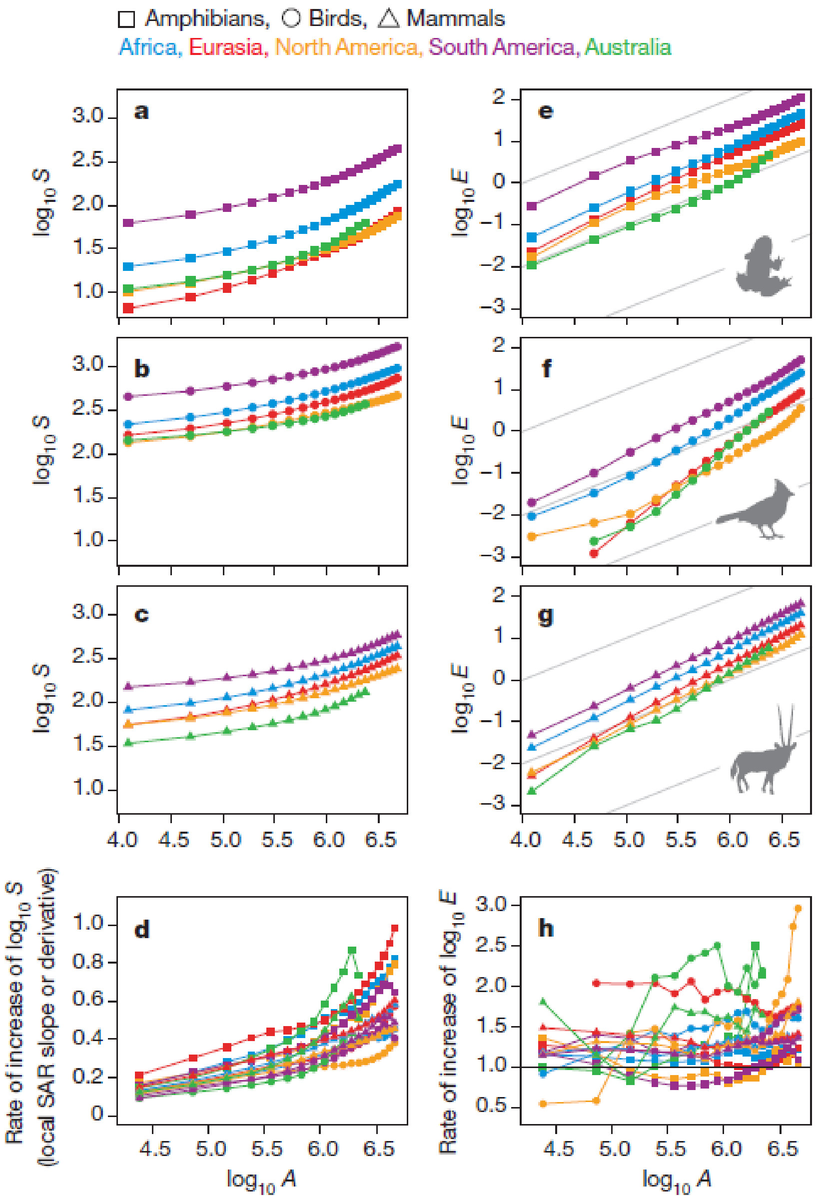
General formulation $S_i = cA_i^z$

- S_i is the number of species present
- *A* is the total habitat/area
- *c* and *z* are parameters





Species Area Empirical Relationship



General results

- Variation in c, but z remarkably narrow-ranged
- Many estimates available for many locations, scales, taxonomic groups

Source: Storch, D., Keil, P., & Jetz, W. (2012). Universal species-area and endemics-area relationships at continental scales. *Nature*, *488*(7409), 78-81.

Habitat loss → Loss of biodiversity

Current rate of species loss

- Several orders of magnitude greater than in fossil records
- Comparable to the most rapid extinction episodes (mass extinctions) identified by paleontologists

One of today's most pressing global environmental problems

Convention for Biological Diversity in Rio de Janeiro 1992

- Stop biodiversity loss by 2010
- Limited success -- failure to even substantially slow down the loss of biodiversity

One way to improve conservation is to more effectively target conservation towards projects and locations with the highest biological returns per dollar

Systematic conservation helps deliver remarkably greater returns on conservation investment than conventional subjective, expert approaches

- Improved targeting/prioritization
- Cost-benefit assessments

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Historical overview of RSS methods

Classical RSS problems

- Kirkpatrick (1983), Ackery and Vane-Wright (1984), Margules (1987)
- *Minimum set problem*
  - Find the minimum number (area) of sites which include all target species at least once
- *Maximum coverage problem*
  - Find the set of sites that contain the most species, given not all species can be preserved

Solutions through heuristic (greedy) algorithms

Quantitatively more rigorous approaches enter starting late 80s

- Cocks and Baird (1989): RSS is a classical integer programming problem
- Underhill (1994): heuristic algorithms often sub-optimal
- Flood of subsequent contributions by operations researchers, conservation biologists and economists (e.g. Camm et al. 1996, Willis et al. 1996, Csuti et al. 1997, Pressey et al. 1997, Williams and ReVelle 1997, Possingham et al. 2000, Polasky et al. 2001, Moilanen et al. 2000s)

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Complementarity and minimum set problem (Underhill 1994)

	Species							
Site	1	2	3	4	5	6	7	8
1	0	0	1	1	1	1	1	0
2	1	1	1	1	0	0	0	0
3	0	0	0	0	1	1	1	1
4	1	0	0	0	0	0	0	0
5	0	0	0	0	0	1	1	0

Complementarity and minimum set problem (Underhill 1994)

	Species							
Site	1	2	3	4	5	6	7	8
1	0	0	1	1	1	1	1	0
2	1	1	1	1	0	0	0	0
3	0	0	0	0	1	1	1	1
4	1	0	0	0	0	0	0	0
5	0	0	0	0	0	1	1	0

- Optimal algorithm: select two sites (sites 2 and 4)

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Complementarity and minimum set problem (Underhill 1994)

	Species							
Site	1	2	3	4	5	6	7	8
1	0	0	1	1	1	1	1	0
2	1	1	1	1	0	0	0	0
3	0	0	0	0	1	1	1	1
4	1	0	0	0	0	0	0	0
5	0	0	0	0	0	1	1	0

- Greedy algorithm: select three sites (first site 1, then site 2, then 3)

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Optimal versus heuristic algorithms

Optimizing algorithms

- guarantee globally optimal solutions
- computationally demanding or infeasible when the number of candidate sites is large and inter-dependencies exist between sites

Heuristic (greedy) algorithms

- approximate optimal solutions
- trade optimality for speed and feasibility
- typically fairly close to the optimum

Choosing between optimal and heuristic algorithms

- Depends on the problem at hand
- If optimal approach is feasible, then use it
- But do not abandon an important problem just because optimality is not feasible; sub-optimal algorithms generally do well

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Critique of the classical RSS problem

Overly simplistic

Species preservation denoted by 0,1 presence-absence in the set

- What qualifies as presence (minimum abundance, habitat area)?
- No benefit from overrepresentation (species presence in more than one reserve site)
- Extinctions are probabilistic events
- Extinctions are not the only concerns (broader benefits from conservation)

Costs are not included or poorly accounted for

- Costs first denoted using a 0,1 variable (c_i=1), then using land area
- Opportunity cost not taken into account
- Key insight on the importance of costs by Ando, Camm, Polasky, Solow (Science 1998)

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Incorporating opportunity cost (Ando et al. 1998)

- RSS problem involving endangered species in the USA (response to a study excluding costs)
- Objective: identify the minimum (cost) sites to increase coverage of target species
- Counties as units of analysis
- Costs measured using county-level data on agricultural land values

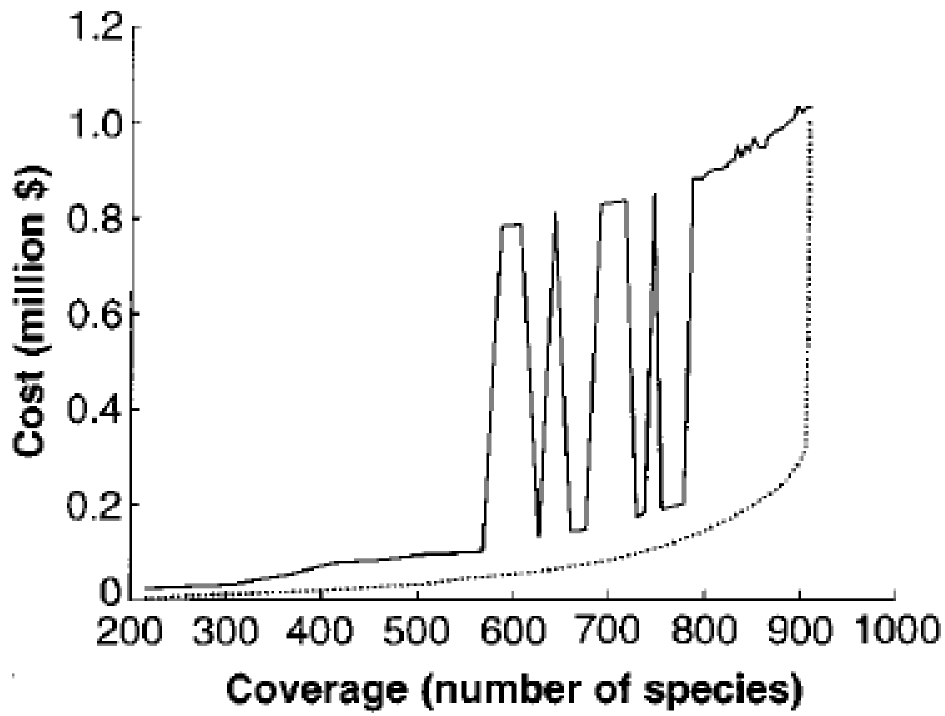

Fig. 1. Cost versus coverage for site-minimizing (solid curve) and cost-minimizing (dotted curve) solutions.

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Site selection with and without opportunity cost (Ando et al. 1998)

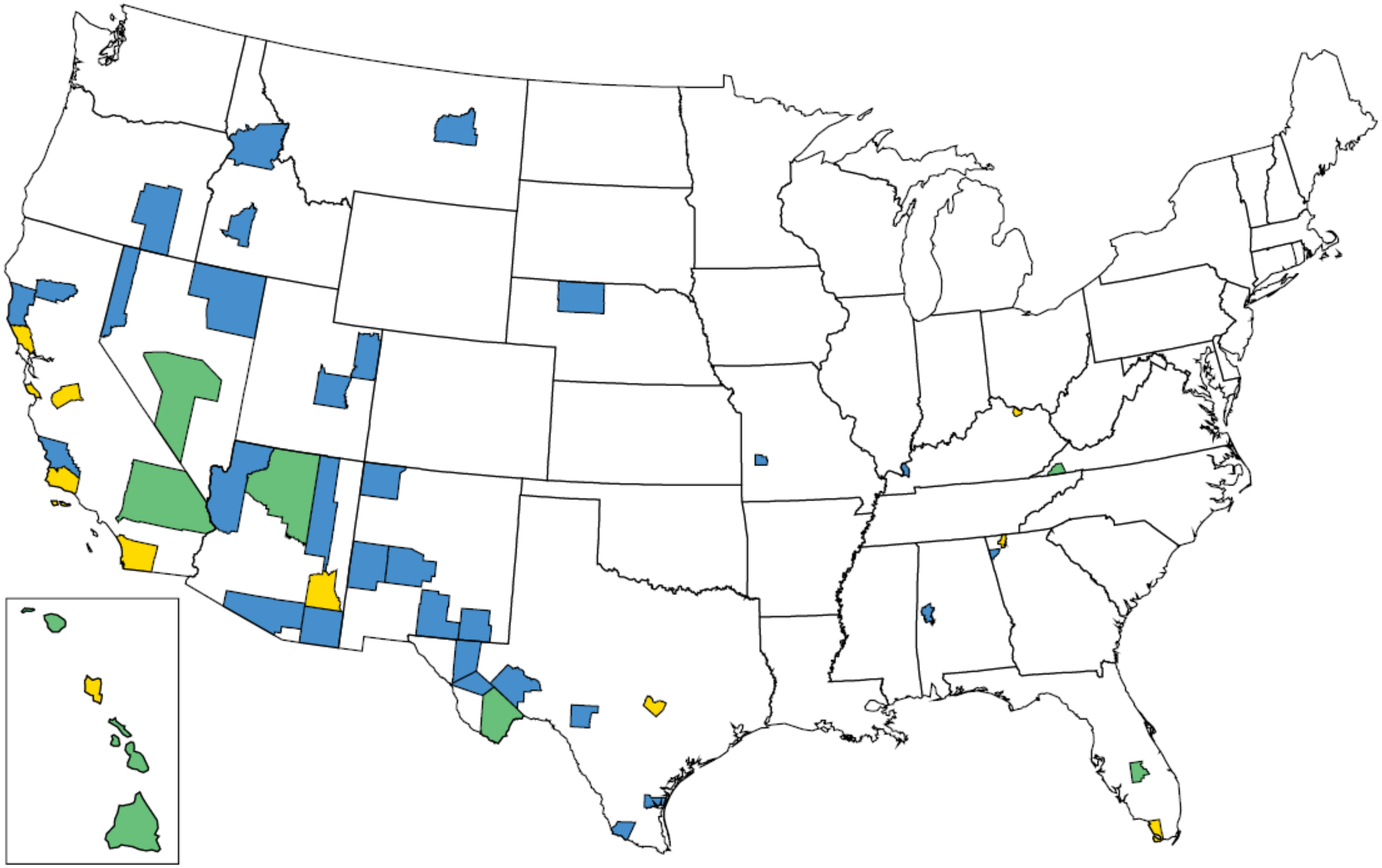

Fig. 2. Selected sites for coverage of 453 species in the United States. Sites in the site-minimizing solution only are shown in yellow, sites in the cost-minimizing solution only are shown in blue, and sites in both solutions are shown in green.

Systematic Conservation: General Problem

Constrained benefit maximization or cost minimization problem

$$\max \quad V \;\; \mathbf{x} \qquad\qquad \min \;\; \sum_i c_i x_i$$

$$s.t. \quad \sum_i c_i x_i \le M \qquad\qquad s.t. \quad V \;\; \mathbf{x} \;\ge Z$$

where

- candidate sites (activities) for protection indexed by i=1,2,…,I
- x_i {0,1} indicates whether site or activity i is selected for conservation
- *V(x)* is the value function (e.g., species, land area)
- variable c_i is the cost of conservation activity
- *M* is the maximum total budget
- *Z* is the minimum ecological target

Nests classical RSS problems

- c=1, J=Z (minimum set)

General Problem Under Exogenous Site Benefits and Costs

Maximization/minimization problem

$$\max \quad V \quad \mathbf{x} \qquad\qquad\qquad \min \quad \sum_i c_i x_i$$

$$s.t. \quad \sum_i c_i x_i \leq M \qquad\qquad\qquad s.t. \quad V \quad \mathbf{x} \geq Z$$

Where

- $V \quad \mathbf{x} = \sum_i b_i x_i$
- b_i is an exogenous ecological endpoint
  - species richness/abundance
  - habitat area protected or restored
  - flow of an ecosystem service to be provided
  - other desirable ecological feature

When b_i's and c_i's are exogenous (i.e., independent of all x_j's), the problem can be solved using a “knapsack” algorithm (Dantzig 1957)

- rank candidate sites in decreasing order of their benefit-cost ratios
- add sites to the reserve until exhausting the budget

Ferraro (JPPAM 2003): riparian buffer acquisition in the Lake Skaneateles watershed near Syracuse, New York

Conservation goal is to acquire conservation easements to limit the need for a costly upgrade to the local drinking water treatment plant

Contribution of each site to lake water quality estimated by scoring functions developed by a scientific panel based on the biophysical attributes of each parcel

Conservation easements were assumed to cost 50% of the assessed land values on each parcel

A knapsack algorithm to determine the optimal set of parcels for a wide range of possible budgets, from near zero to the full cost of all parcels.

Under optimal prioritization approach, about 55% of the maximum possible benefits could be achieved if the budget was equal to 20% of the total cost of all parcels.

Babcock et al. (1997) develops the basic framework and several valuable insights

Ferraro (JPPAM 2003): riparian buffer acquisition in the Lake Skaneateles watershed near Syracuse, New York

Ferraro *Targeting Conservation Investments*

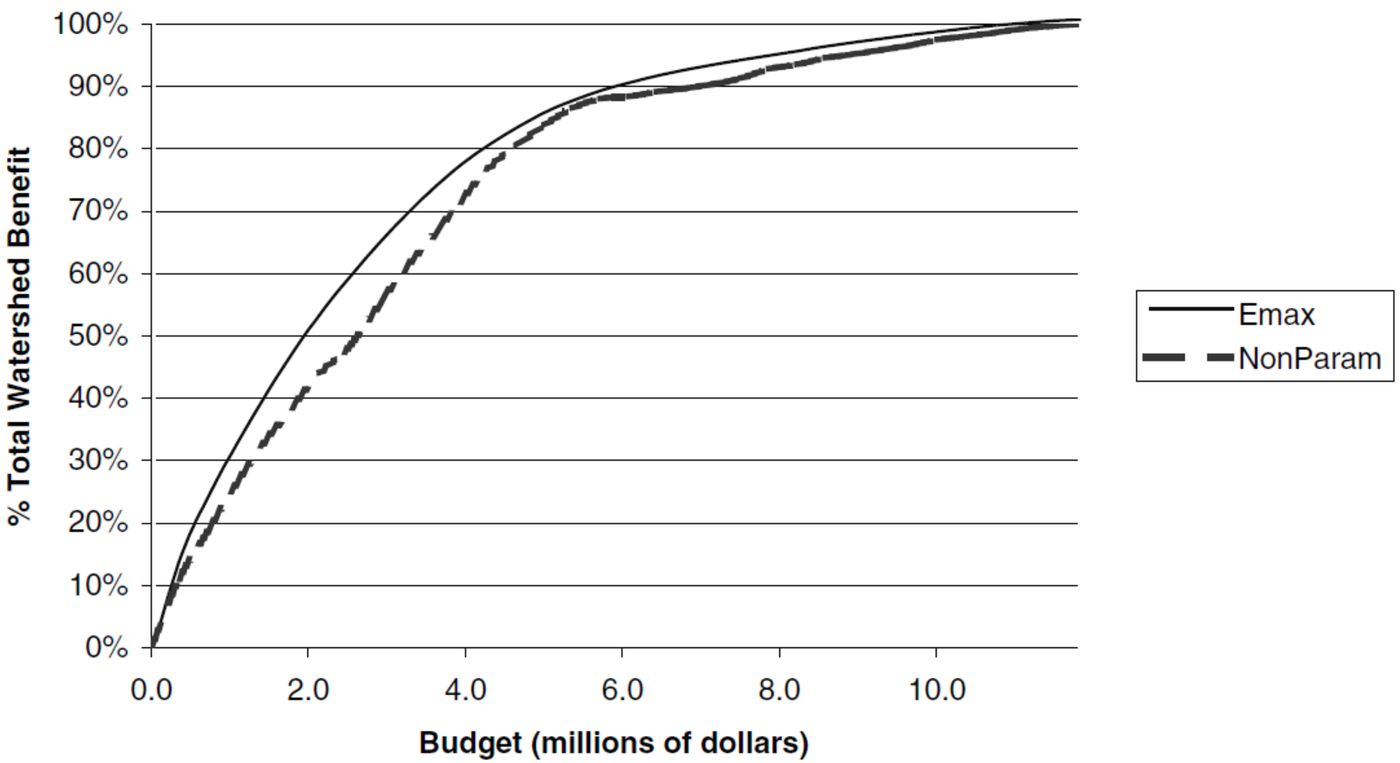

Figure 2. Portfolio performance (interval-scale scoring equation)

Siikamäki et al. (PNAS 2012): Global economic potential for avoiding emissions from mangroves loss

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Coastal Development

Study Framework

Purpose

- Estimate CO_2 emissions from mangrove loss
- Estimate the cost of preventing mangrove loss (thus, emissions)
- Does the value of avoided emissions outweigh conservation costs?

Methodological framework

- Develop fine spatial grid to partition world's land surface (9*9 km cells)
- Identify mangroves (over 25,000 grid cells)
- For each grid cell, estimate carbon storage, loss rates, conservation costs
- Use a knapsack algorithm to minimize the cost of specific emission reduction targets
- Repeat for many reduction targets to trace out the marginal cost curve of avoided emissions

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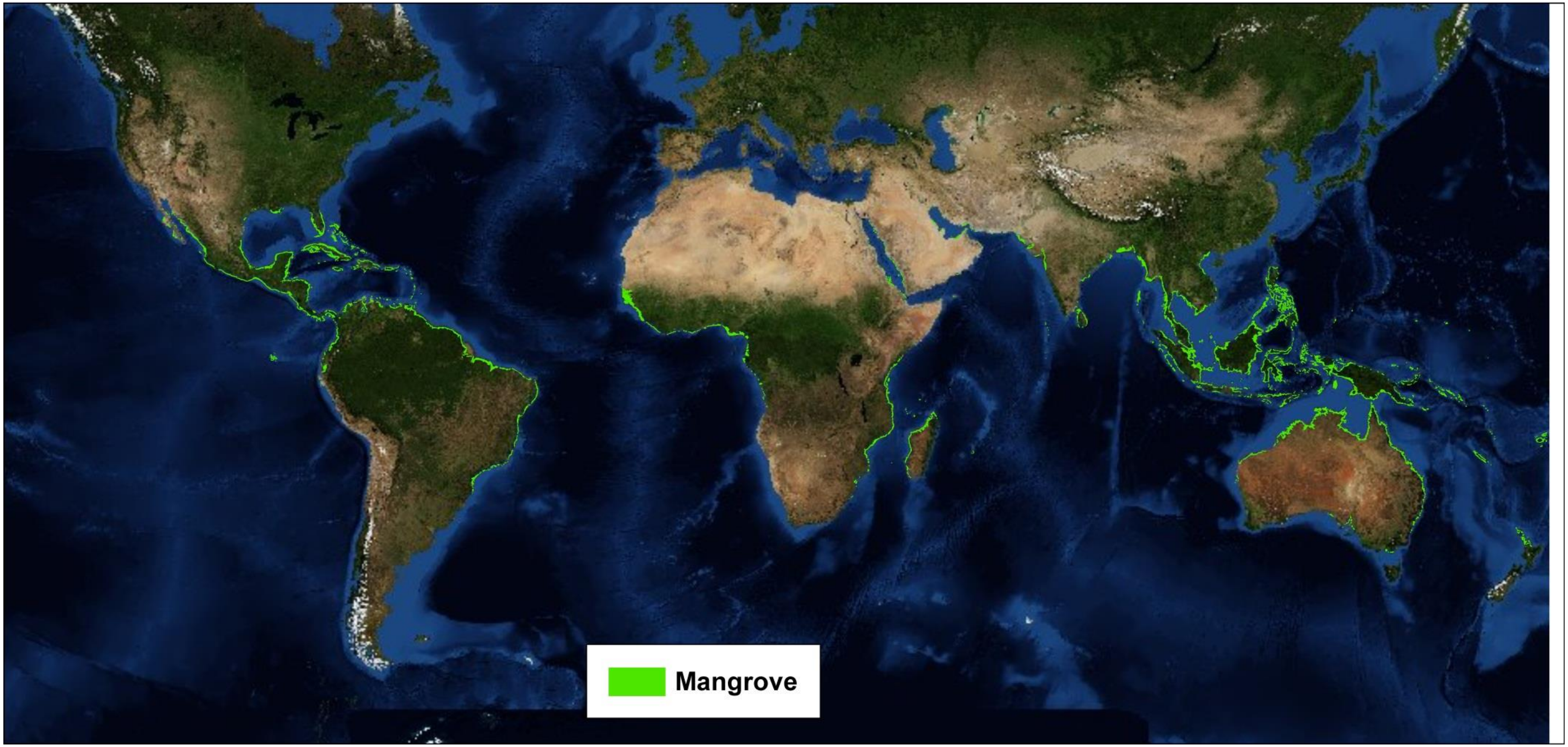
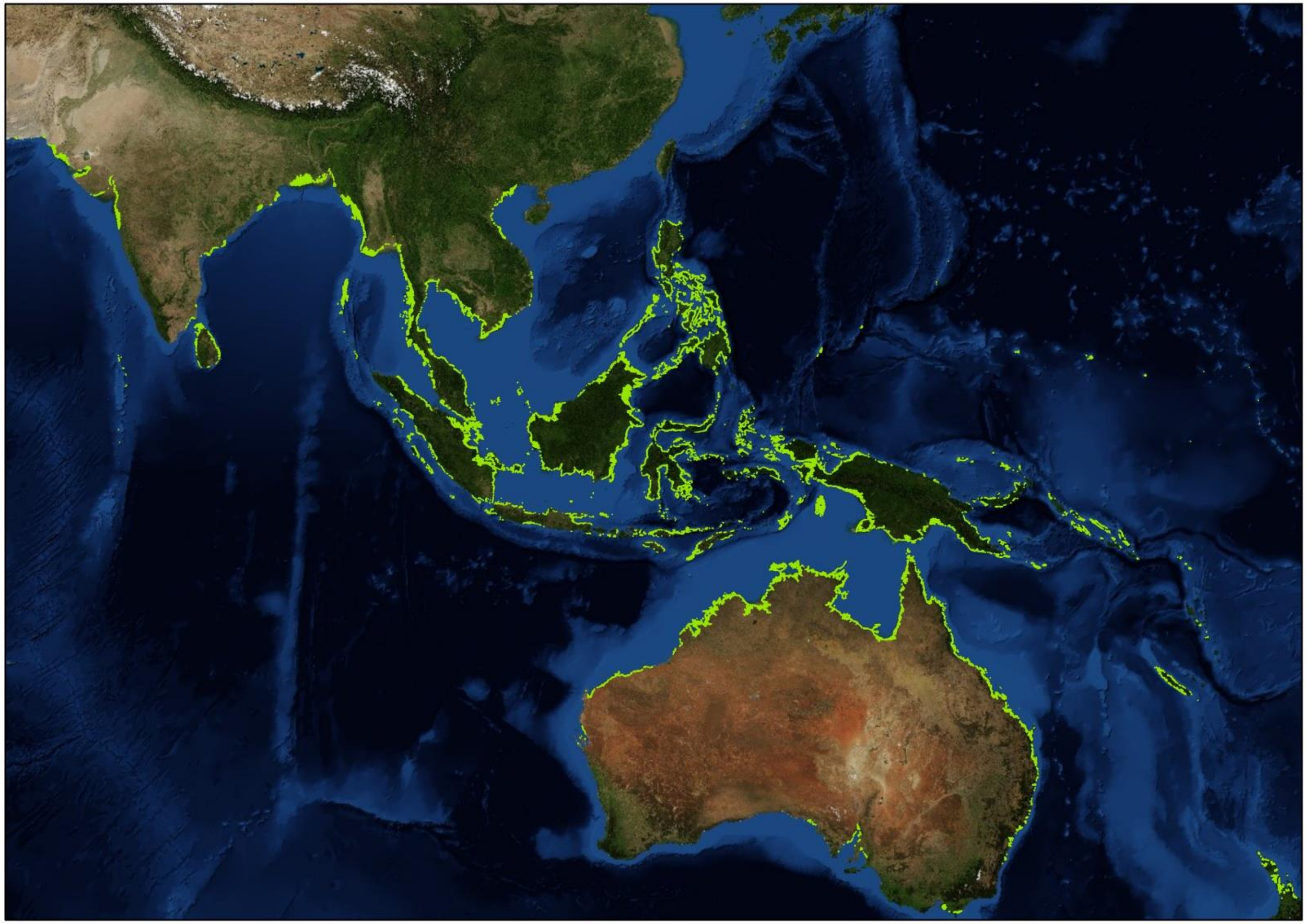
Mangroves

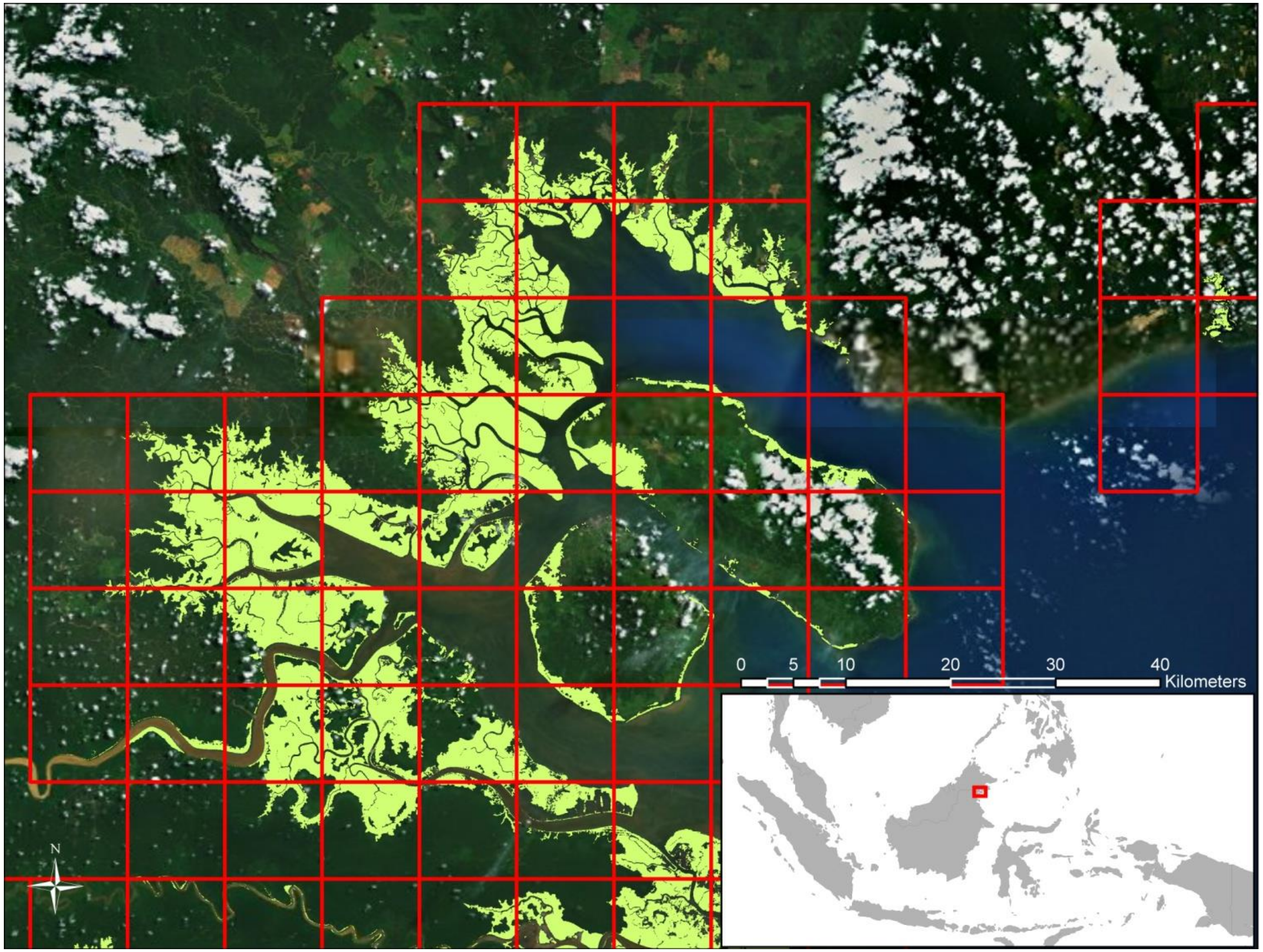


SE Asia, Oceania

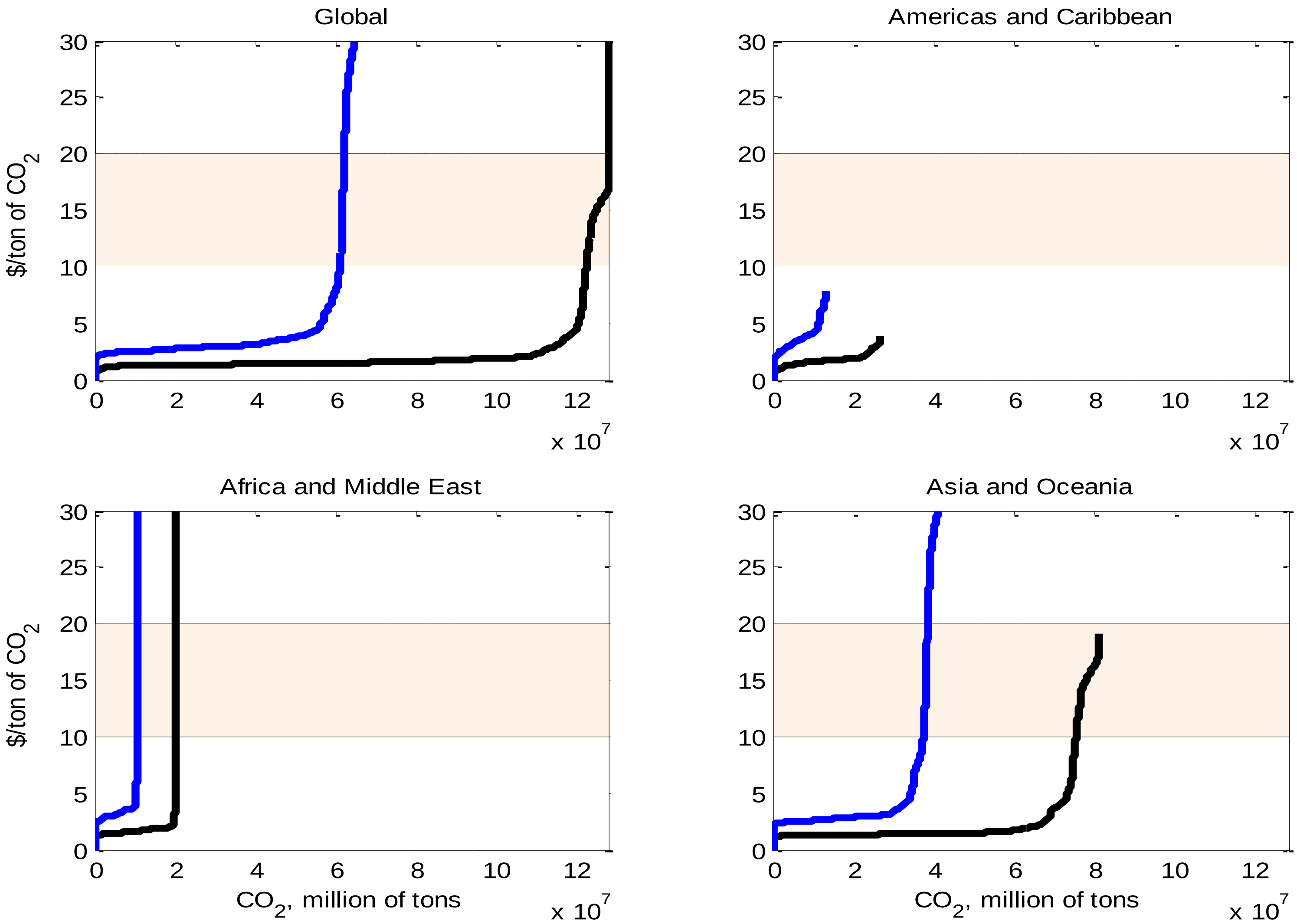


Borneo

Grid cells as units of analysis



Results: Global and Regional Supply of Avoided Emissions



Multi-objective RSS problems

Motivation

- Many conservation programs explicitly address multiple goals
- Single-objective programs generally support multiple objectives
- But multiple goals generally not included in the planning framework

Maximization/minimization problem

$$\max \; V(\mathbf{x}) \qquad s.t. \quad \sum_i c_i x_i \le M$$

$$\min \; \sum_i c_i x_i \qquad s.t. \quad V(\mathbf{x}) \ge Z$$

Where

- $V(\mathbf{x}) = x_i f(y_{i1}, y_{i2}, \ldots, y_{iJ})$
- Common specification $V(\mathbf{x}) = \sum_j \sum_i w_j y_{ij} x_i$
  - w_j is the value placed on endpoint j
- How to specify weights?
  - Ideally, use monetary values (generally missing)
  - Avoid altogether, consider cost-effectiveness and alternative goals

Global Potential for REDD Programs to Protect Biodiversity (Siikamäki and Newbold 2012)

Study Purpose

- Examine global potential of REDD to support biodiversity conservation
- Help design REDD to deliver multiple benefits

Scope and Methods

- Global scope (non-Annex 1 countries): some 2 billion hectares of forest
- About 250,000 million grid cells (9*9 km)
    - For each cell, develop localized estimates of CO_2 emissions and species losses due to deforestation, the cost of preventing it
- Aggregate up to ecoregion level (around 550)
- Use systematic reserve site selection methods to identify the spatial configuration of programs to maximize (i) carbon and (ii) species benefits per dollar invested
- Contrast carbon and biodiversity outcomes and conservation targeting under different program goals

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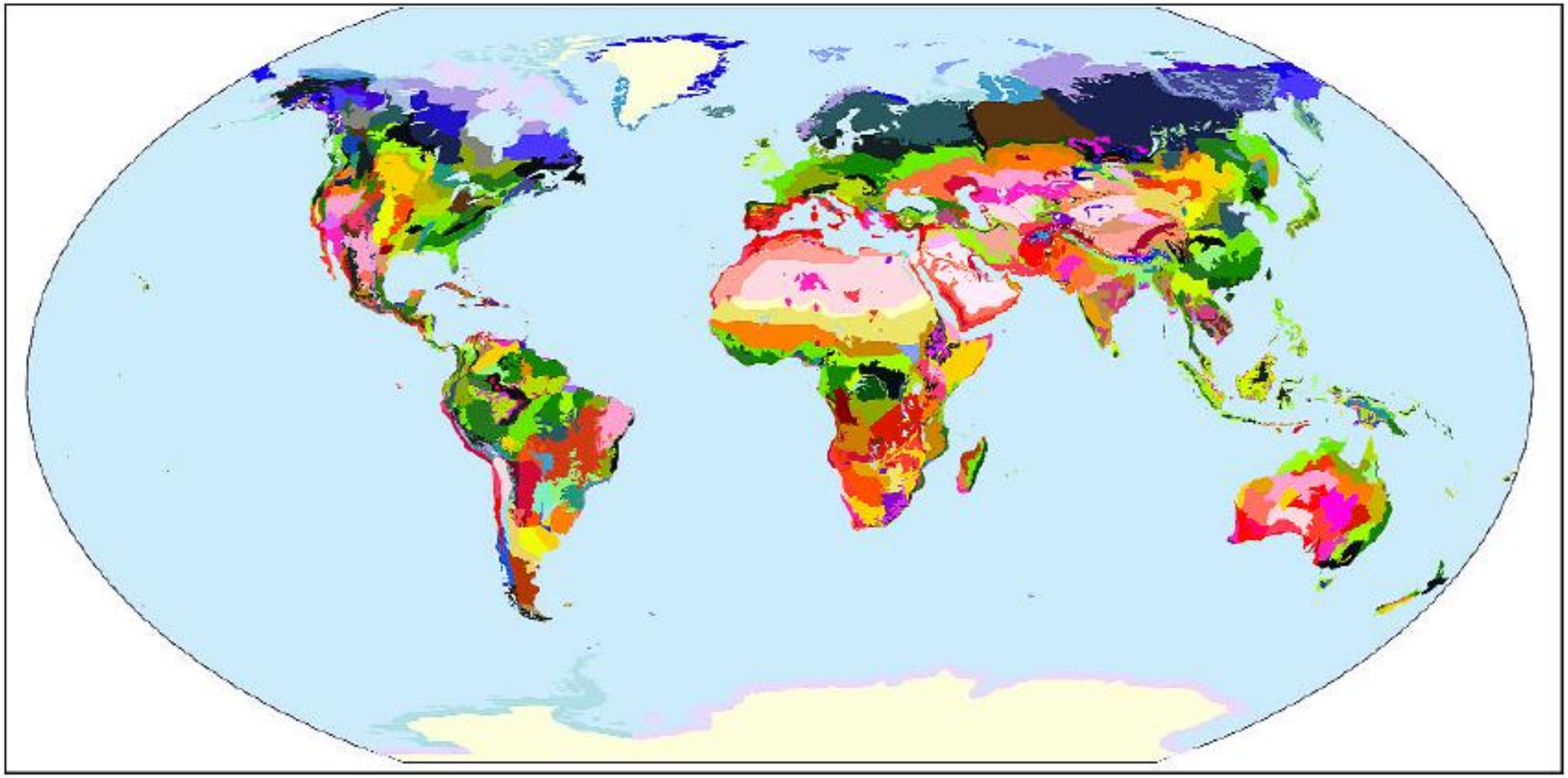
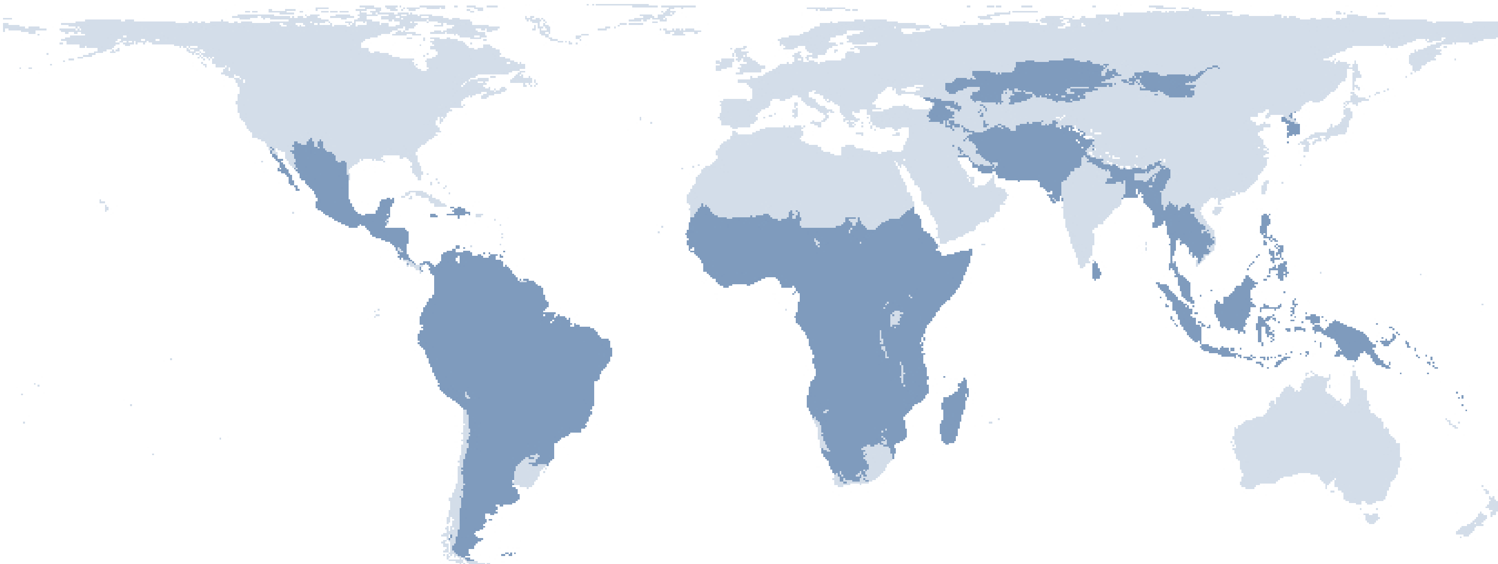
Terrestrial Ecoregions



Source: Olson et al. 2001, BioScience Vol. 51, Issue 11

Forested ecoregions in non-Annex 1 countries with current deforestation (FAO)



Main Spatial Data

Data	Description	Resolution	Source
Land cover	Global Land Survey	30x30 meters	USGS and NASA (2009)
Forest cover loss	Forest cover loss 2000-2005	30x30 meters	Hansen et al. (2010)
Carbon stock	Forest carbon (per ha)	1. 30 min grid (55*55km) 2. 5 min grid	Kindermann et al. (2008) Saatchi et al. (PNAS 2010) Harris et al. (Science 2012)
Biodiversity	Species ranges for mammals, amphibians, reptiles, birds	Overlapping polygons	IUCN, BirdLife International
Opportunity cost of conservation	Potential gross revenues from agriculture (annual opportunity cost)	5 min grid (9*9 km)	Naidoo and Iwamura (2007)
	NPV of agricultural land rental value	Assumptions	World Bank (2010)

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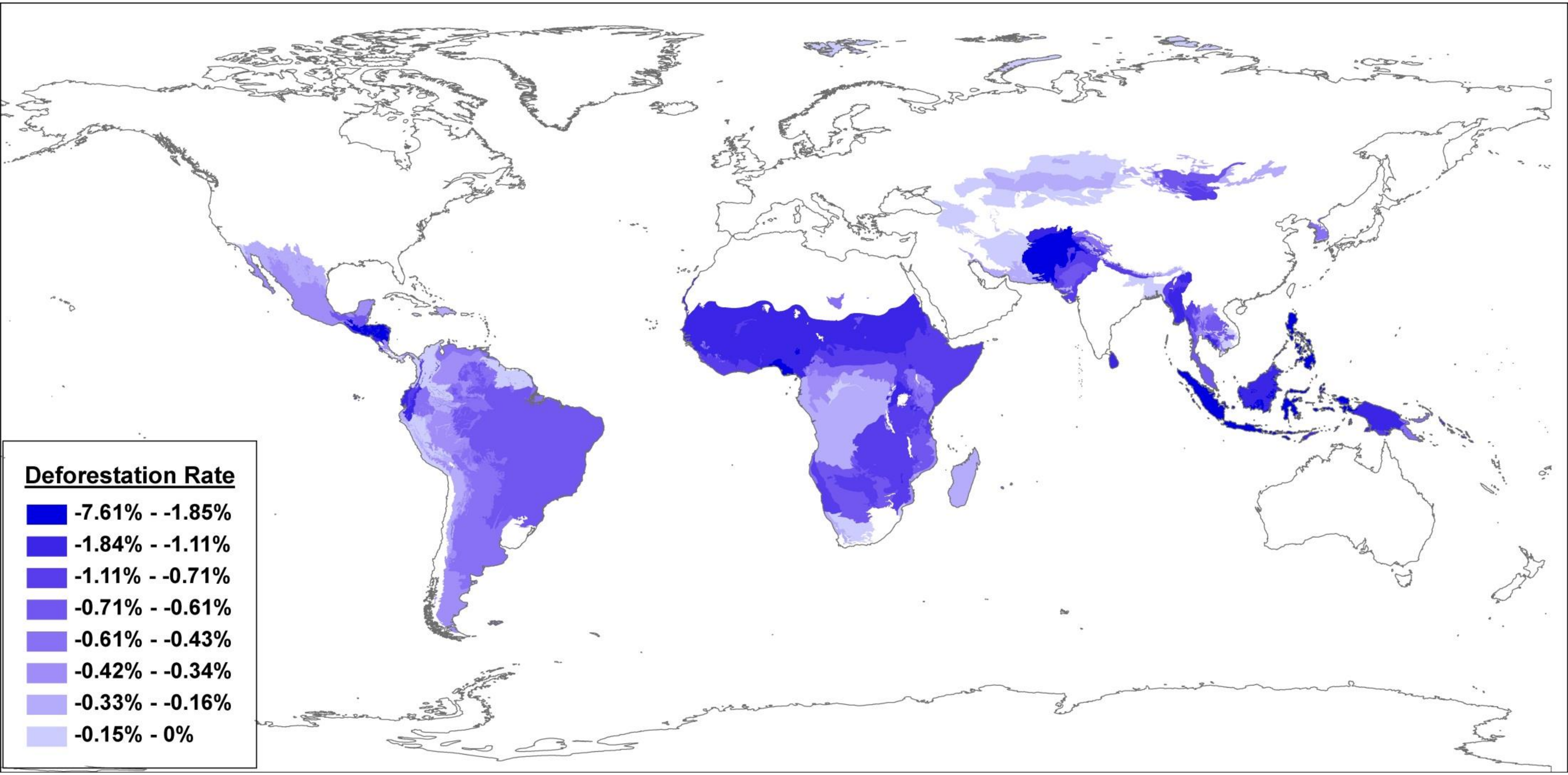
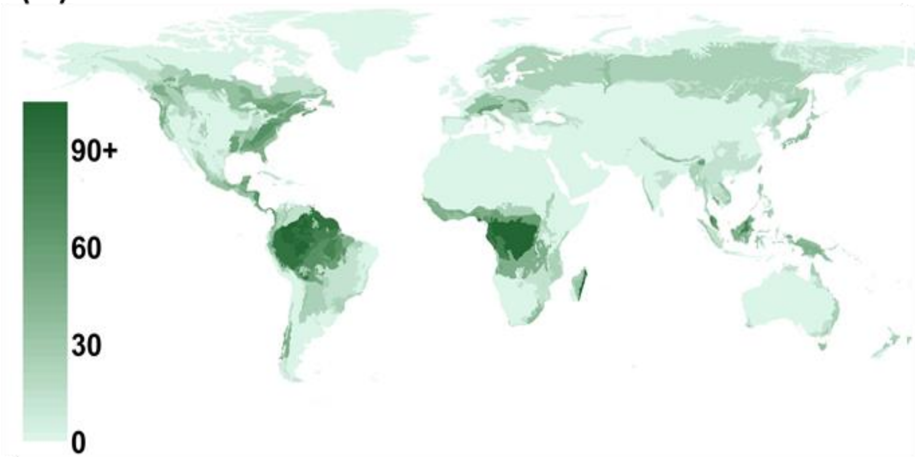
Data: Deforestation Map



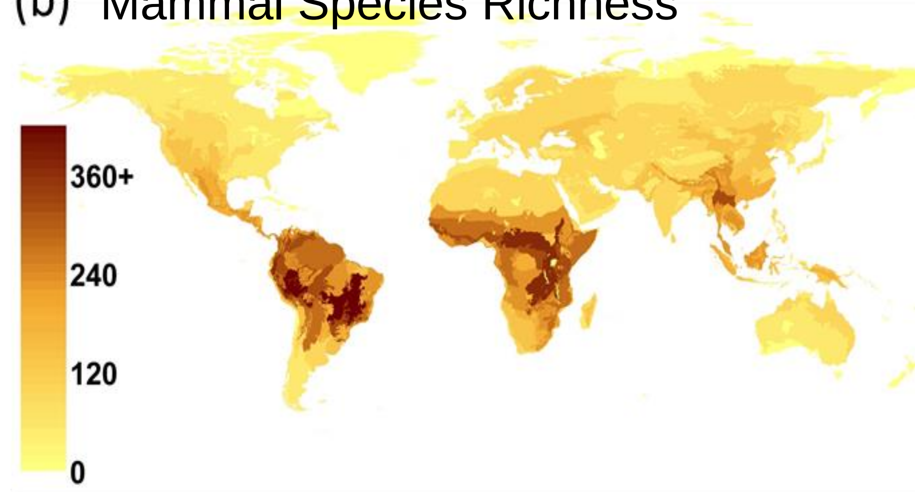
Mapped using data from Hansen et al. 2010

Data: Carbon Stock, Species Richness, and Potential Agricultural Revenues

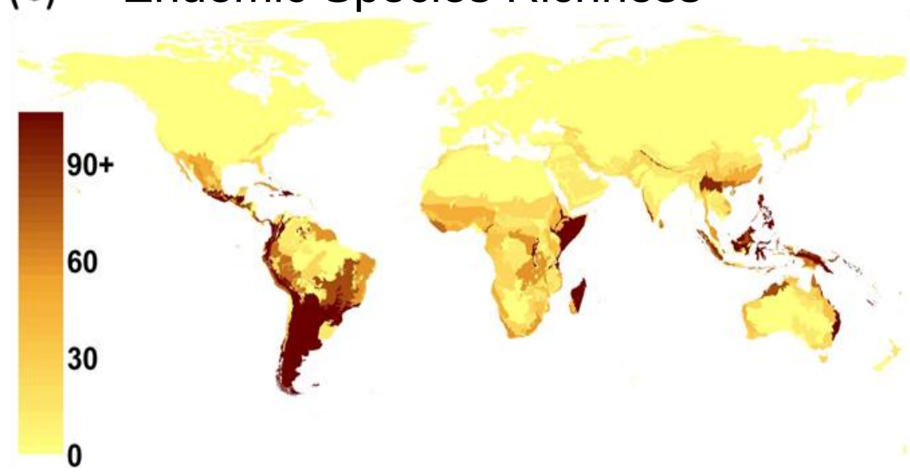
(a) Carbon stock



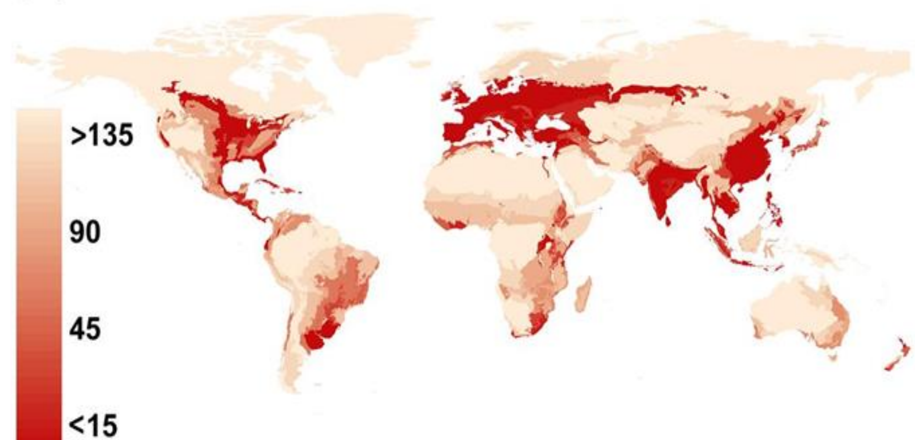
(b) Mammal Species Richness



(c) Endemic Species Richness

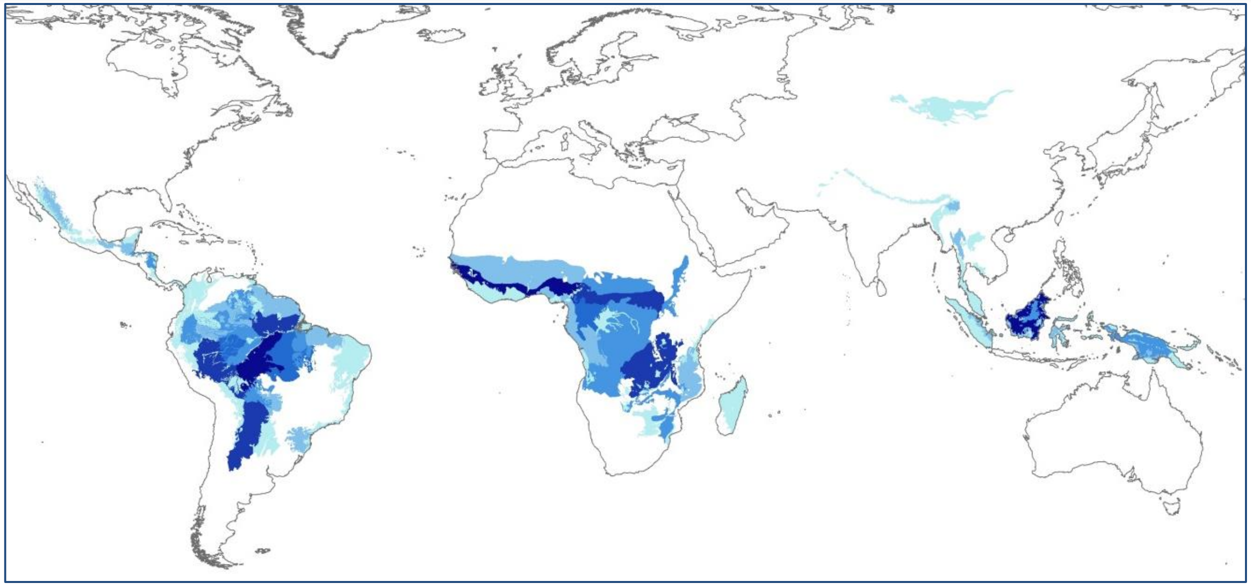


(d) Agricultural Gross Revenue Potential

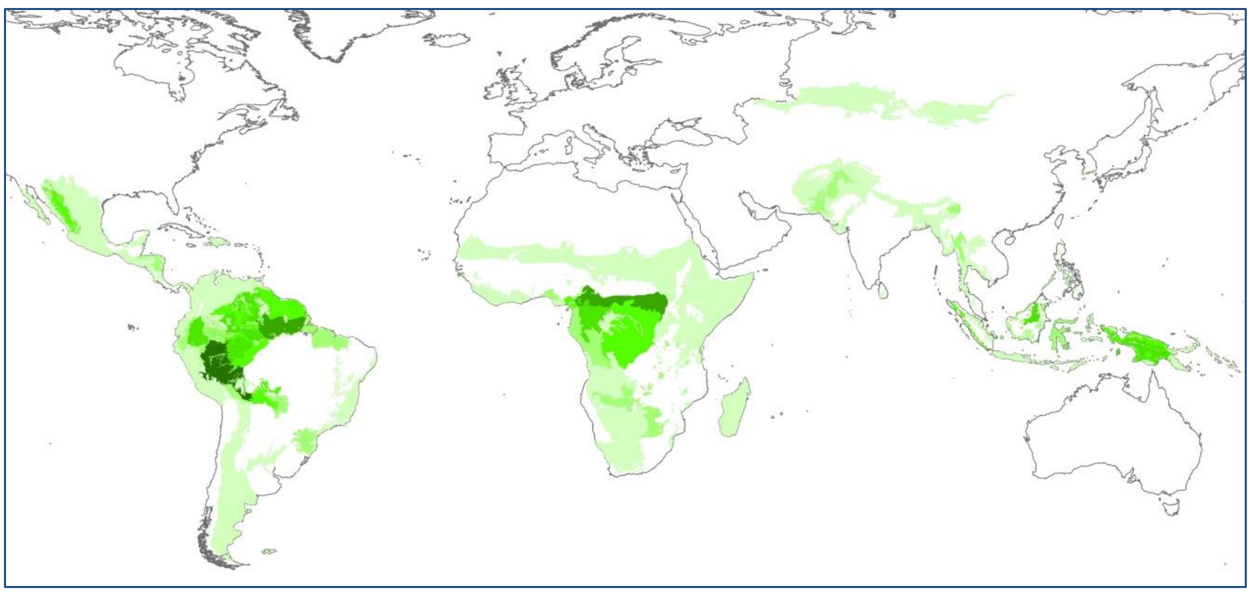


Results from Targeting Conservation under Different Goals: Budget Allocation by Ecoregion

Avoided Emissions

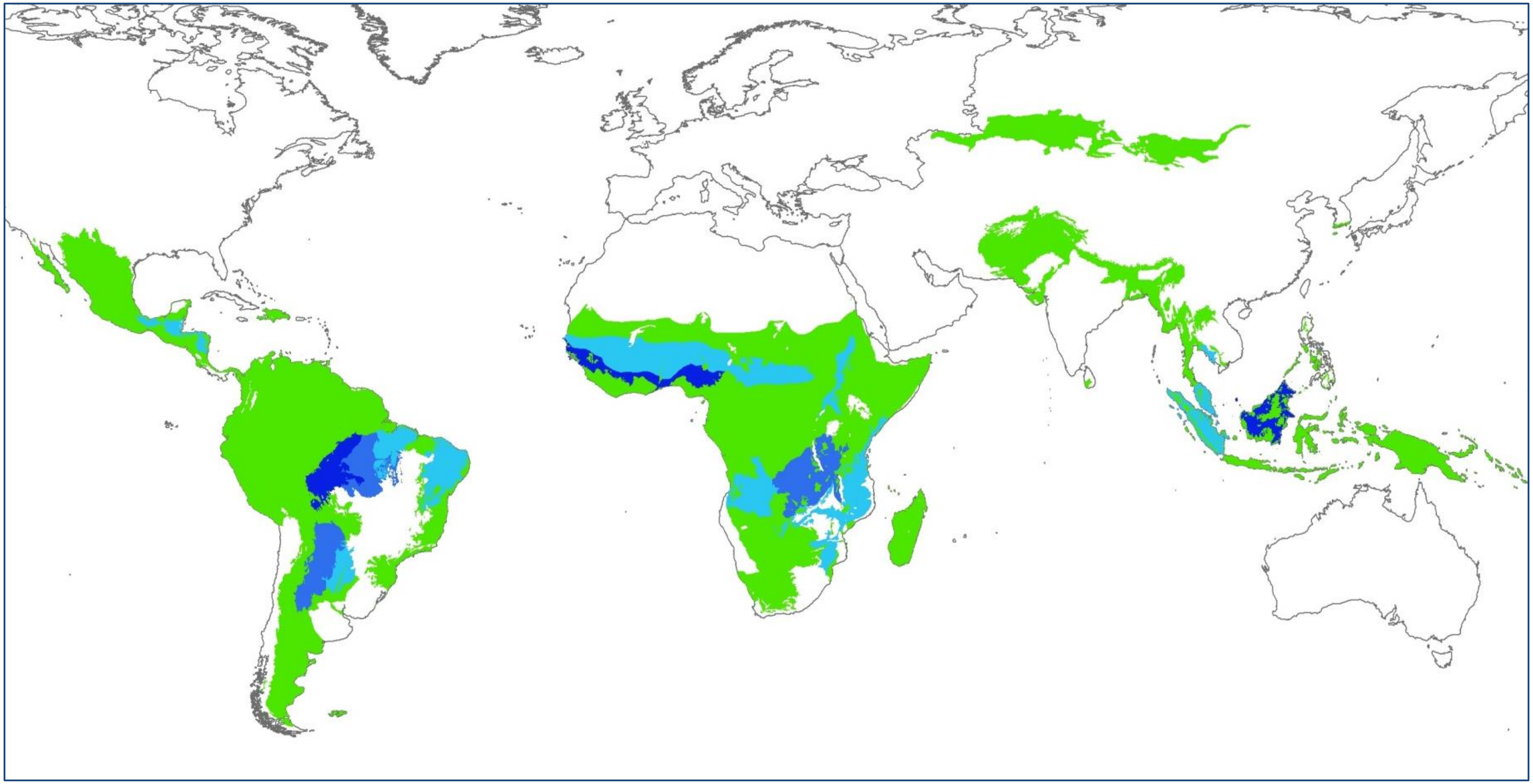


Avoided Species Richness Loss



Budget constraint 30% of max investment
Darker colors indicate greater investment

Results from Targeting Conservation under Different Goals: Differences in Budget Allocation by Ecoregion



- Green denotes greater investment by species program
- Blue denotes greater investment by carbon program
- Budget constraint 30% of max investment

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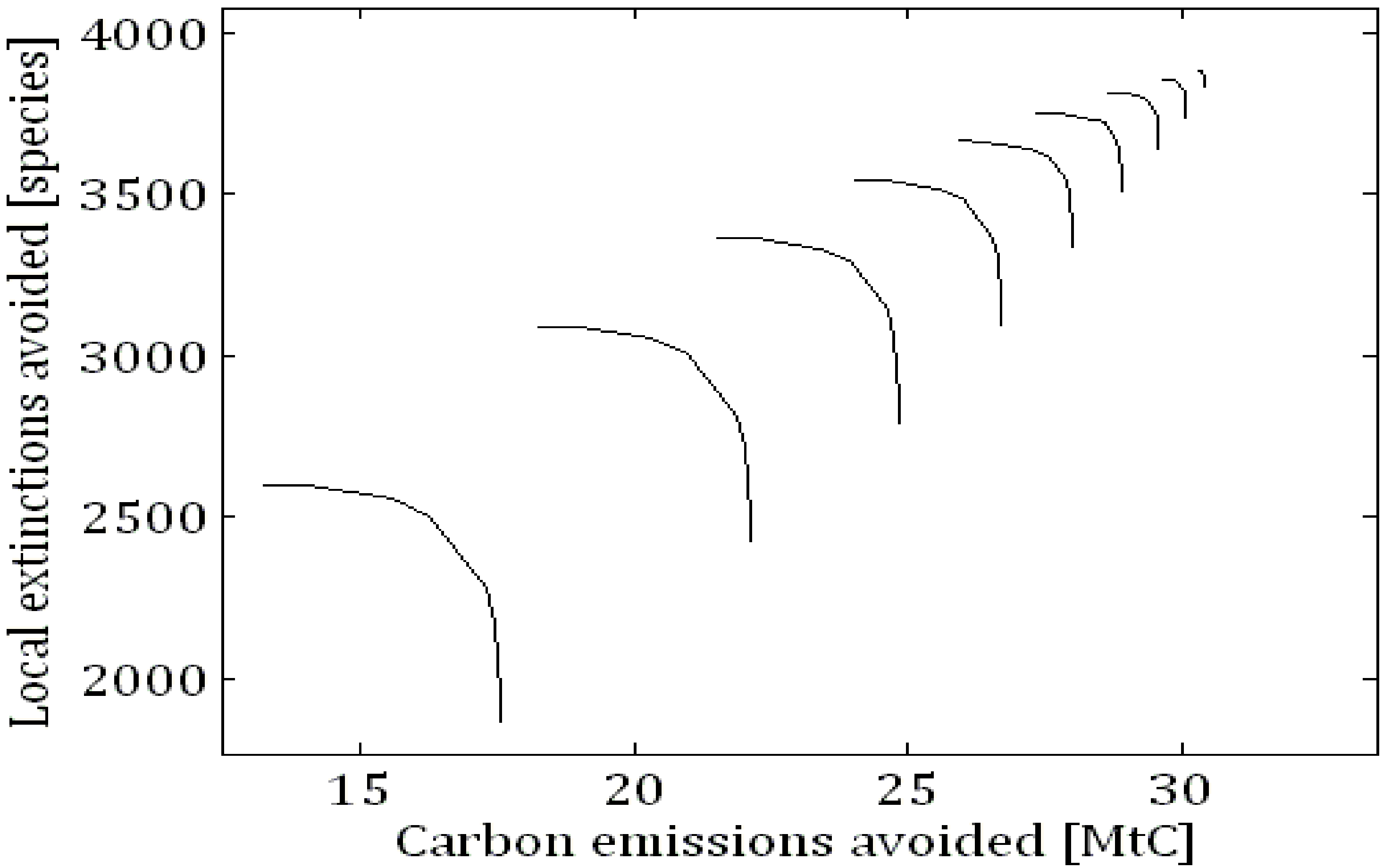
Production Possibilities Frontier (carbon, species)



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RSS and Spatial Ecological Processes

Ecological processes are generally spatial in nature

- Population dynamics
- Environmental connectedness (e.g. water quality, habitat connectivity)

Spatial connectedness and RSS

- benefits from protecting site i, b_i, are endogenous
- $bi=f(x_1,x_2,x_3,\ldots, x_n)$
- Knapsack algorithm fails
- Model the spatial ecological process within the optimization framework
- Computationally demanding (even a small number of sites creates a large number of possible combinations)

Illustration by "Prioritizing Conservation Activities Using Reserve Site Selection and Population Viability Analysis with an Application to Pacific Salmon" by Steve Newbold and Juha Siikamäki, *Ecological Applications* (2009)

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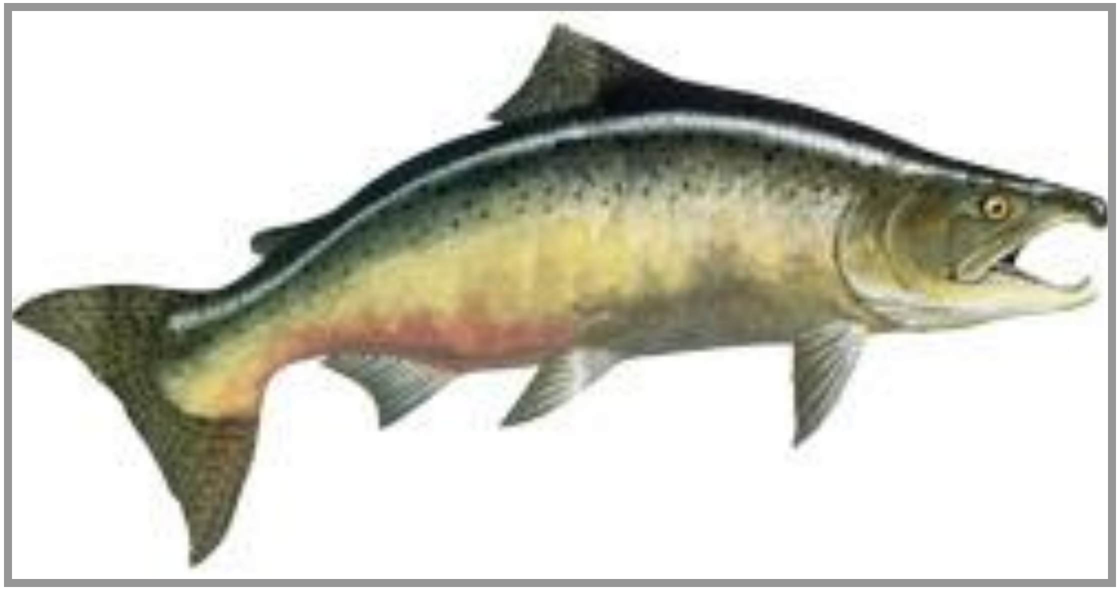
Study Subject: Chinook Salmon



- Also known as King Salmon
- The largest of the salmon species, up to 125lbs
- Least abundant of Pacific Salmon in the NW
- Protected under the Endangered Species Act
- We identify watershed-level conservation priorities intended to minimize the likelihood of extinction

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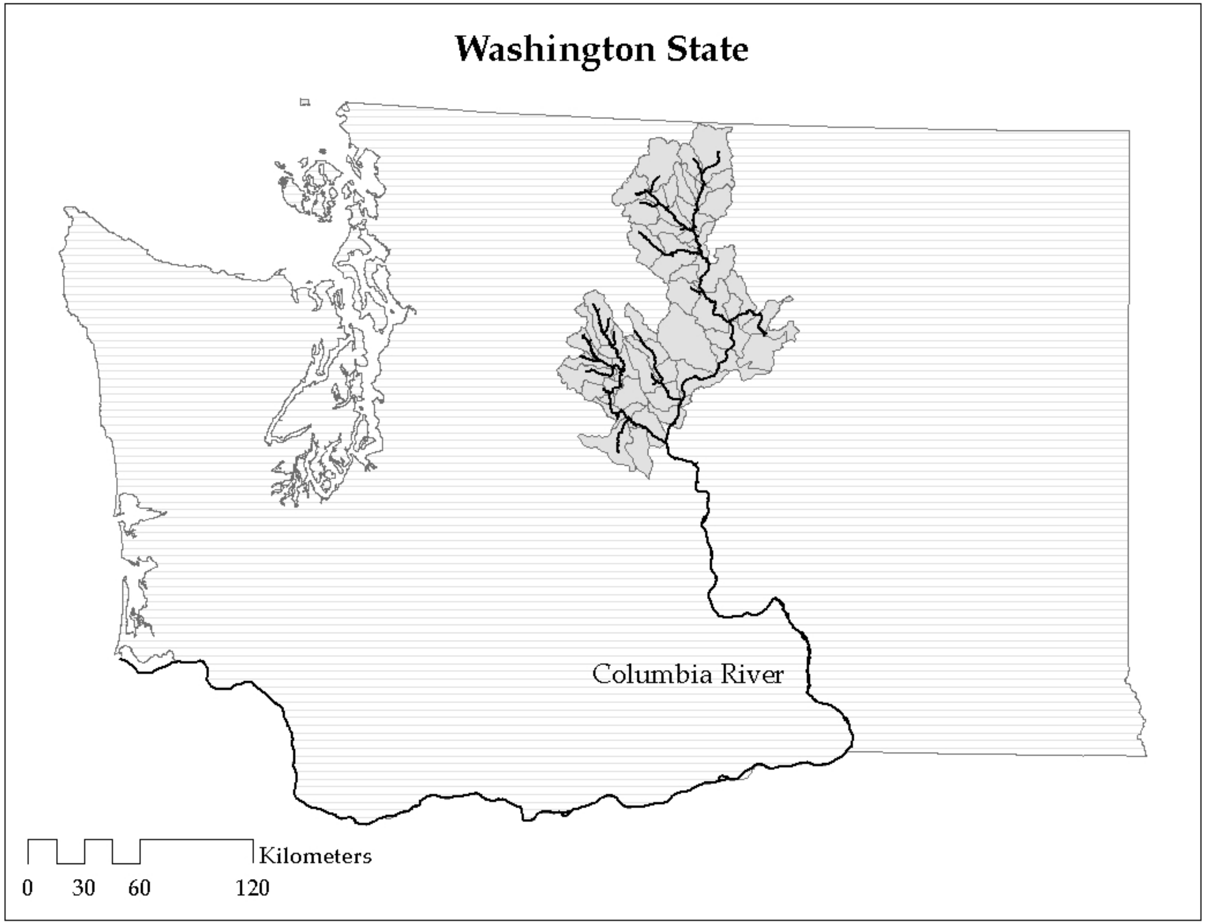
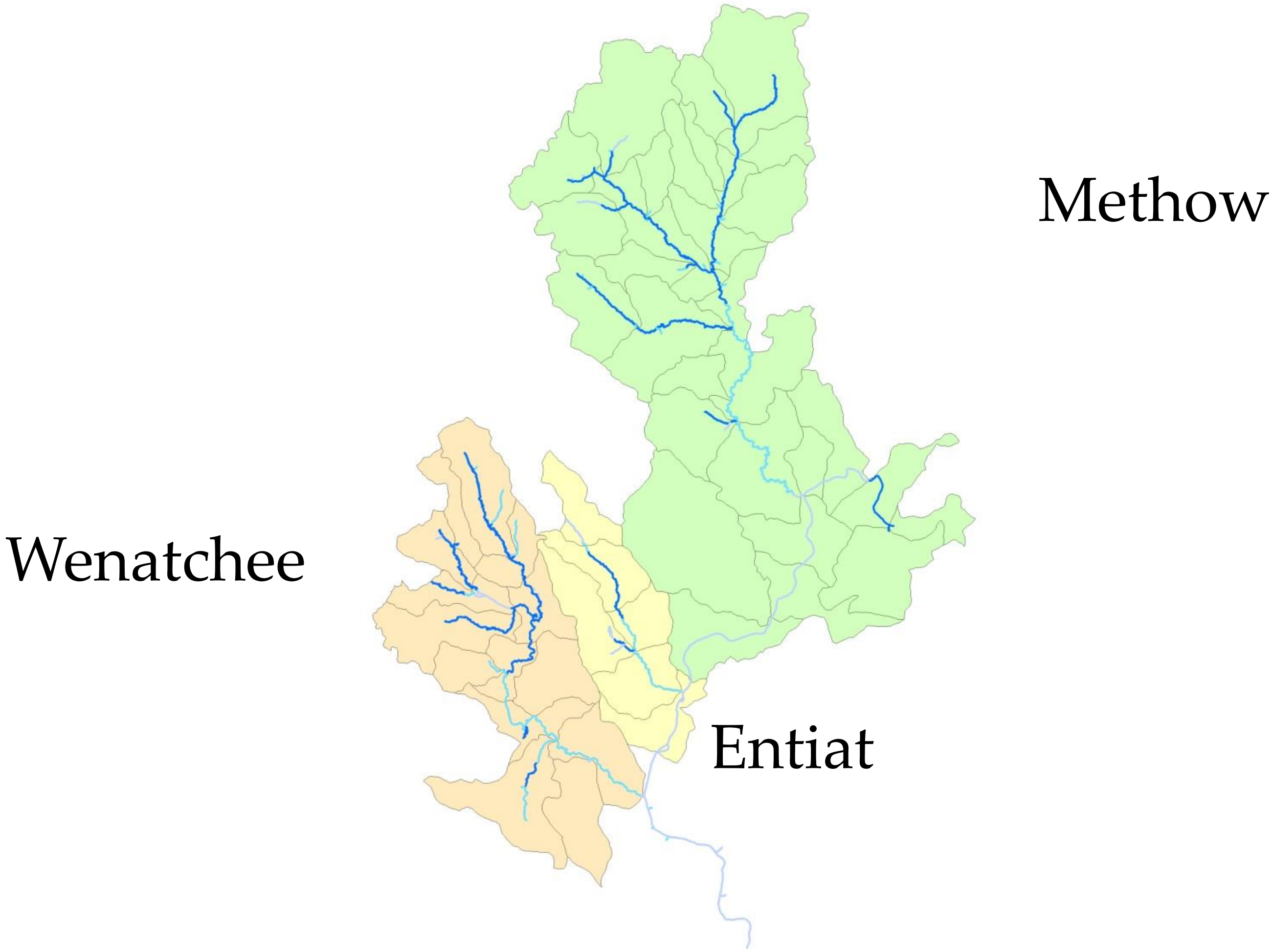
Upper Columbia River Spring Chinook

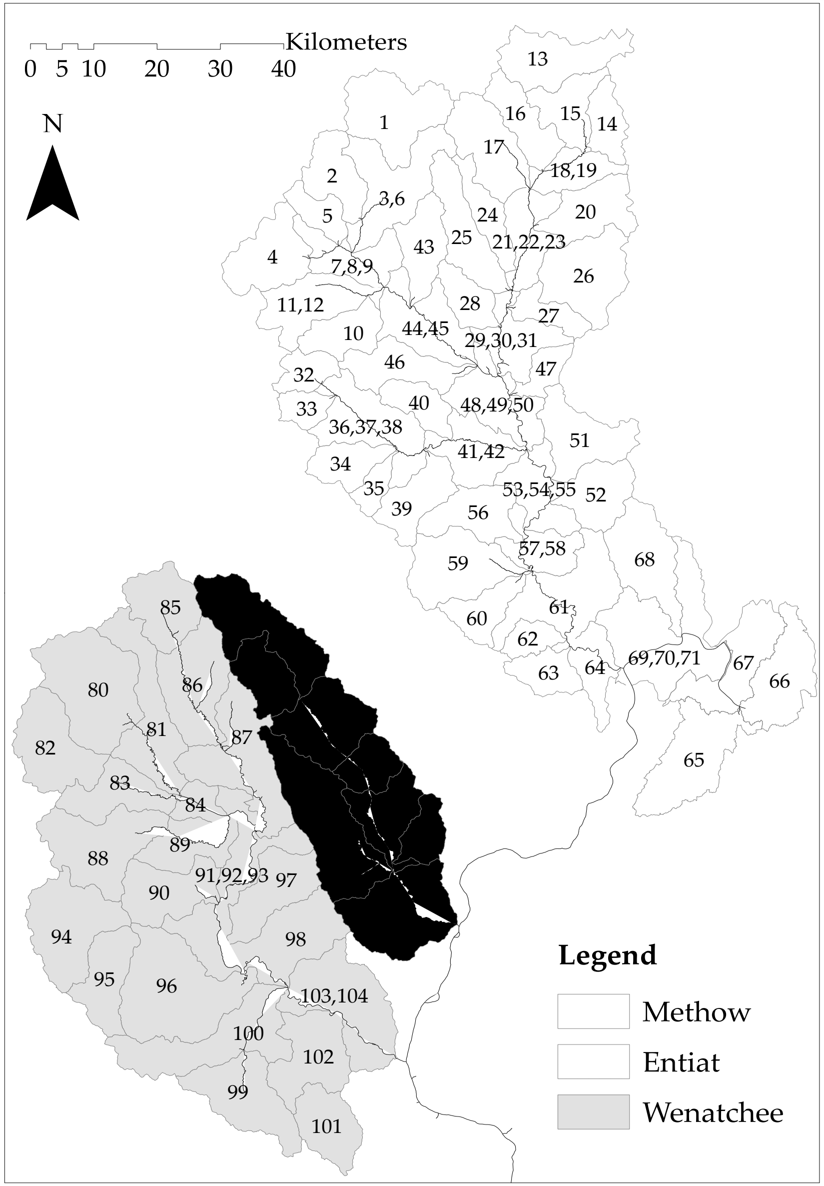
Methow, Entiat, and Wenatchee river basins
- One ESU
- Three stocks
- 2.1 million acres
- 1,000 stream miles
- Listed in 1999



Upper Columbia River Spring Chinook



Watersheds for Prioritization (n=104)



Framework for Prioritizing Watershed

(1) Stochastic dynamic population viability (PV) model

- depicts stochastic salmon population dynamics
- estimates long-run survival probabilities for individual salmon stocks

(2) Habitat quality model

- relates human land uses to the quality of salmon spawning, rearing, and migratory habitat in upstream watersheds

(3) Reserve site selection (RSS) model

- combines the PV and habitat quality models for each stock with estimates of economic costs
- prioritizes watershed protections on the basis of their cost-effectiveness in enhancing long-run persistence of threatened populations

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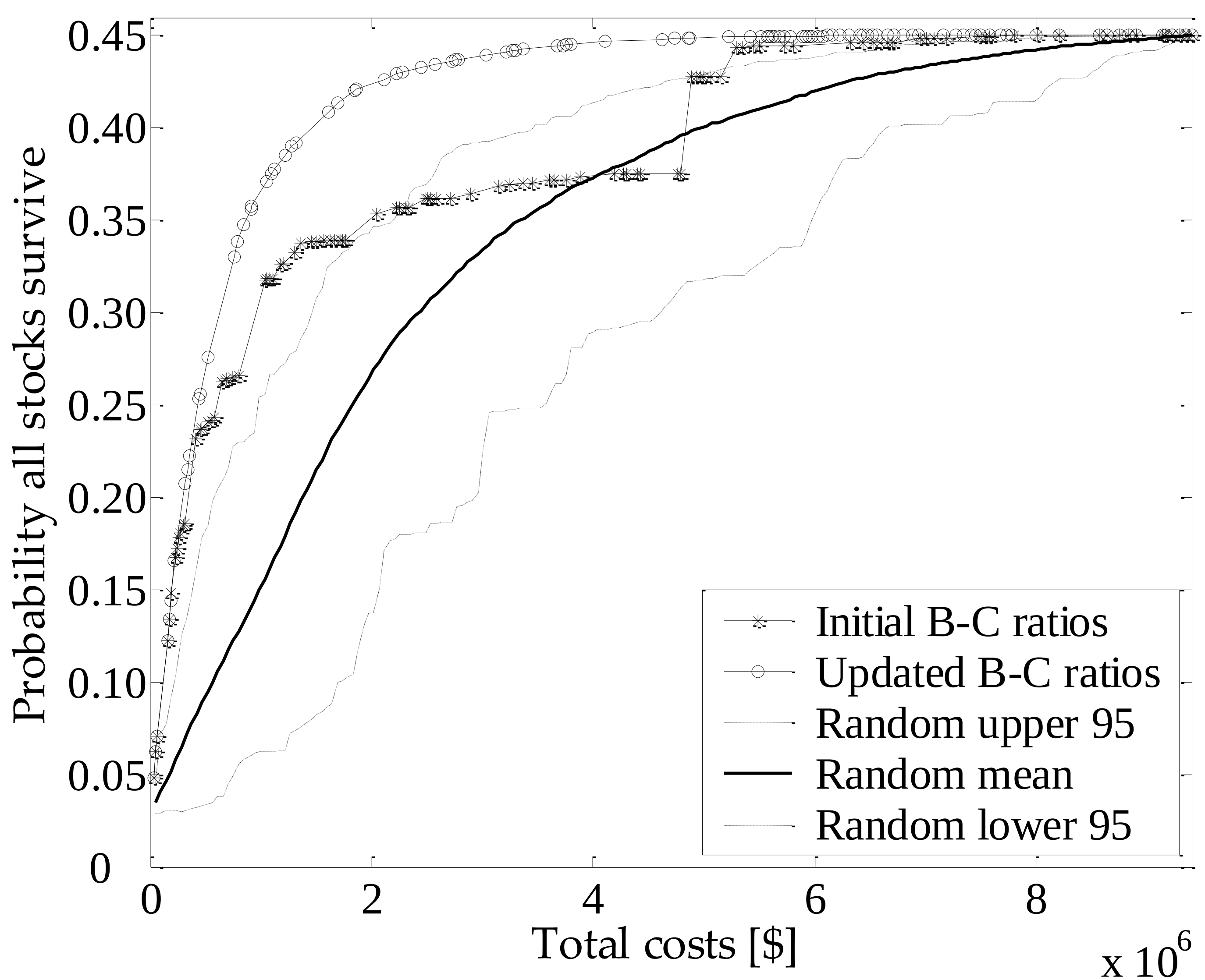
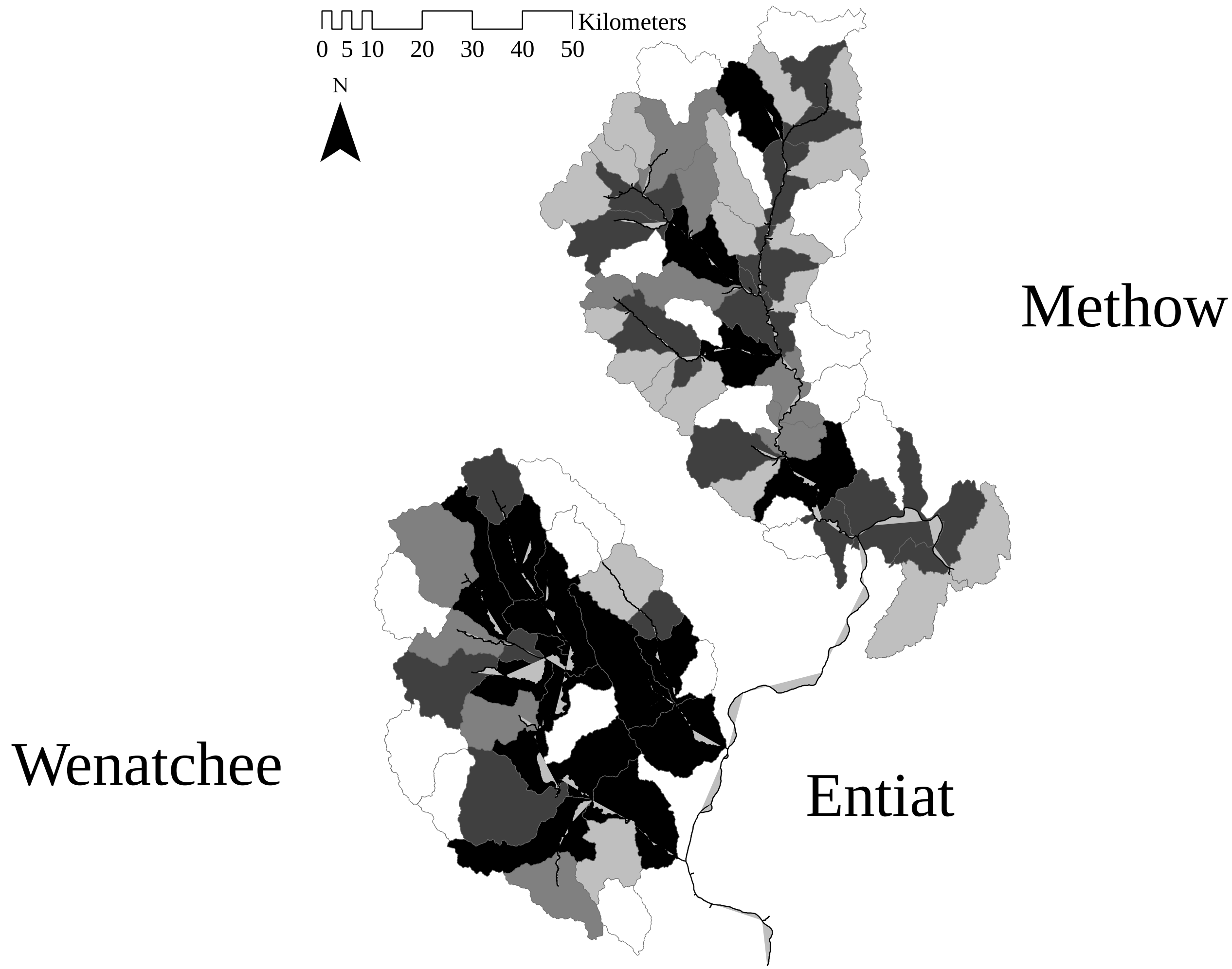
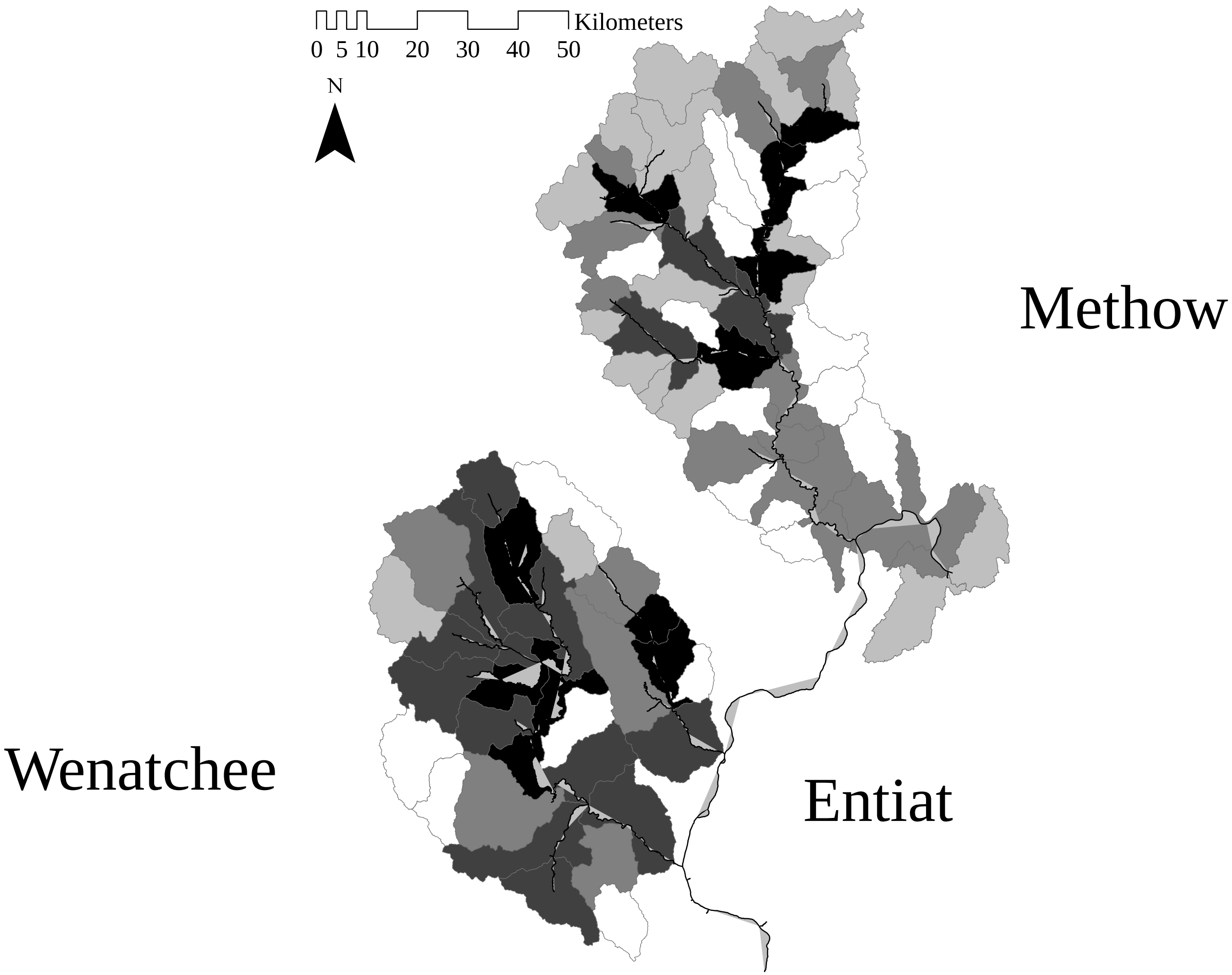
Benefit-Cost Approach: Cumulative Benefits





Habitat ranking (conventional approach)



Benefit Cost ranking

Other essential extensions of RSS methods

1. Dynamic RSS (Costello and Polasky 2004)
   a) Heterogeneous risk of site development, limited annual budget
   b) Irreversible ecological loss due to development
   c) Sites developed in t=1 not available for protection in t+2, t+3,…
   d) Optimize over time using stochastic dynamic programming

2. Meta-population dynamics (Moilanen and Cabeza 2002)
   a) Meta-population model as starting point (Levins 1969, Hanski 1994)
   b) Species occur as a collection of sub-populations
   c) Sub-populations prone to local extinctions
   d) Global extinction from the extinction of all sub-populations
   e) Random re-colonization of extinct patches (proximity to extant sub-populations improves re-colonization)
   f) RSS problem
      a) Minimize expected meta-population extinction risk
      b) Optimize using a genetic algorithm, local sub-search, MC

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Other essential extensions of RSS methods, cont.

3. Uncertain species occurrence (Polasky et al. 2000)
   a) Probabilistic information on species absence/presence
   b) Maximize expected species richness (coverage)

4. Value of information (Polasky and Solow 2001)
   a) Uncertain species occurrence as the base case
   b) Consider investment in data collection explicitly as one of the conservation options
   c) VOI indicates WTP for additional research
   d) Improving data can be a cost-effective approach to preserve species (enables improved targeting)

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Estimating the Cost of Conservation

Critical to identifying cost-effective programs

Essential problem for economists to contribute

A wide range of approaches in the literature

- Agricultural land values (Ando et al. 1997, Murdoch et al. (2007)
- Assessed value of non-urban land (Polasky et al. 2001, Arthur et al. 2004)
- Forecasted from actual acquisition data (Underwood et al. 2009)
- Predicted NPV of resource use (Stewart and Possibgham 2005, Polasky et al. 2008)
- Agricultural revenue potential (Naidoo and Iwamura 2007)
- Easement cost (Ferraro 2003, Newburn et al. 2006)
- Reverse auction (Layton and Siikamäki 2009, White and Sandler 2011)

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Potential key areas for economists' further contributions

Opportunity cost of conservation
- General estimation methods
- Land market feedbacks

Monetary valuation of conservation benefits
- Focus so far entirely on cost-effectiveness
- Cost-effectiveness does tell whether the program worth implementing, what program extent is optimal
- Multi-objective conservation problems calls for valuation inputs

Policy instrument choice in the context of RSS
- Typically, conservation activities can be implemented by assumption
- However, this generally is not the case, depends on policy instruments at hand
- What instrument brings the outcome closest to the first-best optimum?
- Wide open field

Climate change and conservation priorities

EfD: Economics of conservation in the developing country context

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Recommended readings

Conservation prioritization using reserve site selection methods, Newbold and Siikamäki, forthcoming in “Handbook of the Economics of Natural Resources”

Moilanen, Wilson, Possingham, eds. 2009. *Spatial Conservation Prioritisation: Quantitative Methods and Computational Tools*.

Sarkar, Pressey, Faith, et al. 2006. Biodiversity conservation planning tools: present status and challenges for the future. *Annual Review of Environment and Resources* 31:123-159.

Watson, Grantham, Wilson, Possingham 2011. Systematic conservation planning: past, present and future. In Ladle RJ, Whittaker RJ, eds. *Conservation Biogeography*.

Williams, ReVelle, Levin. 2004. Using mathematical optimization models to design nature reserves. *Frontiers in Ecology and the Environment* 2:98-105.

Wilson, Carwardine, Possingham. 2009. Setting Conservation Priorities. *Annals of the New York Academy of Sciences* 1162:237-264.

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Thank You