Decision-Making for Land Conservation:
A Derivative-Free Optimization Framework with Nonlinear Inputs

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Utilizing **mixed-integer nonlinear programming** allows us to evaluate & minimize **extinction risk** when selecting **protected areas.**

1. Background

30x30 Global Initiative

- Protected areas (PA) restrict human activities to preserve vulnerable species and valuable ecological processes.

190+ countries committed to designating 30% of land and sea as protected areas by 2030!

- Given a landscape of parcels, decision-makers select parcels to preserve, balancing financial feasibility with ecological benefit.
- Most spatial conservation planning models are linear.

Population Viability Analysis (PVA)

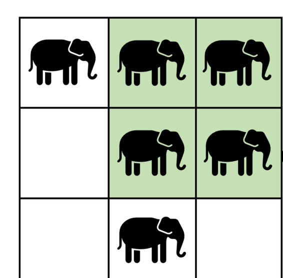
- Ecologists use PVA to estimates a species' extinction risk.
- PVA provides insight on the persistence of a species in PAs and informs practitioners on improvements to increase survival.
- PVA hasn't been used concurrently with site selection; Linear models are not equipped to use PVA.

2. Framework

Our Approach

- *Preserving every parcel* inhabited by a species lowers extinction risk–but not always feasible!
- However, ***preserving a subset*** of parcels can still be beneficial.
- With PVA, we can be informed on the long term impact of our PA.
- We paired PVA + MINLP to evaluate extinction when designating PAs.
- Our framework is the first to use PVA concurrently with site selection.

PA



PVA

Simulate population over 100 years. (Repeat 1000x)

Metrics

Risk	89%
Time	3 years
Abundance	2 elephants

MINLP

- Plug in metrics.
- Record solution.
- Generate new PA.

PA: Randomly generate a set of parcels as the PA. (Parcels shaded green.)

PVA: *RAMAS (Akçakaya & Root, 2013)* simulates species' dynamics.

Metrics:

Risk of Extinction:	Probability abundance is 0 after 100 years.
Time to Extinction:	Median # of years until abundance is 0.
Expected Minimum Abundance:	Smallest abundance in 100 years, averaged over 1000 simulations.

MINLP: Evaluate metrics (Section 3). Then, a new PA is generated and the process is repeated. The best PA is returned as our solution.

3. Optimization Models

MINLP Models

- We explored two MINLP models in our framework.
- Then, we tested each model with 2 grid sizes (Section 4).

Constrained Model:
PA where risk metrics are within "acceptable" gap from B's metrics.

$$
\begin{aligned}
\underset{X\in\{0,1\}^{|P|}}{\text{minimize}} \quad & \sum_{p\in P} c_p X_p \\
\text{subject to} \quad & r(Z) - (\rho_r + r(B)) \le 0 \\
& t(Z) - \rho_t t(B) \ge 0 \\
& a(Z) - \rho_B a(B) \ge 0 \\
& Z_p = B_p X_p, \ \forall p \in P \\
& X_p \in \{0,1\}, \ \forall p \in P
\end{aligned}
$$

Multi-Objective Model:
PA that minimizes weighted sum of risk metrics.

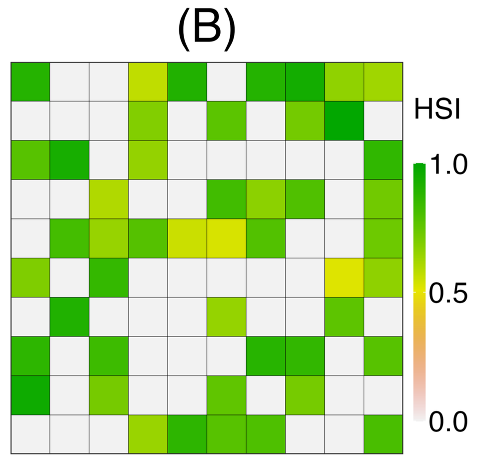
$$
f(X) = \left(\sum_{p\in P} c_p X_p, r(Z), -t(Z), a(Z) \right)
$$

$$
\begin{aligned}
\underset{X\in\{0,1\}^{|P|}}{\text{minimize}} \quad & \sum_{i=1}^{4} \lambda_i f_i(X) \\
\text{subject to} \quad & Z_p = B_p X_p, \ \forall p \in P \\
& X_p \in \{0,1\}, \ \forall p \in P
\end{aligned}
$$

P	Set of parcels.
B	Grid of parcels, each with a habitat suitability index (HSI).
X_p	Binary decision variable, if parcel p is selected to be preserved.
Z	Resulting PA given by X. That is, $Z_p = B_p X_p, \ \forall p \in P$.
c_p	Acquisition cost of preserving parcel p.
$r(Z)$	Risk of total extinction for Z.
$t(Z)$	Median time to extinction for Z.
$a(Z)$	Expected minimum abundance for Z.
ρ	Threshold by which Z's risk metrics can differ from B's.

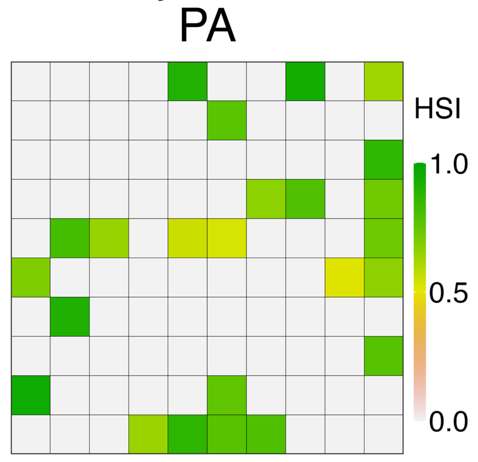
4. Results

All Habitable Parcels (B)



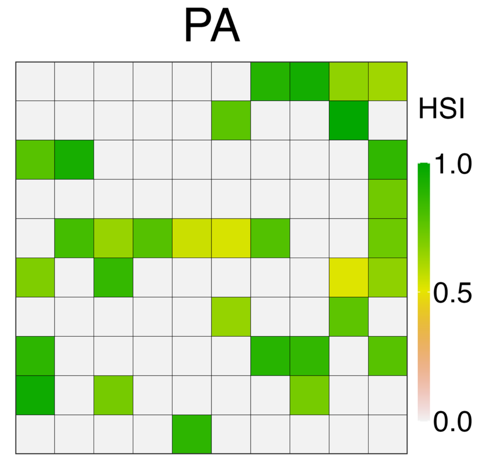
Cost	577
Risk	0
Time	>100
Abundance	61.4

Multi-Objective Model PA



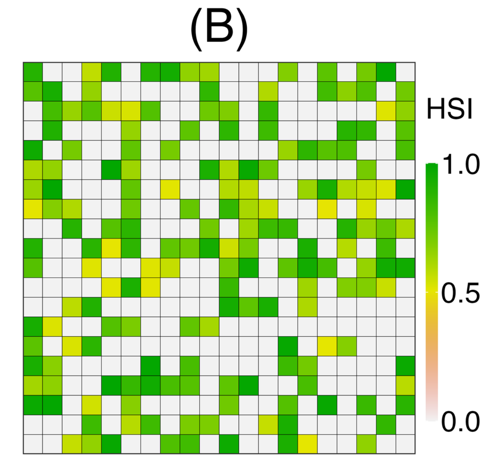
Cost	199
Risk	0.017
Time	>100
Abundance	12.1

Constrained Model PA



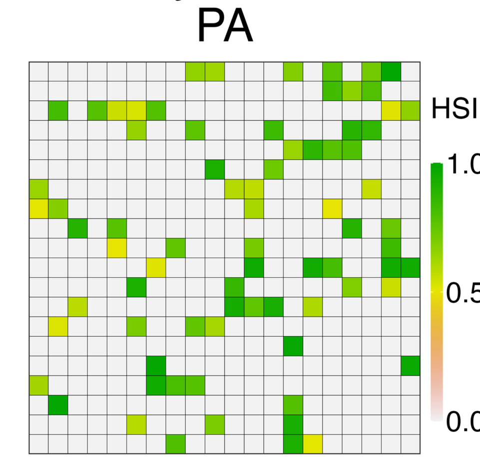
Cost	340
Risk	0
Time	>100
Abundance	33.5

All Habitable Parcels (B)



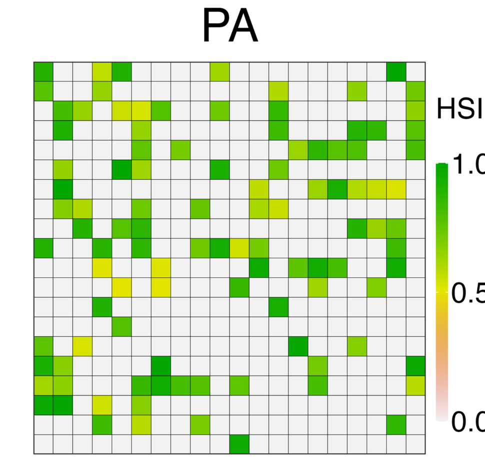
Cost	2137
Risk	0
Time	>100
Abundance	339.6

Multi-Objective Model PA



Cost	874
Risk	0
Time	>100
Abundance	69.4

Constrained Model PA



Cost	1134
Risk	0
Time	>100
Abundance	135.2

Results

- Each model and landscape (10x10 and 20x20) is compared to *B*.
- There is a trade-off between expected minimum abundance and cost.
- Time to extinction indicates species didn't go extinct in >50% of simulations.
- Extinction in 100 years is unlikely, but abundance is still important. There are multiple categories of threatened species, with varying severity, and low abundance is considered in these reports.

Ethical Statement: Historically, PAs have been used as a tool for colonization under the guise of conservation, largely impacting the Indigenous Peoples. Optimization models can yield inequitable decisions, thus this framework–and others like it–should be used with discretion.