Minimising Conservation Loss in Etosha National Park

Optimal Allocation of Rangers, Drones, Cameras & Satellites

Team India | IM^{2}C 2026

India STEM Foundation

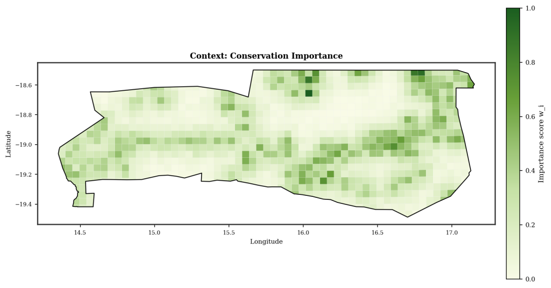
Roadmap

1. The Problem & The Park
2. The Optimisation Model
3. Results, Robustness & Impact
4. Transferability

The Problem & The Park

A Protection Paradox

- **22,935 km^2** of savanna, pan & waterholes — home to endangered black rhino and 114+ mammal species.
- Only **295 staff**, **850 km** fence, 3,551 km of roads.
- Full-park surveillance is **physically impossible**.

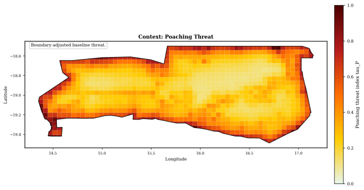


Ecological importance is not spread evenly — protection cannot be either.

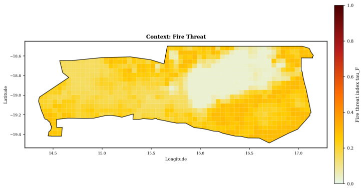
Our question

Given a fixed weekly budget, where should rangers, drones, cameras, and satellites go to protect the most ecological value?

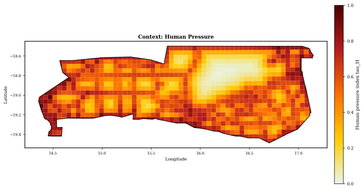
Three Threats to Etosha



Poaching τ^P — boundary-driven, dry season, **irreversible**: top priority.



Wildfire τ^F — fuel-load driven, late-dry season.



H–wildlife conflict τ^H — camp-driven, wet season.

Threats Evolve: Seasonality & Persistence

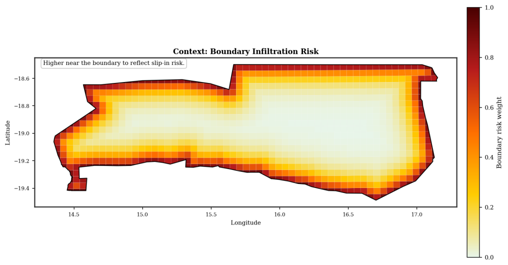
Each threat is a base map, boosted near the fence for poaching (poachers enter through it):

$$\hat{\tau}_i^P(0) = \tau_i^P(0)\left(1 + \beta_{\text{fence}} e^{-d_i^b/\delta_b}\right)$$

then evolves weekly, mean-reverting with seasonal forcing:

$$\tau_i^P(t+1) = \max\left(0, \rho_P \tau_i^P(t) + \mu_P \hat{\tau}_i^P(0) s_P(t) \phi_i(t)\right)$$

Priority: poaching > human–wildlife > wildfire.



Boundary-boosted poaching risk — the $e^{-d_i^b/\delta_b}$ term at work.

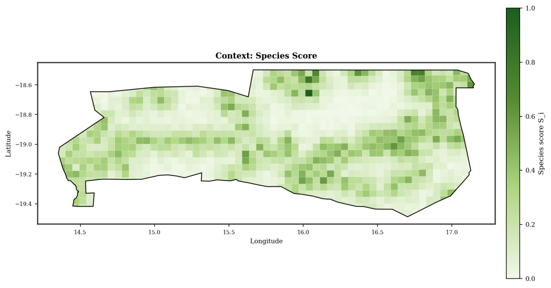
	Poach.	Fire	H–W
Persistence ρ	0.85	0.20	0.60
Peak weeks	20–40	33–45	1–20

From Threat to Priority: Ecological Importance

990 cells of 5×5 km, each scored by species priority $\tilde{S}_i$ (GBIF + IUCN status), combined into

$$w_i \propto \tilde{S}_i(1 + W_w \overline{W}_i) + W_c C_i + W_f \tilde{\Psi}_i$$

- $\overline{W}_i$ waterhole proximity **(40%)**
- C_i connectivity **(20%)**
- $\tilde{\Psi}_i$ fuel-load **(15%)**



Species-priority score feeding into w_i.

Measuring Protection: What “Solved” Means

Protection fraction at week t:

$$P_{\text{frac}}(t) = \frac{\sum_i w_i(t)\left[\tau_i^P p_i^P + \tau_i^F p_i^F + \tau_i^H p_i^H\right]}{\sum_i w_i(t)\left[\tau_i^P + \tau_i^F + \tau_i^H\right]}$$

A cell is **protected** once $P_{\text{frac},i} > 0.5$. This feeds a discounted-horizon objective $\mathcal{L} = \sum_t \gamma^t L(t)$ minimised subject to budget — built next.

Metric	**S0**	**S1**
Discounted loss	5.499	3.282
Protection frac.	0%	31.0%
Weighted coverage	0%	92.3%

S0 = no intervention, S1 = optimised deployment.

The Optimisation Model

Optimisation Framework

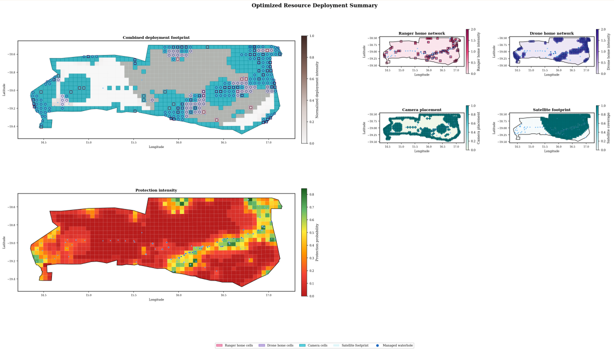
Decision Variables

$$\mathbf{x} = (\mathbf{x}_r, \mathbf{x}_d, \mathbf{u}_c, s)$$

- $\mathbf{x}_r$: Ranger deployment
- $\mathbf{x}_d$: Drone deployment
- $\mathbf{u}_c$: Camera traps
- s : Satellite coverage

Coverage

Rangers	3×3 cells
Drones	5×5 cells
Camera traps	468 eligible cells
Satellite	594 cells



Resource layers considered by the optimisation model.

Protection Model

Effort Fields

$$h_i^r = [\mathbf{W}_r \mathbf{x}_r]_i, \qquad h_i^d = [\mathbf{W}_d \mathbf{x}_d]_i$$

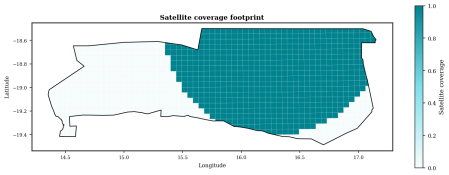
$$W[i,j] \propto w_j \tau_j e^{-\alpha d_{ij}}$$

- Threat-weighted patrol effort
- Exponential distance decay
- Normalised coverage operator

Deployment Rules

- 468 eligible camera locations
- Near waterholes
- Near camps
- Along park boundary
- High-poaching hotspots

$$c^* = \arg\max \sum_i w_i$$



Mixed Integer Nonlinear Optimisation

$$\boxed{\min_{\mathbf{x}} \ \mathcal{L}(\mathbf{x}) + P_{\text{conc}} + P_{\text{overlap}}}$$

$$c_r \|\mathbf{x}_r\|_1 + c_d \|\mathbf{x}_d\|_1 + c_c \|\mathbf{u}_c\|_1 + c_s s \leq B$$

Placement Constraints

- Habitat feasibility
- Eligible home cells
- Capacity limits

Budget

$$B = 2.38 \times 10^6 \text{ N\\$ / week}$$

723 ranger homes

835 drone homes

Regularisation

Concentration Penalty

$$P_{\mathrm{conc}} = \mu_r \frac{\sum x_r^2}{(\sum x_r)^2} + \mu_d \frac{\sum x_d^2}{(\sum x_d)^2}$$

- Prevents excessive clustering
- Encourages spatially distributed patrols

Overlap Penalty

$$P_{\mathrm{overlap}} = \epsilon_o \sum_i \omega_i \left(h_i^r h_i^d + h_i^r u_i^c + h_i^d u_i^c \right)$$

- Reduces redundant surveillance
- Improves resource efficiency

Solution Method

Optimisation Pipeline

Continuous Relaxation

$\Downarrow$ Spectral Projected Gradient

$\Downarrow$ Projection onto Feasible Region

$\Downarrow$ Largest-Remainder Rounding

$\Downarrow$ Integer Deployment

$$\delta = 0.925\%$$

99.08% Optimal

- Integer feasible
- Budget preserved
- Stable solution

Results, Robustness & Impact

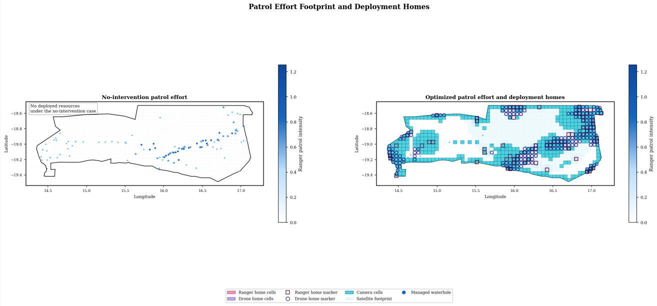
The Optimised Deployment

Resource	Count
Rangers	104
Drones	211
Camera Traps	468
Satellite	1

Budget Utilisation: 99.6%

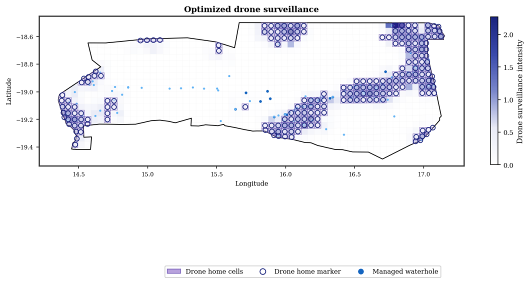
Coverage: 857/990 cells

Weighted coverage: 92.3%

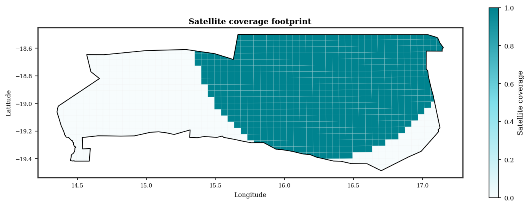


Optimised ranger and drone deployment across the park.

Spatial Deployment



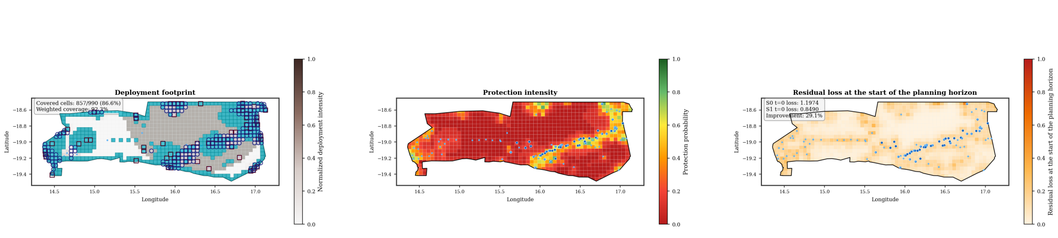
Drone Coverage



Satellite Footprint

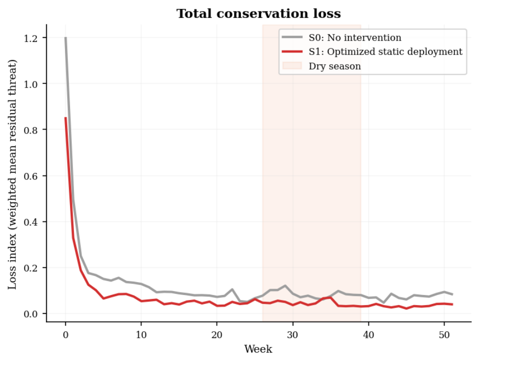
- Drones complement ranger patrols in inaccessible regions.
- Satellite provides daily monitoring over the highest-value habitat.
- Combined deployment maximises spatial protection.

Deployment Footprint, Protection & Residual Loss

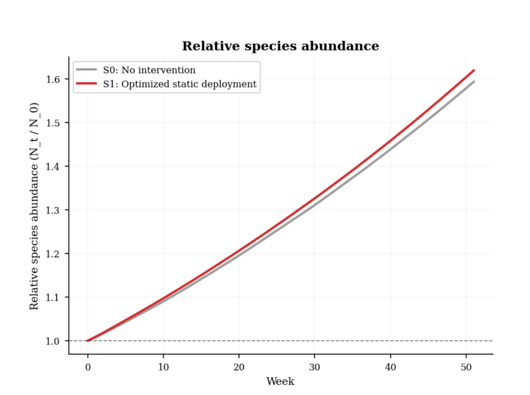


857/990 cells covered (86.6%), 92.3% weighted coverage — protection is near-saturated (dark red) across the boundary corridor and waterhole belt, and residual loss at $t=0$ falls **29.1%** versus no intervention.

Protection Over Time: A 52-Week Simulation



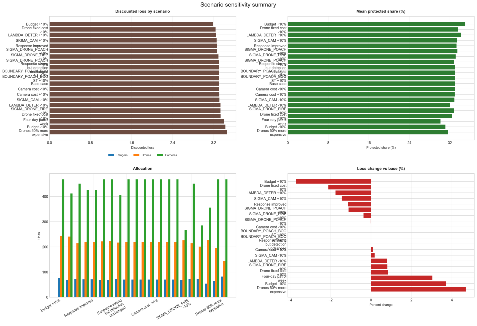
Loss drops **29.1%** at $t=0$ ($1.197 \to 0.849$) and stays below baseline through the dry-season peak (shaded).



Species abundance rises **64%** by week 52 under S1 vs. **62%** under S0 — static deployment, compounding effect.

Robust Under Uncertainty

- We perturbed detection rates, deterrence strength, response effectiveness, and cost coefficients one at a time.
- Result: the optimiser is **structurally stable** — rangers stay on boundary corridors, drones stay on high-connectivity hotspots, cameras stay near waterholes.
- Discounted loss shifts only -3.7% **to** $+4.7\%$ across scenarios.
- Budget and patrol capacity dominate sensitivity; boundary-poaching parameters are already saturated.



Loss, protected share, and allocation across 20 perturbation scenarios.

Limitations: What the Model Simplifies

Ecological scope

- Does **not explicitly include plants and insects**.
- Does **not model detailed food-web interactions** such as predation, competition, or mutualism.
- Strong for **large-scale planning**, but does not capture every ecological interaction inside the park.

Why not the full exact model

- A fully exact mixed-integer nonlinear model would be too expensive to solve at this scale.
- The problem is also **non-convex**, so standard methods cannot guarantee the global optimum.
- We use a practical formulation that is much faster and still gives a very strong solution.

Main idea

These simplifications were made because the full ecological system would need much more data and much more computation.

Transferability

One Framework, Many Reserves

- **Core structure is unchanged**: grid the reserve, score importance, score threats, optimise resource placement under budget.
- Only the **inputs** are recalibrated per site: terrain, access routes, threat composition, species priorities, cost data.

Yellowstone (N. America)

Road-based access, strong seasonality ⇒ roadside patrols, visitor safety, seasonal planning.

Kakadu (Oceania)

Floodplains, wet-season closures ⇒ aerial/satellite monitoring, fire and water-risk management.

Key Takeaways

- **40.3%** cut in discounted loss vs. no intervention, at **99.08%** optimality.
- **104 rangers, 211 drones, 468 cameras, 1 satellite** — 92.3% of ecological importance protected, 99.6% of budget used.
- Spatial logic is **robust** and the framework **transfers**.

Careful, data-driven planning turns a limited budget into a targeted, defensible protection strategy.