Protecting Wildlife at Scale

Optimizing Resource Allocation for Etosha National Park

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Context & Framing the Problem

Challenges:

- Etosha spans $\sim$23,000 km^2 with severe water scarcity.
- Only 295 staff members available.
- $\implies$ Uniform protection will *not* be possible

Our approach:

- Avoid uniform coverage of the park
- Protection is instead defined as the fraction of expected ecological loss prevented.

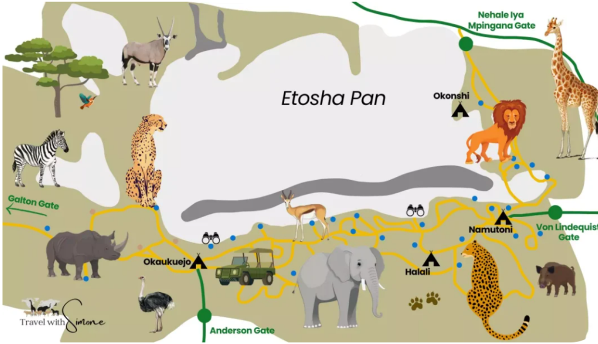


Illustration of Etosha National Park

Staffing & Resources

Active-staff formula:

$$N_{\text{active}} = 6B_{\text{patrol}} + 2B_{\text{drone}} + \left\lceil \frac{B_{\text{sensor}}}{4} \right\rceil + N_{\text{base}}$$

Each position requires roughly:

$\frac{\text{24 hours a day}}{\text{7 hours a shift}} \approx 3.5$ employees. With 83 active staff:

$$\boxed{N_{\text{payroll}} \approx 3.5(83) \approx 291 < 295}$$

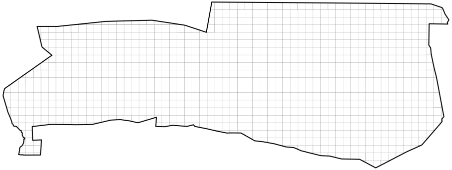
Staffing limit is satisfied!

Grid-Graph Representation of the Park

To begin modelling, we divide Etosha's vast landscape into smaller, computationally manageable components.

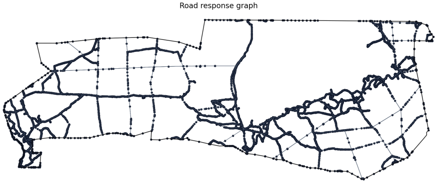
Grid

- Represents ecological value and threat
- Divides the park into 996 cells of 5×5 km
- Captures continuous spatial variation



Graph

- Represents response and mobility
- Nodes represent gates, camps, and road junctions
- Weighted edges represent roads and travel times



Mathematical Framework

Consider a given grid cell g:

Baseline Expected Loss (No Intervention)

$$L_g^0 = A_g C_g \lambda_g$$

Where A_g is cell area, C_g is ecological consequence, and λ_g is threat intensity.

Avoided Loss

$$L_g^{av} = L_g^0 R_g D_g$$

Where R_g, D_g are the response and detection success probabilities

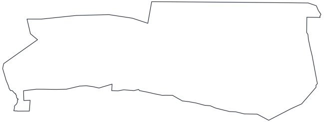
Protection Index: Objective to Maximize

$$PI = \frac{\sum_g L_g^{av}}{\sum_g L_g^0}$$

Higher $PI \implies$ greater proportion of baseline expected loss prevented.

Context Layers

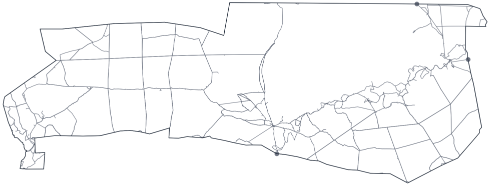
Etosha boundary



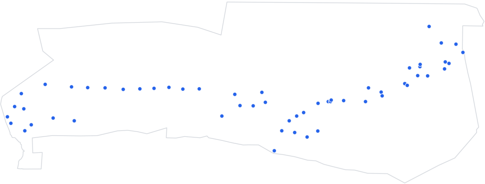
Etosha camps

Etosha gates

Etosha roads



Etosha waterholes



Ecological Value (C_g)

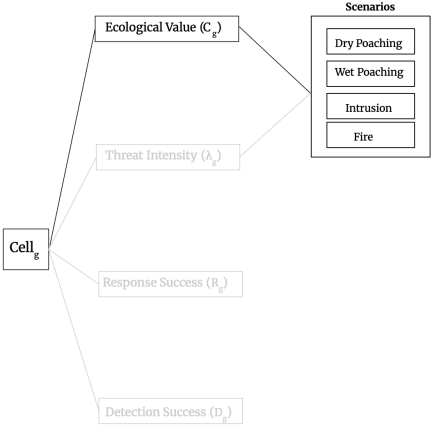
"How ecologically damaging would an event be there?"

Each cell is assigned four ecological value scores:

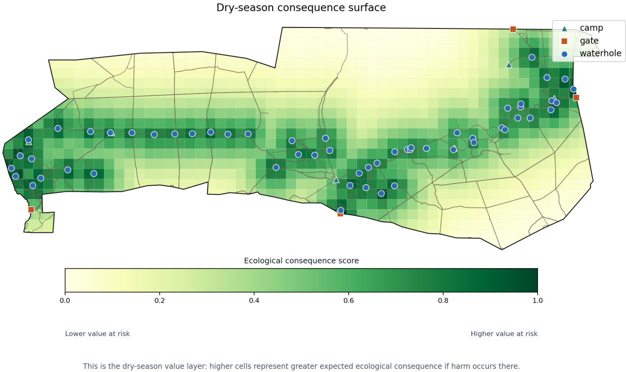
- Dry season poaching value ($C_{poach,dry}$)
- Wet season poaching value ($C_{poach,wet}$)
- Intrusion value ($C_{intrusion}$)
- Fire value (C_{fire})

These scores are based on:

- d_{water}
- d_{fence}
- d_{center}



Dry Season Ecological Value ($C_{poach,dry,g}$)



$$\boxed{R_{\mathrm{dry}} = e^{-d_{\mathrm{water}}/12}}$$

$$\boxed{E_{\mathrm{dry}} = e^{-d_{\mathrm{water}}/18}}$$

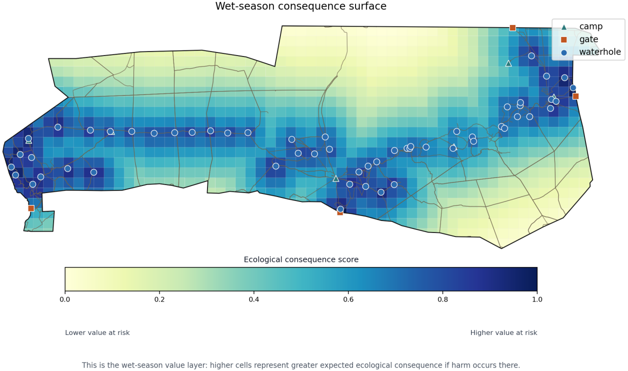
$$\boxed{H_{\mathrm{dry}} = e^{-d_{\mathrm{water}}/22}}$$

where:

- R_{dry} is the rhino-use proxy;
- E_{dry} is the elephant-use proxy;
- H_{dry} is the general-herbivore-use proxy.

$$\boxed{C_{\mathrm{poach,dry,g}} = \mathrm{norm}(1.0R_{\mathrm{dry,g}} + 0.6E_{\mathrm{dry,g}} + 0.3H_{\mathrm{dry,g}})}$$

Wet Season Ecological Value ($C_{poach,wet,g}$)



$$\boxed{R_{\text{wet}} = e^{-d_{\text{water}}/24}}$$

$$\boxed{E_{\text{wet}} = e^{-d_{\text{water}}/28}}$$

$$\boxed{H_{\text{wet}} = e^{-d_{\text{water}}/35}}$$

where:

- R_{wet} is the rhino-use proxy;
- E_{wet} is the elephant-use proxy;
- H_{wet} is the general-herbivore-use proxy.

$$\boxed{C_{\text{poach,wet,g}} = \text{norm}(1.0R_{\text{wet,g}} + 0.6E_{\text{wet,g}} + 0.25H_{\text{wet,g}})}$$

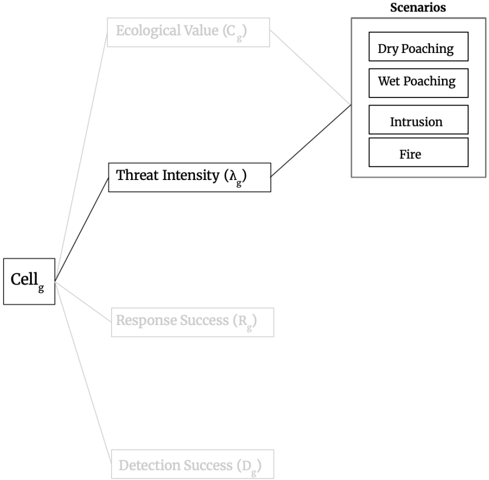
Threat Intensity (λ_g)

"How exposed is this cell to that event?"

Each cell is assigned four threat scores:

- $\lambda_{poach,dry}$
- $\lambda_{poach,wet}$
- $\lambda_{intrusion}$
- λ_{fire}

These scores are based on: d_{water}, d_{entry}, d_{road}, d_{fence}, d_{center}, slope, & elevation.



Poaching & Intrusion Threat Intensities

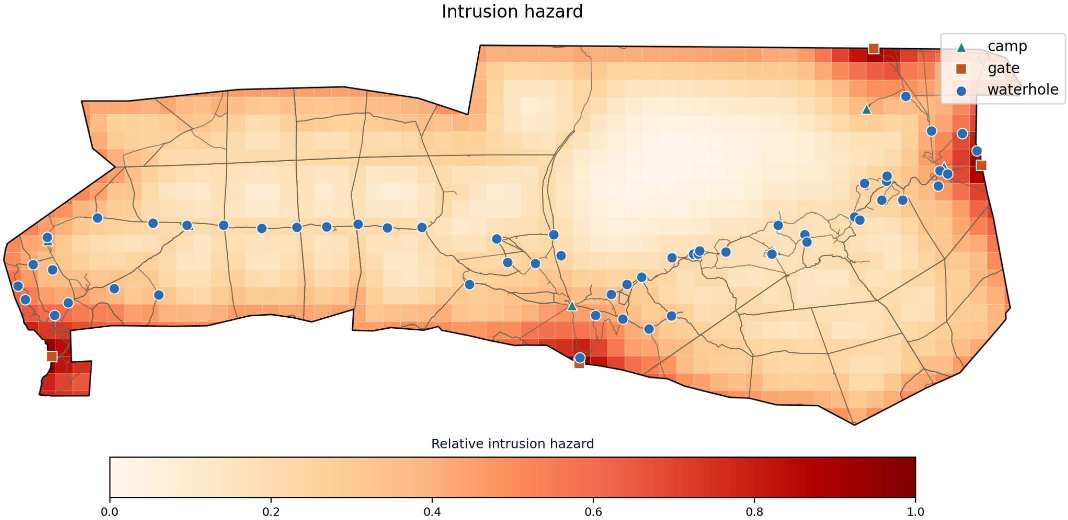
General Form

$$\boxed{\lambda_{s,g} = \mathrm{norm}\left[w_{s,0} R_{s,g} + \sum_{i=1}^{m_s} w_{s,i} \exp\left(-\frac{d_{i,g}}{\tau_{s,i}} \right) \right]}$$

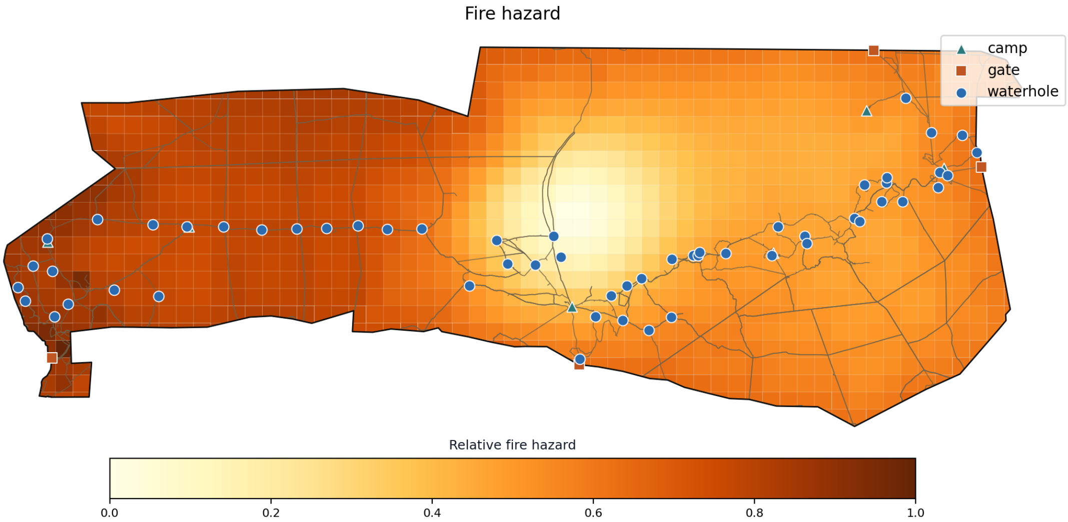
$$s \in \{\text{dry-season poaching}, \text{wet-season poaching}, \text{intrusion}\}$$

- $w_{s,i}$: weight assigned to feature i (sum to 1)
- $R_{s,g}$: rhino-use proxy (poaching)
- $d_{i,g}$: distance from cell g to feature i
- $\tau_{s,i}$: decay-distance parameter

Intrusion Threat Heatmap



Fire Threat Heatmap

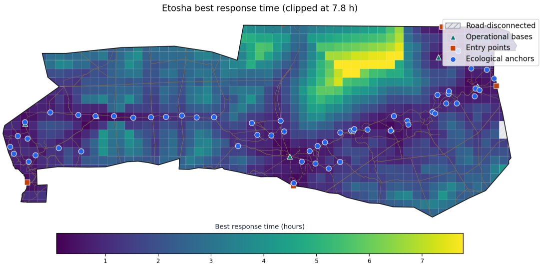


Can Rangers Respond in Time (R_g)?

Detection without intervention is merely observation.

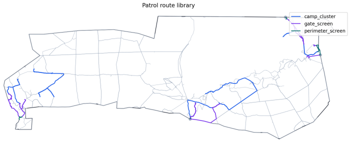
- **Terrain-Aware Mobility:** We calculate travel speed using road classes and slope penalties, transitioning to **Tobler's hiking function** for off-road approach.
- **Response Probability:** Best response time (τ_g) is converted to success probability via a logistic curve.

$$R_g = \frac{1}{1 + \exp(\kappa(\tau_g - \tau_0))}$$



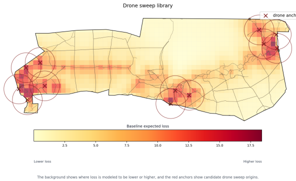
Detection: Three Complementary Assets

<u>Detection:</u> "How likely are we to detect harmful activity in cell g?"



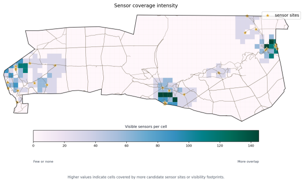
Patrol Routes ϕ_{rg}

$$\phi_{rg} = 1.5 \exp\left(-\frac{d_{rg}}{10}\right)$$



Drone Sorties ψ_{dg}

$$\psi_{dg} = 1.8 \max\left\{0,\ 1 - \frac{\|\mathbf{c}_g - \mathbf{a}_d\|_2}{16}\right\}$$



Sensor Sites χ_{sg}

$$\chi_{sg} = 0.95 \exp\left(-\frac{d_{sg}}{8}\right).$$

Influence Matrices

These functions produce three separate matrices. Each entry measures how strongly a candidate asset influences a particular cell (assuming the cell is in adequate proximity to that asset.)

Detection Surrogate: From Assets to Detection

$$\boxed{\text{asset choices} \to M_g \to S_g \approx D_g}$$

Monitoring score

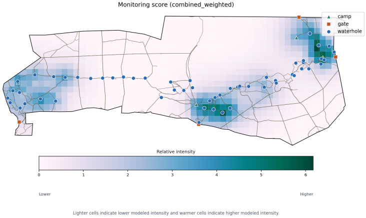
$$M_g = \sum_r \phi_{rg} y_r + \sum_d \psi_{dg} z_d + \sum_s \chi_{sg} x_s$$

- M_g: total monitoring intensity score of cell g
- D_g: true detection probability
- S_g: piecewise-linear surrogate for D_g

Why use a surrogate?

$$D_g^{\text{exact}} = 1 - \left(1 - P_g^{\text{patrol}}\right)\left(1 - P_g^{\text{drone}}\right)\left(1 - P_g^{\text{sensor}}\right)$$

- exact detection has overlap effects
- $D_g^{\text{exact}} \approx P_g^{\text{patrol}} + P_g^{\text{drone}} + P_g^{\text{sensor}}$. Higher order terms make the model nonlinear



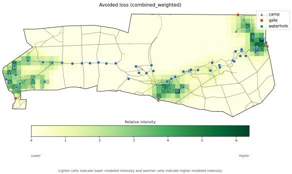
Monitoring intensity M_g

Surrogate mapping:

$$(m_j, s_j): \quad M_g = m_j \Rightarrow S_g = s_j$$

- increasing
- diminishing returns (ie concave)
- bounded

MILP: Turning the Surrogate into a Deployment



Avoided ecological loss

Resource constraints

$$\sum_r y_r \le B_P$$

$$\sum_d z_d \le B_D$$

$$\sum_s x_s \le B_S$$

The deployment cannot exceed the available patrol, drone, or sensor capacity.

Decision variables

$$y_r,\ z_d,\ x_s \in \{0,1\}$$

- y_r: choose patrol route r
- z_d: choose drone sortie d
- x_s: choose sensor site s

Surrogate interpolation

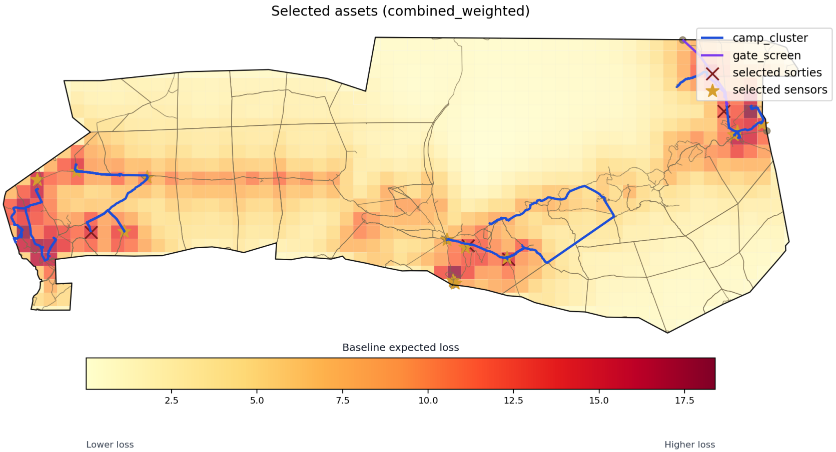
$$M_g = \sum_j m_j \lambda_{gj}, \qquad S_g = \sum_j s_j \lambda_{gj}$$

$$\sum_j \lambda_{gj} = 1, \qquad \lambda_{gj} \ge 0$$

The weights λ_{gj} interpolate between calibrated anchor points, converting M_g into S_g.

Objective

$$\max \sum_{g \in G} L_g^0 R_g S_g$$



The shaded background shows pre-optimization loss, while the overlaid lines and markers show the assets selected by the optimizer.

Results: The Hotspot-First Strategy

Hotspots = top 10% of cells ranked by baseline loss (minimum avg. monitoring score threshold required)

Table 1: Scenario-level Etosha results

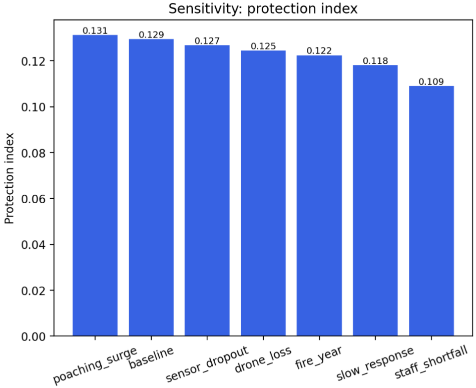
Scenario	Protection index	Avoided loss	Hotspot PI
Dry poaching	0.148	506.0	0.244
Wet poaching	0.136	570.4	0.253
Combined weighted	0.129	534.4	0.250

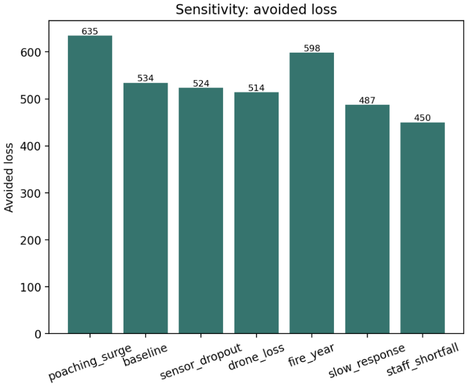
⇒ **12.9%** of expected loss is prevented across the whole park.

⇒ In the hotspots, **25%** of expected loss is prevented.

⇒ **Our strategy protects hotspots much more strongly than the park as a whole.**

Sensitivity Analysis





Greatest harm comes from `staff_shortfall`.

Model remains robust

Increased threats $\Leftrightarrow$ larger baseline loss $\Leftrightarrow$ larger avoided loss ($L_g^{av.} = L_g^0 R_g D_g$)

Data and Research

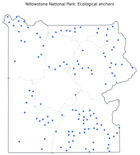
Our model uses open-source, real-world data:

- **OpenStreetMap:** Park boundaries, road networks, camps, and gates.
- **OpenTopography (DEM):** Elevation and slope data for mobility and line-of-sight.
- **NASA FIRMS & NASA POWER:** Wildfire history and weather data for the threat layer.

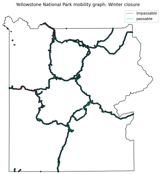
Yellowstone Generalization

Unchanged: loss objective, grid–graph response, detection surrogate, and MILP.
Changes: Hydrology, seasons, threats, winter road closures.

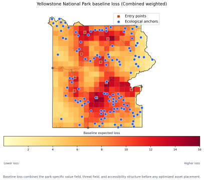
Road map



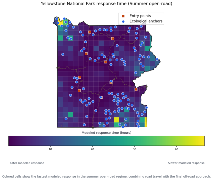
Visitor & ecological anchors



Winter mobility graph



Combined baseline loss



Summer response time

Rerun data

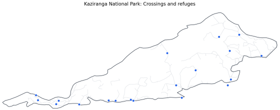
Cells	408
Access bases	9
Eco. anchors	120
Winter closures	19
Combined PI	0.141

Median response: 3.08 h → 3.49 h

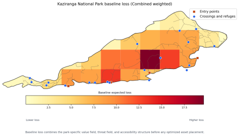
Kaziranga Generalization

Unchanged: loss objective, grid–graph response, detection surrogate, and MILP.
Changes: crossings, refuges, flooding, road closures.

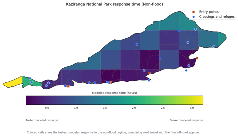
Road map



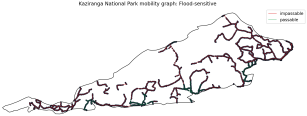
Crossings and refuges



Combined baseline loss



Non-flood response time



Flood mobility graph

Recalibration

Ecology: 11 crossings and 8 refuges.

Mobility: flooding reduces road edges.

Threat: Poaching remains.

Rerun data

Cells	28
Access bases	4
Eco. anchors	19
Corridor segments	219
Combined PI	0.405

Median response: 0.88 h $\rightarrow$ 1.31 h

Strengths & Limitations

Strengths

- Clearly defined protection
- Realistic Etosha data
- Detailed graphs & maps
- Incorporates ecological importance
- Robust & Generalizable

Limitations

- Efficiency-equity trade off
- Assumptions/proxies
- Surrogate
- Limited candidates
- Solely allocation-based

Conclusion

Main ideas

- Identify where ecological loss is greatest and where threats are most intense.
- Account for whether harmful activity can be detected and whether rangers can respond in time.
- Use a MILP to select the feasible combination of patrols, drones, and sensors that maximizes avoided loss.

Takeaways from our Model

- Supported by real open-source data, the hybrid grid–graph structure combines continuous value and threat with discrete mobility networks
- The model's separates the transferable parts (optimization) from park-specific ecology, threats, access, and seasonal conditions.
- The Yellowstone and Kaziranga generalizations successfully adapt to winter closures, flooding, etc.