Greater China IMMC2026033 Team Introduction

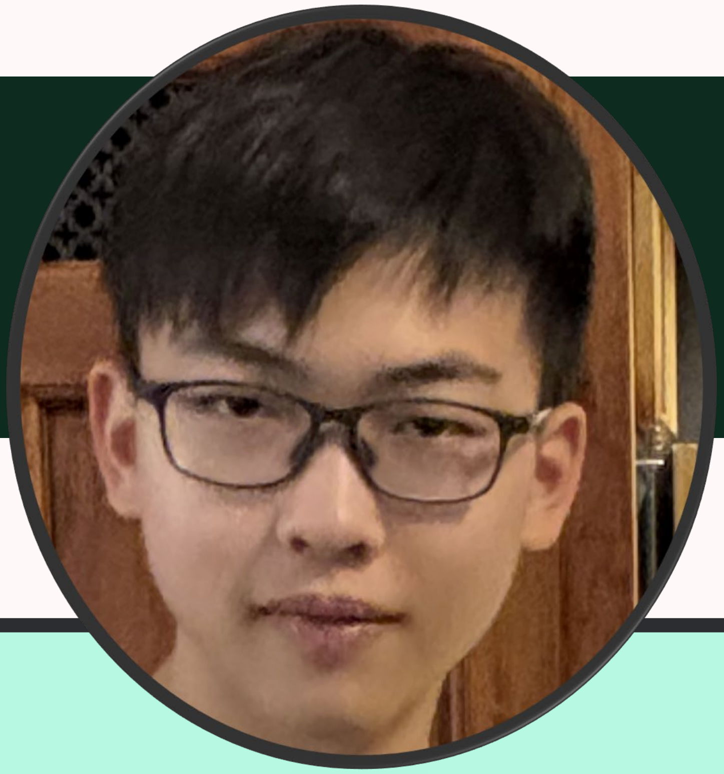
School Introduction

- We are from Shanghai High School International Division (SHSID)

School Introduction

- Here are some photos of our campus

Team Introduction



Ricky Wen

- 9th grade
- Responsible for designing & implementing the model, as well as sensitivity analysis

I love the process of taking an abstract equation and watching it transform into something that actually works. It takes patience, creativity, and quite a lot of debugging to create a model, but when it runs smoothly and everything clicks into place, that feeling is pure magic.

My Hobbies

- Coding
- Not sleeping
- Automation games
- Classic roguelikes

Team Introduction

Austen Lu

- 9th grade
- Responsible for writing the paper, general research, and collecting & washing data

I am a ninth-grade student passionate about applying mathematics to real-world problems. Solving everyday challenges with mathematical thinking gives me a strong sense of accomplishment and motivates me to continuously learn, explore new ideas, and develop better solutions.

My Hobbies

- Tennis
- Biology
- FPS Games

Team Introduction

Jeremy Yang

- 9th grade
- Responsible for writing the paper, creating graphics, and designing visuals

Math and modeling give me a clear, structured way to make sense of complex problems. While the real world is often ambiguous and overwhelming, modeling forces me to think logically, break things down into their core components, and test my assumptions rigorously. There's a quiet satisfaction in watching a finished model work.

My Hobbies

- Sports (badminton, soccer, etc.)
- Video games
- Math (of course)

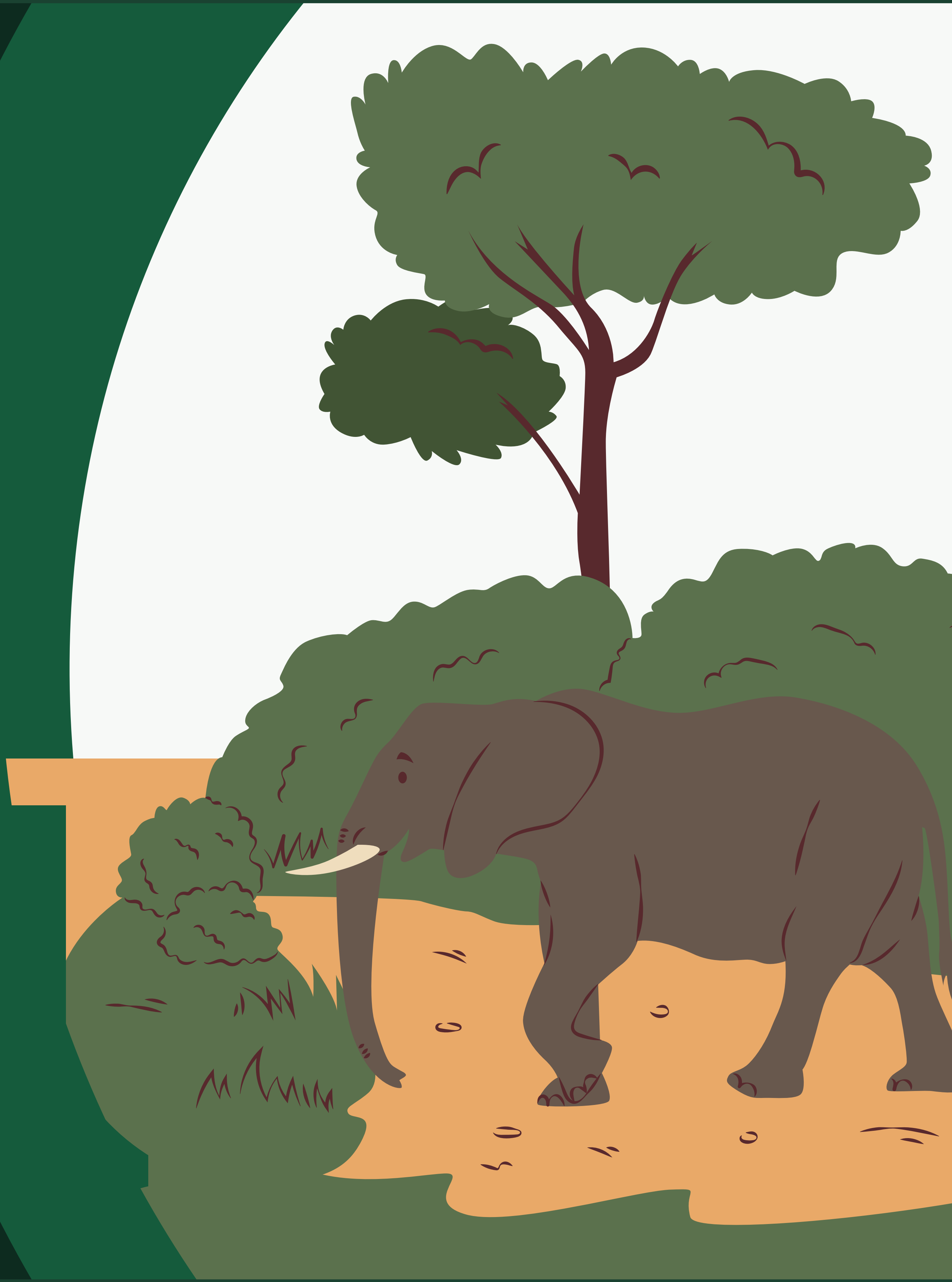
Team Introduction

Protecting Wildlife At Scale:

A Framework for Wildlife Protection in Etosha National Park

Optimizing protection for 22,935 km² of critical habitat with a limited budget

Contents



Background

- Etosha National Park covers a vast 22,935^2 km, creating a massive geographical challenge.

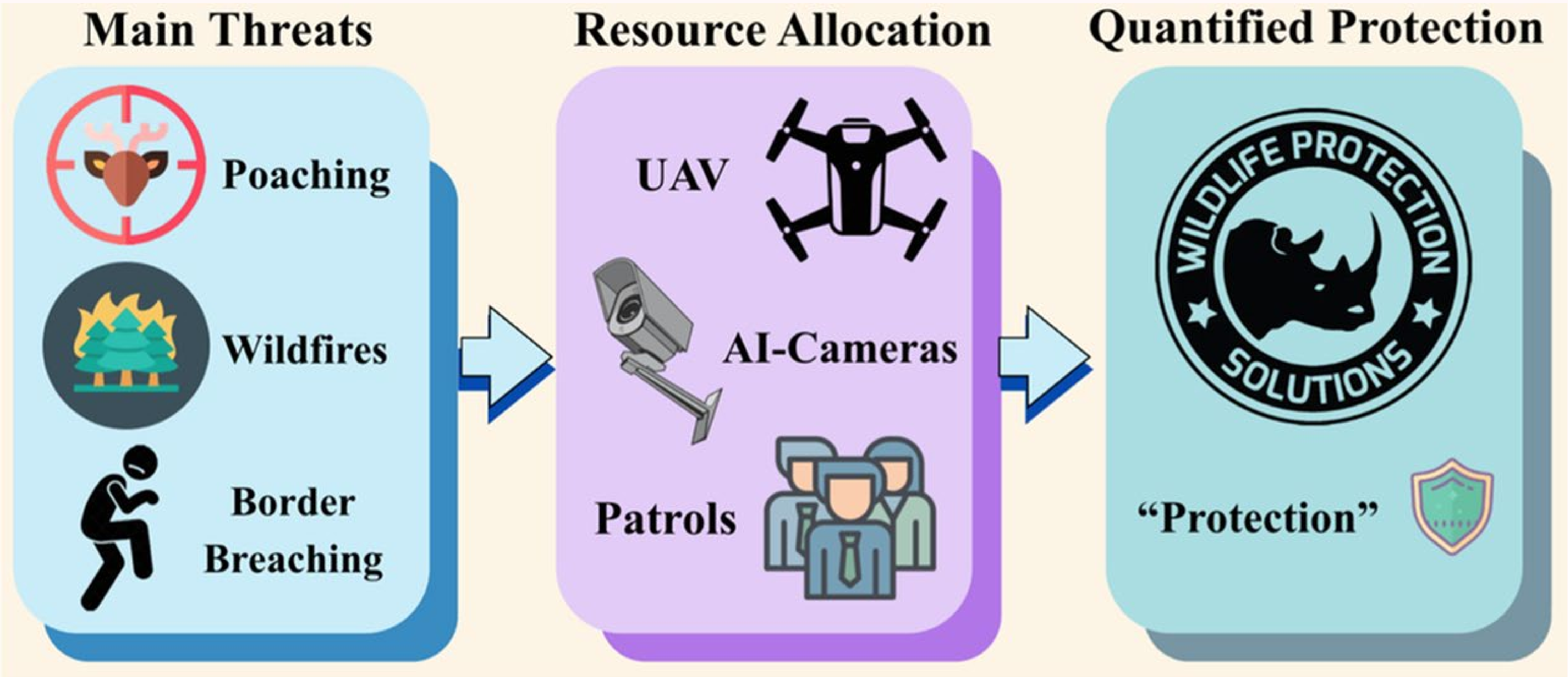
A partial map of Etosha National Park.
Source: etoshanationalpark.org

Background

- Etosha National Park covers a vast $22,935^{2}$ km, creating a massive geographical challenge.
- A limit of 295 personnel creates a significant gap between resources and area.

Background

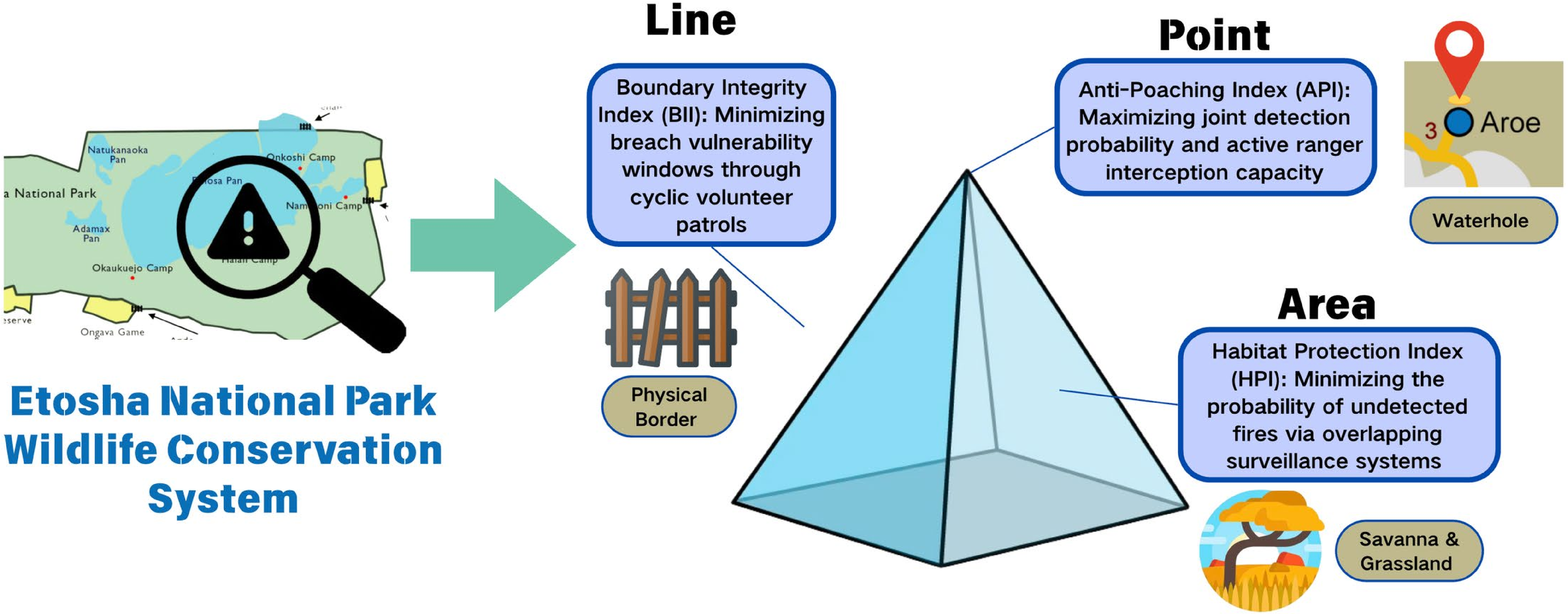
- We identify three primary threat vectors: point-based, area based, and linear-based risks.



Background

- We identify three primary threat vectors: point-based, area-based, and linear-based risks.
- Consequently, we develop a mathematical framework to optimize these limited defensive assets.

Background


Natukanaoka Pan
Onkoshi Camp
National Park
Adamax Pan
Okaukuejo Camp
Ongava Game
Etosha National Park Wildlife Conservation System
Line
Boundary Integrity Index (BII): Minimizing breach vulnerability windows through cyclic volunteer patrols
Physical Border
Point
Anti-Poaching Index (API): Maximizing joint detection probability and active ranger interception capacity
3
Aroe
Waterhole
Area
Habitat Protection Index (HPI): Minimizing the probability of undetected fires via overlapping surveillance systems
Savanna & Grassland

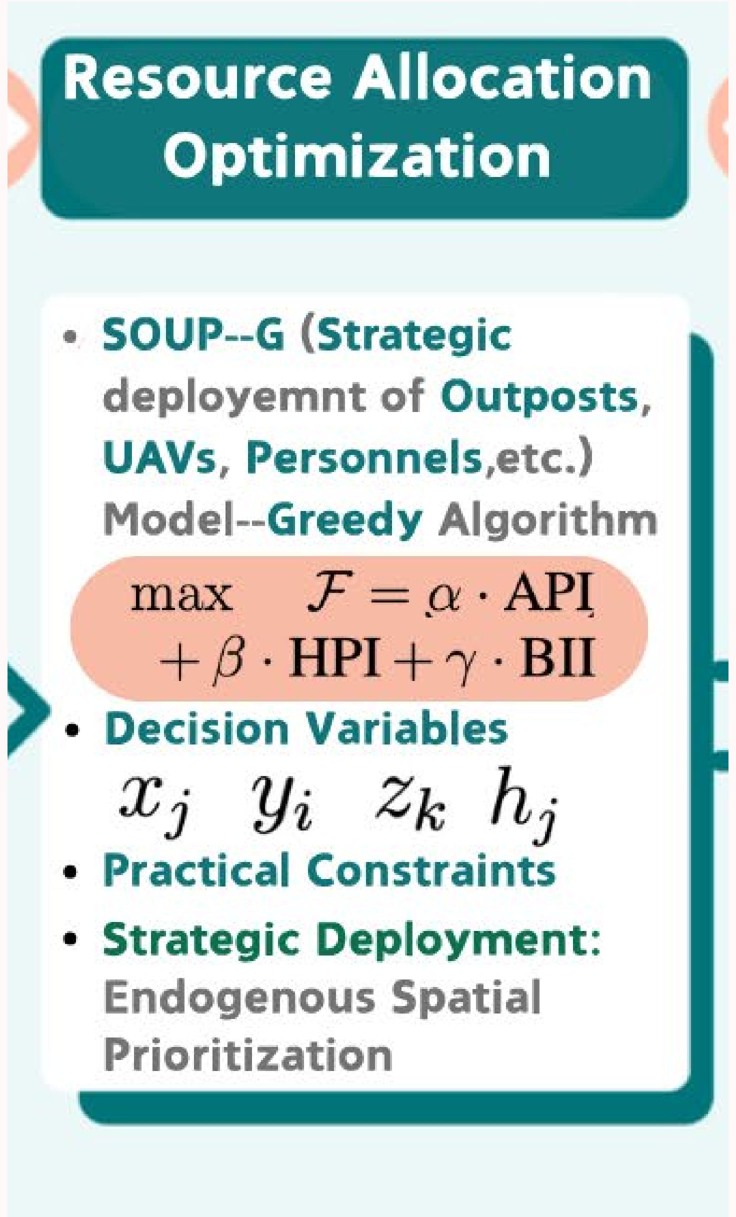
Our Work (Problem 1)

- We established a risk matrix to prioritize poaching, wildfires, and breaches.
- We translated "protection" into a quantitative Spatial Triad: point-based (API), area-based (HPI), and line-based (BII) indices.

Our Work (Problem 2)

- We developed a **constrained nonlinear optimization model** to maximize a composite protection score across a high-resolution grid.

- To solve this, we implemented a **Cost-Benefit Greedy Algorithm** that deploys assets based on marginal protection gain.



Our Work (Problem 3-7)

- Extended the model into temporal dimensions (seasonal/diurnal).
- Used inverse optimization to develop a Tiered Dynamic Deployment strategy.
- Conducted elasticity stress tests to prove technology can substitute for labor.
- Validated global transferability in Lorentz and Yellowstone.
- Analyzed model strengths and weaknesses and drafted a letter to the IMMC.

PART 02

Problem 1:
Conservation Priorities and Defining Protection

Fundemental Assumptions

- Assumption 1: Short-Term Asset Permanence
- Assumption 2: Sufficient Personnel for Constant Surveillance
- Assumption 3: Independence of Threat Factors
- Assumption 4: Predictable Poacher Behavior

Variables and Notations

Category	Symbol	Description
Sets & Indices	$\mathcal{G}$	The set of all discrete 1 km $\times$ 1 km grid cells comprising the park
	(r, c)	The spatial coordinate index (row, column) for a specific grid cell
	k	Index for boundary fence segments ($k \in \mathcal{S}$)
	s	Temporal scenario index (e.g., Dry-Day, Dry-Night, Wet-Day, Wet-Night)
Decision Variables	$N_{\text{ranger}}(r, c)$	Number of mobile ranger squads deployed at grid (r, c)
	$N_{\text{uav}}(r, c)$	Number of UAVs allocated to grid (r, c) for aerial sweeps
	$N_{\text{cam}}(r, c)$	Number of fixed AI cameras installed at grid (r, c) (max 3 per waterhole)
	N_{vol}	Total number of volunteers deployed for cyclic boundary patrols

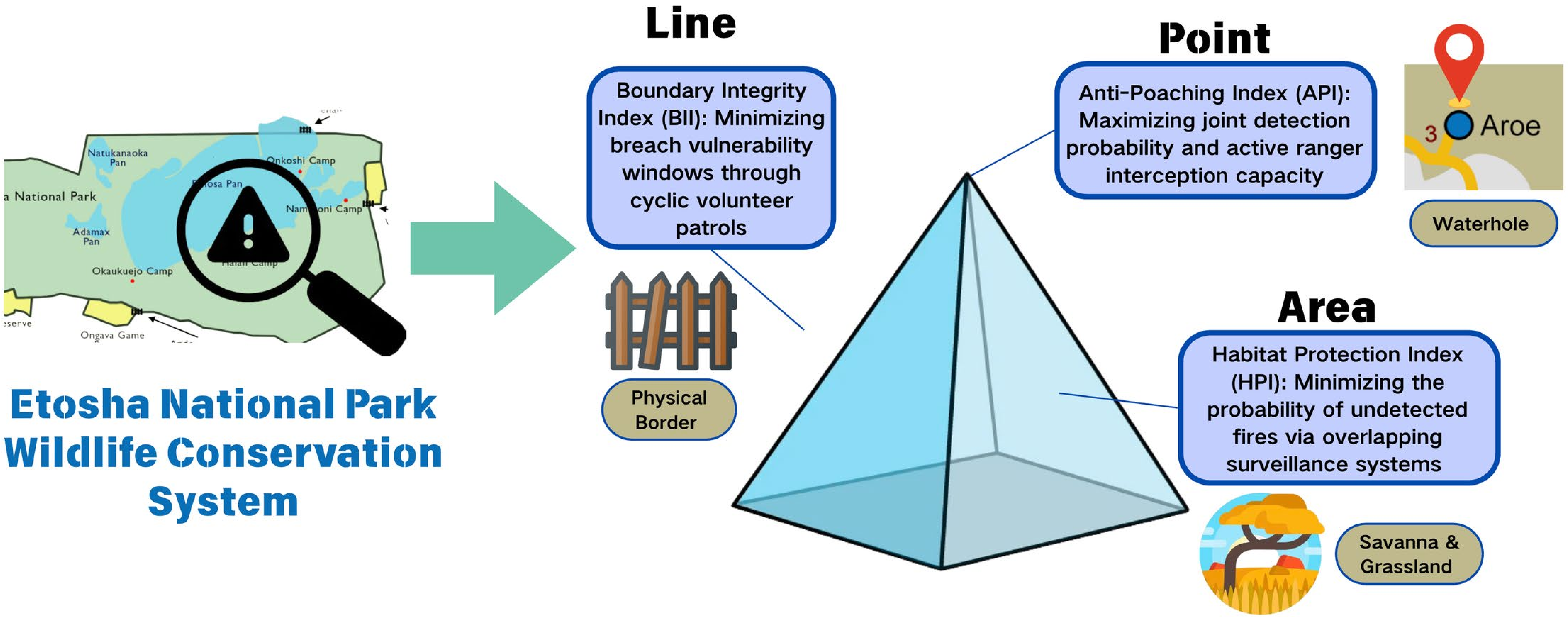
Variables and Notations

	$\mathcal{F}$	Global Comprehensive Protection Score (Objective Function)
	API, HPI, BII	Aggregate sub-indices: Anti-Poaching, Habitat Protection, Boundary Integrity
Protection Metrics	$V_{\text{API}}(r, c)$	The point-level poaching protection value computed for grid (r, c)
	$P_{\text{miss}}(r, c)$	The joint probability of a wildfire going undetected at grid (r, c)
	I_k	The physical intactness probability of boundary segment k
	$S_{\text{ranger}}, S_{\text{uav}}$	Distance-weighted patrol and aerial surveillance strength at a given grid
	P_{detect}	The joint probability of successfully detecting a poaching threat
Detection & Strength	$P_{\text{patrol}}, P_{\text{camera}}$	Independent threat detection probabilities of specific resource classes
	k_{patrol}	Saturation coefficient converting patrol strength into probability
	κ	Efficiency saturation multiplier for stacked AI cameras

Variables and Notations

Risks & Weights	α, β, γ	Global priority weights assigned to poaching, wildfire, and boundary threats
	$R_{\text{poach}}(r, c)$	Localized inherent poaching risk weight for grid (r, c)
	$R_{\text{fire}}(r, c)$	Localized inherent wildfire risk weight for grid (r, c)
	w_k	Normalized vulnerability weight of boundary segment k

Spatial Triad Framework



API (Anti-Poaching Index)

- Represents point-based risk at high-traffic nodes, specifically maximizing the probability of intercepting poachers.

$$\mathrm{API} = \frac{\sum_{(r,c)\in\mathcal{G}} R_{\text{poach}}(r,c)\cdot V_{\text{API}}(r,c)}{\sum_{(r,c)\in\mathcal{G}} R_{\text{poach}}(r,c)},$$

HPI (Habitat Protection Index)

- Represents area-based risk across core biomes, focusing on minimizing the probability of a fire going undetected.

$$\mathrm{HPI} = \frac{\sum_{(r,c)\in\mathcal{G}} R_{\mathrm{fire}}(r,c)\cdot\left(1 - P_{\mathrm{miss}}(r,c)\right)}{\sum_{(r,c)\in\mathcal{G}} R_{\mathrm{fire}}(r,c)},$$

BII (Boundary Integrity Index)

- Represents line-based risk along the park perimeter, securing fences through optimized patrol frequencies and volunteer cycles.

$$\mathrm{BII} = \sum_{k \in \mathcal{S}} w_k \cdot I_k = \frac{\sum_{k \in \mathcal{S}} w_k \max\left(0,\ 1 - \frac{\lambda_k \cdot \left(T_{\text{find}} + T_{\text{fix}}\right)}{T_{\text{total}}}\right)}{\sum_k w_k}$$

Objective Function

- Goal: Maximize Score ($F = API \times W_p + HPI \times W_a + BII \times W_l$)

Table 4.1: Risk Matrix for Etosha National Park Conservation Challenges [2]

Threat Type (k)	**Primary Target & Spatial Feature**	**Severity** (S_k)	**Likelihood** (L_k)	**Risk Score** ($\mathcal{R}_k$)	**Priority Level**
Poaching	Black rhinoceros (Endangered, Point-based)	5	4	20	**High**
Wildfires	Savanna/grassland (Area-based)	3	4	12	**Medium-High**
Boundary Breaches	Human-wildlife conflict (Line-based)	3	3	9	**Medium-Low**

- From the risk matrix, we get $F = API \times \frac{20}{41} + HPI \times \frac{12}{41} + BII \times \frac{9}{41}$

PART 03

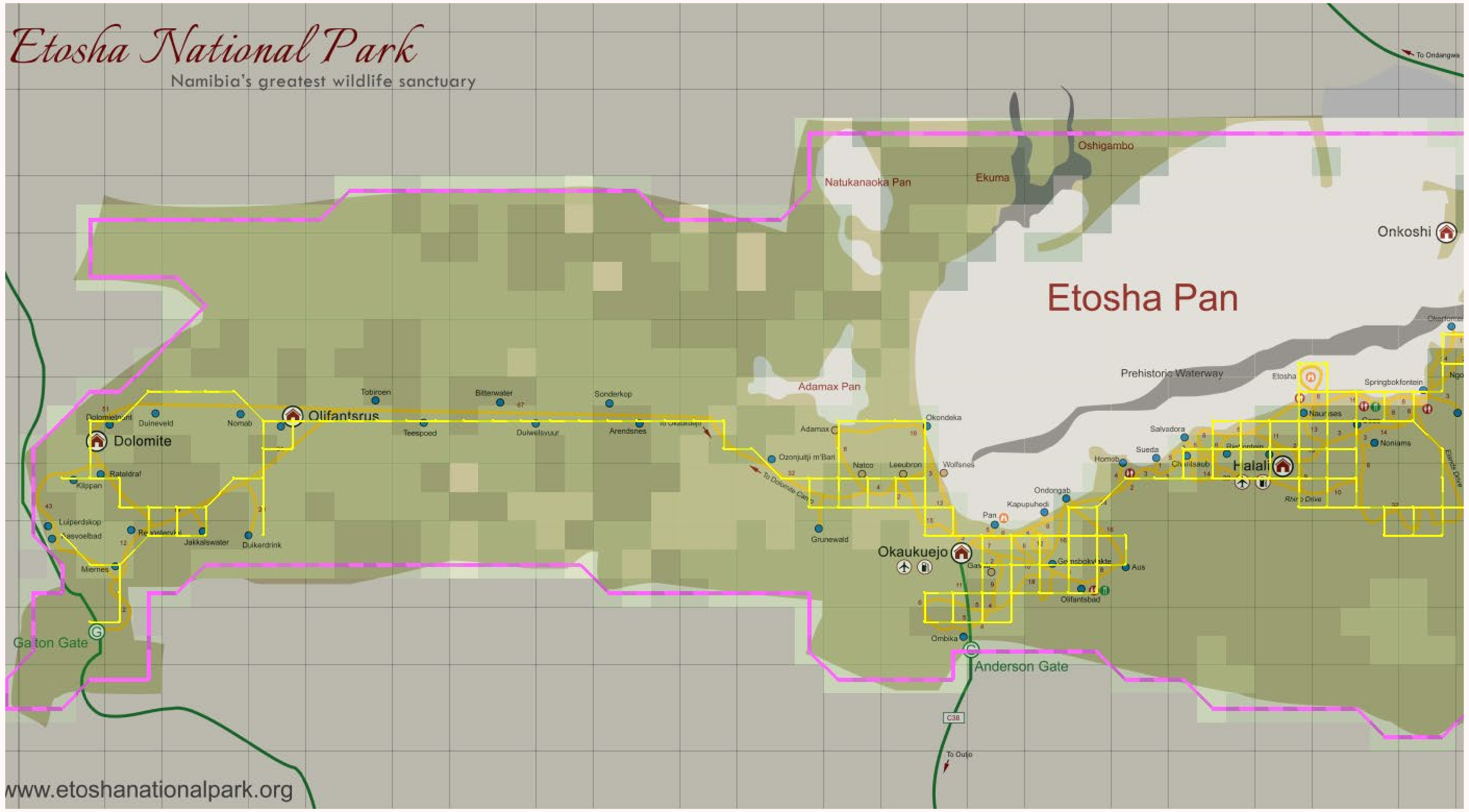
Problem 2: Resource Allocation Model

Node-Based Network

We create blue nodes at waterholes and gray nodes at road intersections, then use the road lengths on the official Etosha map to create a bidirectional graph.

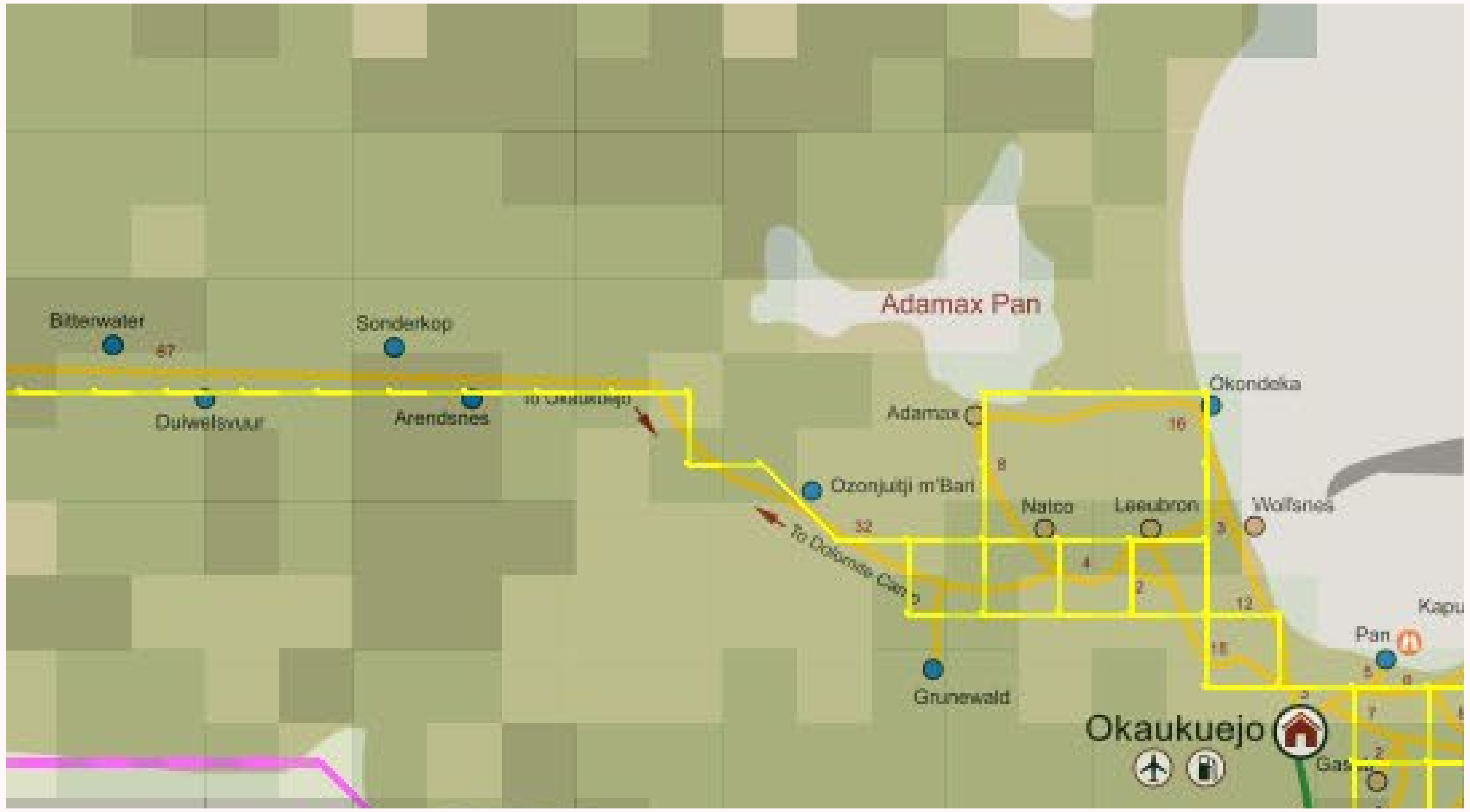
This is used to calculate distances between waterholes, gates, camps, etc. which are used in the calculation of the Animal Protection Index.

Grid-Based Discretization



After subdividing the map into a grid of squares, we then assign each square a biome type based on a biome map of Etosha, each biome having its own traversal resistance, fire risk, etc. to model ranger poacher interactions offroad.

Grid-Based Discretization



Our main resource allocation model is based off of this grid, discretizing unit assignment locations.

We assume each unit (ex. a ranger squad) has a fixed radius of patrol, with decreasing efficiency with distance.

Grid-Based Discretization

Our decisions for the constants used in the modeling process, including the different radii for fire and poacher detection amongst other things, although not extensively discussed in our paper due to length limits, were based off of real-world data and estimations.

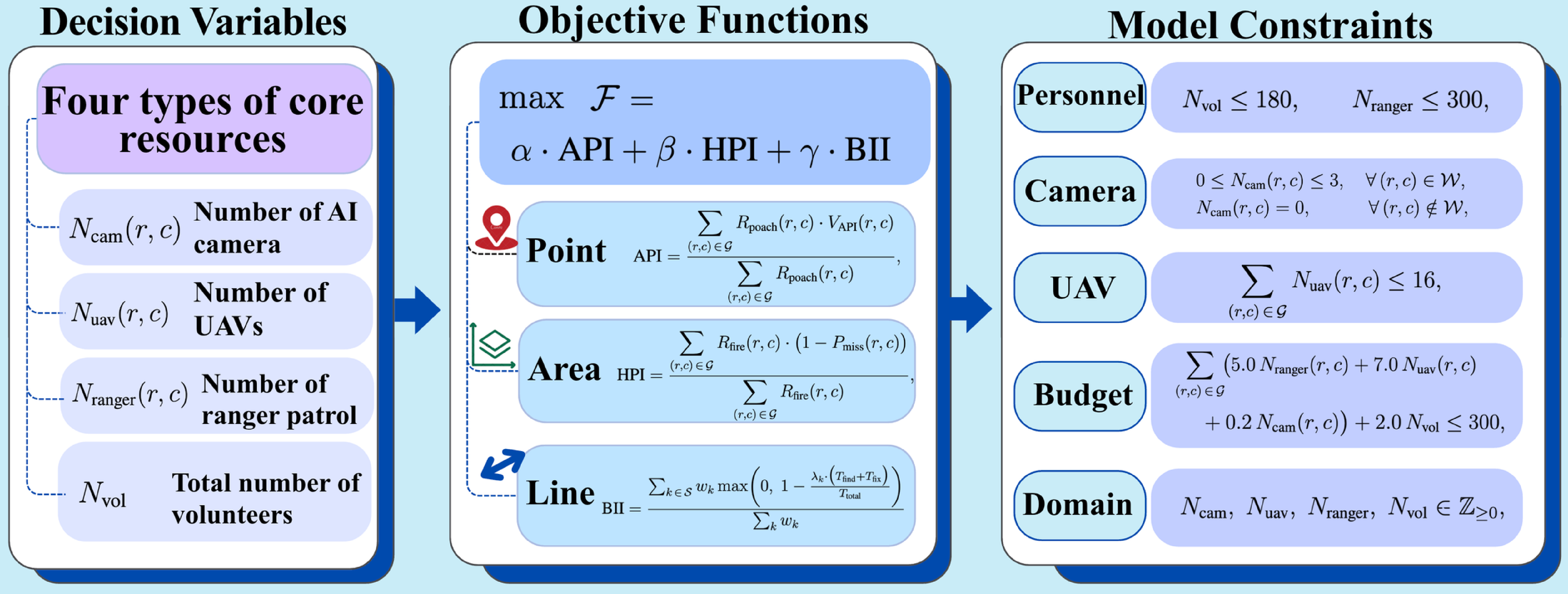
0.6	0.8	0.6
0.8	1.0	0.8
0.6	0.8	0.6

Model Governance Framework

- Defining variable constraints for resource allocation.

$$
\text{s.t.}\quad
\begin{cases}
\displaystyle\sum_{(r,c)\in\mathcal{G}} \big(5.0\,N_{\text{ranger}}(r,c) + 7.0\,N_{\text{uav}}(r,c) + 0.2\,N_{\text{cam}}(r,c)\big) + 2.0\,N_{\text{vol}} \le 300, & \text{(Global Budget)}\\
\displaystyle\sum_{(r,c)\in\mathcal{G}} N_{\text{uav}}(r,c) \le 16, & \text{(UAV Fleet Limit)}\\
N_{\text{vol}} \le 180, \qquad N_{\text{ranger}} \le 300, & \text{(Personal Capacity)}\\
0 \le N_{\text{cam}}(r,c) \le 3, \quad \forall\,(r,c)\in\mathcal{W}, & \text{(Camera Saturation)}\\
N_{\text{cam}}(r,c) = 0, \qquad \forall\,(r,c)\notin\mathcal{W}, & \text{(Camera Placement)}\\
N_{\text{cam}},\ N_{\text{uav}},\ N_{\text{ranger}},\ N_{\text{vol}} \in \mathbb{Z}_{\ge 0}, & \text{(Integrality)}
\end{cases}
$$

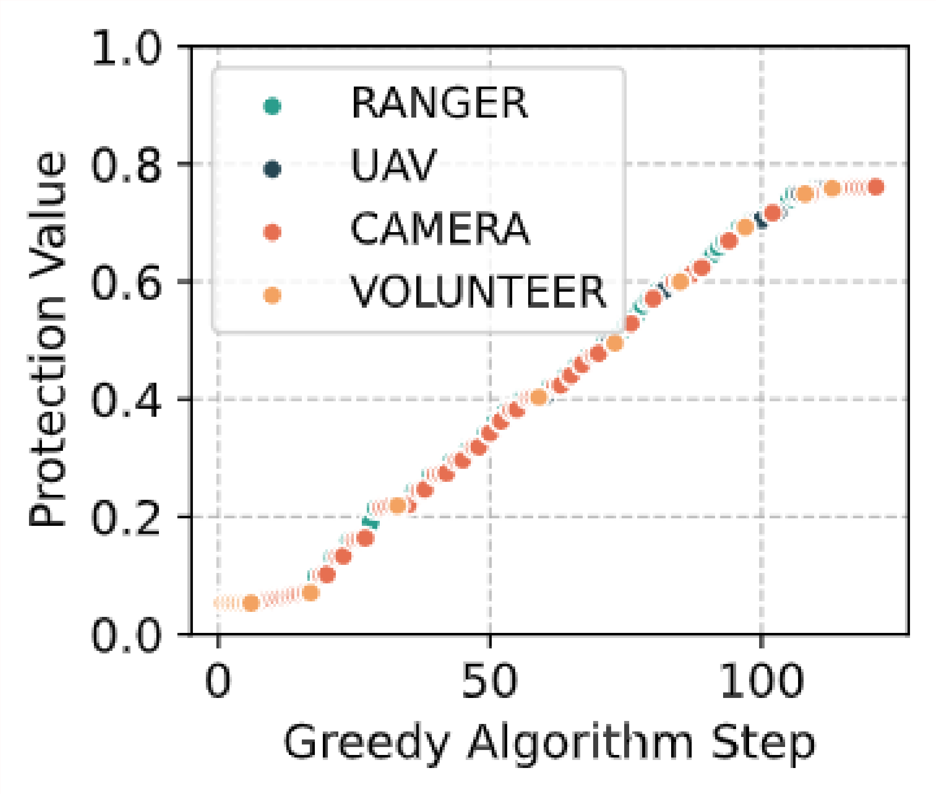
Model Governance Framework



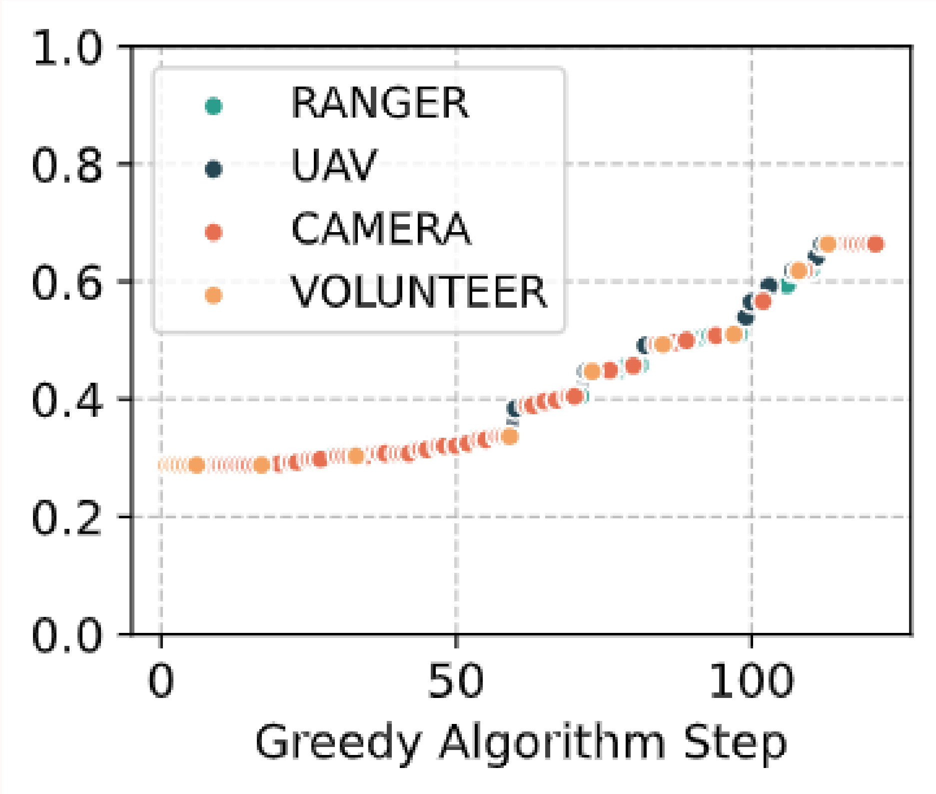
Optimization Process

- The optimization process of the model can be split into four phases:
- Phase 1: Perimeter Foundation
- Phase 2: Detection Mesh
- Phase 3: Ranger-Camera Clusters
- Phase 4: Budget Exhaustion

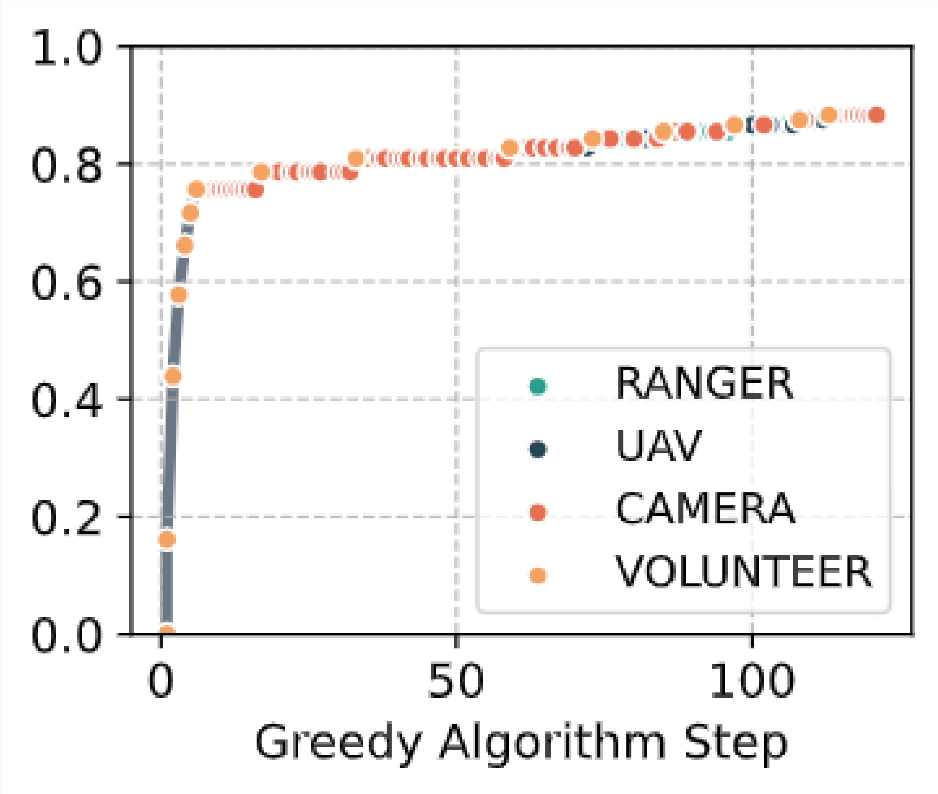
Optimization Process



API

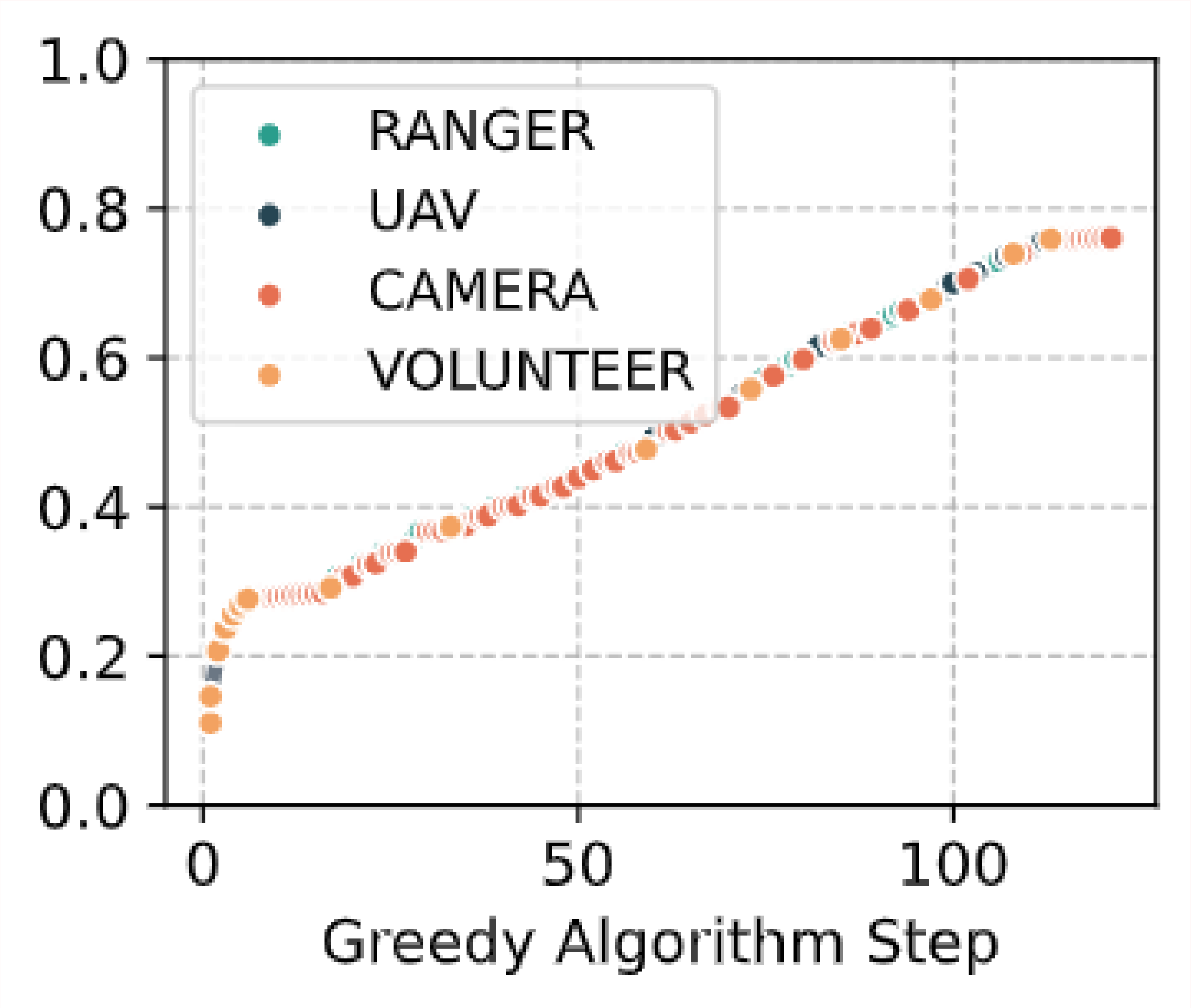


HPI



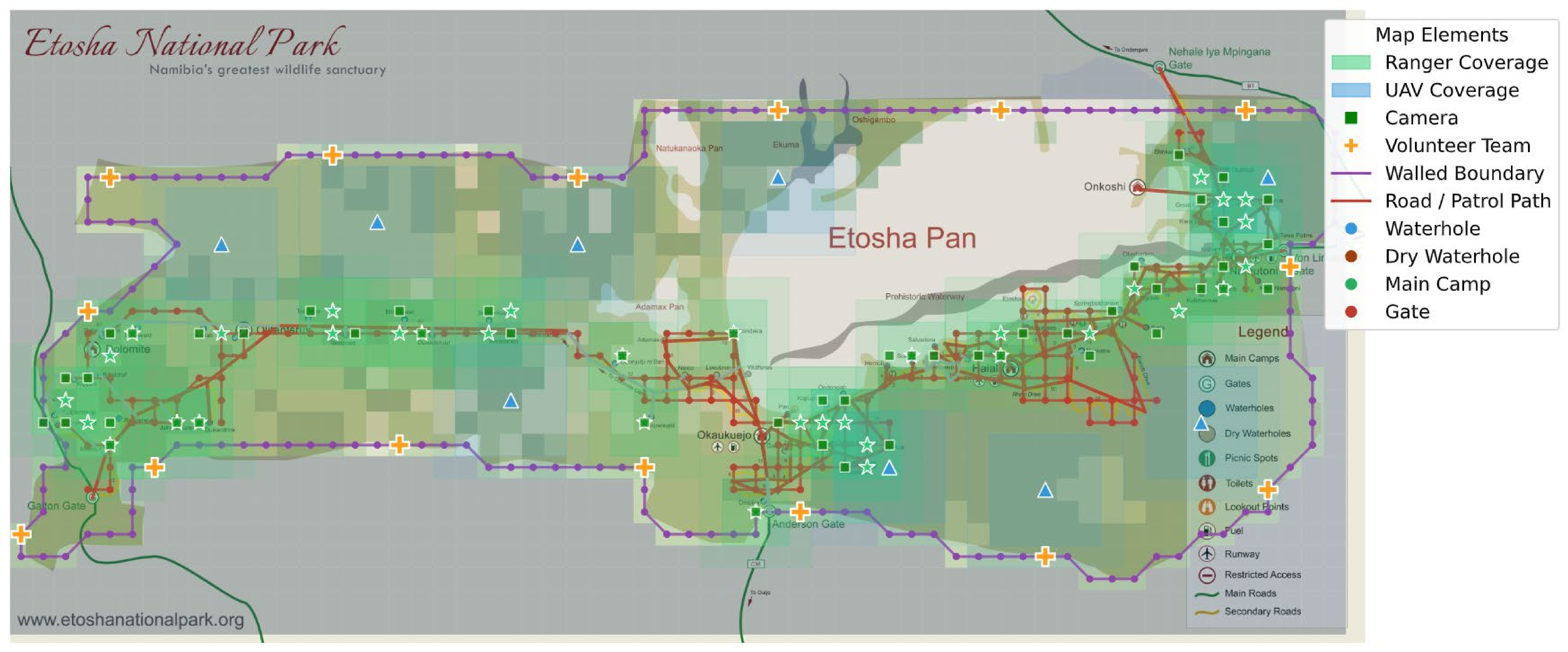
BII

Optimization Process



F-score

Optimization Result



Optimization Result

Allocation Summary

Table 5.4: Optimal Resource Allocation Summary

Resource Type	Units Deployed	Budget Cost	$\mathcal{F}$ Contribution	Primary Index
Rangers	195 (39 squads)	195.0	0.345	API
UAVs	9 (54 personnel total)	63.0	0.090	HPI
AI Cameras	59	12.0	0.036	API
Volunteers	90 (15 teams)	30.0	0.194	BII
Baseline	—	0.0	0.122	—
Total	249 personnel	**300.0**	**0.787**	—

PART 04

Problem 3: Protection over Time and Staffing Needs

Temporal Analysis

- Visualization of the four distinct temporal scenarios affecting Etosha's vulnerability.

Temporal Analysis

- We analyzed 4 scenarios across Seasonal (Dry/Wet) and Diurnal (Day/Night) scales, with the baseline situation modeled before being for the base Day scenario.
- In the night, the detection efficiency of units is reduced rather significantly, and poaching risk increases as a result. However, fire detection is more efficient.
- In the wet season, fire risks are lower, but road impedance increases, increasing travel times.
- In the dry season, animal density increases near waterholes, and fire risks are greater.

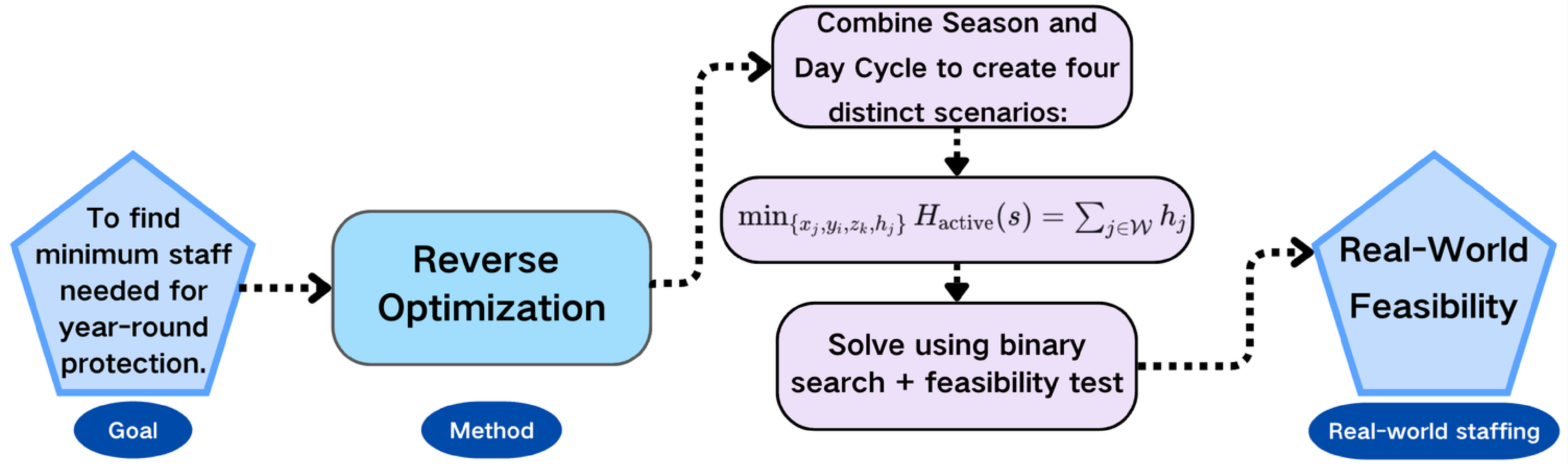
Temporal Analysis

- Forward evaluation revealed that the "static" 300-unit model fails during Wet-Night scenarios, falling below the required threshold.

Inverse Optimization & Staffing

- Minimize active personnel (H_{active}) while maintaining the baseline protection score ($F \geqslant 0.700$).
- We used a Binary Search paired with our Greedy Heuristic to calculate the "Human Cost" of safety in adverse conditions.

Inverse Optimization & Staffing



Scenario (s)	$\mathcal{F}_{\text{static}}(s)$	Gap	$H^{\min}_{\text{active}}(s)$	UAVs	Total Est. Staff	Ratio (Total)
Dry-Day (Baseline)	**0.787**	0.000	**105**	16	**201**	1.00×
Dry-Night	**0.565**	0.135	**195**	16	**291**	1.45×
Wet-Day	**0.612**	0.088	**125**	16	**221**	1.10×
Wet-Night	**0.560**	0.140	**290**	16	**386**	1.92×

Inverse Optimization & Staffing

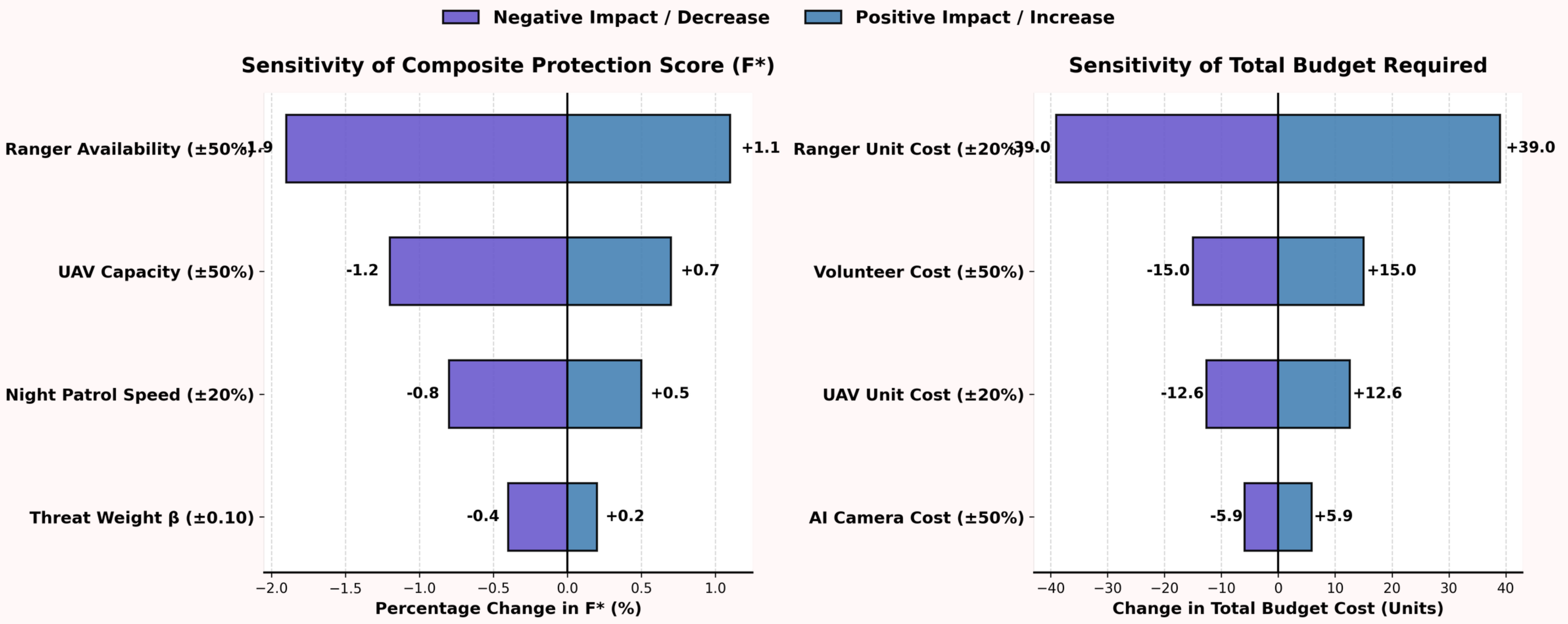
- To meet safety standards in the Wet-Night scenario, the park requires 1.92 more staff than the baseline Dry-Day allocation, falling under the $F \geqslant 0.700$ threshold when only 300 units are available.

- This would suggest a more dynamic schedule is required, with less staff present during the dry season as compared to the wet season, along with more staff being on night shifts.

PART 05

Problem 4: Sensitivity and Scenario Analysis

Sensitivity Analysis



Sensitivity Analysis

- Budget Sensitivity: Staffing costs (Rangers) show the highest impact on budget requirements, while technology costs are relatively inelastic.
- Even under a 50% increase in resource costs, the Greedy Algorithm internally compensates by re-routing funds.
- Key Finding: The protection system is structurally resilient; performance does not drop catastrophically when specific resource prices fluctuate.

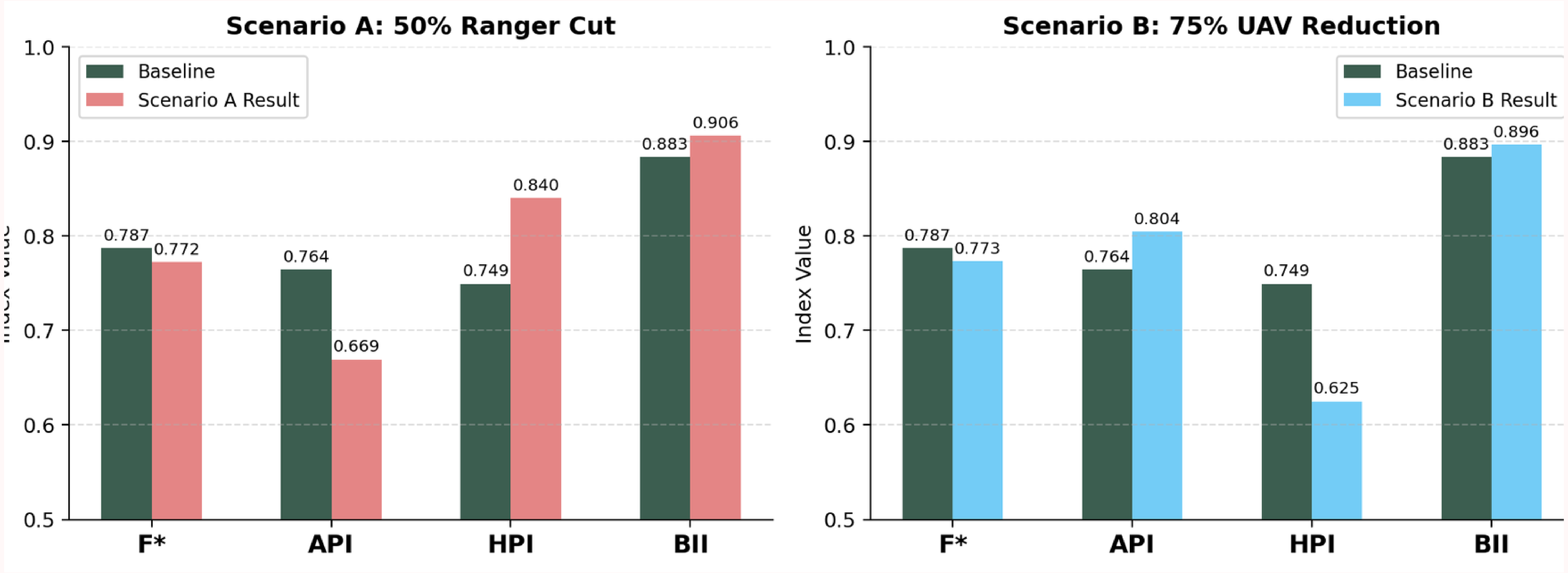
Sensitivity Analysis

- Resource Allocation Shift under Perturbed Priority Weights:

α (Poach)	β (Fire)	γ (Breach)	**Rangers**	**UAVs**	**Cameras**	**Volunteers**	$\mathcal{F}^*$
0.534	0.200	0.266	220	5	55	102	0.796
0.488	0.293	0.220	195	9	59	90	**0.787**
0.434	0.400	0.166	170	13	50	73	0.783
0.385	0.500	0.115	165	15	50	60	0.792

- The low elasticity proves our initial weights are robust; the model is not overly sensitive to weighting fluctuations, validating our Problem 1 risk matrix.

Scenario Analysis



$$\frac{\Delta F}{F} = -1.91\%$$

$$\frac{\Delta F}{F} = -1.78\%$$

PART 06

Problem 5: Model Strengths and Limitations

Model Strengths

- Geometric Logic: Successfully unifies Point, Area, and Line threats into a single grid-based matrix.
- Probabilistic Redundancy: Correctly models the "diminishing returns" of overlapping sensors.
- Operational Clarity: Produces an integer-based deployment blueprint, not just abstract theory.

Model Weaknesses

- Data Dependency: High sensitivity to empirical values like detection radii and biome resistance.
- Static Snapshot: Lacks game-theoretic mechanisms to account for poachers reacting to new patrol patterns.
- Myopic Heuristic: The Greedy Algorithm may settle into local optima by only evaluating immediate gains.

PART 7

Problem 6: Model Adaptation to Other Protected Areas

Universal Model Components

- The discretization of the park into computational grid cells and the division of threats into Point (API), Area (HPI), and Line (BII) indices.
- The joint detection probability framework ($P_{detect} = 1 - \Pi\,(1 - p_i)$), which mathematically handles overlapping sensor networks.
- The algorithmic solver evaluating the marginal gain-to-cost ratio (ΔF/Cost) to distribute constrained resources remains universally applicable.

Adaptation 1- Lorentz

- Recalibrate resistance matrices using Digital Elevation Models (DEMs)
- Substitute optical cameras with Acoustic AI Sensors to bypass cloud cover and detect chainsaw/voice frequencies.
- Shift risk weights from waterholes to river confluences, logging camps, and monsoon refuges.
- Expected Shift: UAV usage transitions from broad visual surveillance to targeted nocturnal thermal scanning of river corridors.

Adaptation 2- Yellowstone

- Significantly shift weights to Wildfire Index; reduce focus on poaching.
- Replace dry-season waterholes with Geothermal Basins (wintering grounds).
- High-visitor corridors receive elevated weights to mitigate vehicle collisions and bear-human conflict.
- Recalibrate weights using timber moisture and beetle-kill mortality maps rather than grass dryness.
- Expected Shift: Summer focus on wildfire UAV swarms; Winter focus on thermal basin monitoring.

PART 8

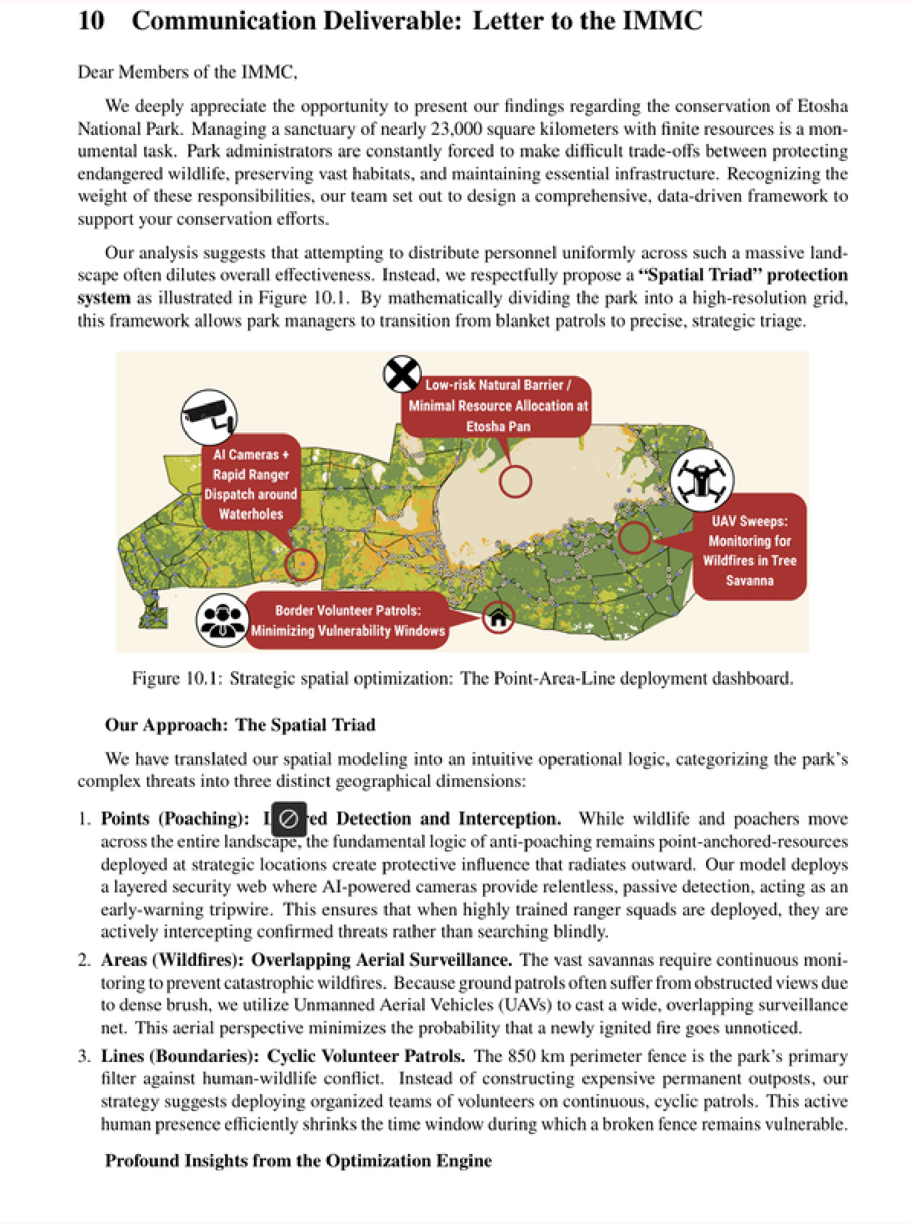
Problem 7: Communication Deliverable: Letter to the IMMC

Recommendation Letter

- Synchronizes resource deployment with Point, Area, and Line geographical risk factors.
- Mitigates protection gaps from seasonal and diurnal shifts through adaptive staffing.
- Maximizes the protective output of a constrained 300-unit resource budget.
- Prioritizes high-value biodiversity nodes to ensure long-term ecological resilience.

Key Words:

- Spatial Triad Optimization
- Multi-Asset Synergy
- Adaptive Temporal Deployment
- Dynamic Risk Triage



10 Communication Deliverable: Letter to the IMMC

Dear Members of the IMMC,

We deeply appreciate the opportunity to present our findings regarding the conservation of Etosha National Park. Managing a sanctuary of nearly 23,000 square kilometers with finite resources is a monumental task. Park administrators are constantly forced to make difficult trade-offs between protecting endangered wildlife, preserving vast habitats, and maintaining essential infrastructure. Recognizing the weight of these responsibilities, our team set out to design a comprehensive, data-driven framework to support your conservation efforts.

Our analysis suggests that attempting to distribute personnel uniformly across such a massive landscape often dilutes overall effectiveness. Instead, we respectfully propose a **"Spatial Triad" protection system** as illustrated in Figure 10.1. By mathematically dividing the park into a high-resolution grid, this framework allows park managers to transition from blanket patrols to precise, strategic triage.

Figure 10.1: Strategic spatial optimization: The Point-Area-Line deployment dashboard.

Our Approach: The Spatial Triad

We have translated our spatial modeling into an intuitive operational logic, categorizing the park's complex threats into three distinct geographical dimensions:

1. **Points (Poaching): I[illegible]ed Detection and Interception.** While wildlife and poachers move across the entire landscape, the fundamental logic of anti-poaching remains point-anchored-resources deployed at strategic locations create protective influence that radiates outward. Our model deploys a layered security web where AI-powered cameras provide relentless, passive detection, acting as an early-warning tripwire. This ensures that when highly trained ranger squads are deployed, they are actively intercepting confirmed threats rather than searching blindly.
2. **Areas (Wildfires): Overlapping Aerial Surveillance.** The vast savannas require continuous monitoring to prevent catastrophic wildfires. Because ground patrols often suffer from obstructed views due to dense brush, we utilize Unmanned Aerial Vehicles (UAVs) to cast a wide, overlapping surveillance net. This aerial perspective minimizes the probability that a newly ignited fire goes unnoticed.
3. **Lines (Boundaries): Cyclic Volunteer Patrols.** The 850 km perimeter fence is the park's primary filter against human-wildlife conflict. Instead of constructing expensive permanent outposts, our strategy suggests deploying organized teams of volunteers on continuous, cyclic patrols. This active human presence efficiently shrinks the time window during which a broken fence remains vulnerable.

Profound Insights from the Optimization Engine

PART 9

Conclusion

Conclusion

- Our combination of a node-based and grid-based approach lets us accurately model the intricacies of Etosha National Park. By combining two simpler approaches, we obtain more coverage without creating an overly complex model.
- Furthermore, our Spatial Triad framework actually offers coverage of multiple factors at play when it comes to wildlife preservation instead of just poaching, as wildfires and other threats can be just as if not more harmful.
- One of our core principles has always been simplicity. Instead of creating an elaborate framework with lots of parameters and relations, we focus on creating a more basic model and putting more of our time into polishing and solidifying our constants and modeling choices.

Conclusion

- Our end result is a genuinely actionable and specific plan that is understandable & intuitive at first glance and makes sense when considered from general principles.
- Our consideration of different climates and subsequent sensitivity analysis further demonstrates the robustness of our model.
- Finally, as the base assumptions of our model are fairly generic, it is highly adaptable to many different situations, without being constrained by being overly tailored to the circumstances of Etosha National Park.

Thank You For Listening