Spatial Optimization Framework for Wildlife Protection - Etosha

#2026048 Qianyu Jorlanda Chen

More Resources, No Improvement?

---A spatial-temporal resource allocation model for wildlife protection in Etosha

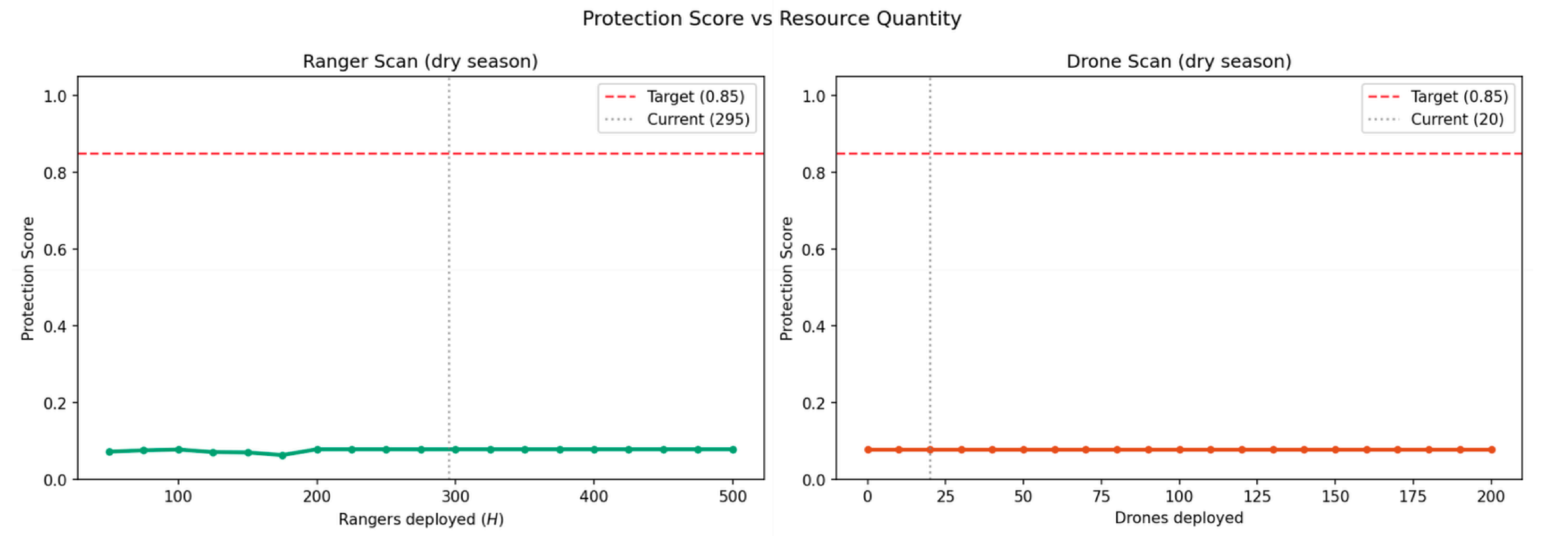


Figure 6: Protection Score as a function of ranger count (left) and drone count (right) in the dry season. Both curves are effectively flat, indicating that neither additional rangers nor additional drones improve protection under the current three-camp configuration.

More Rangers. More drone. Almost no improvement.... What is the real bottleneck?

The Etosha Protection Challenge

Park Area: 22,935 km²
Park Staff: ~295 personnel
Waterholes: 86

Threats:

- Poaching
- Wildfire
- Border intrusion risk
- Tourism disturbance
- Human-wildlife conflict

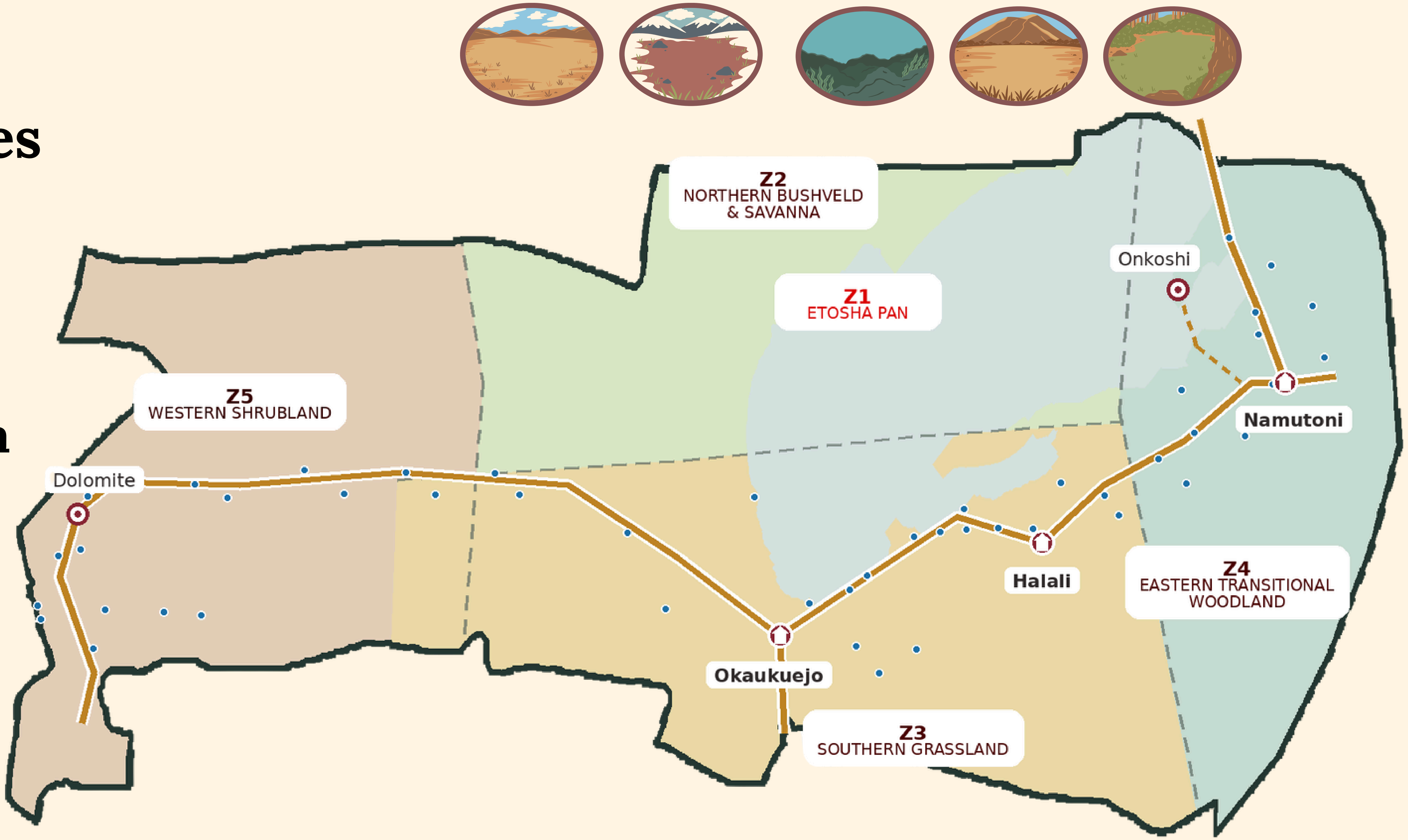
$$r_j(i,t) = r_j^{\text{base}}(i)\theta_j(t)$$

$r_j^{\text{base}}(i)$: baseline spatial intensity of threat j in cell i
$\theta_j(t)$: season-specific multiplier for threat j
$r_j(i,t)$: season-adjusted threat intensity in cell i

The Etosha Spatial-Temporal Model

<u>Three linked spatial layers</u> convert park geography into seasonal resource-allocation units

Layer 1 — Five Management Zones



Z1 — Etosha Pan
Z2 — Northern Bushveld and Savanna
Z3 — Southern Grassland
Z4 — Eastern Transitional Woodland
Z5 — Western Shrubland

Five model-defined zones establish terrain-specific travel speeds, zone-level constraints, and regional management priorities.

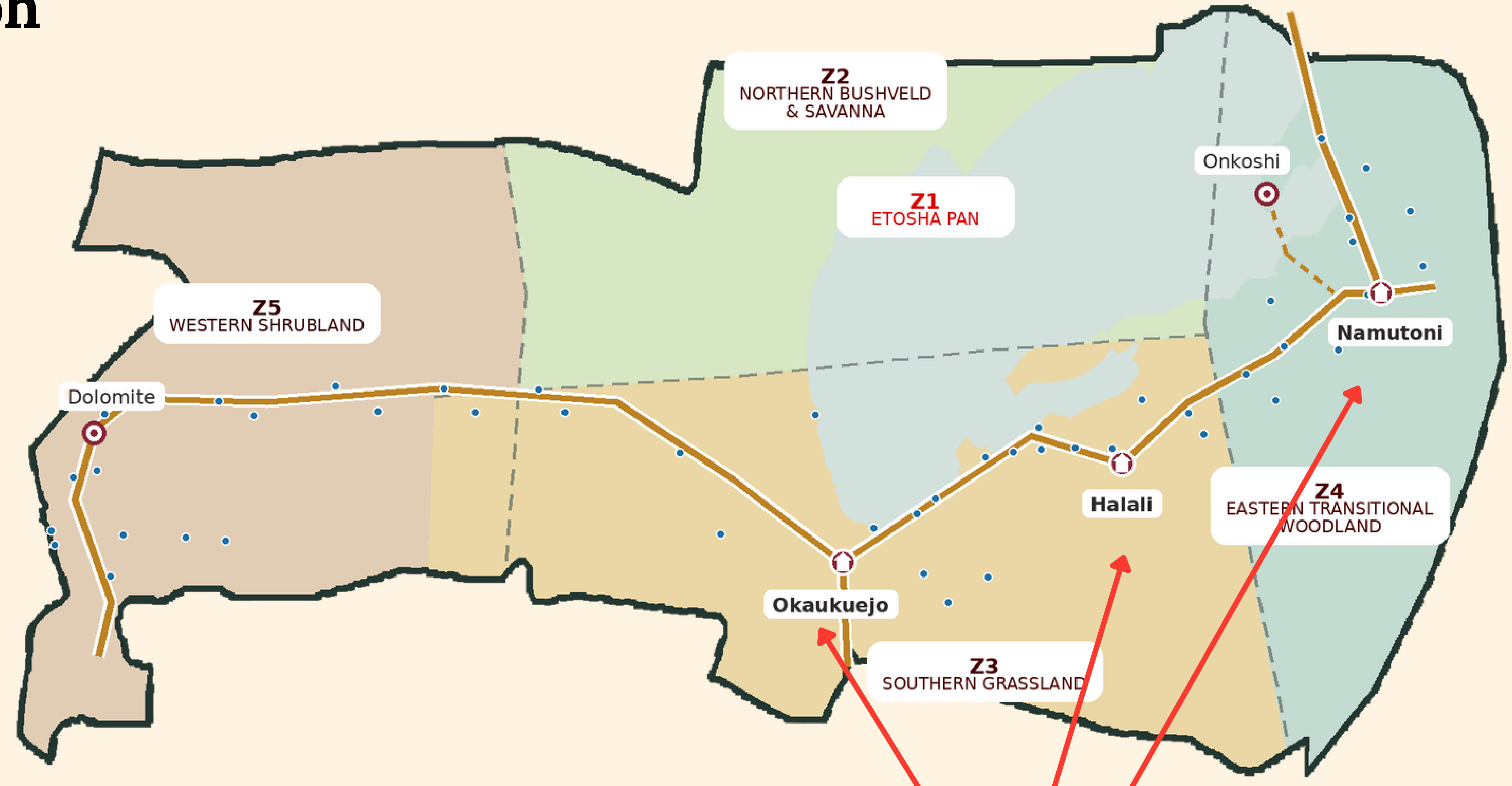
The Etosha Spatial-Temporal Model

<u>**Three linked spatial layers**</u> **convert park geography into seasonal resource-allocation units**

Layer 2 - Waterhole-Road Graph

$$G = (N, E, W)$$

N: 86 permanent or seasonal waterhole nodes (blue dots)
E: road segments connecting the nodes (gray dotted lines)
W: road-distance weights assigned to the edges (what weights)



selected patrol camps (posts)

The Etosha Spatial-Temporal Model

<u>Three linked spatial layers</u> convert park geography into seasonal resource-allocation units

Layer 3 - Adaptive Grid

$$A_{\text{cell}}(i) = \begin{cases} 25\ \text{km}^2, & i \in I_{\text{fine}}, \\ 100\ \text{km}^2, & i \in I_{\text{coarse}}. \end{cases}$$

$$i \in I_{\text{fine}} \quad \text{if} \quad R_{\text{base}}(i) > 0.5$$

or adjacent to a waterhole,

or within 10 km of the park boundary.

Fine-resolution cells: 380

- **more important and fast changing**
- **detailed allocation decisions**

Coarse-resolution cells: 113

- **low risk**
- **lower computational complexity**

The Protection Score

Valuable species/habitat → Threat detected → Team responds → Threat controlled

$$P(i,s,t) = \underbrace{w_s}_{\text{priority}} \underbrace{V_{i,s}}_{\text{ecological value}} \underbrace{C(i,t)Q(i,t)}_{\text{effective coverage}} \underbrace{[1 - R(i,s,t)]}_{\text{remaining safety}}$$

0.85

i	a spatial cell
s	a species
t	a season/time period
w_s	species s's conservation priority
$V_{i,s}$	a habitat value for species s cell i

$C(i,t)$	detection coverage: P (threat detected in cell i during time t)
$Q(i,t)$	ability to respond prompty after threat detected in i during t
$R(i,s,t)$	threat risk specific to species s, spatial cell i, and time t

$$C_{eff} = C \times Q$$

Protection requires both detection and intervention.

$$C_{eff} = C(i,t) \times Q(i,t)$$

Detection Coverage

$$C(i,t) = 1 - e^{-c(i,t)}$$

$C(i,t)$ P (detecting a threat) $(0 \leqslant C \leqslant 1)$

$c(i,t)$ aggregated raw detection intensity

Combies the detection contributions of nearby rangers, drones, cameras, and towers.

Exponential form: diminishing returns

- as C(i,t) → 1, each additional resource provides progressively smaller gains

Response Capability

$$Q(i,t) = exp\left[-k\frac{d(i,post)}{v_{terrain}(i)}\right]$$

$Q(i,t)$	P(sucessful interception | detection)
$d(i,post)$	distance from i to closest ranger post
$v_{terrain}(i)$	terrain-adjusted patrol speed
k	response decay coefficient

$$C_{eff} = C(i,t) \times Q(i,t) \qquad C(i,t) = 1 - e^{-c(i,t)} \qquad Q(i,t) = exp[-k\frac{d(i,post)}{v_{terrain}(i)}]$$

Given:

A grassland cell 20 km from the neearest ranger post

d = 20 km. v = 50 km/h. k=1.83 hr^-1

travel time: $\frac{d}{v} = \frac{20}{50} = 0.4h = 24min$

response capability: $Q = e^{-1.83(0.4)} \approx 0.48$

even if high detection coverage: $C = 0.90$

effective coverage: $C_{eff} = 0.90 \times 0.48 \approx 0.43$!

High detection coverage can still produce low effective coverage.

Optimizing Integer Resources & ILP

Given limited and indivisible resources, how does the model decide what to deploy, where, and in which season?

Decision Variable: $n_k\,(i,t) \in Z_{\geqslant 0}$

$n_k\,(i,t)$ number of units of resource type k assigned to cell i during season t

$k \in \{ranger, drone, camera, tower\}$

$$c(i,t) = \sum_k \sum_{i' \in N_k(i)} n_k(i',i)\eta_k(i',t)$$

i' cell in which resource is deployed

i targeted cell receiving detection coverage

$N_k\,(i)$ the set of neighboring cells from which resource k can provide coverage to cell i

$n_k\,(i',t)$ the number of units of resource k deployed in cell i′ during time period t

$\eta_k(i',i)$ the distance-adjusted detection contribution of resource k deployed in cell i′ to target cell i

jointly generate the raw detection intensity c(i,t)

True nonlinear detection probability:

$$C(i,t) = 1 - e^{-c(i,t)}$$

Linearized approximation:

$$\widetilde{C}(i,t) \approx \min\{1, c(i,t)\}$$

Optimizing Integer Resources & ILP

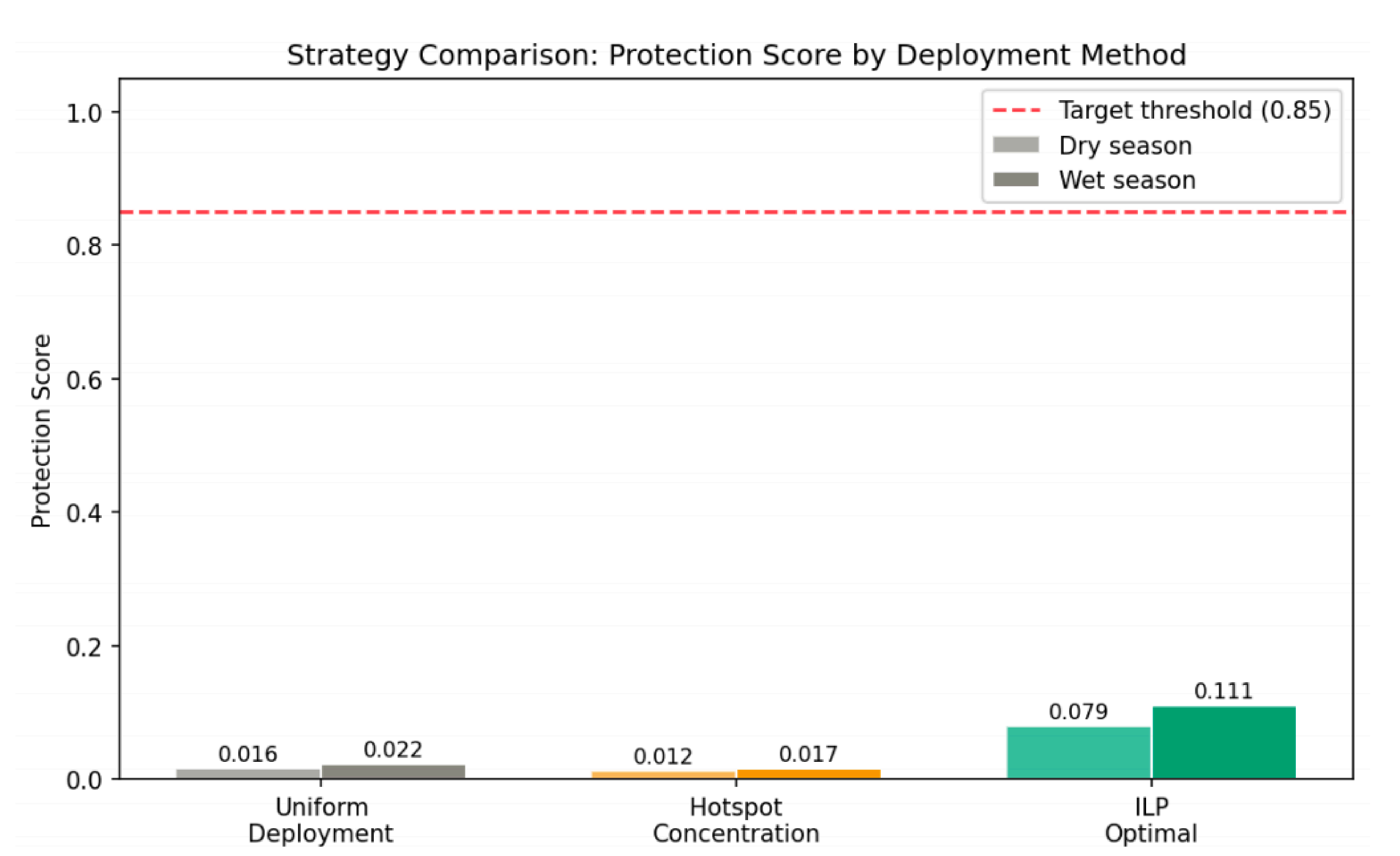
Protection score function: $P(i,s,t) = w_s\, V_{i,s}\, C(i,t)\, Q(i,t)\, [1 - R(i,s,t)]$

ILP objective function: $$\max \sum_{i,t} \left[\sum_{s} w_s V_{i,s} Q(i,t)\,(1 - R(i,s,t)) \right] \widetilde{C}(i,t)$$

Constraints:

1. **deployment not exceed the available number of each resource**
2. **rangers cannot be assigned to cells outside the modelled patrol range**
3. $$\frac{1}{|I_z|} \sum_{i \in I_z} \widetilde{C}(i,t) \geq \Gamma_z$$ **(min average linearized coverage across all cells in zone z, set geographically)**
(aim to prevent the optimizer from disgarding certain zones for a higher objective value)

Does Optimization actually help?



equal spatial spread across 493 cells

concentrate around waterhole adjacent squares

joint optimization

ILP Relative Performance

≈5.0× Uniform
≈6.6× Hotspot

Remaining Resource Gap

0.111 / 0.85 ≈ 13.1% !

Conclusion

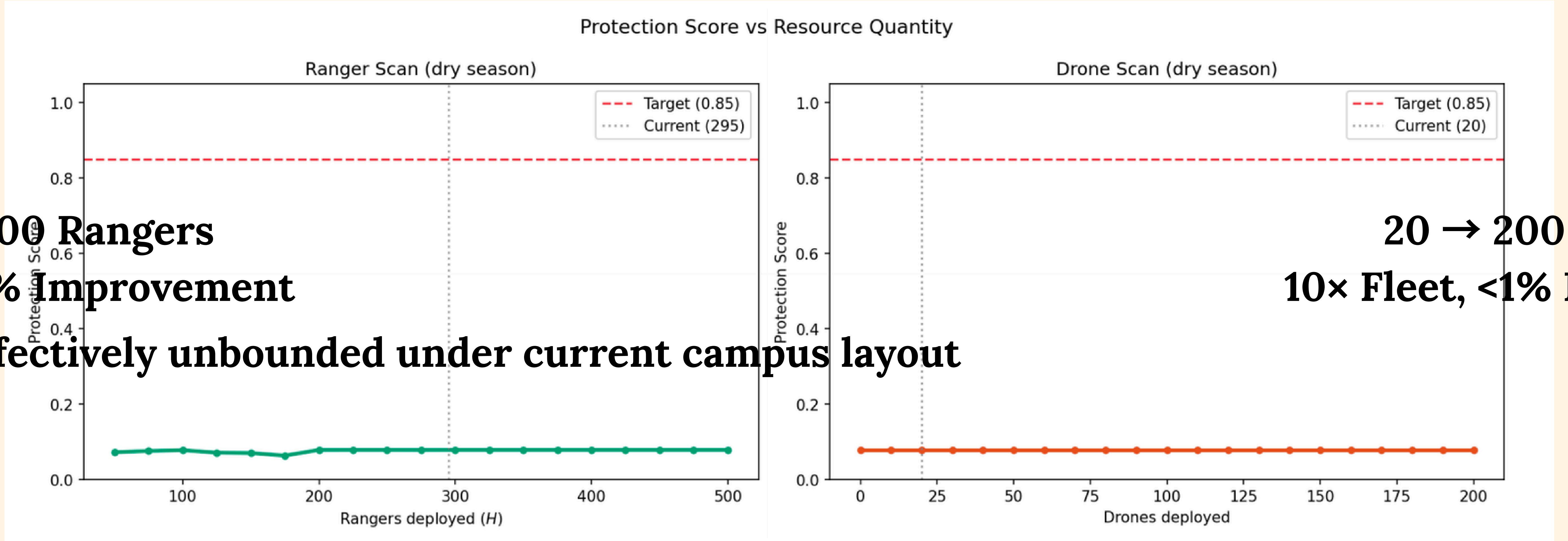
Optimization works, but it cannot close the protection gap with the current system.

Does Optimization actually help?

Would adding more rangers and drones close the gap?

Clarification:
Protection Score is a normalized composite index, not the percentage of animals or park area protected.

More ranger and drones are not the immediate answer



295 → 500 Rangers
2× Fleet, <1% Improvement

20 → 200 Drones
10× Fleet, <1% Improvement

H_{min} **is effectively unbounded under current campus layout**

More Resources	Detection (C)	Response (Q)	Protection
Rangers and drones increase	Rises with diminishing returns	Remains constrained by distance	Stays near 0.079

$\overline{Q} \approx 0.22 \quad C_{eff} = C \times Q$ **so when rangers ↑, C ↑, Ceff & P not greatly affected**

Immediate action: maintain 295 rangers, use two-shift scheduling

Changing Response Geography Unlocks Protection

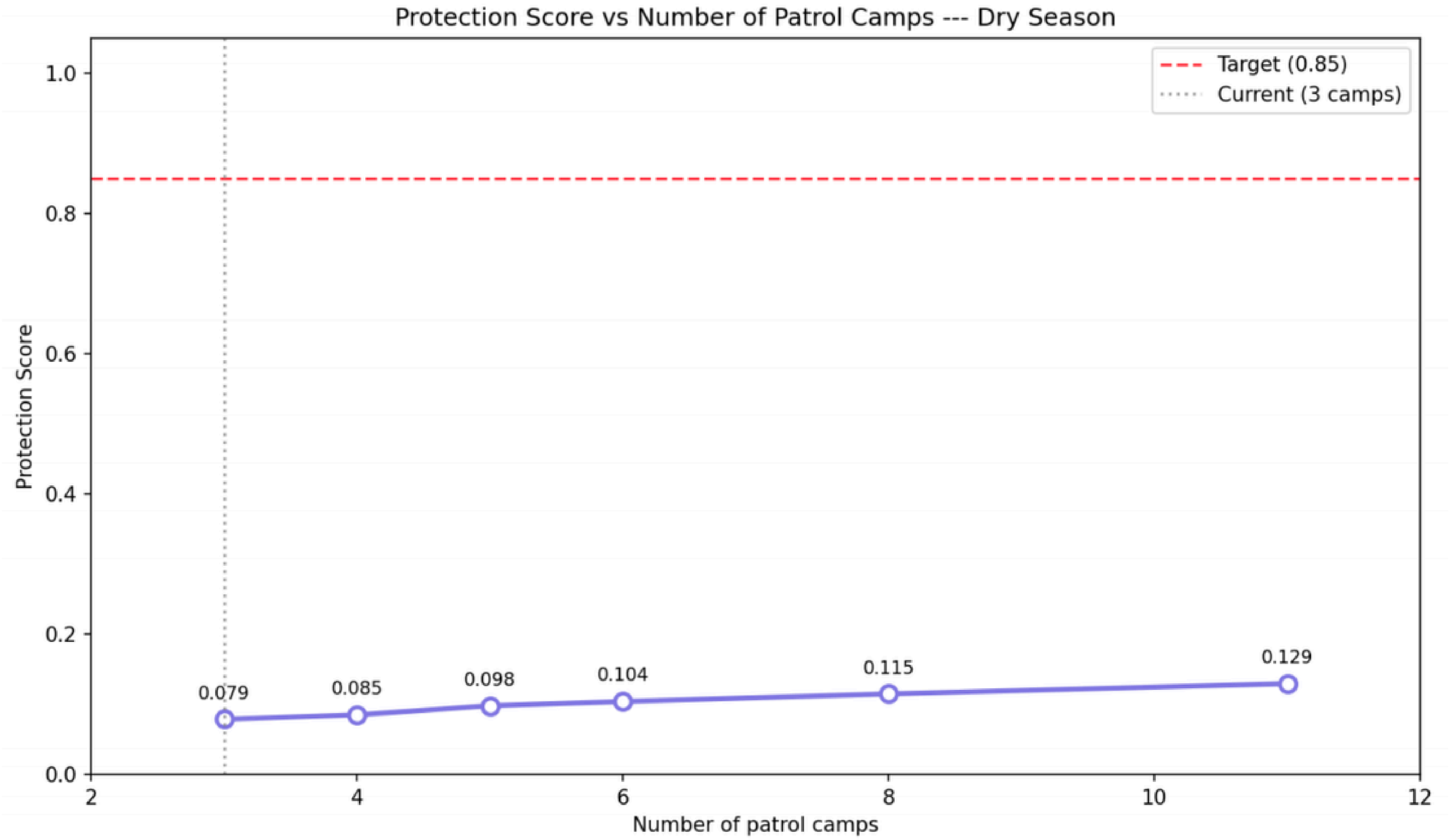


Figure 7: Protection Score vs total number of patrol camps (dry season). Each additional camp raises Protection by improving response capability Q in previously remote cells. Even with 11 camps, the 0.85 target remains out of reach under current resource levels.

$3 \to 11$ total posts

$0.079 \to 0.129$

Protection score increase by:

$$\frac{0.129 - 0.079}{0.079} \approx 63\%$$

Compared with <1% improvement from major ranger or drone expansion

Why does camp expansion work

$$Q\left(i,t\right)=exp[-k\frac{d\left(i,post\right)}{v_{terrain}\left(i\right)}]$$

New posts change d, the variable that additional headcount cannot change.

Shorter road distance d

↓

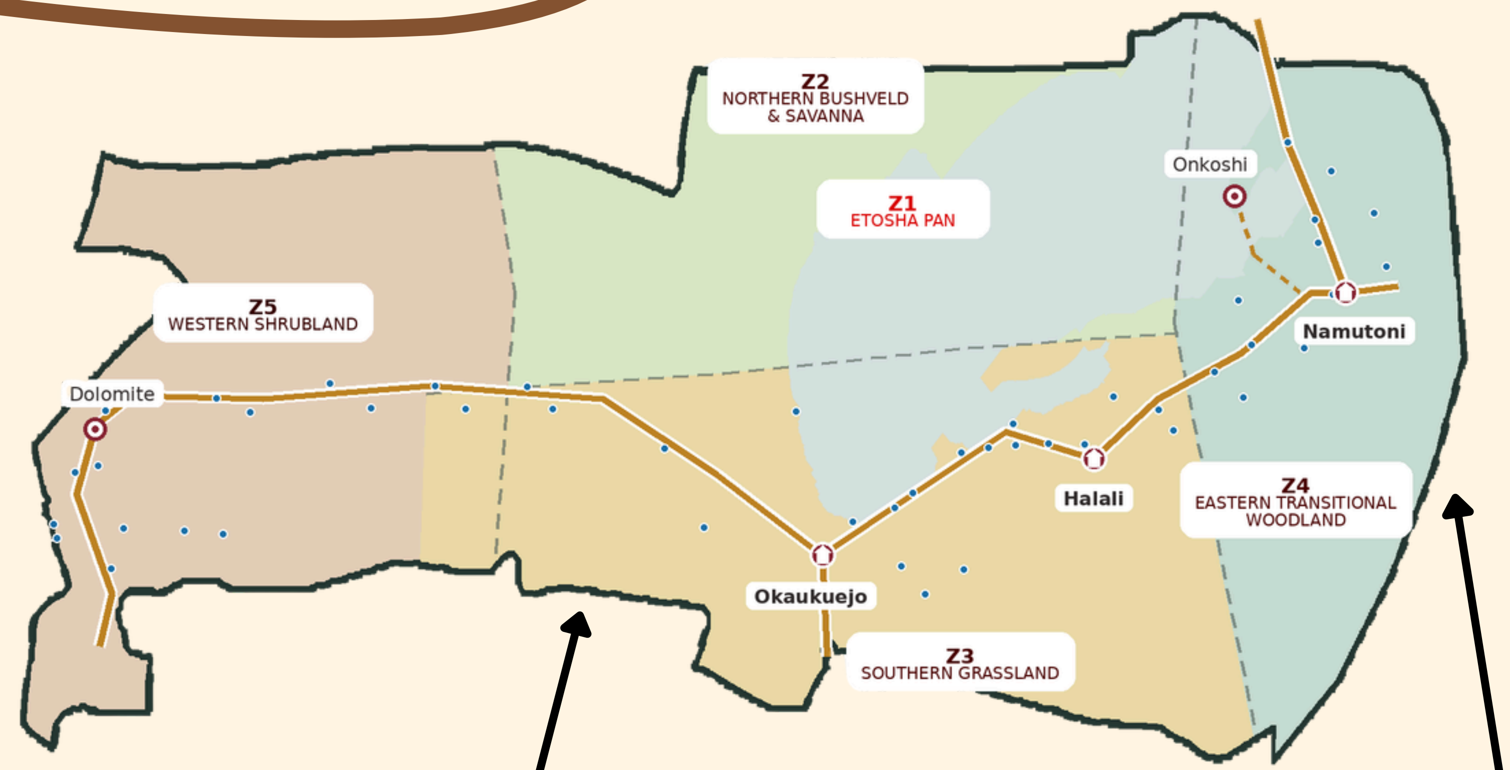
Higher response capability Q

↓

Higher effective coverage Ceff=CQ

↓

Higher Protection Score



Recommendation: southern grassland boundary + eastern perimeter

Large response gap + High threat intensity + High ecological importance

Implementation

IMMEDIATE / low cost

Maintain 295 ranger-equivalent units
Use two-shift: ≈148 per shift
Optimize deployment by dry & wet season

Near Term

Add 2-3 forward operating posts in recommended (priority) regions
First 2 posts: ≈24% modeled improvement

Long Term

Progress toward 8–11 total response posts
Calibrate the model using observed response times
Then reassess ranger and drone expansion

+63%

Stress Test

Sensitivity analysis and adverse-scenario testing under dry-season conditions

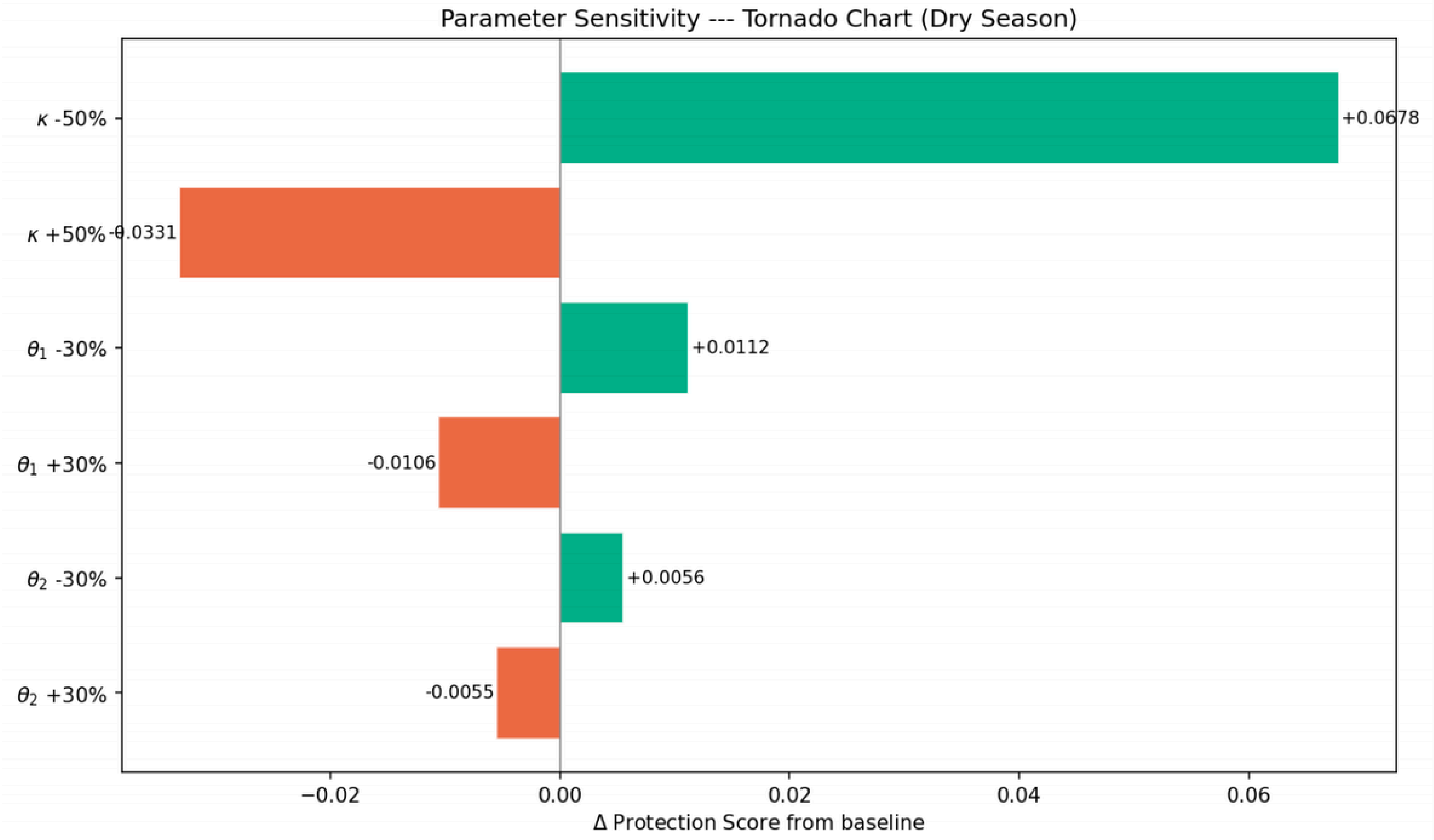


Figure 8: Tornado chart of parameter sensitivity (dry season). Bars show ΔProtection Score relative to baseline (0.0786) under $\pm 50\%$ perturbation of κ and $\pm 30\%$ perturbation of θ_1, θ_2.

Response dynamics dominate sensitivity

$$|\Delta P|_\kappa \approx 0.068$$

$$|\Delta P|_{\theta_1,\theta_2} \leq 0.0112$$

Protection is far more sensitive to response capability than to moderate changes in threat intensity.

Stress Test

Sensitivity analysis and adverse-scenario testing under dry-season conditions

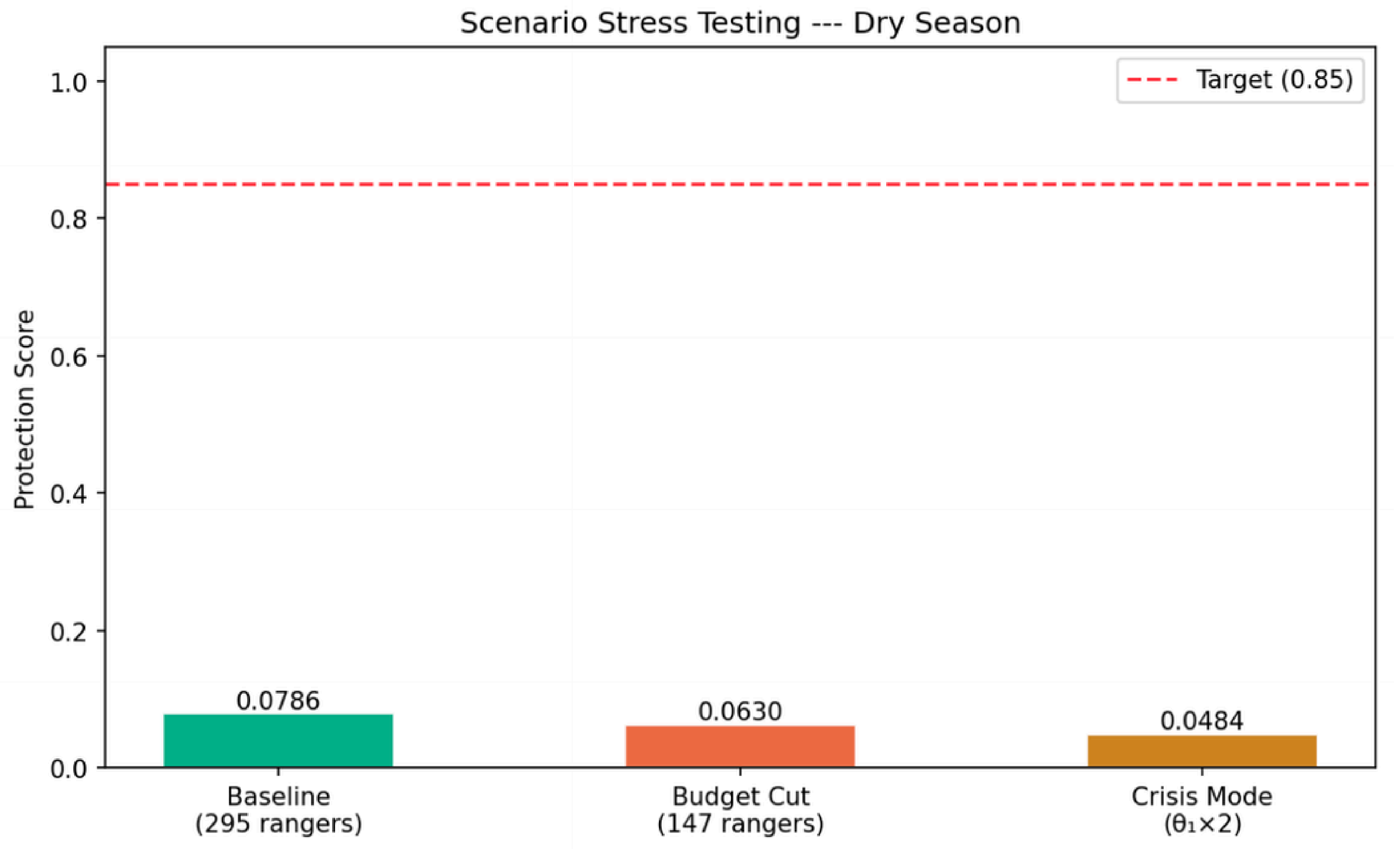


Figure 9: Protection Score under baseline and two adverse scenarios (dry season). Budget Cut reduces Protection by 20%; Crisis Mode by 38%.

Scenario A: 50% Ranger Budget Cut

H = 295→147

P: 0.0786→0.0630 (-20%)

Scenario B: Poaching Crisis

θ1×2

P: 0.0786→0.0484 (-38%)

Cross Park Adaptation

Fixed:
Protection Score P(i,s,t)
ILP objective & constraints
Coverage and response functions C,Q
Temporal decay–recovery structure

RECALIBRATE — Park-Specific Inputs:
Species & habitat weights
Threat profiles & seasonal factors
Terrain speed & detection radii
Zones, mobility network & response posts

Cross Park Adaptation

	Etosha	**Tumucumaque**	**Gunung Leuser**
Mobility	Road network	River network	Steep terrain / foot patrol
Key Threat	Poaching	Illegal mining	Poaching + logging
Bottleneck	**Response (Q)**	**Detection (C)**	**Response (Q) amplified**
Strategy	Forward response posts	Camera traps + river patrols	Terrain-optimized posts

Strengths and Limitations

Strengths

Provably optimal allocation through ILP
Multi-scale & seasonal, integrating geography, risk, detection and response

Limitations

Static wildlife movement
Limited ground-truth calibration: parameters rely on published estimates

Effective protection requires the right resources, in the right places, at the right times.

THANK YOU

Resource Page

Resource Page

Resource Page