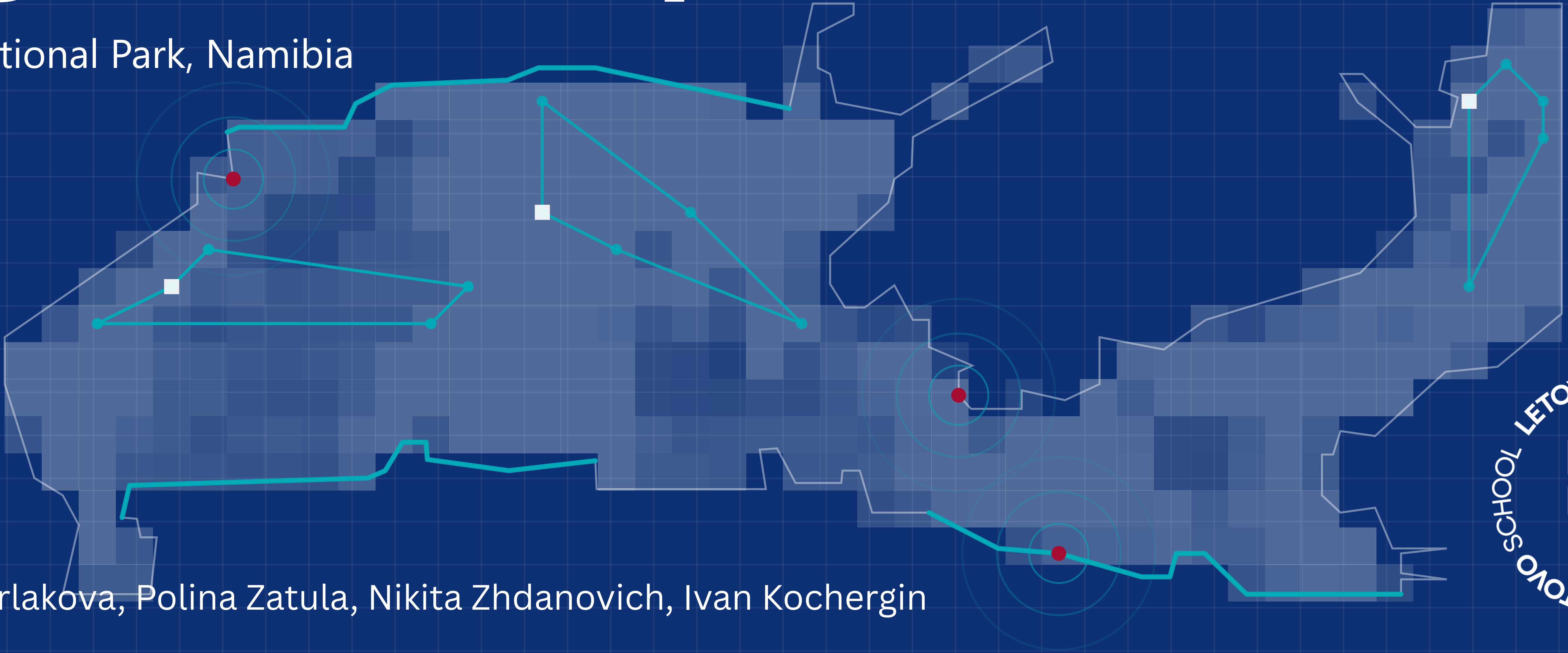
Team 2026068, Letovo School, Moscow, Russia

Resource allocation in large national parks

Etosha National Park, Namibia



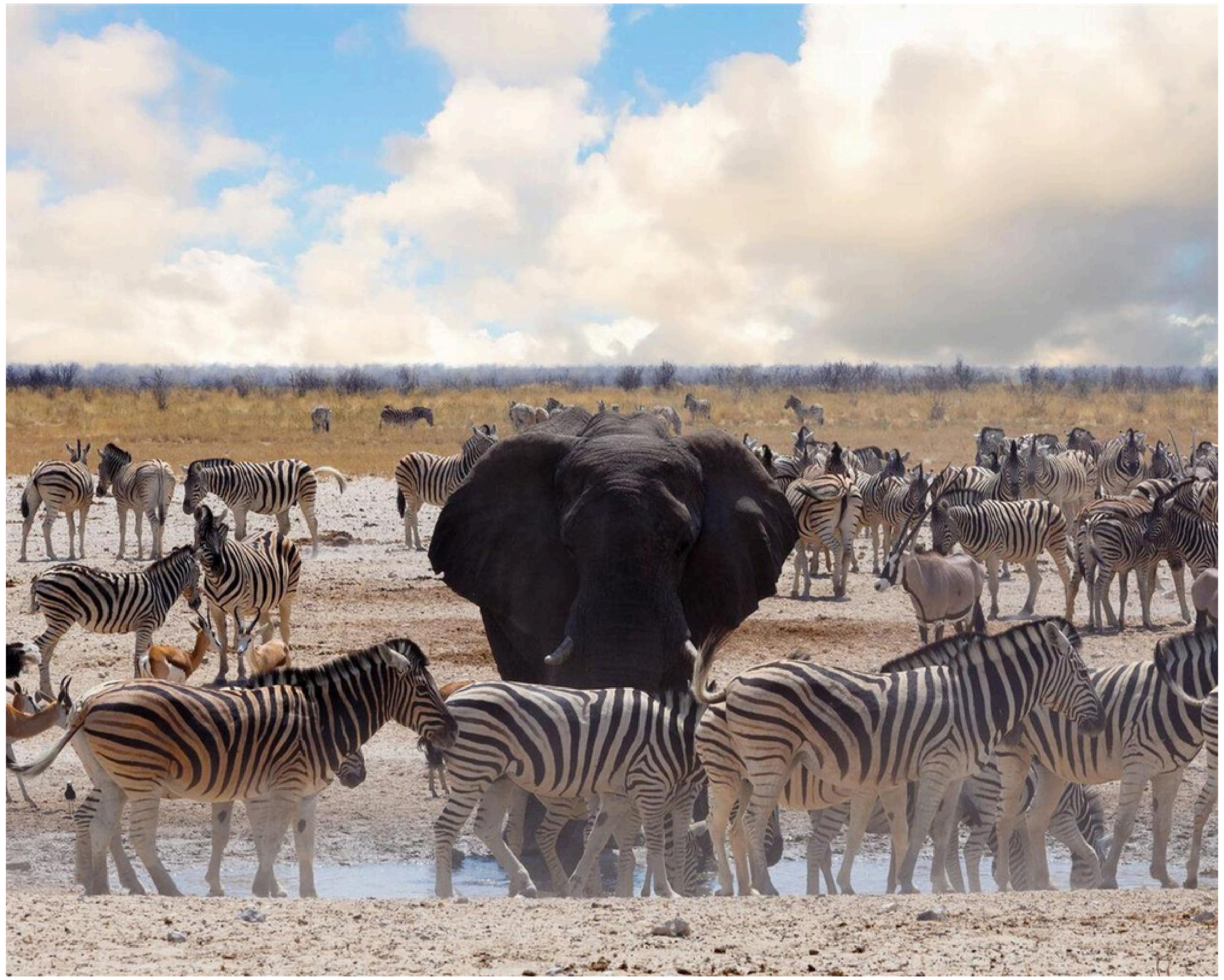
Uliana Shurlakova, Polina Zatula, Nikita Zhdanovich, Ivan Kochergin

Photo by Anastasia Yangirova, 2016

Etosha National Park, Namibia

The park covers 22,935 km^2 and is patrolled by 295 ministry staff.

That is one person for every 78 square kilometres.



What the IMMC asks

Coordinate limited human and technological resources to protect wildlife across the park over time, and define protection in a way that can be measured.

Six requirements follow from this:

1. identify and prioritise the threats
2. build an allocation model
3. estimate protection over time and the staffing it needs
4. test sensitivity to assumptions
5. state the limitations
6. adapt the approach to two other continents.

Research

Direct anthropogenic threats

- Road-related wildlife mortality
- Organized poaching and illegal wildlife trade
- Wire snaring and passive trapping
- Illegal harvesting of biological resources

Boundary & ecosystem threats

- Wildlife dispersal beyond park boundaries
- Transboundary disease transmission
- Wildfire

excluded

Internal anthrax/rabies outbreaks · plastic waste · unsafe tourist proximity · tourist-caused fires

Threat prioritization

$$\mathrm{Risk}_{i,season} = \mathrm{Structural\ impact}_i \times \mathrm{Seasonal\ likelihood}_{i,season}$$

Structural impact: Analytic Hierarchy Process (AHP)
Pairwise comparison of five criteria on the Saaty 1–9 scale; threat ratings were assigned on anchored 1–5 scales.

Criterion	Spatial extent	Severity	Reversibility	Recurrence	Response window
AHP weight	**0.5028**	**0.2602**	**0.1344**	**0.0678**	**0.0348**

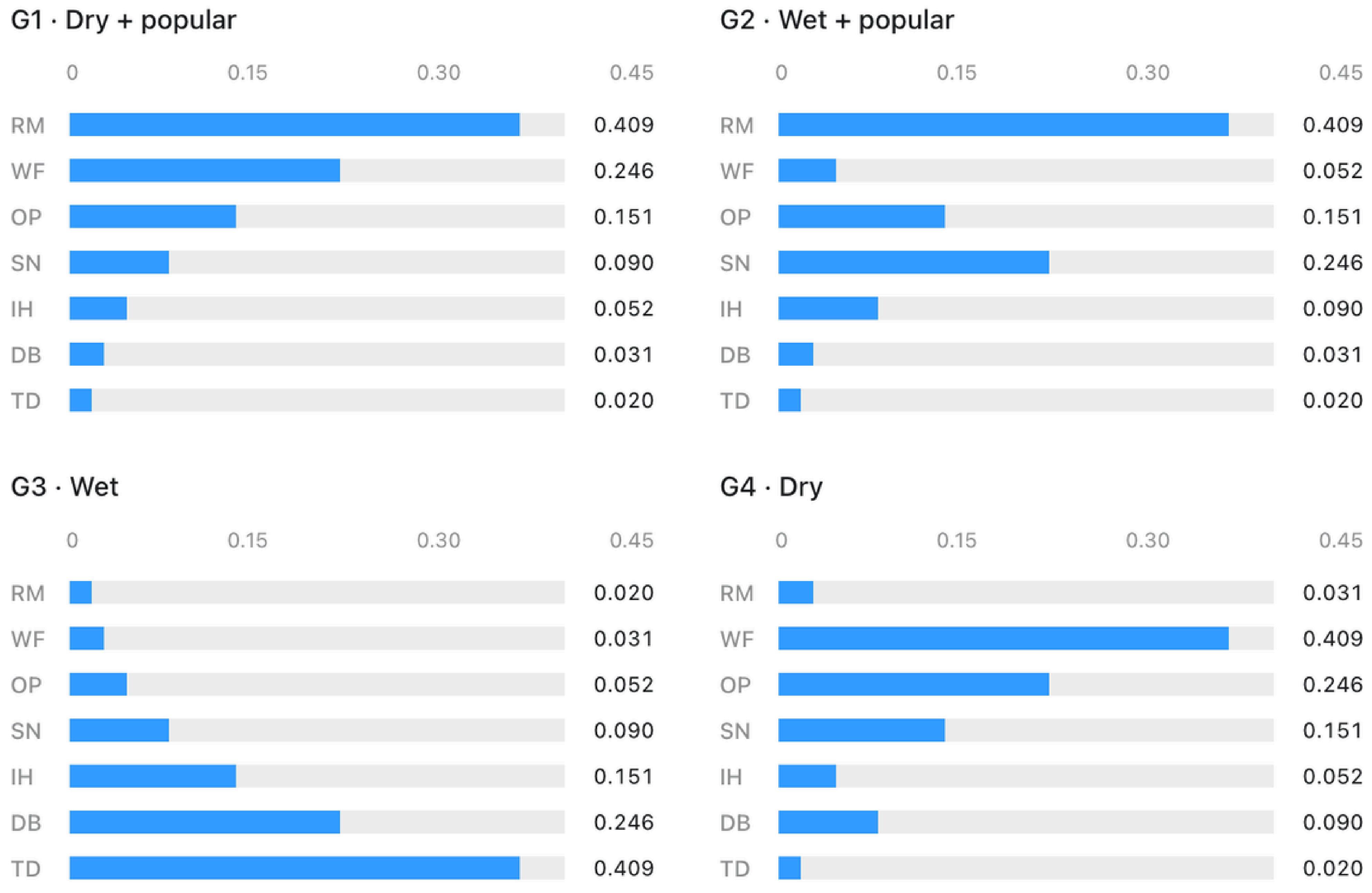
Threat	WF	TD	OP	DB	SN	IH	RM
Impact weight	**0.1922**	**0.1627**	**0.1611**	**0.1448**	**0.125**	**0.1157**	**0.0986**

WF — wildfire
TD — transboundary disease
OP — organized poaching
DB — wildlife dispersal
SN — snaring
IH — illegal harvesting
RM — road mortality.

Threat prioritization

Seasonal likelihood: regime-specific AHP ranking

Within each regime, expert likelihood rankings were converted into relative weights using the same AHP procedure.



RM — Road mortality WF — Wildfire OP — Organized poaching SN — Snaring IH — Illegal harvesting
DB — Wildlife dispersal TD — Transboundary disease

Recommendations per threat

THREAT	IMPACT WEIGHT	WHAT WE RECOMMEND
Wildfire	0.1922	Satellite alerts, crews sent past a severity cutoff
Transboundary disease	0.1627	Screening at the entrances, sick animals removed on patrol
Organized poaching	0.1611	Boundary acoustics at the entrances, GPS on the roads
Wildlife dispersal	0.1448	Fence gaps repaired, marked gates left as crossings
Snaring	0.1250	Corridors revisited often enough to free a trapped animal
Illegal harvesting	0.1157	The same gates and roads as poaching
Road mortality	0.0986	Lower speed limit, enforced from the GPS traces

The four in bold go into the model. For the other three, the recommendation above is the whole answer.

What the countermeasures cost

CHANNEL	ROLE	UNIT COST (USD)
Ranger teams	Respond to any detected event	65,000 per team / year
Vehicle GPS	Accountability on the roads	90,000 whole fleet
Boundary acoustics	Early detection at the fence	750 per km
Fence repair	Seals unintended crossings	standing procedure
Fire monitoring	Satellite products, 15-min cycle	standing procedure
Speed enforcement	Reads the GPS traces	free with GPS

***Full perimeter coverage would cost 618 000, more than twice the budget we recommend.**

Protection, defined

Protection is the reduction of expected damage caused by people to populations of priority species, achieved by detecting an event and responding to it in time.

The plan

A PLAN DECIDES

Ranger teams

as many as we can fund

Vehicle GPS

all vehicles or none

Boundary acoustics

0 to 850 km of fence

A PLAN IS VALID IF

- It fits the annual budget
- It keeps at least two teams, or nobody can answer an alert
- Every route ends back at its own base within one shift

Under a fixed budget, we want the valid plan with the lowest expected damage.

Problem formalization

maximise $E\,[\,\text{Protection}\,(K, G, U)\,]$

subject to $c_K \cdot K + c_G \cdot G + c_U \cdot U \leq B$

$K \geq K_{min}$

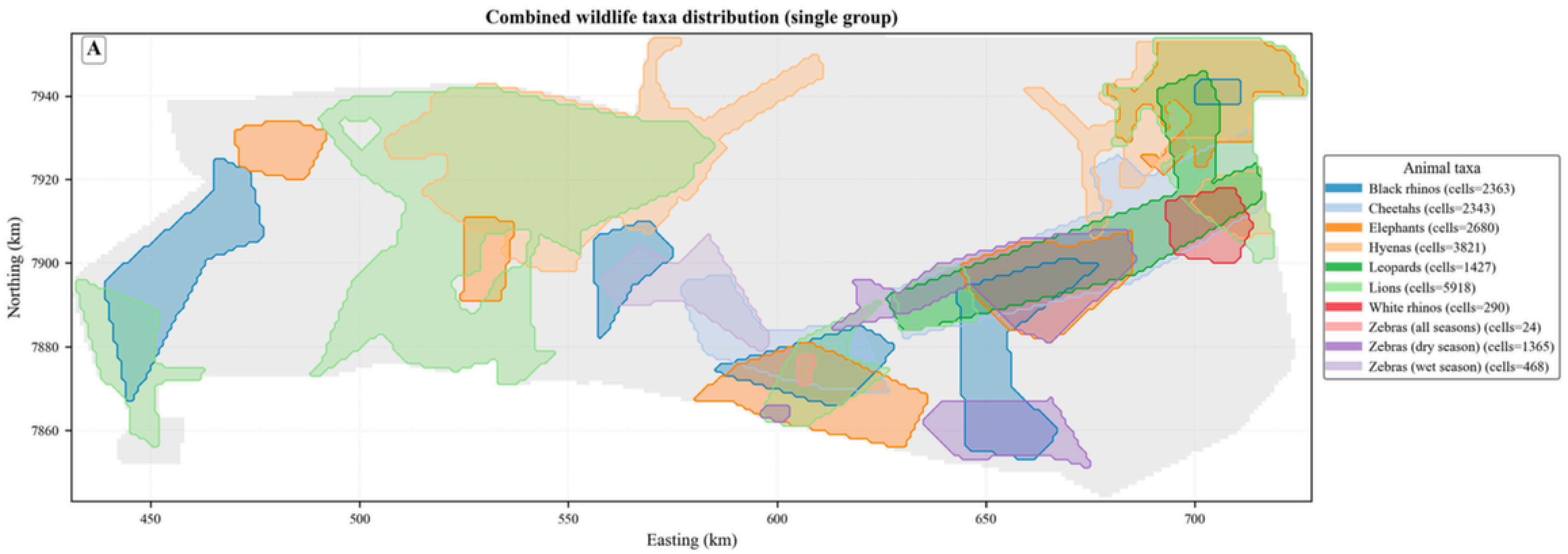
$\text{Time}\,(\text{route}) \leq H$ for every team

WHERE

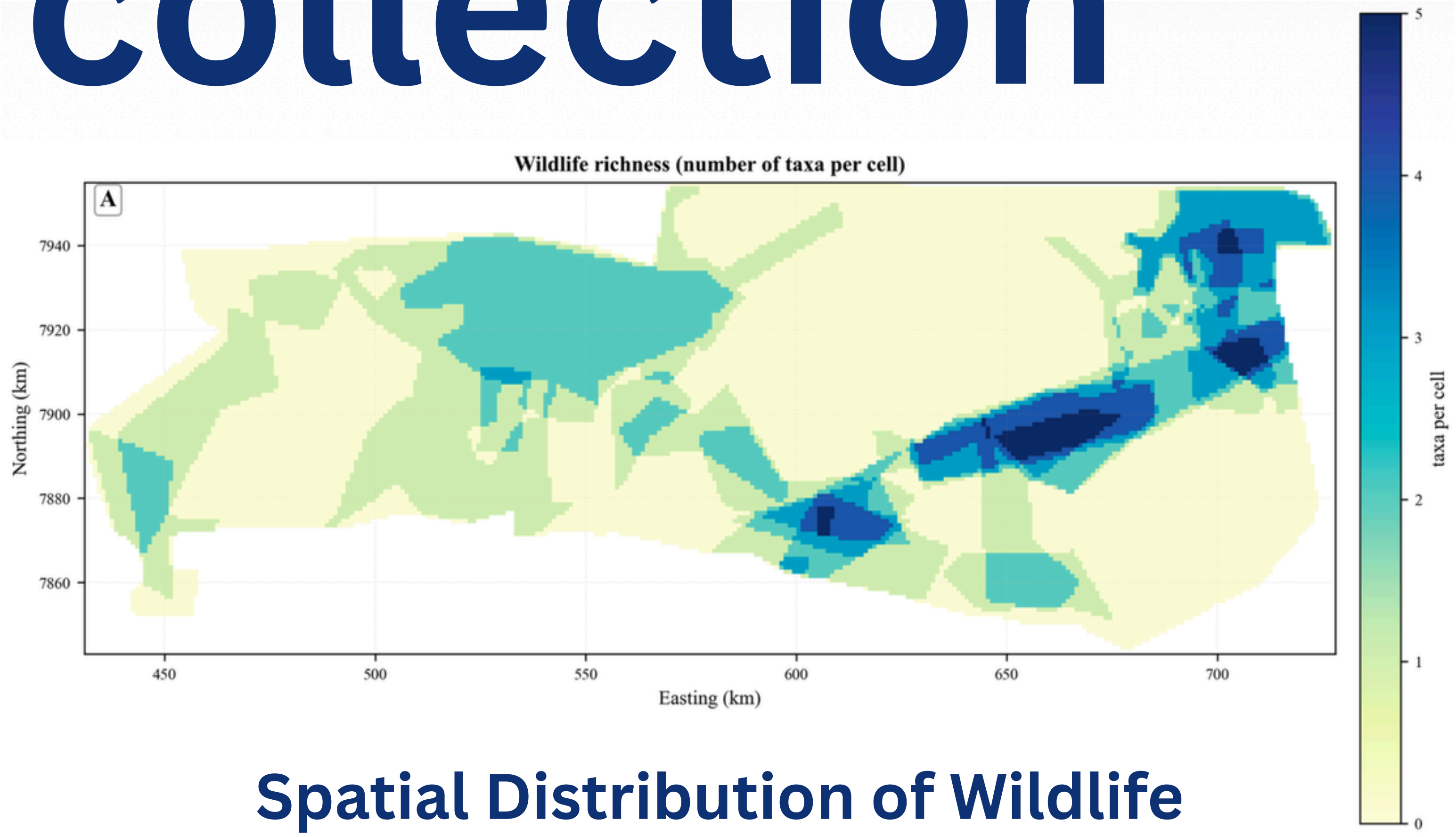
K	ranger teams, 65,000 USD each	**B**	the annual budget
G	GPS, whole fleet or none, 90,000	K_{min}	two teams
U	km of boundary acoustics, 750 per km	**H**	one shift, ending at the base

The objective has no closed form, so we simulate it and search the valid plans.

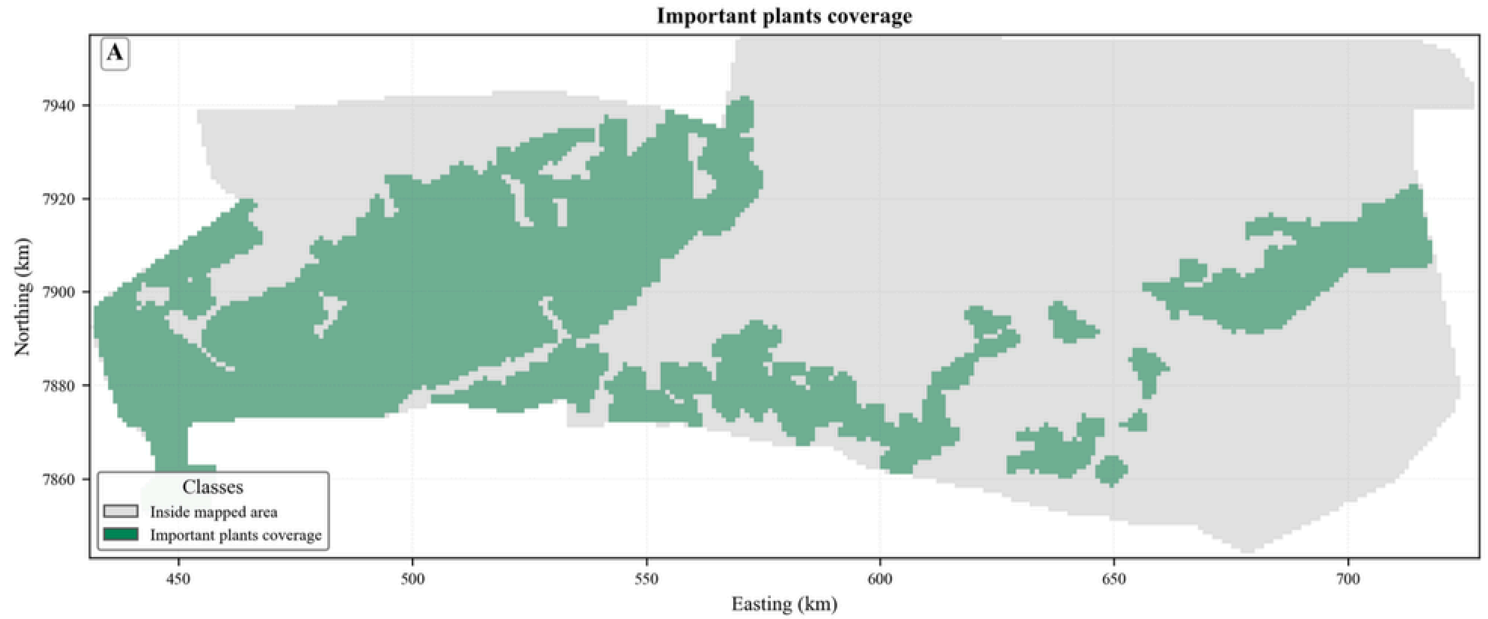
Spatial data collection



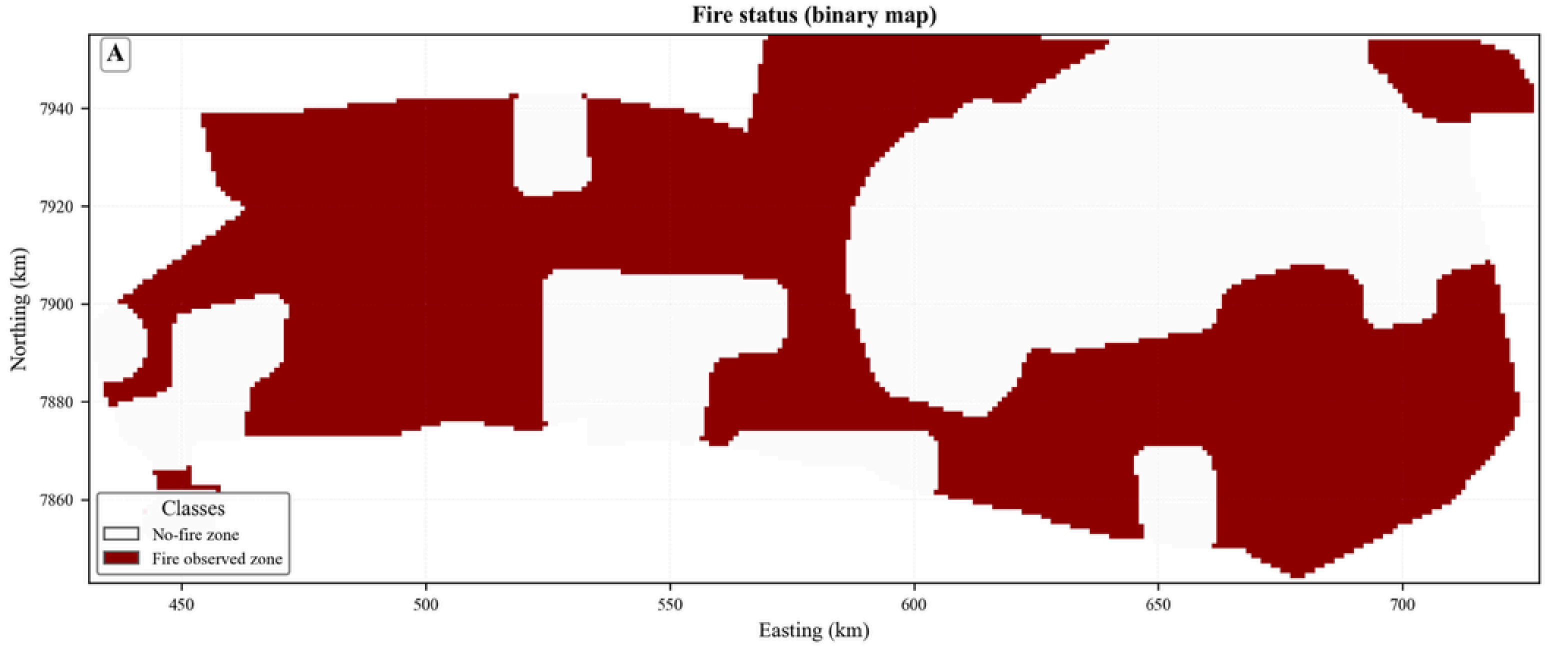
Combined spatial distribution of key wildlife taxa



Spatial Distribution of Wildlife Richness (Taxa per Cell)

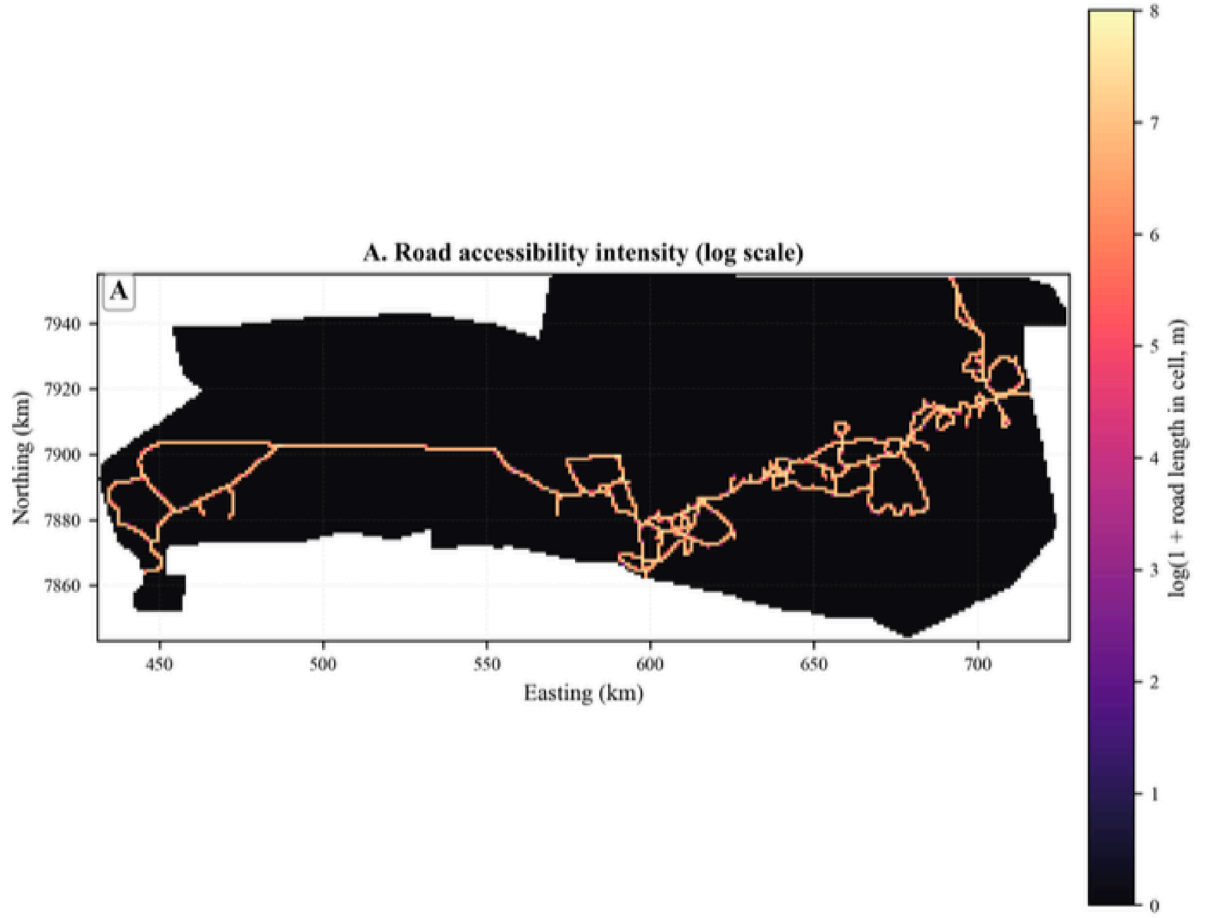


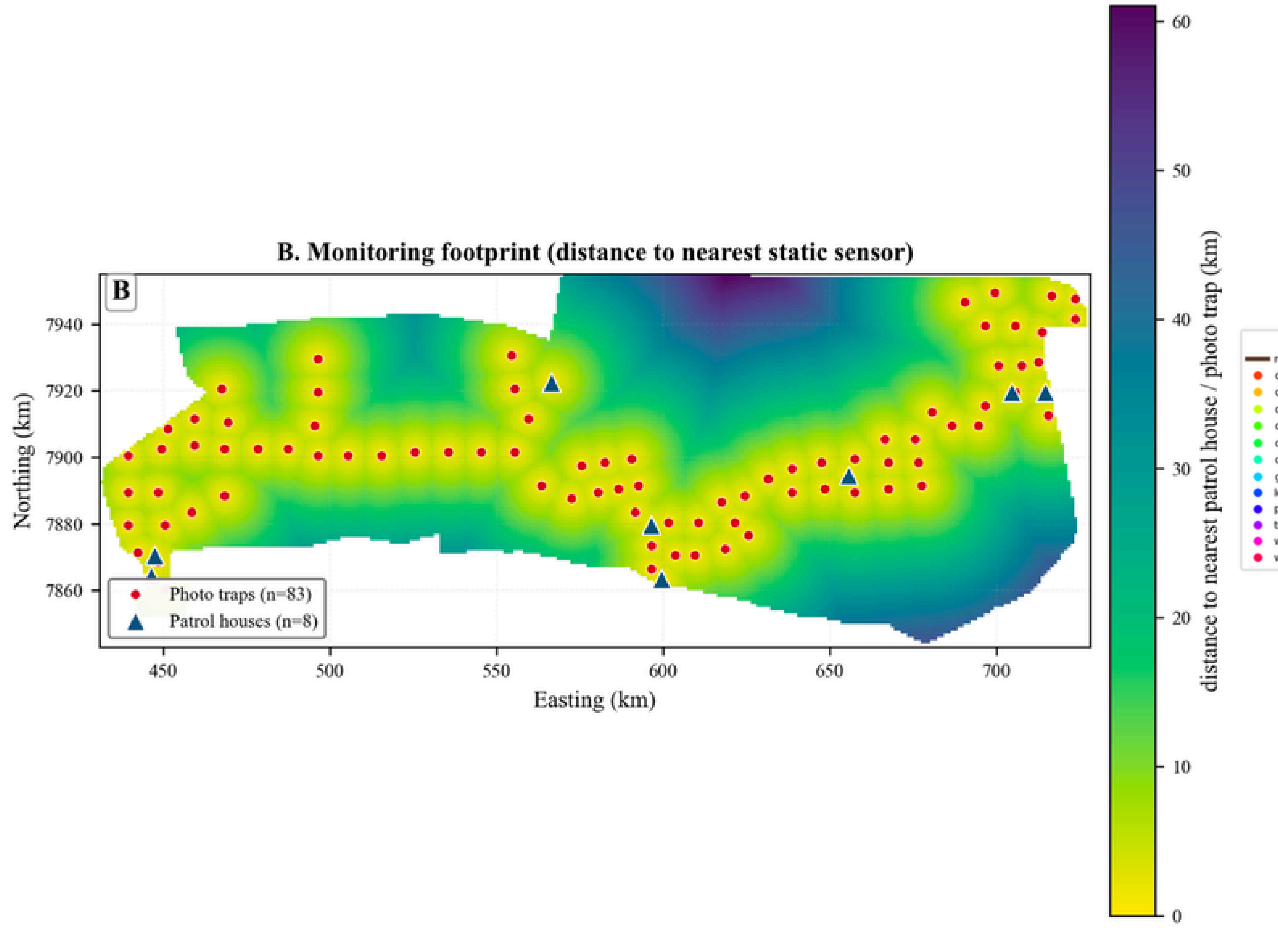
Coverage of important plant areas



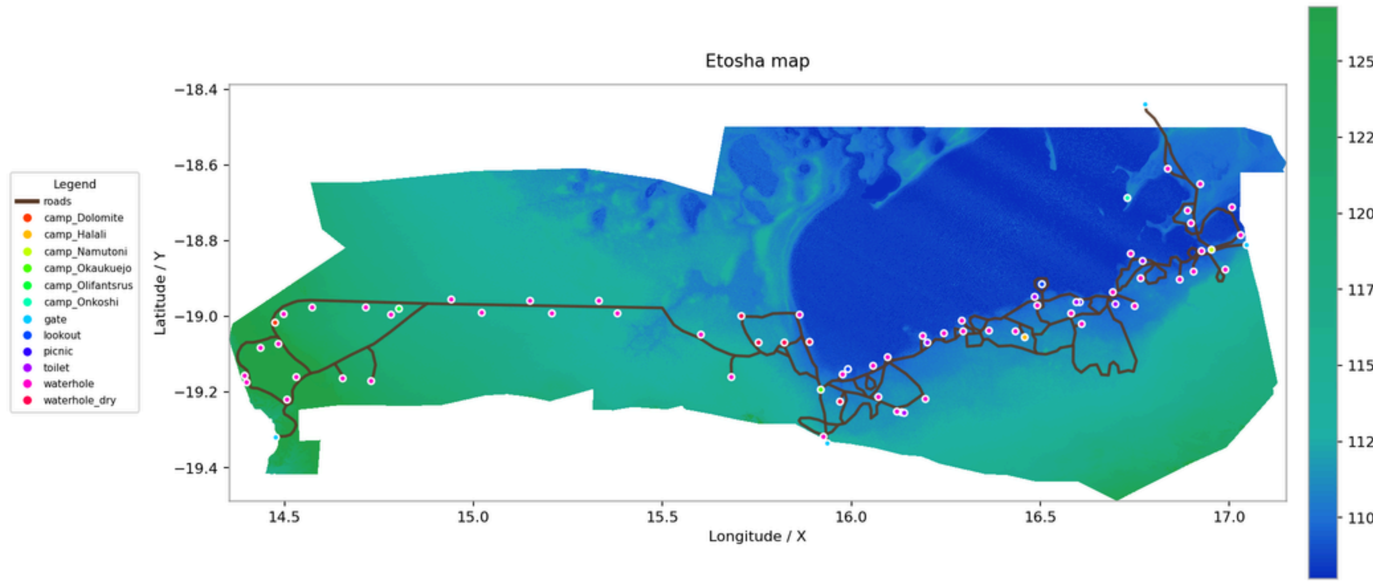
Fire status map (observed fire vs. no-fire zones)

Spatial data collection





Infrastructure and Monitoring Footprint



Etosha map

1. **Data was digitized in QGIS**
2. **Processing in Python using GeoPandas, Shapely, Rasterio**
3. **UTM projection and 1 km × 1 km grid**
4. **Plotting charts using Matplotlib.**

The mobility graph

- 1 km * 1 km grid. Each cell a node; edges join the 8 neighbours
- Each node stores three types of information: ecological value, accessibility, existing protection.
- Shortest paths computed using Dijkstra's algorithm.
- Edge weight = travel time, not geographic distance.

$$T(i, j) = \frac{\text{distance}(i, j)}{v(i, j) \times 1000}$$

Formula for calculating the edge weight

Priority map construction

<u>Intrinsic cell store:</u> $S_i = (A_i + 0.5H_i + 0.5B_i)(1 - 0.5M_i)$

Wildlife, water and plants raise a cell;
existing coverage lowers it, so effort flows to gaps.

T_i = {elephant,lion,giraffe} - wildlife taxa in cell i
a_t - importance weight of taxon t
$A_i = \sum_{t \in T_i} a_t$ - wildlife score

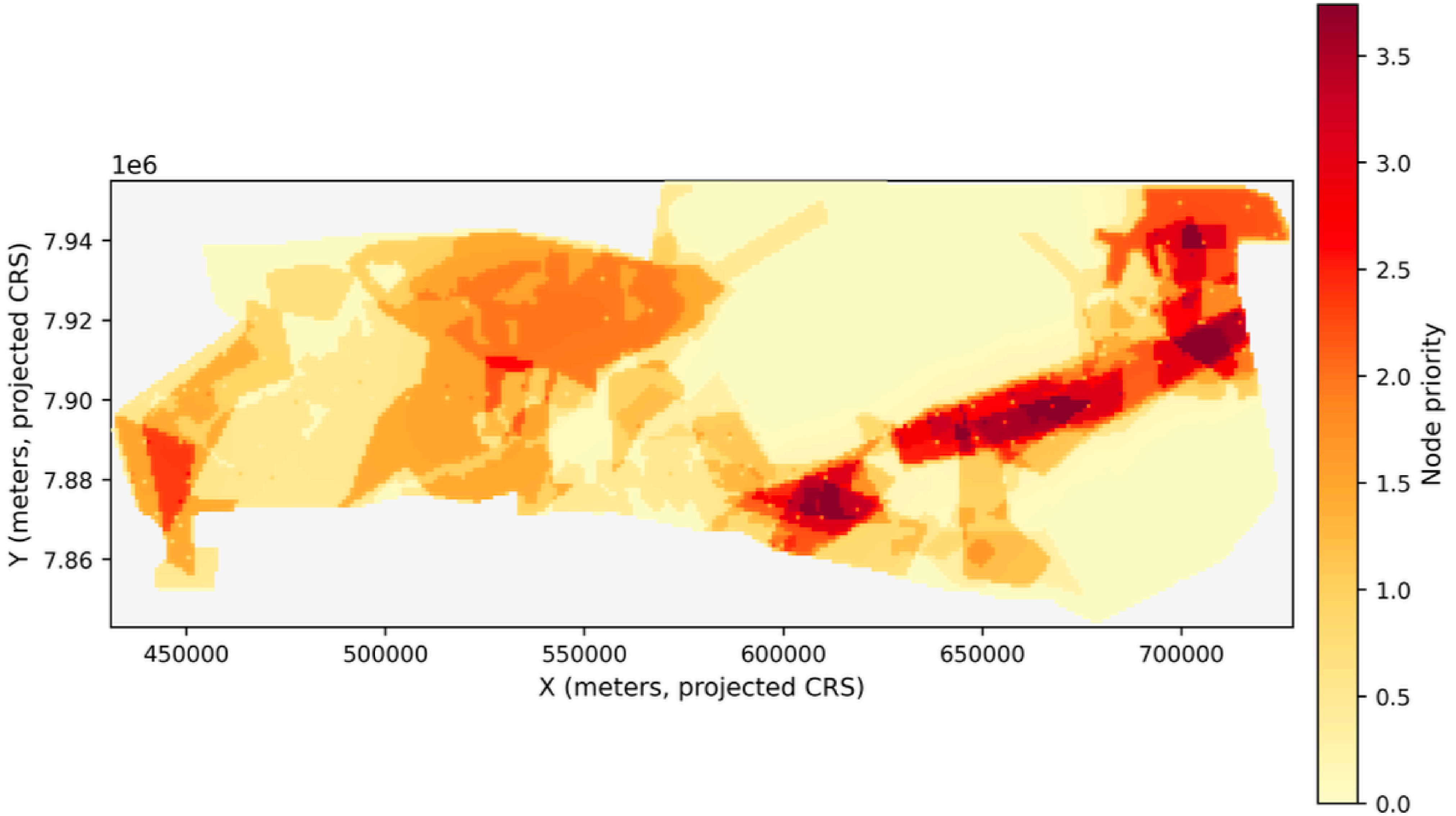
H_i - water source indicator (0/1)
B_i - plant conservation indicator (0/1)
M_i - existing monitoring indicator (0/1)

Priority map construction

<u>**Exponential depth mixing**</u>

$$P_i = w_0 S_i + w_1 \overline{S_N}(i) + w_2 \overline{S_F}(i)$$

Near and far neighbourhoods (forward K = 1000 by travel time) mix with exponentially decaying weights.



P_i **- final priority score**

S_i **- intrinsic score**

$\overline{S_N}(i)$ **- the average intrinsic score of eight neighbor cells**

w_0, w_1, w_2 **- exponential weights**

$\overline{S_F}(i)$ **- the average value for the 1000 cells closest in time to the path**

Budget planning

The plan is found in a fixed order, and only the last step needs a search.

1 **Response capacity first**

An alarm is useless if no team can reach it, so the first money funds at least two ranger teams.

2 **GPS, whole fleet or none**

Half a fleet only tells a violator which vehicles to avoid, so we track every vehicle or none of them.

$p = G / G_{full}$

the tracked share

$1 - p$ slip through

3 **Simulate the rest**

Whatever budget is left is split between more teams and more sensors, and the simulation settles the mix.

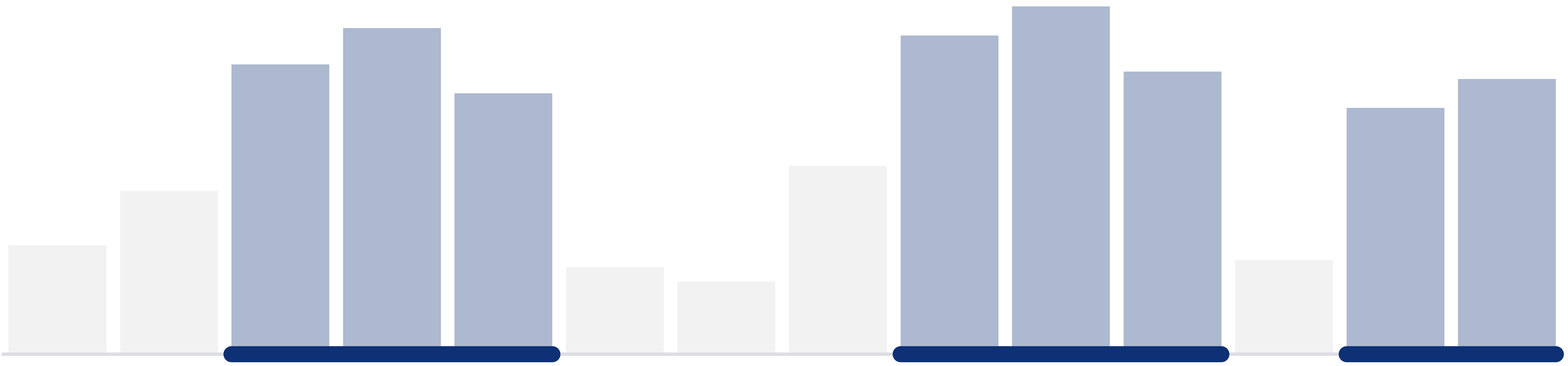
Sensor placement

The plan funds only part of the 850 km boundary, so this step picks which stretches of fence get the sensors.

Every stretch is scored by the crossings it would catch. The greedy pass takes the highest scores first and stops when the funded kilometres run out.

WHERE THE FUNDED KILOMETRES GO

expected crossings caught, by boundary stretch



funded acoustic sensors

low-traffic stretches left open

Each team’s daily routes

For each team the plan funds, the day is built one stop at a time.

PICKING THE NEXT STOP

$$\text{score} = \Delta p^{a} / \Delta t^{b} \cdot \xi / \Omega$$

Δp priority gained · Δt extra minutes · a, b weights · ξ variety nudge · Ω overlap penalty

EVERY ROUTE OBEYS

Visit each area once
no priority counted twice

No repeated legs
so routes vary day to day

Home within the shift
back to base before it ends

The timeline of a single event

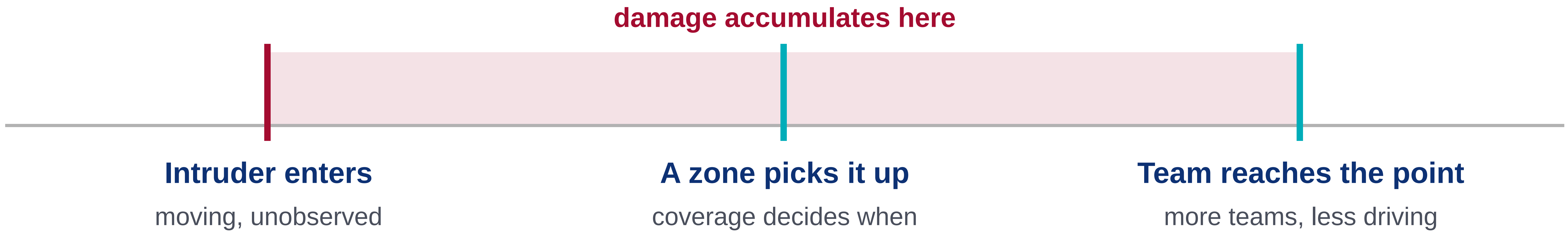
WATCHED ZONES, ALWAYS ON

Boundary acoustics
the fenced boundary
fixed

Vehicle GPS
the road network
fixed

Camera trap
300 m around a point
fixed

Ranger on patrol
1 km around the team
moves with the route



The nearest team drives to where the signal came from. We do not model pursuit, so the second phase is travel time to that point.

The Monte Carlo engine

Each hour the engine draws one event: which threat, where it enters, what it came for. Every draw comes from a distribution we set in advance. Damage starts when the intruder reaches what it came for, and stops when a team arrives. **A simulated year holds 8,760** of these events, and no two years land the same way, so we average across runs.

Which threat, per cent

	POACHING	SNARING	HARVESTING	DISEASE
Dry, March to June	52.4	32.2	11.2	4.2
Wet, December to February	7.5	12.8	21.5	58.2

Where it enters

50% boundary, 50% road network

boundary cells weighted by priority squared

What it came for

water 70%

animals 20%, plants 10%

The protection metric

The engine returns a raw amount of wildlife lost, which means nothing on its own. We rescale it against two reference points: doing nothing, and the best case we allow for.

ProtectionLevel (B) = $(L_0 - L(B)) / (L_0 - L_{min})$

0 **1**

no better than doing nothing losses down to our best case

$L(B)$	wildlife lost over a year at budget B, averaged over runs
L_0	what we lose spending nothing
L_{min}	the lowest loss we allow for

The scale measures how far a plan moves us from one reference point to the other.
One does not mean no damage.

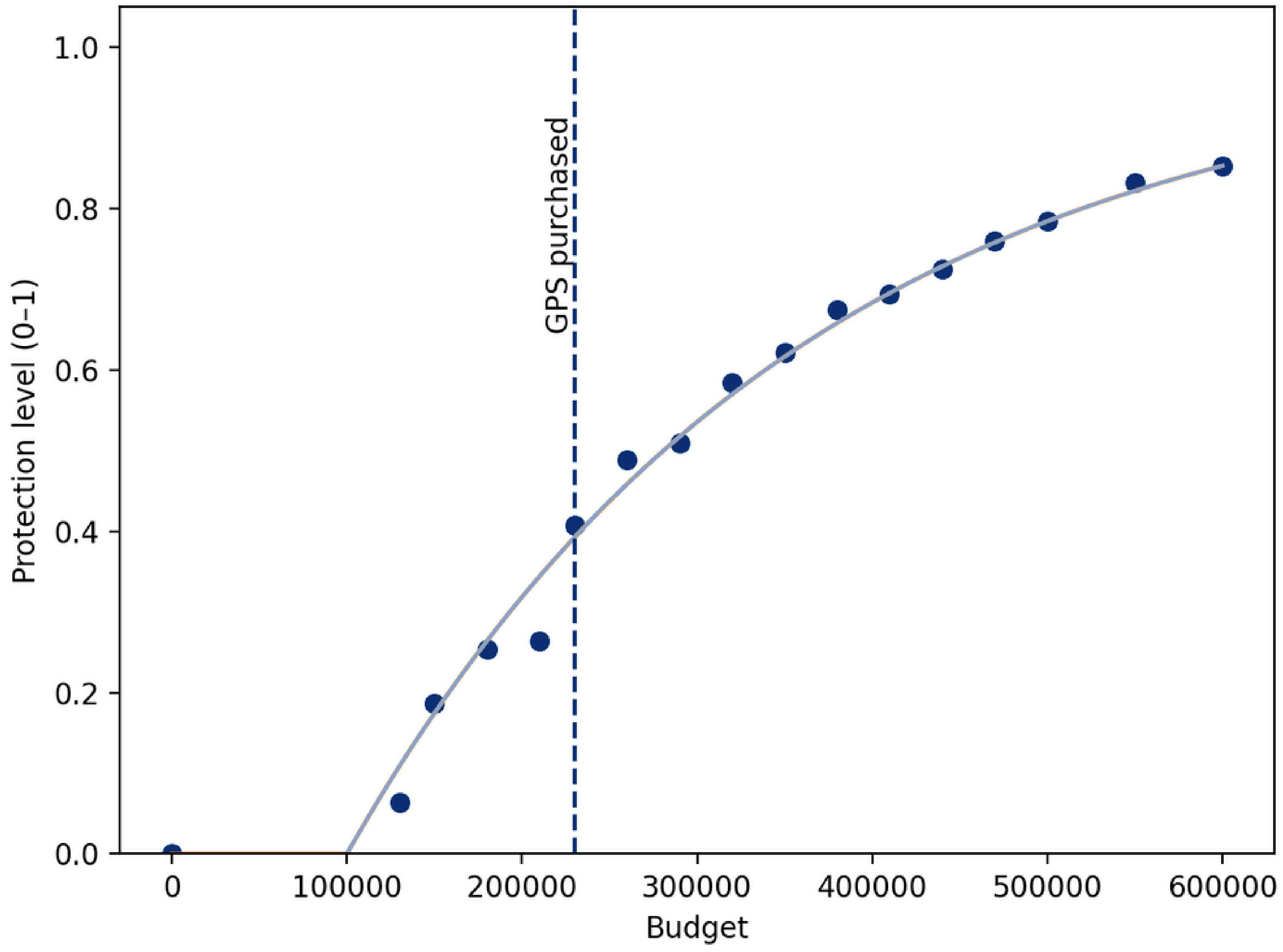
Results

≈ 300,000 budget units
>50% protection level

ProtectionLevel (B) = $\left[\dfrac{L_0 - L(B)}{L_0 - L_{min}}\right]_0^1$

Protection = reduction in expected ecological loss relative to the no-budget baseline.

Loss increases when detection or ranger response is delayed.



Results

FIELD CAPACITY

3 independent patrol teams

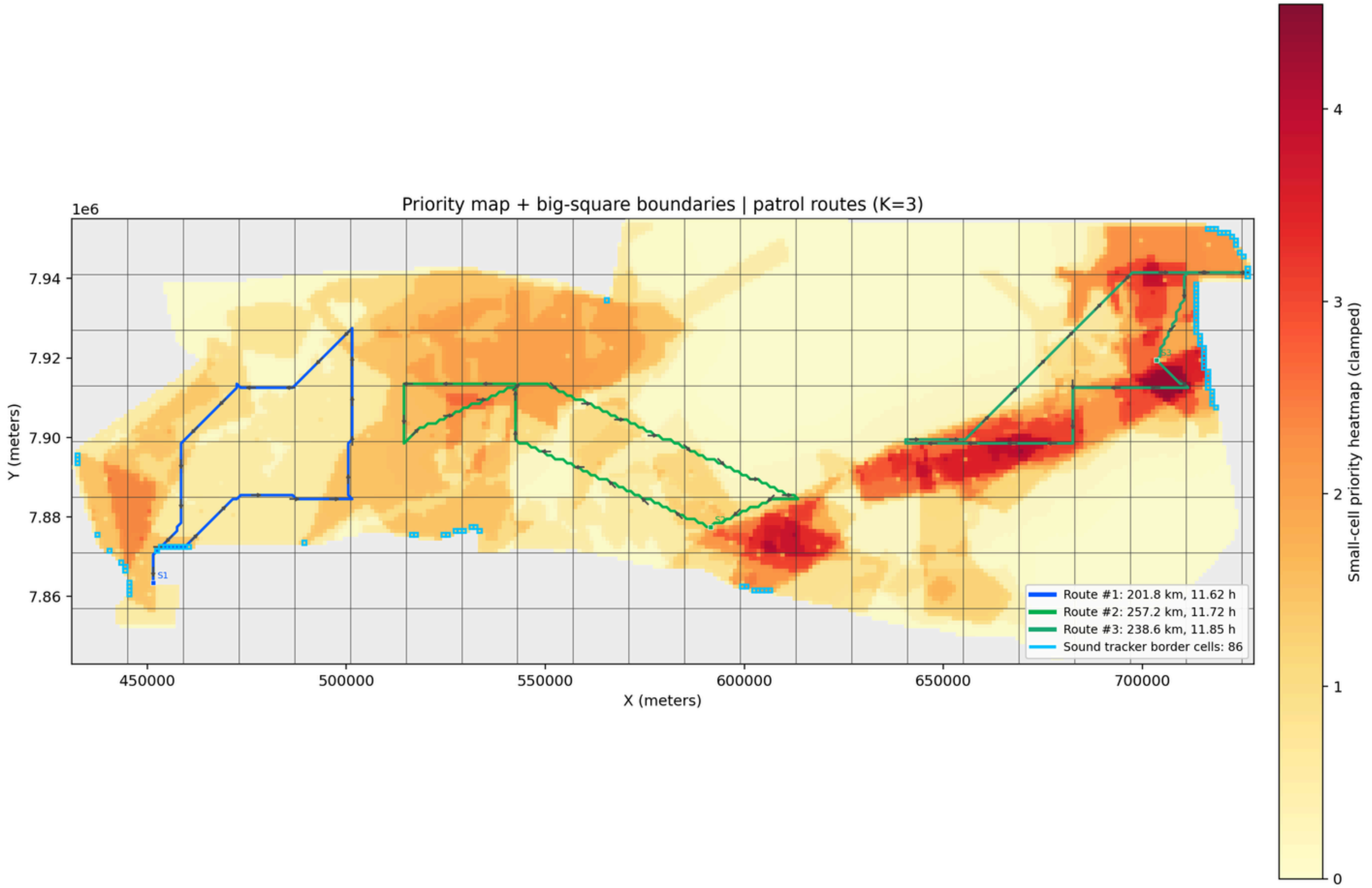
15 rangers in active field capacity

5 rangers per team, not the total park staff

THREE ROUTES, EACH INSIDE ONE SHIFT

ROUTE 1	ROUTE 2	ROUTE 3
201.8 km	**257.2 km**	**238.6 km**
11.62 h	11.72 h	11.85 h

Sound tracker border cells: 86



The ranking holds under stress

Every recommendation rests on the threat ranking, so we tried to break it.

WHAT WE SHOOK

IMPACT: HOW BAD IT IS

criterion weights, ±20%

every rating, ±1

one threat's ratings together

LIKELIHOOD: HOW LIKELY, BY SEASON

the seasonal risk order

and how it sets the weights

We ran the whole check again in a dry season and a wet one.

THE BAR, SET IN ADVANCE

Reliable only if the order barely moves (rank correlation $\rho \geq 0.9$) and the top threats keep their places.

WHAT HELD

It held. The ranking stayed, and so did the plan it drives; only the two nearly tied threats can swap.

Model limitations

The model makes three simplifications, each with the step that would close it.

THE SIMPLIFICATION	HOW WE WOULD CLOSE IT
Weights are relative they rank the threats rather than measure event rates	recalibrate against incident records as they build up
Two fixed speeds 60 km/h on roads and 30 off them, whatever the season or road condition	calibrate speed by road quality and season before the staffing number is final
The 1 km grid is coarse micro-hotspots and off-road paths fall between cells	refine the cells from ranger field observations

Transfer to other national parks

	Wood Buffalo National Park NORTH AMERICA, boreal wetland	**Altai State Nature Biosphere Reserve** ASIA, mountainous and road-free
TERRAIN	Flat boreal forest, marsh and peat bog around the Peace and Athabasca delta.	Mountain ranges and more than 1,000 lakes, no roads and only rare trails, entry by permit.
THREATS	Disease leads: brucellosis and tuberculosis. Then oil-production leaks and poaching of bison, moose and reindeer, which stays limited here.	Poaching and illegal fishing lead, then resource extraction, fires, climate change and tourism near the border.
SPECIES	Wood bison, wolves, grizzly and black bears, moose, reindeer, whooping crane.	Snow leopard, Altai mountain sheep, musk deer, wolverine, golden eagle, and plants such as Rhodiola rosea.
MOBILITY	Winter runs October to April and freezes the bog, so vehicles work then and foot patrols take over in summer.	Foot and air all year, and deep snow slows every winter trip.
WHAT BREAKS	Travel times flip between the seasons, so one mobility graph cannot serve both.	A patrol lasts 2 to 2.5 weeks, not the one shift we assume, and without roads vehicle GPS has nothing to track.

The graph, the weighting, the priority score, the routing and the protection metric all carry over untouched

Thank you for your attention!

Documented examples for each modelled threat

Threat	Examples
Road-related wildlife mortality	A Ministry of Environment and Tourism vehicle hit a rhino in 2015.
Organised poaching & wildlife trade	Poachers drove cattle through fence gaps to cover tracks; rhino horns were hidden for later extraction.
Wire snaring & passive trapping	62 active snares were seized in three days near Okaukuejo in 2023.
Illegal harvesting of resources	Confiscations and arrests in 2024–2025 documented continued incursions into the park.
Wildlife dispersal beyond boundaries	A pride of six lions left Etosha and killed livestock between Casablanca and Oshivel.
Transboundary disease transmission	Rabies in kudu in 1977 originated in neighbouring agricultural areas and later spread to lions in 1983–84.
Wildfire	A 2,545 km^2 fire occurred in October 2020; large fires also occurred in 2021 and 2025.

Why some factors were not modelled in the baseline

Internal anthrax	Treated as an endemic seasonal ecological process; park-wide control measures are not operationally feasible.
Internal rabies	Historically about 2% of recorded wildlife deaths; not a major baseline distribution factor.
Plastic waste	No significant wildlife mortality identified in the report; bag restrictions and enforcement already exist.
Unsafe tourist proximity	Documented safety incidents, but no confirmed population-level environmental impact.
Tourist-caused fires	No documented Etosha fires directly linked to tourist behaviour during the reviewed period.

AHP: deriving criterion weights

1 Order the criteria

Spatial extent > Severity > Reversibility > Recurrence > Response window

2 Map rank gaps to Saaty judgments

Adjacent = 3; two ranks apart = 5; three = 7; four = 9. Reciprocals fill the lower triangle.

3 Normalise and average

Each column is normalised; criterion weights are row averages and are renormalised to sum to 1.

Pairwise comparison matrix

1	3	5	7	9
⅓	**1**	3	5	7
⅕	⅓	**1**	3	5
⅐	⅕	⅓	**1**	3
⅑	⅐	⅕	⅓	**1**

Consistency Ratio (CR) ≈ 0.053

Below the conventional 0.10 threshold: the criterion comparisons are internally consistent.

Key caveat: consistency checks logical coherence, not whether the underlying expert judgement is objectively true.

APPENDIX

From scores to structural-impact weights

Each threat receives an anchored ordinal score from 1 to 5 under every criterion; higher always means worse impact.

Threat	Extent	Severity	Reversibility	Recurrence	Response
RM	2	3	2	3	3
WF	**5**	**4**	**5**	**3**	**5**
OP	3	5	5	3	5
SN	2	4	4	4	4
IH	3	2	3	4	2
DB	4	3	3	3	2
TD	4	4	4	3	3

Anchored examples

- **Spatial extent**

  1: <1% of usable habitat; 5: >30%.

- **Reversibility**

  1: days–weeks; 5: >10 years or effectively irreversible.

- **Response window**

  1: days–weeks; 5: minutes or no actionable window.

$$\widetilde{W}_i = \sum_{c=1}^{5} w_c \cdot \frac{s_{i,c}}{5}$$

then normalize across threats

Worked example: deriving wildfire's impact weight

Every number below comes directly from the AHP criterion weights and the wildfire score row.

1. Multiply each criterion weight by wildfire's normalised score

Criterion	AHP weight	WF score	Contribution
Spatial extent	0.5028	5 / 5	0.5028 × 1.0 = 0.5028
Severity	0.2602	4 / 5	0.2602 × 0.8 = 0.2082
Reversibility	0.1344	5 / 5	0.1344 × 1.0 = 0.1344
Recurrence	0.0678	3 / 5	0.0678 × 0.6 = 0.0407
Response window	0.0348	5 / 5	0.0348 × 1.0 = 0.0348

Raw wildfire score = 0.5028 + 0.2082 + 0.1344 + 0.0407 + 0.0348 = 0.9208

2. Normalise across all seven threats

Raw scores

RM 0.4726 WF 0.9208
OP 0.7718 SN 0.5989
IH 0.5546 DB 0.6936
TD 0.7795

Total raw score = 4.7917

Final wildfire impact weight

0.9208 / 4.7917 = 0.1922

Interpretation: 0.1922 is wildfire's share of total structural impact — before seasonality is applied.

Seasonality changes operational priorities

Each month belongs to exactly one regime; regime weights sum to 1 across the seven threats.

Regime	Season	Months	Likelihood ranking	Top composite risk*
G1	Dry + popular	Jul–Sep	RM > WF > OP > SN > IH > DB > TD	**WF**
G2	Wet + popular	Oct–Nov	RM > SN > OP > IH > WF > DB > TD	**RM**
G3	Wet	Dec–Feb	TD > DB > IH > SN > OP > WF > RM	**TD**
G4	Dry	Mar–Jun	WF > OP > SN > DB > IH > RM > TD	**WF**

Why rank gaps become numeric weights

The rank-to-weight mapping is 0.4092, 0.2460, 0.1512, 0.0903, 0.0525, 0.0309 and 0.0198 for ranks 1–7. These are relative likelihood weights, not event probabilities.

*Computed by multiplying the report's structural-impact and regime likelihood weights; not an additional reported table.