

2026 INTERNATIONAL MATHEMATICAL MODELLING CHALLENGE

PROTECTING AREA: WILDLIFE HABITAT

SUMMARY

Etosha National Park is a very large and diverse protected area, so the same protection strategy cannot work equally well in every part of the park. In our study, we focused on two major threats: wildfire and poaching. We do not treat them as completely separate problems, because they affect some of the same sectors, put pressure on the same staff and equipment, and become more difficult when they happen under the same seasonal conditions. This means that a uniform patrol system is unlikely to be the most effective way to protect the park. Instead, Etosha needs a system that helps managers identify which sectors need the fastest and strongest attention.

To study this problem, we divided the park into sectors and evaluated each sector using several types of factors. For wildfire, we considered fuel load, dryness, wind, ecological sensitivity, human-related pressure, and response difficulty. For poaching, we considered remoteness, accessibility, proximity to waterholes, wildlife concentration, surrounding social pressure, and the strength of surveillance. We then combined these factors into two separate risk models and finally into one integrated threat map. Our goal was not to predict the exact location of every incident, but to compare sectors and understand where limited resources could have the greatest effect.

The model suggests that Etosha has a clear spatial pattern of risk. Northwestern sectors appear more vulnerable to wildfire because of dry biomass, wind exposure, and slower response conditions. Northern and remote sectors show higher poaching risk because monitoring is weaker and rapid interception is more difficult there. Waterholes and ecotone zones are especially important because even when the probability of an incident is not the highest, the possible ecological damage can still be very large. In this way, the model highlights not only where threats are likely, but also where they may cause the most serious consequences.

After identifying these priority areas, we used the model to think about where a rapid-response base and limited resources should be placed. In the locations we considered, the Adamax Pan area performed best because it helps balance response time between two important directions: the fire-prone northwest and the poaching-vulnerable north. Our results also suggest that fixed deployment is not enough. During periods of higher dryness, more capacity should be shifted toward fire response, while in other periods stronger anti-poaching coverage may be more effective. This makes seasonal reallocation an important part of the protection strategy.

The main conclusion of our work is that Etosha should be protected through a risk-based and adaptive system rather than through equal territorial coverage. A sector should receive higher priority when high threat, high vulnerability, and weak response capacity come together. Such an approach can improve early fire detection, strengthen anti-poaching efforts, and make better use of limited staff and equipment. Even though our model is simplified and depends on proxy indicators, it still provides a practical framework for supporting park management decisions.

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LETTER TO DECISION MAKERS

Etosha National Park: A Risk Oriented Protection Strategy

Dear Decision Makers,

Etosha National Park is one of the most important protected areas in Namibia, but it is also very large and difficult to manage evenly. Different parts of the park face different levels of danger, and limited staff and equipment cannot provide the same level of protection everywhere at the same time. In our work, we focused on two major threats to the park: wildfire and poaching.

A main idea of our study is that these two threats should not be treated as completely separate problems. They affect some of the same areas, depend on some of the same seasonal conditions, and compete for the same response resources. For example, when staff and vehicles are moved to deal with a fire, other sectors may temporarily become less protected. In the dry season, this challenge becomes even more serious, because fire danger increases while animals may also gather around key water points and become easier targets.

Because of this, we think that a uniform protection system is unlikely to be the most effective approach for Etosha. Instead, management may benefit from a more targeted system that identifies which sectors need the most attention, which threats are most important in each area, and where response time matters most.

To study this, we divided the park into sectors and compared them using several factors. For wildfire, we considered conditions such as dry biomass, wind, dryness, ecological sensitivity, and response difficulty. For poaching, we considered remoteness, proximity to waterholes, accessibility, surveillance strength, and surrounding social pressure. We then combined these into one integrated threat map. The purpose of this map is not to predict every event exactly, but to help compare sectors and support decisions under limited resources.

Based on this work, we would suggest four practical directions.

First, place rapid-response capacity where it can serve more than one major risk direction.

In our model, the Adamax Pan area performs well because it helps reduce response delay between the fire-prone northwest and the poaching-vulnerable north. This does not mean it is the only possible solution, but among the locations we considered, it gave the best balance. A base is most useful not because it is centrally located on a map, but because it reduces delay to the sectors where delay causes the greatest damage.

Second, move from equal patrol coverage toward risk-based deployment.

We do not suggest ignoring lower-risk areas, but we do think that the most limited resources should be concentrated in sectors where high threat, high vulnerability, and weak response capacity come together. In some places this means stronger anti-poaching patrols. In others it means faster fire detection and quicker local response. In the most sensitive sectors, both functions may need to be strengthened at the same time.

Third, improve early detection, not only response.

Our results suggest that in both fire management and anti-poaching work, earlier detection can greatly improve outcomes. Satellite monitoring, drones, fixed observation points, and rapid local reporting

may be especially valuable near waterholes, ecotone areas, remote northern sectors, and high fire-risk northwestern zones. In many cases, reducing the time between incident start and incident detection may be just as important as increasing the number of units available for response.

Fourth, use seasonal reallocation of personnel and effort.

Etosha's threat profile changes during the year. In drier periods, more attention may need to go to wildfire response. In other periods, anti-poaching coverage may deserve relatively greater emphasis. For this reason, a fixed year-round staffing pattern may not be the best option. A more flexible system could help the park use existing staff and equipment more effectively.

We believe that these steps could improve protection in several ways. They could reduce response time in the most critical sectors, increase the chance of stopping fires early, improve the likelihood of intercepting poaching threats in time, and make better use of limited staff and equipment. The value of this approach is not simply in adding more resources, but in using available resources more carefully.

Our study also suggests that some places deserve especially high priority. Waterholes, ecotone zones, remote northern sectors, and sectors where several risks overlap are likely to need more focused attention than areas with lower combined risk and easier access. In a park as large as Etosha, not all sectors have the same conservation value or the same level of operational difficulty, so treating them in exactly the same way may reduce overall effectiveness.

At the same time, we understand that our model is simplified. It is based partly on proxy indicators and is meant as a decision-support framework rather than an exact prediction system. Even so, we think it can still be useful because it offers a structured way to compare sectors, think about priorities, and organize limited resources more strategically.

Our overall conclusion is simple: Etosha may be better protected through a system that is predictive, spatially differentiated, and seasonally adaptive, rather than one based mainly on equal coverage and reactive response. We hope this work can contribute, even in a small way, to thinking about how conservation resources can be used more effectively in a complex protected area.

Sincerely,

Team

1. INTRODUCTION

Etosha National Park is one of the largest protected areas in Africa and one of the most important parts of Namibia's conservation system. Official sources describe it as the country's flagship park, and the Protected Planet database gives its area as 22,941 km². Because of its size, Etosha should not be viewed as one uniform space. Different parts of the park vary in ecological importance, accessibility, visibility, and vulnerability.

In this study, we focus on two major threats: wildfires and poaching. These threats affect not only separate parts of the park, but also the overall protection system. They can damage biodiversity, disturb animal movement, and make it harder for the park to respond quickly. For this reason, we do not consider wildfire and poaching as fully separate problems. In many cases, they are connected through ecological, social, and spatial factors.

This also explains why uniform patrolling and purely reactive response may not be enough for Etosha. Risk is not distributed evenly across the park, and it also changes by season. During the dry period, fire danger becomes much higher, especially when hot and windy conditions make fires spread more easily. If resources are spread equally across the whole park, some of them may be used in places where the immediate threat is relatively low, while more dangerous sectors may remain underprotected. Because of this, we think a more effective approach is a predictive one, in which resources are directed to the places and times where damage is more likely.

Based on this idea, our study develops an integrated model for wildfire and poaching risk. We combine both threats into one spatial framework and then use this framework to think about how limited resources should be allocated. This includes identifying priority monitoring zones, comparing sector risks, and considering where a response base and protection forces could be placed most effectively. In the following sections, we explain our assumptions, present the wildfire and poaching models, combine them into an integrated risk map, and then apply the results to resource allocation.

2. ASSUMPTIONS AND NOTATION

2.1. Assumptions

To build an integrated protection model for Etosha National Park, we first need several working assumptions. These assumptions help us simplify a very complex real-world system and make it possible to compare different parts of the park in a consistent way. Our goal is not to reproduce every detail of the park exactly, but to create a model that is useful for analyzing risk and thinking about resource allocation.

1. The park can be divided into sectors for analysis.

We assume that Etosha can be represented as a set of sectors or zones. Conditions inside one sector are not completely identical, but they are similar enough for comparison. This makes it easier to evaluate which parts of the park are more threatened, more vulnerable, or harder to protect.

2. Risk in each sector can be described using a limited number of key factors.

We assume that the most important differences between sectors can be captured through observable natural, social, and infrastructural factors. These include things such as fuel load, humidity, wind,

remoteness, proximity to waterholes, visibility, and accessibility. This does not include every possible influence, but it allows the model to stay manageable and still reflect the main patterns of risk.

3. Wildfire risk and poaching risk change by season.

We assume that both threats vary over time rather than staying constant throughout the year. During the dry season, fire danger becomes higher because vegetation dries out and burning conditions become more severe. At the same time, seasonal changes in water and animal movement can also affect poaching risk. This assumption is important because it allows us to think about adaptive protection instead of one fixed strategy for the whole year.

4. Response time depends on both distance and accessibility.

We assume that the danger of a sector is influenced not only by the chance of an incident, but also by how quickly the park can respond. Even if two sectors have similar threat levels, the more remote or less accessible one may need higher priority because intervention there is harder and slower.

5. Limited resources can be reallocated depending on the type of threat.

We assume that at least part of the park's staff, equipment, and monitoring capacity can be shifted between wildfire response and anti-poaching work when needed. In reality, this flexibility may not be perfect, but the model assumes that some reallocation is possible. Without this assumption, it would be much harder to study how protection can be improved under changing seasonal conditions.

6. Missing data can be approximated by proxy indicators.

We assume that when direct data are not available, indirect indicators can still be used. For example, fire danger may be estimated through biomass, humidity, and wind, while poaching risk may be estimated through remoteness, access routes, and proximity to waterholes. This makes the model more realistic for situations where complete field data are unavailable.

7. Integrated risk depends on threat, vulnerability, and response capacity together.

We assume that a sector becomes especially important when three things come together: a relatively high probability of threat, a high level of ecological or conservation vulnerability, and weak response capacity. In other words, risk is not defined by one factor alone, but by the interaction of several factors.

8. Sector conditions are treated as stable within one modeling period.

We assume that during a single time step or season, the main characteristics of a sector do not change enough to require constant recalculation. This is a simplification, but it allows the model to compare sectors more clearly and focus on broader seasonal patterns rather than very short-term fluctuations.

These assumptions create the basis for the rest of our model. They simplify the real situation, but they also help us move from a general description of threats to a more structured comparison of sectors and protection priorities.

2.2. Notation

Symbol	Definition
i	Index of a park sector
t	Index of time or season
F_i	Fuel load (biomass) in sector i
$H_i(t)$	Humidity level in sector i at time t
$W_i(t)$	Wind factor in sector i at time t
$P_i^{fire}(t)$	Probability of fire ignition or development in sector i
$P_i^{poach}(t)$	Probability of poaching activity in sector i
$SEVI_i(t)$	Social-ecological vulnerability index of sector i
$R_i(t)$	Integrated risk of sector i , combining the main threats and response constraints
D_i	Distance from the base point or response center to sector i
$C_i(t)$	Response capacity in sector i , reflecting the park's ability to respond quickly and effectively to an incident
$N_{fire}(t)$	Size of the firefighting unit at time t
$N_{ap}(t)$	Size of the anti-poaching unit at time t
$E_i(t)$	Sector protection effectiveness index
L	Location of the base, camp, or other response-force deployment point

3. DATA, SPATIAL LOGIC, AND RISK FACTORS

3.1. Spatial Partitioning of the Territory

In our model, Etosha National Park is treated as a large and spatially diverse system rather than as one uniform protected area. The park covers about 22,935-22,941 km² and includes different landscape types, such as the salt pan, savanna zones, shrub areas, and places with different vegetation density and water availability. Because of this, different parts of the park do not face the same level or type of risk.

For this reason, we divide the park into sectors that can be used as basic units of analysis. This step is important because it allows us to compare different parts of Etosha in a structured way. Instead of describing the park only in general terms, we can look at each sector separately and evaluate its fire risk, poaching risk, ecological importance, accessibility, and response difficulty.

We use sectors because the park is too large and too heterogeneous to model as a single continuous space in a simple way. A sector-based approach makes it easier to connect geography with

management decisions. For example, one sector may be more exposed to wildfire because of vegetation and wind, while another may be more vulnerable to poaching because it is remote, harder to monitor, or closer to key wildlife areas. If we treat the whole park as one average space, these important differences would be lost.

This partitioning also helps us later when we combine the two threats into one integrated framework. Once the park is divided into sectors, we can assign comparable values to each one and identify which areas need more attention. In this way, spatial partitioning becomes the basis for the rest of the model, including risk comparison, priority setting, and resource allocation.

At the same time, we understand that sectors are only a modeling simplification. Real conditions inside each sector are not perfectly uniform, and some local details are inevitably lost. However, for the purpose of this study, sector-based analysis provides a practical balance between realism and manageability. It allows us to represent the park's spatial complexity without making the model too detailed to use.

3.2. Ecological Risk Factors

The ecological part of our model includes the natural conditions that influence both the probability of threats and the scale of their possible consequences. These factors are important because wildfire and poaching do not develop in an ecological vacuum. They depend strongly on vegetation, weather, animal behavior, and the spatial structure of habitats.

For wildfire, the main ecological factors are fuel load, fuel moisture, wind conditions, and the possibility of natural ignition. In a savanna system like Etosha, these variables are especially important. During the rainy season, vegetation grows and biomass accumulates. Later, during the dry season, this biomass becomes flammable fuel. Because of this, fire risk depends not only on dryness at the present moment, but also on how much vegetation has built up over time. Wind also matters, since it can increase fire intensity and make fires spread faster across open areas.

At the same time, our model does not look only at where a fire may start. It also considers where fire may cause especially serious ecological damage. Some sectors are more sensitive than others because of their habitat structure or ecological role. In particular, ecotone areas and transition zones are important because disturbance there can affect more than one habitat type at once. Even if such areas do not always have the highest ignition probability, they may still deserve higher attention because the ecological consequences of fire can be greater.

Waterholes are another key ecological factor in Etosha. They are important not only because they support wildlife, but also because they shape animal movement and concentration patterns. In the dry season, animals often gather around a limited number of water points, which makes these places ecologically valuable and at the same time more vulnerable. This matters especially for the poaching part of the model, since sectors near important waterholes may face higher risk when animal presence becomes more predictable.

For these reasons, ecological variables in our study are used in two ways. First, they help us estimate where threats are more likely to occur. Second, they help us identify where the consequences of those threats may be especially serious. This makes the ecological layer an essential part of the overall risk model.

3.3. Social and Infrastructure Risk Factors

In addition to ecological conditions, our model also includes social and infrastructure-related factors. These are important because risk in Etosha is shaped not only by the natural environment inside the park, but also by human activity, access patterns, and the practical ability of the park to monitor and respond.

One important factor is the position of a sector relative to the outer boundary of the park. Sectors closer to the perimeter may be more exposed to outside pressure, especially if the surrounding land is more actively used by people. In the Greater Etosha landscape, the areas around the park are not uniform: some are linked to communal settlements and agriculture, while others are connected to private land use. Because of this, the same type of sector inside the park may face different levels of pressure depending on what lies around it. In our model, this means that risk depends not only on internal park conditions, but also on the broader social and economic setting of nearby areas.

Infrastructure also matters a great deal. Roads, gates, camps, staff locations, and observation points affect how quickly a threat can be detected and how fast a response team can arrive. Etosha has an uneven network of entrances, camps, and monitored locations, so not all sectors are equally easy to reach or supervise. Because of this, two sectors with similar ecological risk may still have different management priority if one of them is more remote or less connected to patrol routes. In practice, a sector near a road or camp may be easier to protect than a sector that is harder to access and less frequently observed.

For poaching risk, we also consider the social vulnerability of communities near the park as an external source of pressure. We do not use this idea to judge local people. Instead, we use it as a way to represent a broader pattern that appears in many conservation settings: when economic opportunities are limited and links to legal livelihoods are weaker, pressure on protected resources may become higher. In this sense, social variables in the model are not moral labels. They are indirect indicators that help explain why some borderland sectors may face stronger poaching pressure than others.

Another important issue is the strength of observation and control. A sector becomes more vulnerable when it is remote, connected to possible transit routes, and at the same time weakly covered by patrols or observation points. This means that danger is not determined by remoteness alone. What matters more is the combination of access opportunity and weak surveillance. Because of this, infrastructure in our model is not treated only as a background detail. It is part of the core explanation of why some sectors are harder to protect and why the same threat may have different practical meaning in different parts of the park.

Overall, social and infrastructure factors help us connect spatial risk with real management conditions. They show that effective protection depends not only on where threats are likely to happen, but also on where the park can realistically observe, reach, and respond in time.

3.4. Seasonal Dynamics of Factors

An important part of our model is that risk factors in Etosha are not constant throughout the year. Both wildfire risk and, to some extent, poaching risk change with seasonal conditions. Because of this, it would be unrealistic to treat the park as if the same level of danger existed in every month.

For wildfire, the late dry season is especially important. By this time, vegetation has usually become much drier, and fire conditions are more dangerous than earlier in the year. In savanna ecosystems,

the difference between the early dry season and the late dry season can be very significant: the same area may be relatively safer at one point and much more fire-prone later, depending on fuel dryness and weather conditions. This means that fire danger should be seen as a moving seasonal pattern rather than a fixed background value.

Another important point is that seasonal change is not exactly the same every year. The transition from lower-risk to higher-risk fire conditions depends on how fuel and weather develop over time. In addition, early controlled burning may reduce the scale of more destructive fires later in the season. For this reason, our model assumes that fire-risk thresholds should not be treated as constant for the whole year. They need to reflect the actual seasonal dynamics of biomass, dryness, and weather.

Seasonality also matters for the broader protection system, because changes in ecological conditions affect how resources should be used. When fire danger becomes higher, faster detection and stronger fire-response capacity become more important. In other periods, when conditions are less extreme, protection effort may be distributed differently. This supports one of the main ideas of our study: effective protection in Etosha should be adaptive, not fixed.

Overall, seasonal dynamics are included in the model because they help explain why the same sector cannot be treated in exactly the same way at all times of the year. A sector's priority depends not only on where it is located, but also on when it is being evaluated. That is why seasonality is not just an additional detail in the analysis, but one of the main factors that shapes the logic of risk across the park.

4. FIRE RISK MODEL

4.1. Nature and Causes of Fire Outbreaks

Wildfires in Etosha National Park have more than one cause, so they should not be explained only by drought or only by human activity. In our model, it is more useful to separate fire causes into two main groups: natural ignition and anthropogenic ignition. This helps us describe fire risk in a way that is closer to the real conditions of the park.

The natural part of fire risk is mainly connected with dry thunderstorms and lightning. However, lightning by itself does not automatically create the most dangerous fires. A fire becomes especially serious when ignition happens in a place where a large amount of dry biomass has already accumulated and where conditions are favorable for fire spread. In other words, the ignition source matters, but it is only one part of the problem. Fuel conditions are just as important.

This is why the most dangerous fire years in Etosha may follow relatively wet periods rather than the driest ones. After wetter conditions, more grass and vegetation can grow. Later, during the dry season, this vegetation dries out and becomes flammable fuel. Because of this, fire danger depends not only on present dryness, but also on earlier rainfall and vegetation growth. For a savanna ecosystem like Etosha, this pattern is especially important, since the same area may look relatively safe in one year and much more dangerous in another.

At the same time, human-related ignitions are also an important part of the picture. In some sectors, they may even be the main source of danger. Fires may be started deliberately, for example to distract rangers, disturb patrol routes, or affect animal movement. Another possible source is fire spreading into the park from nearby agricultural or inhabited areas, especially in buffer zones where the boundary between protected land and surrounding land use is more open and permeable. Because of

this, wildfire in Etosha should be understood not only as a natural hazard, but also as a risk shaped by the park's broader social and spatial setting.

Fire risk is also uneven across the park. Northwestern sectors appear especially important because they combine dry biomass, wind exposure, and more difficult control conditions. Ecotone corridors may not always be the most likely places for ignition, but they can still be very important because even a relatively local fire there may lead to large ecological damage. By contrast, southern and eastern buffer areas may face a stronger anthropogenic component, since these zones are more influenced by nearby infrastructure, transport, and surrounding economic activity.

Seasonal timing is another key part of the fire problem. Peak fire danger usually occurs in the late dry season, especially from August to November, when fuel moisture is lowest, wind effects become stronger, and the biomass accumulated earlier becomes most dangerous. For this reason, fire risk in Etosha should be treated as a changing seasonal and spatial variable rather than a fixed background condition. In our model, this means that fire risk depends at the same time on the ignition source, the amount of fuel, the season, and the location of the sector.

4.2. Probability of Ignition

To describe risk quantitatively, we first introduce the probability of ignition in a sector. Let i denote a park sector and t a moment in time or seasonal step of the model. Then the natural probability of fire occurrence can conveniently be defined as a function of three basic factors: fuel load, current humidity, and the background ignition probability associated with lightning:

$$P_{fire,i}^{nat}(t) = p_i^{lig}(t) + \frac{F_i(t)}{F_{avg}} \left(1 - \frac{H_i(t)}{100}\right).$$

Here, $F_i(t)$ denotes the dry biomass load in the sector, F_{avg} is the average fuel load across the park, $H_i(t)$ is fuel moisture as a percentage, and $p_i^{lig}(t)$ is the background probability of natural ignition, reflecting the intensity of dry thunderstorms in the given sector and season. The meaning of the formula is straightforward: the probability of ignition rises when fuel exceeds the average and humidity is lower. At the same time, lightning provides a minimal natural background of ignition even in sectors where biomass is only moderately distributed.

However, for Etosha the natural component alone is insufficient. Some ignitions are linked to human activity, and therefore the model introduces an additional block of anthropogenic ignition. Let $A_i(t)$ denote the aggregate anthropogenic pressure in the sector, which may include borderland pressure, population density in adjacent areas, transport and tourism load, as well as proximity to potential entry zones. Then the anthropogenic ignition probability can be defined in nonlinear form:

$$P_{fire,i}^{hum}(t) = \frac{\alpha A_i(t)}{1 + \beta A_i^2(t)}.$$

The total ignition probability for a sector can then be written as the combination of the natural and anthropogenic components:

$$P_{fire,i}(t) = \min \{1, P_{fire,i}^{nat}(t) + P_{fire,i}^{hum}(t)\}.$$

The upper bound of one is needed only to ensure the correct interpretation of the result as a probability. In substantive terms, this model shows that fire in Etosha is the result of a combination of natural and human factors. Northwestern sectors typically receive high values due to fuel load and wind exposure, while southern and eastern buffer zones may show a relatively larger contribution from anthropogenic

ignition. Thus, fire probability ceases to be an abstract characteristic of the “dry season” and becomes a sector-specific indicator.

4.3. Fire Intensity and Spread Potential

As a baseline estimate of intensity, we use a dependence on fuel, humidity, and wind:

$$I_{fire,i}(t) = F_i(t) \cdot 0.0001 \cdot 18000 \cdot \left(1 - \frac{H_i(t)}{100}\right) \cdot \left(1 + \frac{W_i(t)}{10}\right).$$

But intensity alone still does not exhaust the full danger. For park management, it is also important to account for the fire’s spread potential, that is, the probability that an ignition will move beyond a local patch and affect a significant area. Such potential depends not only on the parameters of the fire itself, but also on the spatial connectivity of fuel, landscape openness, and sector configuration. Therefore, we introduce an additional indicator:

$$S_i(t) = I_{fire,i}(t) \cdot C_i,$$

where C_i is the coefficient of spatial connectivity and fire “passability” in the sector. In open, wind-exposed zones of the northwest, C_i will be higher than in more fragmented areas. Thus, the model distinguishes between merely intense fire and fire capable of rapidly turning into large-scale spread.

Ecologically sensitive sectors occupy a special place in this logic. Ecotone zones may not always lead in ignition probability, but for them even a medium-intensity fire implies disproportionately high damage, since it affects transitional habitats and disrupts spatial links between ecosystems. Therefore, fire danger should be measured not only by the physical force of the fire, but also by its capacity to become an ecologically severe event. This is precisely why the final index in the next subsection will take into account not only P_{fire} and I_{fire} , but also the vulnerability of the sector itself.

4.4. Final Sectoral Fire Risk Index

After separately describing ignition sources, fire probability, and fire intensity, we can proceed to the final sectoral fire-risk index. For the purposes of this study, the index must be simple enough to be used in an integrated protection model, but sufficiently informative to reflect the real heterogeneity of the territory. Therefore, let the fire risk of sector i at time t be defined as a weighted combination of four components:

$$R_i^{fire}(t) = w_1 \tilde{P}_{fire,i}(t) + w_2 \tilde{S}_i(t) + w_3 \tilde{V}_i + w_4 \tilde{D}_i, w_1 + w_2 + w_3 + w_4 = 1.$$

Here, $\tilde{P}_{fire,i}(t)$ is the normalized ignition probability, $\tilde{S}_i(t)$ is the normalized intensity-and-spread potential, $\tilde{V}_i$ is the ecological vulnerability of the sector, and $\tilde{D}_i$ is the logistical difficulty of response, including remoteness, road accessibility, and expected arrival time of forces. Normalization is required only so that all components are measured on a comparable scale from 0 to 1.

Such a structure allows a natural interpretation of the result. A sector receives a high final risk not only when fire can easily start there, but also when a possible fire would be intense, fast-spreading, ecologically sensitive, and difficult to suppress. This is especially important for comparing different zone types. For example, northwestern sectors may receive high values because of fuel, wind, and the difficulty of rapid response; ecotone corridors because of vulnerability; and southern and eastern buffer zones because of the elevated anthropogenic component in ignition probability.

5. POACHING MODEL

5.1. Drivers of Poaching and Threat Logic

Poaching in Etosha National Park is not random, and it is not spread evenly across the territory. In our model, we treat it as the result of several factors working together. These factors affect both the chance of illegal entry and the level of damage that poaching can cause. Because of this, poaching should be viewed not as a constant background problem, but as a changing threat that depends on season, location, and the strength of park protection.

The first important factor is economic pressure. High outside demand for rhino horn and its high market value create a strong incentive for illegal hunting even when penalties exist. This does not tell us exactly where an incident will happen, but it helps explain why poaching remains a repeated and persistent threat. In our model, this kind of pressure acts as a general background driver that increases the effect of local risk conditions.

The second factor is the geography of the park itself. Etosha is very large, and control cannot be equally strong everywhere. Remote northern and northwestern sectors, and areas farther from roads, camps, and regular patrol routes, are more difficult to monitor and harder to reach quickly. Because of this, some parts of the park create better opportunities for concealed entry and delayed interception. This is one of the main reasons why poaching risk is uneven across sectors.

The third factor is ecological. During the dry season, animals tend to gather around a smaller number of waterholes, and their movements become more predictable. This makes waterholes especially important in the poaching model. They are not only ecological nodes, but also places of increased vulnerability. When animals are easier to locate, poaching becomes easier as well. The danger becomes even greater when these waterhole areas are also remote and weakly controlled.

The fourth factor is social pressure around the park. Poverty, unstable employment, limited legal income opportunities, and the involvement of intermediaries can create conditions in which illegal activity is more likely to receive support. In our model, we do not use this idea to judge local communities. Instead, we treat it as an external pressure factor that may increase poaching risk in some borderland sectors.

The fifth factor is infrastructure and surveillance capacity. A sector becomes especially vulnerable when it is remote, connected to possible entry or transit routes, and at the same time not well covered by observation points, staff presence, or transport infrastructure. In other words, the highest risk does not come from remoteness alone, but from the combination of access opportunity and weak control. That is why poaching risk in our model depends not only on wildlife presence, but also on how manageable a sector is from the park's point of view.

Taken together, these factors show why poaching in Etosha should be analyzed as a spatial and dynamic threat. It becomes strongest where ecological opportunity, weak surveillance, difficult access for rangers, and outside pressure reinforce one another. This logic forms the basis for the next step of the model, where we estimate poaching probability by sector rather than describing it only in general terms.

5.2. Sectoral Probability of Poaching

Let i denote a park sector and t the seasonal step of the model. Then the probability of poaching in a sector is conveniently defined not as a simple linear sum of factors, but as a logistic function:

$$P_i^{poach}(t) = \frac{1}{1 + \exp[-Z_i(t)]}$$

where

$$Z_i(t) = \alpha_0 + \alpha_1 W_i(t) + \alpha_2 D_i + \alpha_3 S_i + \alpha_4 A_i - \alpha_5 C_i + \alpha_6 W_i(t) D_i.$$

Here, $W_i(t)$ reflects vulnerability associated with proximity to waterholes and seasonal animal concentration; D_i is the remoteness of the sector from bases, camps, and regular patrols; S_i denotes the social vulnerability of adjacent areas; A_i is the accessibility of the sector through roads, borders, and transit routes; and C_i is the strength of control and deterrence, that is, observation density, patrol regularity, and the probability of rapid interception. The last term, $W_i(t) D_i$, describes an amplification effect: a sector becomes especially risky when high animal predictability is combined with a low probability of rapid intervention.

5.3. Vulnerability of Protected Assets and Expected Damage

Estimating the probability of illegal activity alone is insufficient for conservation management. One sector may frequently experience intrusion attempts but cause only moderate damage; another may have only a moderate probability of incident, yet if the violation succeeds it may lead to extremely severe consequences. Therefore, after calculating $P_i^{poach}(t)$, it is necessary to separately assess the vulnerability of protected assets and the expected damage.

Let us introduce the conservation vulnerability index of a sector:

$$V_i^{poach}(t) = \beta_1 H_i(t) + \beta_2 M_i + \beta_3 R_i.$$

Here, $H_i(t)$ reflects the concentration of animals around waterholes and other attraction points; M_i denotes the sensitivity of movement corridors and key routes; and R_i represents the presence of rare, highly valuable, or particularly vulnerable species. The meaning of the formula is that a sector becomes critically important not only when it contains “many animals,” but also when it plays a disproportionately important role in preserving the population or the spatial connectivity of habitats.

On this basis, expected damage can be described as the product of incident probability and sector vulnerability:

$$L_i^{poach}(t) = P_i^{poach}(t) \cdot V_i^{poach}(t).$$

5.4. Final Sectoral Poaching Risk Index

After assessing poaching probability and expected damage, we can proceed to the final sectoral index suitable for later integration with the fire-risk model. For this purpose, let the poaching risk of a sector be defined as a weighted function of four components:

$$R_i^{po}(t) = \omega_1 (\widetilde{P_i^{poach}})(t) + \omega_2 (\widetilde{V_i^{poach}})(t) + \omega_3 (1 - \widetilde{Q_i}(t)) + \omega_4 \widetilde{F_i}(t).$$

Here, $(\widetilde{P_i^{poach}})(t)$ is the normalized probability of poaching, $(\widetilde{V_i^{poach}})(t)$ is the normalized vulnerability of protected assets, $\widetilde{Q_i}(t)$ is the integrated indicator of control and response capacity, and $\widetilde{F_i}(t)$ is an additional destabilizing factor associated, where relevant, with concurrent fires or other events that distract protection forces. The higher Q_i , the lower the final risk; the higher fire-related destabilization, the greater the probability that the sector will become less manageable precisely at the moment of threat.

6. RISK INTEGRATION AND A UNIFIED THREAT MAP

6.1. Why Fires and Poaching Must Be Considered Jointly

Etosha National Park is a large protected area, and also a spatially uneven system in which different threats can affect the same parts of the park at the same time. For this reason, wildfire and poaching should not be treated as completely independent problems. They are different in nature, but they overlap in space, season, vulnerable areas, and, most importantly, in the limited resources available for protection and response. Looking at them separately may be useful during the modeling process, but it is not enough for making practical management decisions.

This is especially important in Etosha because the distribution of risk is already uneven across the park. Northwestern sectors tend to be more exposed to wildfire, while northern and more remote sectors are more vulnerable to poaching. At the same time, some places—especially waterholes and ecotone zones—are important regardless of which threat appears first. Even if the type of danger is different, the same sector may still deserve high priority because of its ecological value and its role in the broader protection system.

Another reason to study the two threats together is that the park does not respond to them with two completely separate systems. Fires and poaching both require rangers, transport, monitoring, communication, and management attention. When resources are limited, protecting against one threat can affect how much capacity remains for the other. Because of this, two separate risk descriptions are not enough. What is needed is a common framework that allows sectors to be compared according to their combined importance.

For our study, this is why we move from two separate models to one integrated risk perspective. The goal is not only to identify where fire risk is high and where poaching risk is high, but also to understand where these threats overlap, where consequences may be greatest, and where limited resources should be directed first. In this way, joint analysis becomes the basis for a more realistic and more useful protection strategy for Etosha.

6.2. The Logic of Risk Interaction

The connection between wildfire and poaching in Etosha can be explained through several interacting mechanisms. These threats are different, but they can still strengthen each other in practice. This is one of the main reasons why we do not treat them as two completely separate parts of the protection problem.

The first mechanism is resource diversion. When a large fire breaks out, the park may need to move rangers, vehicles, drones, communication support, and management attention toward the fire zone. As a result, some other sectors may temporarily receive weaker monitoring and slower response. If this happens in northern or remote sectors, poaching risk may increase not because local conditions changed by themselves, but because protection capacity was reduced at that moment.

The second mechanism is linked to changes in spatial vulnerability after a fire. Fire can change how a sector functions from a protection point of view. In some cases, it may open visibility and make an area easier to observe. In other cases, it may disrupt patrol routes, block usual access paths, or push animals toward a smaller number of safe areas and water points. This means that after a fire, the same sector may no longer have the same level of accessibility, predictability, or protection as before. In this sense, fire changes not only ecological conditions, but also the operational structure of the park.

The third mechanism is seasonal synchronization. During the dry season, wildfire danger becomes higher, but at the same time animal movements around waterholes may also become more predictable. This means that both threats can intensify during the same period. On one side, the chance of ignition and rapid fire spread increases. On the other side, wildlife may become easier to locate in concentrated areas. Because of this, season should not be seen as just a separate parameter inside two unrelated models. It acts as a common background that can strengthen both threats at once.

The fourth mechanism is related to pressure in borderland and buffer areas. In places where access is easier, transport links are stronger, and the boundary between the park and outside activity is less protected, both kinds of risk may rise together. The probability of human-caused ignition can become higher, and the same conditions may also make illegal intrusion more likely. This makes some sectors especially sensitive, not simply because they face two risks, but because they occupy an important place in the park's overall protection system.

Taken together, these mechanisms show that wildfire and poaching interact through real management conditions rather than only through abstract theory. They affect the same resources, the same seasonal periods, and in some cases the same strategic sectors. This is why an integrated model is useful: it helps show not only where each threat is present, but also where their interaction may create greater overall risk for the park.

6.3. Integrated Sector Risk

After building separate fire-risk and poaching-risk models, the natural next step is to introduce a single integrated indicator for each sector. For the purposes of this study, it is important that this indicator remain sufficiently simple to interpret while still reflecting the key elements of the real conservation situation. A convenient form is the following index:

$$R_i^{int} = (\alpha R_i^{fire} + \beta R_i^{poac} + \gamma R_i^{fire} R_i^{poach}) \cdot \frac{V_i}{1 + C_i}.$$

Here, R_i^{fire} is the sectoral fire risk, R_i^{po} is the sectoral poaching risk, V_i is the vulnerability of the sector, and C_i is the response capacity, including accessibility, arrival speed, observation density, and the park's overall ability to respond rapidly to an incident. The coefficients α and β specify the relative importance of the two threat types, while the coefficient γ captures their interaction effect. If $\gamma > 0$, the simultaneous presence of two high risks raises the total threat faster than the simple sum of the individual components.

6.4. A Unified Threat Map as the Basis for Managerial Decisions

The main result of integrating the two risk models is a unified threat map in which each sector receives one final risk score. This is important because it turns the model from a set of separate formulas into a tool that can support practical decisions. Instead of looking at fire risk and poaching risk separately, park management can compare sectors within one common framework. The map shows not only where risk is high, but also why it is high. In some sectors, the main problem may be wildfire. In others, poaching may be more important. In some places, both threats may be serious at the same time, especially when vulnerability is high and response capacity is weak.

This kind of map also helps move away from uniform patrolling as the main protection principle. If risk is uneven across the park, then resources should not be spread only according to geography or simple territorial balance. Instead, they should be directed more strongly toward sectors where the expected benefit of protection is higher. In practical terms, this means giving more attention to the

areas where staff, drones, mobile teams, and equipment are most likely to prevent serious damage. In this way, the unified map supports a more predictive and targeted form of management rather than a purely reactive one.

The unified threat map is also important because it connects the analytical part of the study with the next stage of the model. Once each sector has an integrated risk score, it becomes possible to think more clearly about where to place the response base, how to reduce response time, and how to improve coverage of the most dangerous areas. In other words, optimization is no longer just a general logistics problem. It becomes a direct continuation of the spatial risk analysis.

For our study, this is one of the main advantages of the integrated approach. A unified map makes it easier to compare sectors, identify priorities, and link risk assessment to real protection decisions. Because of this, it serves as the bridge between understanding the park's threats and deciding how limited resources should actually be used.

7. OPTIMIZING BASE PLACEMENT AND RESOURCE ALLOCATION

7.1. Problem Formulation

After constructing the integrated threat map, the next task is no longer to provide additional description of fires and poaching, but to choose the best response strategy under severely limited resources. It is at this stage that the mathematical model acquires practical meaning: it must not merely show where risk is higher, but indicate how park forces should be positioned so as to reduce expected damage. Such a transition follows logically from the entire previous structure of the study: if risk differs by sector, then protection cannot remain the same across the whole territory.

For Etosha National Park, uniform allocation of forces is not an effective strategy for four reasons. First, the park's territory is very large, and therefore it is physically impossible to ensure equally dense and equally rapid presence in every sector. Second, integrated risk is distributed unevenly across the territory: northwestern sectors are more sensitive to fire, northern ones to poaching, and a number of buffer zones experience increased anthropogenic pressure. Third, sectors differ in arrival time and logistical accessibility, so even identical risk has different practical meaning if forces can reach one sector quickly but another only with significant delay. Fourth, the park is limited in staff numbers, equipment, patrol capacity, drones, and observation means, and therefore the key task is not full territorial coverage, but maximizing the effect of each resource employed.

Under this formulation, the problem can be expressed as the minimization of total expected damage:

$$\min J = \sum_i \frac{R_i \cdot \tau_i}{C_i}.$$

7.2. Optimizing the Location of the Rapid-Response Base

The choice of the rapid-response base location is naturally described as a spatial optimization problem of the facility-location type. The idea is to find such a deployment point L from which the weighted average delay in reaching the most dangerous sectors will be minimized. Dangerous sectors are not treated equally: the higher the sector risk, the greater its weight in the objective function.

For this study, it is convenient to use the following function:

$$\min Z(L) = \omega_f \sum_i R_i^{fire} d(L, i) + \omega_p \sum_j R_j^{poac} d(L, j) + C_{log}(L).$$

Here, L denotes the base location; $d(L, i)$ is the distance or, in a more practical interpretation, travel time from the base to the sector; R_i^{fire} and R_j^{poach} act as importance weights reflecting fire and poaching risk; and $C_{log}(L)$ is the logistical cost of the location itself, that is, its suitability in terms of access, supply, route stability, and the feasibility of establishing a multifunctional base. This formulation shows that the base should be chosen not according to proximity to one problem alone, but as a compromise point that reduces total response delay across several critical directions at once.

Within the model under consideration, such a point is the Adamax Pan area. Its advantage lies in functioning as a buffer position between two critical threat directions. On the one hand, this zone makes it possible to reduce the deployment time of mobile firefighting units into the northwestern sectors, where high biomass, wind exposure, and difficult control are combined. On the other hand, Adamax Pan remains sufficiently close to the northern sectors, where vulnerability to poaching is higher and rapid interception is especially important. Thus, the choice of Adamax Pan is not an intuitive compromise, but the result of mathematical logic: this point minimizes weighted response delay across the set of the most dangerous directions and at the same time avoids excessive attachment of the base to only one threat.

7.3. Allocation of Limited Resources Across Sectors

After choosing the base point, a second task arises: how should limited resources be distributed across the park's sectors? The existence of a base alone does not yet guarantee an effective system, because it is necessary to determine which forces and means should be directed first of all to a given sector. For Etosha, this is especially important because protection depends not on nominal presence, but on the ability to detect a threat in time and to intercept or localize it quickly.

The model should distinguish at least four types of resources: ground patrols, mobile firefighting teams, drones or other aerial surveillance means, and early-detection assets, including fixed or semi-fixed observation points. Their allocation should not be uniform, because each resource type has maximum effect under different spatial conditions. Ground patrols are especially important for sectors with elevated poaching vulnerability and a real possibility of rapid physical interception. Mobile firefighting teams should be concentrated where the risk of ignition and spread is high and suppression time is critical. Drones are most useful in remote areas and corridors where rapid threat detection is needed despite low density of ground presence. Early-detection systems are most worthwhile in sectors where gaining even a few minutes can substantially reduce the scale of damage.

To formalize allocation, we may introduce the sector protection effectiveness index:

$$P_i = \frac{R_i \cdot V_i \cdot q_i}{\tau_i}.$$

Here, P_i is the sector priority for resource placement, R_i is integrated risk, V_i is sector vulnerability, q_i is the probability of successful interception or early suppression when a resource is present, and τ_i is arrival time. The meaning of the index is that priority is assigned not simply to the most dangerous sector, but to the one where the combination of high risk, high vulnerability, and a realistic possibility of successful intervention makes resource placement most effective. In other words, the optimization is oriented not toward symbolic presence, but toward maximizing the probability of actual damage prevention.

In practice, this implies the following allocation architecture. Sectors with maximum fire risk and high logistical remoteness should receive reinforcement in the form of mobile firefighting teams and early-detection assets. Northern sectors with high poaching risk should receive priority in ground patrols and drones. Combined sectors, where high vulnerability, difficulty of observation, and seasonal animal concentration intersect, require a mixed regime: patrol presence, aerial monitoring, and reduced readiness time for deployment. Thus, resources are distributed not geometrically, but in accordance with the function of expected utility for the protection system.

7.4. Dynamic Seasonal Reallocation of Personnel

Even the optimal initial allocation of resources cannot remain fixed throughout the year. This is because the structure of risks in Etosha changes seasonally: during the dry season, fire pressure rises sharply, while in periods of lower fire activity the relative importance of anti-poaching coverage increases. Consequently, a permanent staffing scheme in which roles are rigidly and permanently assigned turns out to be suboptimal.

Therefore, the model must provide for seasonally adaptive distribution of personnel across three blocks: firefighting, anti-poaching, and technical-logistical support. The firefighting block is responsible for mobile suppression teams, operational response, and interaction with early-detection assets. The anti-poaching block is oriented toward patrolling, observation, interception, and control of vulnerable directions. Technical-logistical support ensures communication, equipment maintenance, supply, drone coordination, and the stability of the base itself.

This logic can be expressed in simple form through a dryness index $K_{dry}(t)$:

$$S_{fire}(t) = S_0 + \alpha K_{dry}(t),$$

$$S_{poach}(t) = S_1 + \beta(1 - K_{dry}(t)).$$

Here, $S_{fire}(t)$ is the size of the firefighting block at time t , $S_{poach}(t)$ is the size of the anti-poaching block, and $K_{dry}(t)$ is the seasonal dryness coefficient, varying from lower values in the wet period to higher values in the dry season. The interpretation of the formulas is straightforward: the greater the dryness and, therefore, the fire danger, the larger the share of personnel directed into the firefighting function; when fire pressure decreases, part of the released resources can be redirected to strengthening anti-poaching coverage. This very kind of personnel elasticity is already built into the working model and is one of the key managerial decisions.

7.5. Practical Implication for the Park Protection System

Accordingly, protection effectiveness is determined not by the number of patrols in itself and not by the nominal amount of equipment, but by the system's ability to reach critical sectors in time and operate at those points where even a small delay can lead to disproportionately large damage. This is exactly why optimization of the base and resources serves as the principal bridge between the analytical risk map and the real protection system.

8. RESULTS, SCENARIO COMPARISON, AND SENSITIVITY ANALYSIS

8.1. Logic of Result Evaluation

After building the integrated risk model and the protection optimization framework, the next step is to evaluate whether this system is actually useful for management. A model may look internally

consistent, but that alone does not mean it improves real decisions. For this reason, we evaluate the results mainly through one practical question: does the proposed approach help the park use limited resources more effectively?

In our case, result evaluation is based on comparing different protection strategies, identifying which sectors become priorities, and testing whether the main conclusions remain stable when important parameters change. This makes the results section important not only for checking the model, but also for showing whether the model has practical value.

8.2. Comparison of the Baseline and Optimized Scenarios

The comparison of scenarios shows that the baseline protection model performs poorly in a park with such uneven risk distribution. Its main weakness is that it spreads limited resources too evenly across the territory, even though threat levels differ strongly from sector to sector. As a result, some moderate-risk areas still receive attention, while the most dangerous sectors—especially the northwestern fire-prone zones and the remote northern sectors vulnerable to poaching—remain less protected than they should be. In this situation, response time to the most critical areas remains too long.

The risk-oriented scenario improves this pattern. When resources are allocated according to the integrated threat map rather than simple territorial balance, the most sensitive sectors receive stronger coverage. This leads to faster response in areas where delay is especially costly, and it increases the chance of intervention before a fire spreads or a poaching group leaves the sector. The improvement is especially visible in the northwestern sectors for wildfire control and in remote northern sectors for anti-poaching response.

The strongest overall result comes from the **Smart Shield** scenario. This scenario combines three improvements at once: a strategically placed base in the Adamax Pan area, seasonal redistribution of personnel, and a hybrid monitoring system that improves early detection. Taken together, these elements reduce expected integrated risk, improve the chance of early fire suppression, strengthen timely interception of poaching threats, and shift the system from delayed response toward more preventive management.

8.3. Spatial Results and Priority Zones

One of the clearest outputs of the model is the identification of several priority spatial clusters. The unified threat map shows that Etosha should not be viewed as one field of equal danger. Different parts of the park require different kinds of intervention.

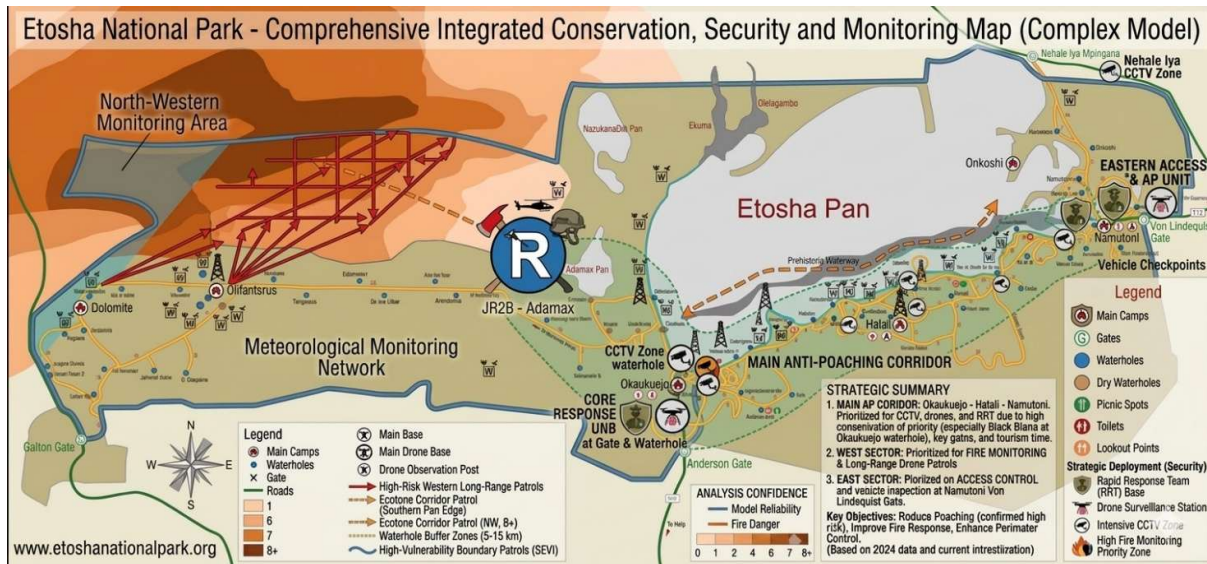
The first priority cluster is the **northwestern part of the park**, where wildfire risk is highest. In these sectors, the combination of dry biomass, wind exposure, and more difficult access makes early detection and fast local response especially important. These areas need stronger fire-response readiness, especially in the late dry season.

The second cluster is formed by **northern and other remote sectors**, where poaching vulnerability is higher. In these areas, the main issue is not only patrol presence itself, but the park's ability to detect intrusion quickly and respond before offenders can leave the area. For this reason, these sectors need stronger observation, mobile patrolling, and aerial monitoring.

The third cluster includes **waterholes and ecotone zones**. These places do not always have the highest probability of a specific event, but they often rank high in expected damage. Their ecological

value, concentration of animals, and sensitivity of habitat connections make them especially important. They therefore deserve elevated priority even when one separate threat is only moderate.

Finally, the **southern and eastern buffer zones** stand out because of stronger anthropogenic pressure. Their importance comes not only from internal park conditions, but also from their connection to more active surrounding land use, transport access, and higher probability of human-caused ignition or illegal entry. These sectors require stronger preventive control and better management of the park boundary.



8.4. Sensitivity Analysis of the Model

To check whether the main conclusions depend too strongly on a few chosen coefficients, we tested the model under reasonable changes in key parameters. This is important because some variables in the model are based on proxy indicators and expert weights rather than direct operational data.

The results show that changing the relative weight of fire risk increases the priority of northwestern sectors, while increasing the weight of poaching risk gives more importance to remote northern sectors and waterhole areas. However, these changes do not alter the overall logic of the solution. In all cases, uniform patrolling remains weaker than risk-based allocation.

The model is also sensitive to the seasonal dryness coefficient. As dryness rises, the fire component becomes stronger and seasonal redistribution of personnel becomes more important. This supports the idea that flexible staffing is not just an additional improvement, but one of the core conditions of an effective protection system.

Another important finding is that **response speed and detection quality** have especially large effects on overall performance. Slower arrival or weaker detection sharply reduces effectiveness, while better detection and faster response produce disproportionately strong gains. This means that investments aimed at reducing delay and improving early warning are especially valuable. Even under less favorable assumptions, the Smart Shield scenario still performs better than the baseline scenario.

Overall, the sensitivity analysis suggests that while the ranking of some middle-level sectors may shift, the central structure of the solution remains stable. Three conclusions stay consistent: risk-based

allocation is preferable to uniform coverage, the Adamax Pan area remains the strongest base option among those considered, and seasonal personnel redistribution is an important part of the strategy.

8.5. Interpretation of Results and Significance for Park Management

The main practical conclusion is that Etosha is likely to be protected more effectively through a system that is predictive, spatially differentiated, and seasonally adaptive. The model shows that the greatest benefit does not come from spreading resources “a little everywhere,” but from directing them in advance to the sectors where high risk, high vulnerability, and limited response capacity come together.

This matters for management because it changes the logic of protection itself. Instead of treating patrol coverage as an even territorial obligation, the park can use risk information to decide where early detection matters most, where rapid response is most valuable, and where limited personnel and equipment can prevent the largest damage. In this sense, the model supports a shift from mainly reactive protection toward more targeted and preventive management.

9. MODEL LIMITATIONS, TRANSFERABILITY, AND CONCLUSION

9.1. Model Limitations

The model we propose is not a full digital copy of Etosha National Park. It is a simplified analytical framework designed to compare sectors, identify spatial priorities, and help think about how limited resources can be used more effectively. Its purpose is not to predict every single fire or poaching incident exactly, but to turn a complex protection problem into a form that can support practical decisions.

This means that the model has several important limitations.

First, some of the variables are based on proxy indicators rather than direct field data. This was necessary because we did not have access to a complete internal dataset for the park. As a result, some factors in the model should be understood as reasonable approximations rather than exact measurements.

Second, not all parameters can be calibrated precisely without internal operational information. In particular, the model would become stronger if it could use real incident archives, detailed patrol routes, actual detection times, and real response-time data. Without this type of information, some coefficients and relationships remain partly theoretical and comparative rather than fully calibrated.

Third, the wildfire part of the model simplifies some environmental processes. It does not fully represent all local topographic effects, fine-scale wind behavior, or microclimatic variation across the park. These factors may influence how fires behave in reality, especially under changing weather conditions.

Fourth, the poaching model cannot completely capture the hidden and adaptive behavior of offenders. Illegal activity is difficult to observe directly, and poachers may change routes, timing, or methods in response to patrol patterns and enforcement pressure. Because of this, the poaching model should be seen as a structured estimate of relative sector risk rather than an exact behavioral prediction.

Fifth, logistical accessibility and seasonality are represented in an aggregated way. In our model, sectors and seasonal phases are used to describe broader patterns, but the model does not include a

fully detailed road network or day-to-day changes in conditions. This reduces complexity and makes comparison easier, but it also means that some operational detail is left out.

Even with these limitations, we think the model remains useful. Its value lies not in reproducing the park perfectly, but in helping compare sectors, understand major patterns of risk, and think more clearly about where protection effort may have the greatest effect.

9.2. Transferability of the Model to Other Parks

Although this model was developed for Etosha, its general structure can also be applied to other protected areas. The main idea remains the same: different threats can be integrated into one risk framework, and protection decisions can be based not only on threat probability, but also on vulnerability and response capacity. In this sense, the model offers a broader framework for predictive conservation rather than a solution limited only to one park.

Several elements of the model are especially transferable. These include combining multiple threats into a single risk map, treating risk as the interaction of threat, vulnerability, and response difficulty, choosing a base location in a strategic way, and using seasonal reallocation of resources instead of fixed year-round deployment. These ideas can be useful in many other protected areas where management faces uneven risk and limited operational capacity.

At the same time, transferability does not mean that the same variables and weights can be used everywhere without change. Each park has its own ecological structure, terrain, climate, access conditions, and surrounding social context. Because of this, the model must be recalibrated for each new case. For Etosha, the most important factors include grassy biomass, waterholes, seasonal wildlife concentration, remoteness of sectors, and outside socio-economic pressure. In another protected area, the key drivers may be very different.

This difference becomes clear in the comparison with the Grampians example mentioned in the source material. In that case, the risk system is shaped by mountainous terrain and forested eucalyptus ecosystems rather than by a relatively open savanna landscape. Instead of grass biomass, more attention must be given to forest litter dryness and the flammability of canopy oils. Instead of mostly flat spatial logic, slope, rocky relief, and topographically accelerated fire spread become more important. Social and infrastructure priorities also change: rather than borderland pressure and anti-poaching patrol logic, management may need to focus more on tourist movement, roads, campsites, evacuation routes, and public warning systems.

Because of this, the resource system must also change from park to park. In steep or mountainous terrain, ordinary ground response may become less effective, while aerial firefighting, thermal drones, automated lightning detection, and weather monitoring networks may become more important. This shows that the transferable part of the model is its logic and structure, not the exact parameter values.

So, the model is transferable in architecture, but not in raw form. What can be moved from one park to another is the approach: identify the main threats, measure vulnerability and response difficulty, compare sectors, and allocate resources according to combined priority. What must be adapted each time is the specific content of the model.

9.3. Conclusion

The main conclusion of this study is that Etosha National Park is likely to be better protected through a predictive, spatially differentiated, and seasonally adaptive system rather than through uniform patrol coverage and mainly reactive response. This conclusion does not come from one observation

alone. It follows from the full structure of the model and from the way different parts of the analysis support each other.

Our study shows that wildfire and poaching in Etosha should be understood as part of one interconnected risk system. They are distributed unevenly across the park, they can reinforce one another, and they create the greatest management difficulty in sectors where high threat, high vulnerability, and weak response capacity come together. For this reason, limited resources should not be spread evenly across the territory. They should be directed first to the sectors where this intersection is strongest.

The integrated threat map makes this kind of prioritization possible. It helps compare sectors within one framework and links risk analysis to practical decisions about monitoring, response, and deployment. On this basis, the model also supports the idea that base placement and seasonal redistribution of personnel can improve protection more effectively than static and uniform coverage.

At the same time, we recognize that the model is simplified and cannot replace field expertise or operational knowledge inside the park. It should be understood as a decision-support framework rather than a perfect prediction system. Even so, it still provides a useful way to organize complex information and translate it into clearer spatial and managerial priorities.

In this sense, the final contribution of the study is practical as well as analytical. It shows how a large and complex protected area can be represented as a structured system of decisions. By doing this, it becomes easier to move from general concern about threats toward a more focused strategy for protection.

REFERENCES

Etosha National Park (n.d.). Poaching news and updates. Retrieved April 2026, from

<https://www.etoshanationalpark.org/news/tag/poaching>

The Namibian (n.d.). Rhino protection intensified after recent poaching in Etosha National Park. Retrieved April 2026, from

<https://namibian.org/blog/rhino-protection-intensified-after-recent-poaching-in-etosha-national-park>

Club of Mozambique (2023). Rhino poaching surges 93 percent in Namibia. Retrieved April 2026, from

<https://clubofmozambique.com/news/rhino-poaching-surges-93-percent-in-namibia/>

Save the Rhino International (n.d.). Ministry of Environment and Tourism programme. Retrieved April 2026, from

<https://www.savetherhino.org/programmes/ministry-of-environment-and-tourism/>

Arxiv (2022). Research paper on environmental modelling. Retrieved April 2026, from

<https://arxiv.org/abs/2202.07977>

BusinessDay (2023). Namibia rhino poaching surges mainly in Etosha National Park. Retrieved April 2026, from

<https://www.businessday.co.za/bd/world/africa/2023-01-30-namibia-rhino-poaching-surges-93-mainly-in-etosha-national-park/>

Ministry of Environment, Forestry and Tourism (2023). Poaching update report 2022–2023. Retrieved April 2026, from

<https://www.meft.gov.na/files/files/poaching%20update%202022%202023.pdf>

Commonwealth Opinion (2023). Namibia rhino poaching almost doubles in 2022. Retrieved April 2026, from

<https://commonwealth-opinion.blogs.sas.ac.uk/2023/namibia-rhino-poaching-almost-doubles-in-2022-with-etosha-hit-hard/>

Arise News (2023). Authorities investigate increase in rhino poaching. Retrieved April 2026, from

<https://www.arise.tv/namibian-authorities-investigate-rhino-poaching-increase-in-namibia/>

SpatialNode (2025). Etosha fire analysis (dNBR). Retrieved April 2026, from

<https://www.spatialnode.net/projects/etosha-2025-fire-dnbr-505a31>

Copernicus Programme (2026). Fire in the Etosha National Park, Namibia. Retrieved April 2026, from

<https://www.copernicus.eu/en/media/image-day-gallery/fire-etosha-national-park-namibia>

Green Belarus (2023). Record number of rhinos killed by poachers in Namibia. Retrieved April 2026, from

<https://greenbelarus.info/articles/31-01-2023/brakonery-v-namibii-v-proshlom-godu-ubili-rekordnoe-kolichestvo-nosorogov>

Rossaprimavera (n.d.). Reports on poaching and environmental issues. Retrieved April 2026, from

<https://rossaprimavera.ru/news/1bb0c58c>

<https://rossaprimavera.ru/news/36c34e9f>

The Economist Namibia (2025). Wildfire burns through Etosha National Park. Retrieved April 2026, from

<https://economist.com.na/56767/environment/etosha-national-park-fire-burns-through-2545-square-kilometres/>

University of Namibia Repository (n.d.). Environmental research materials. Retrieved April 2026, from

<https://repository.unam.edu.na/items/9463c5ce-3ab5-4c14-ac39-1d04e5f3b475>

Preprints.org (2026). Recent fire regimes in Etosha National Park. Retrieved April 2026, from

<https://www.preprints.org/manuscript/202601.1481>

Preprints.org (2025). Mathematical modelling formulas (4, 5). Retrieved April 2026, from

<https://www.preprints.org/manuscript/202511.1925>

Weather and Climate (n.d.). Climate data for Etosha National Park. Retrieved April 2026, from

<https://weather-and-climate.com/average-monthly-min-max-Temperature,Etosha+National+Park-na,Namibia>

African Safaris (n.d.). Best time to travel to Namibia. Retrieved April 2026, from <https://www.africansafaris.co.nz/blog/when-is-a-good-time-to-travel-to-namibia/>

SafariBookings (n.d.). Etosha climate overview. Retrieved April 2026, from <https://www.safaribookings.com/etosha/climate>

Facebook (n.d.). Satellite map of wildfire impact in Etosha National Park. Retrieved April 2026, from <https://www.facebook.com/photo.php?fbid=1466655178292695>

Namibia Wildlife Resorts (n.d.). Etosha National Park overview. Retrieved April 2026, from <https://www.nwr.com.na/etosha-national-park/>

Reuters (2024). Namibia investigates surge in rhino poaching. Retrieved April 2026, from <https://www.reuters.com/world/africa/namibia-investigates-surge-rhino-poaching-etosha-park-2024-04-02/>

Reuters (2025). Wildfires ravage Namibia's flagship national park. Retrieved April 2026, from <https://www.reuters.com/business/environment/wildfires-ravage-third-namibias-flagship-national-park-2025-09-29/>

Associated Press (n.d.). Environmental and wildlife reports. Retrieved April 2026, from <https://apnews.com/>

BBC News (n.d.). Poaching in Africa overview. Retrieved April 2026, from <https://www.bbc.com/news>

The Namibian (n.d.). Local reports on poaching incidents. Retrieved April 2026, from <https://namibian.com.na/>

REPORT ON THE USE OF AI

During the preparation of this work, the team used several artificial intelligence tools as supporting instruments for searching materials, summarizing background information, improving clarity of wording, and preparing visual elements. AI tools were used to assist the working process, but they did not replace the team's own reasoning, model design, or final interpretation of results.

ChatGPT (OpenAI)

Used for improving the clarity and structure of the text, refining wording, and helping with editing and language consistency.

Perplexity AI

Used for source search, quick fact-checking, and clarification of reference information.

Google Gemini

Used for brainstorming, alternative wording, and general idea exploration during early drafting.

NotebookLM

Used for summarizing background documents and extracting key points from longer materials.

Gemini Nano Banana 2

Used for combining map layers, preparing schematic visual materials, and improving the presentation of spatial analysis.

Overall, AI tools were used for:

- searching and checking background sources;
- summarizing selected materials;
- improving wording, grammar, and text clarity;
- translating selected fragments;
- formatting figures, maps, and document layout;
- supporting the visual presentation of results.

At the same time, the team independently chose the research problem, selected the main variables and assumptions, built the model structure, compared scenarios, interpreted the results, and wrote the final conclusions.

GRAPHS AND MAPS

