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B		2302094

Mitigating Human-Wildlife Conflict in Maasai Mara: A Model-Based Policy Framework

Summary

To address the issue of human-wildlife conflict (HWC) in Kenya's wildlife preserve Maasai Mara, we carry out several policies and strategies based on 2 major models. We design management strategies that are stable and effective in various ecosystems in the long term through careful calculations and evaluations.

The following are the major strategies and policies that we have developed: **build electric fences** around the village to restrict animal entrance and limit the expansion of agricultural land, **finance residents** on a regular basis to make up for loss of potential farm land, **arrange the layout** of the preserve by restricting tourism areas and the distribution of roads. Lastly, arrange **patrol teams** and impose **tougher penalties** on poachers.

The first two policies are evaluated using Model I, which considers an independent system consisting of a human settlement and surrounding wild land. Building a electric fence around the settlement reduces the damage made by wildlife on agriculture, thus increasing the income made by a certain area of land. As a result, humans will expand less, which provides more habitat for wildlife and reduces their threat. To evaluate the feasibility of the policy, we use **cellular automata** (CA) to simulate the interactions between humans and wildlife, and then we use analytic hierarchy process (AHP) to quantify the damage inflicted on wildlife. Then we use **analytic hierarchy process** (AHP) to quantize the damage made to wildlife. Finally we draw the conclusion that building fences will greatly decrease the damage made to animals with agriculture income stable.

The last two policies are based on the results of Model II, We constructed the EPT model, which consists of three sub-models: the economic effects sub-model, the partial life-cycle sub-model, and the transfer and movement sub-model. Six different strategies to allocate the land of the preserve are proposed by changing the layout of roads or the areas of wild areas, tourist and road areas respectively. We feed the output of the EPT model into the TOPSIS evaluation algorithm to identify the optimal strategy for preserve management. Also we discover that even slight poaching will pose severe threat on wildlife. Thus, we suggest arranging patrol teams and toughening penalties to reduce poaching.

On top of that, we increase the number of iterations to observe the **long-term effects** of the above policies. Through analysis, we conclude that the fence policy is more beneficial to the development of both animals and residents in the long run. Similarly, for Model II, choosing the optimal plan through TOPSIS can keep the population of various wildlife species stable or slightly increasing while maintaining considerable tourism income. Therefore, our policies can maintain long-term stability and human-nature balance.

To further verify the **universality** of our policies, we apply our models to other ecosystems of different types. To implement precise prediction and analysis for the preserve with unique properties, we adjust the parameters in our model accordingly and gain specific results.

Finally, mathematical expectations of wildlife population dynamics and human benefits gained by **sensitivity analysis** indicates our model is robust when the relative weight in AHP, or animal birth rate in Model II is slightly altered.

Keywords: Cellular automata TOPSIS AHP HWC Human-wildlife balance

Contents

1 Introduction

1.1 Background

Kenya, a well-known tourist destination in Africa, attracts visitors from all over the world who seek to experience the beauty of its wildlife. There are vast migrations of millions of wildebeest, thrill of chasing cheetahs and antelope, and warmth and cuteness of animal family members. It is the most primitive appearance of natural society. As the "animal kingdom" of Kenya, Maasai Mara is one of the most shining and well-known areas. The preserve covers an area of almost 1,510 square kilometers in Kenya. Additionally, there are many local people living in the reserve who depend on agriculture as a source of income.

Although tourism and agricultural activities bring considerable benefits to the area, they also have a negative impact on local wildlife. Therefore, in 2013, Kenya's parliament passed the Wildlife Conservation and Management Act to provide more equitable sharing of resources and allow alternative, community-based management efforts [9]. Human activities can affect animal reproduction, reducing their birth rate, and the expansion of human habitats can increase animal mortality, both leading to a decline in wildlife populations. Furthermore, animals that enter human settlements can damage crops and prey on domesticated animals, adversely affecting residents. However, blindly banning farming and tourism to protect wildlife would result in unbearable economic losses for local residents. Therefore, a balance must be struck between protecting wildlife and ensuring people's income.

In this essay, we first develop a village model using cellular automata (CA) simulation. We then select the best strategies for tourism area management and road distribution based on our EPT model and the evaluation algorithm TOPSIS. Next, we test the models in the long term to confirm the reliability and efficiency of our strategies and policies. Finally, we attempt to apply our policy to other nature reserves to verify its effectiveness and universality.

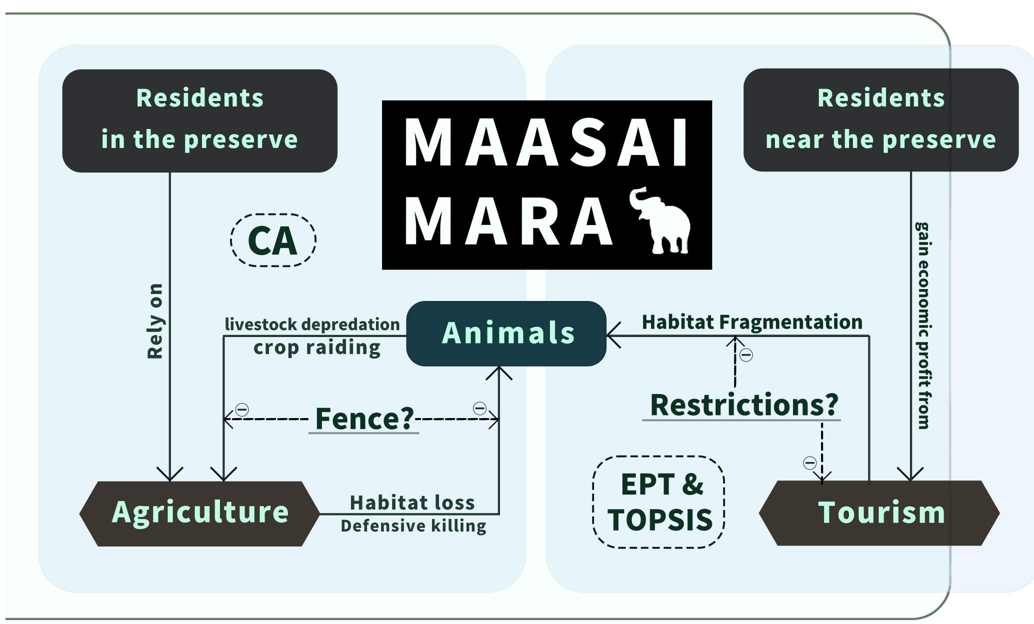


Figure 1: Relationship between different groups and our model

1.2 Restatement of the Problem

Focusing on one large game preserve, the Maasai Mara, our task is to determine alternate ways to manage the resources within and outside the current boundaries of the park. Specifically, we should

- Consider policies and management strategies for different areas within the current preserve that will protect wildlife and other natural resources while also balancing the interests of the people who live in the area.
- Develop and describe a methodology to determine which policies and management strategies will result in the best outcomes. Discuss how to rank and include descriptions and analyses of the models used to predict the interactions between animals and people, as well as the resulting economic impacts in the area within and around the preserve.
- Given the proposed plan, provide predictions about the long-term trends that will result from our recommendations. Analyze and provide estimates of the certainties and impacts of the possible long-term outcomes. Also, describe how the approach could be applied to other wildlife management areas
- Provide our two-page non-technical report for the Kenyan Tourism and Wildlife Committee discussing our proposed plan and its value for the preserve.

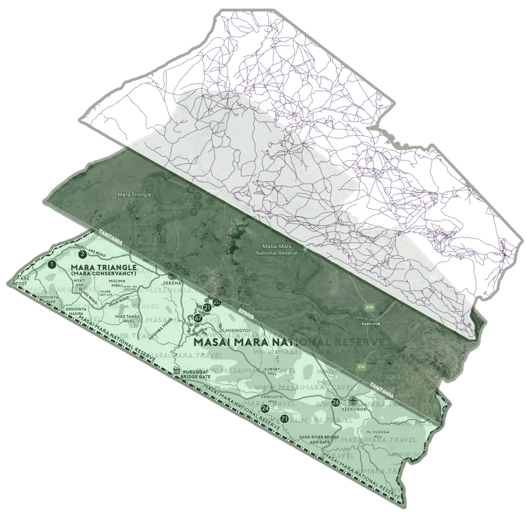


Figure 2: Map of Maasai Mara with regional road network and facilities [11][17]

2 Assumption and Justification

- **The scope of our analysis is limited to Elephants, Lions, Buffalo, Hippos, and Rhinos,** as these are considered the most significant animals in the Kenyan wildlife reserve and are included on the "Big Five Animal List." Although these species are of high ecological and cultural importance, they can also cause economic harm to nearby human communities, for example, by preying on livestock or destroying crops. Additionally, we assume that the proportion of these animal species in the reserve is representative of that across the entire country. We acknowledge that there may be other species that play important ecological roles, but we focus on these five for practical reasons. Finally, we assume that the proportion of these animal species in the reserve is representative of that in the entire country.

- **Animals will distribute randomly in the whole reserve.** In order to streamline the model, we assume that the animal population is initially distributed randomly throughout the reserve, without taking into account the influence of human residents and roads. We further simplify the model by assuming that animals move independently and without considering group behaviors such as foraging.
- **Neglect the interactions among animals.** To simplify the model, we don't take into account the conflicts between different species and the social habits of the same species like living in groups or living along the river. Also, we neglect the individual differences between animals such as size and age.
- **The natural growth rate of each animal is constant and dependent only on the animal species**. In a short run, we can approximately consider the natural growth rate of each certain kind of animal to be a constant. As there are complex biological relationships among animals including intraspecific struggle and interspecific competition, natural growth rate is used uniformly to describe the growth law of the number of each animal under the combined influence of species relationship and species characteristics. It is important to note that this constant is not correlated with the effects generated by human activities.
- **The money from outside donations was distributed equally to each residents, with donations coming in regularly.** Since the development of environmental protection policies will inevitably reduce residents' income, and every time these policies are made, there will be external donations and subsidies, so we assume that these money will come in at regular intervals and be evenly distributed to each resident.

3 Notation

Symbol	Definition
$\mathcal{R}, \mathcal{T}, \mathcal{H}$	Landscapes: road, tourist area and habitat, respectively
$\mathbb{S}_{\mathcal{R}}, \mathbb{S}_{\mathcal{T}}, \mathbb{S}_{\mathcal{H}}$	Area of corresponding landscapes
$\boldsymbol{D_W}$	Wildlife damage indicator
$\boldsymbol{D_A}$	Agriculture damage indicator
$\mathbb{E}$	Economic benefit indicator
$\mathcal{J}, \mathcal{A}$	Juvenile state and adult state of animals, respectively
P	Matrix for describing animals' transfer proportion between two landscapes
W, U	Matrix for updating animals' landscape status and life status. respectively
V	Distance measurement of strategies ranked by TOPSIS

4 Model I: Village-centered Simulation

4.1 Policy I

- **Build electric fences around the village** to prevent animals from damaging crops and livestock.
- **Restrict the expansion of agricultural land** to protect the habitat of animals.
- **Give the local people a financial subsidy** to make up for the economic loss caused by banning them from expanding agricultural land.

4.2 Model Overview

In this model, we consider each village and a circular area around it separately. The village is represented as a square, and the circular area is the main range of human activities. When animals enter the village, they damage crops and livestock, leading to a decline in residents' income. Therefore, inhabitants have been expanding agricultural land within the range of activities to compensate for the resulting losses. Meanwhile, animals are negatively affected by the expansion of human habitat due to competition for living space and natural resources.

We have developed a program that uses cellular automata to simulate this process over the course of one year, with weekly updates. Our goal is to investigate the impact of building a fence to protect crops and livestock, and assess whether this policy can enable residents to maintain adequate income without expanding their agricultural land. Next, we will use the analytic hierarchy process to estimate and express the degree to which this policy reduces disturbance to animals.

4.3 Assumptions in this Model

- **After building electric fences, the village will not suffer any crops and livestock damage caused by animals.**
- **When animals come into the village area, they will be immediately killed. If animals are found in the newly expanded area, they will also be killed immediately.**
- **We only consider a square area and its inner circle as the area of human activity. Each simulation starts with the same composition of animals.**
- **Neglect all kinds of contingencies.** There are many kinds of unpredictable contingencies that greatly affect the number of animals, as well as the production and life of humans. To simplify the model, we neglect these contingencies, such as wars and plagues.

4.4 Cellular Automata (CA) Simulation

To simulate the situation of Human-Wildlife Conflict (HWC) with/without our policy, we divide the land into squares (with an edge length of 1km), which can either be wild land or farmland. Each square contains a certain number of each kind of animal. Animals in one square can randomly move to one of the adjacent squares, and the moving rate is determined by the animal species. Without fences and policies, locals might expand their farmland, and animals might enter the farmland and be killed by people who want to protect their crops. With our fence policy, people are forbidden from expanding their farmland, while animals will not enter fenced farmland. We will explain the process of farmland expansion as well as animal movement in detail.

To model the expansion of farmland, we use logistic regression (LR). LR is a machine learning regression technique that assesses the relationships between dependent variables (binary or continuous) and a set of independent variables [13].

By using logit transformation of the dependent variable, LR could be expressed by:

$$LogitY = \ln(\frac{\pi(x)}{1-\pi(x)}) = \alpha + \Sigma_{i=1}^{n}\beta_i x_i + \epsilon \tag{1}$$

$$\pi(x) = \frac{e^{\alpha+\Sigma_{i=1}^{n}\beta_i x_i}}{1+e^{\alpha+\Sigma_{i=1}^{n}\beta_i x_i}} \tag{2}$$

where for each specific x, $\pi(x)$ explains the interest of the expected outcome, i.e. farmland expansion.

To calculate $\pi(x)$, we estimate the parameter α and β_i by maximum likelihood method[6]. As we only need to care about discrete x values, i.e. $x \in \{0, 1, 2, 3, 4\}$, the calculated results of farmland expansion possibility are listed below, where the adjacent cell refers to the cells that share an edge.

Adjacent cell number x	0	1	2	3	4
Possibility π	0.002	0.230	0.513	0.829	0.913

According to the data [10] [5], we calculate the average population of animals, and generate our initial state of CA with respect to this result.

Table 1: Animal population in whole Maasai Mara and population per unit area

Animal	**buffalo**	**Hippopotamus**	**lion**	**elephant**	**rhinocero**
Population in Maasai Mara	9466	4170	900	2500	50
Population per square kilometer	6.27	2.76	0.60	1.66	0.03

As the distribution of animal populations is concentrated on the scale of $1km^2$, we adjusted the initial distribution of animals to be more concentrated. We chose three representative animals for visualization, and the results of the HWC simulation process are shown in Figure 3. The different shades of green represent the number of animals in each square, while the central brown area represents the farmland.

It is clear that when farmland expansion is not restricted, HWC results in severe habitat loss for animals and a high number of animal deaths as they rush into the farmland. These factors together contribute to the significant decline in animal populations. In contrast, when our fence policy is applied, the situation improves considerably, and the number of animal populations in the area can be maintained at a dynamic balance. Although sudden changes in the curve may occur due to a whole herd of animals entering or leaving the statistical range, the overall population remains relatively stable. A comparison of the two scenarios is presented in Figure 4, which demonstrates the effectiveness of our fence policy in maintaining animal populations.

4.5 Wildlife Damage

In order to measure the importance of different animals to the whole ecosystem, we need to use analytic hierarchy process (AHP) to determine the relative importance of each animal based on the number of animals in the reserve. Therefore, we have the following judgment matrix:

Importance	**Elephant**	**Lion**	**Buffalo**	**Hippo**	**Rhinoceros**
Elephant	1	1/3	5	2	1/5
Lion	3	1	7	5	1/3
Buffalo	1/5	1/7	1	1/2	1/9
Hippo	1/2	1/5	2	1	1/7
Rhinoceros	5	3	9	7	1

By looking at the value table of average random consistency index(RI), we can know that $RI = 1.12$. Then, we use the MATLAB to calculate the eigenvalue of maximum $l_{max} = 5.1549$. And we can

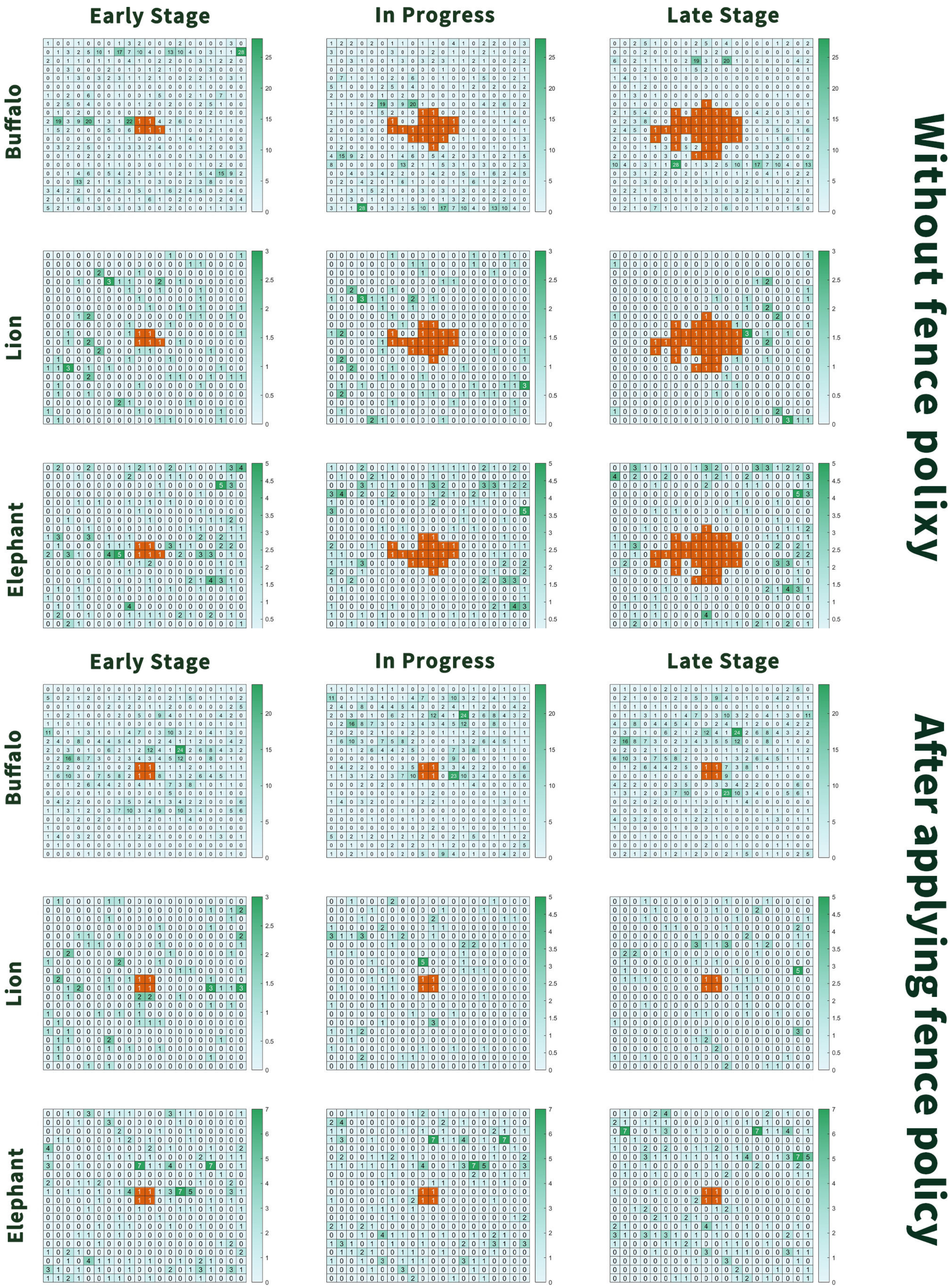


Figure 3: CA simulation without/with fence policy

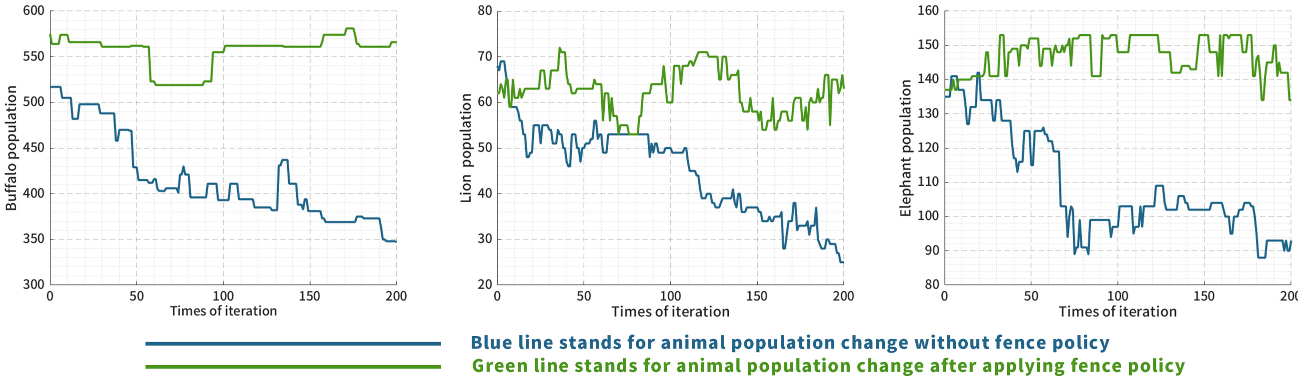


Figure 4: The change in number of three animals

calculate the coincidence indicator(CI):

$$\boldsymbol{CI} = \frac{(l_{max} - n)}{n - 1} = 0.0387 \tag{3}$$

Therefore, we can calculate the consistency ratio(CR):

$$\boldsymbol{CR} = \frac{CI}{RI} = 0.0346 \tag{4}$$

which is smaller than 0.1, so the result passes the consistency check. Finally, we use the eigenvalue method for weight to calculate the relative importance of each animal:

Animal	Relative Importance
Elephant	0.1196
Lion	0.2639
Buffalo	0.0362
Hippo	0.0623
Rhinoceros	0.5179

Now, we can introduce a new concept called wildlife damage which can reflect the extent of damage caused by human life:

$$\begin{aligned}\boldsymbol{D_W} =& N_E * RI_E + N_L * RI_L + N_B * RI_B + N_H * RI_H + N_R * RI_R \\ =& N_E * 0.1196 + N_L * 0.2639 + N_B * 0.0362 + N_H * 0.0623 + N_R * 0.5179\end{aligned} \tag{5}$$

where N_E, N_L, N_B, N_H, N_R means the number of elephants, lions, buffaloes, Hippos, Rhinoceros respectively.

When this value is bigger during the process, then it means the damage to the animal is becoming severe. We calculated $\boldsymbol{D_W}$ using the data gained by CA simulation and found that, without electric fences, $\boldsymbol{D_W} = 29.4754$, which is much higher than that with fences (0.1047). Thus, it's evident that the application of the electric fence can significantly reduce the threat that humans pose on animals. The policy is effective in protecting wildlife.

4.6 Agriculture Damage

In order to measure the damage caused by human-wildlife conflicts (HWC), we need to know how often HWC happen in Maasai Mara and how much damage each HWC will cause. According to a study focusing on HWC pattern duing 2005–2016 in Kenya [7], there are around 3400 incidences reported in Narok where Maasai Mara located in. Therefore, we can estimate the frequency of HWC in each village in this reserve:

$$\boldsymbol{f_A} = \frac{S_{Mara} \times 3400}{S_{Narok} \times 10 \times 52.15 \times n_v} = 0.01\,\text{times/week} \tag{6}$$

where n_v represents the number of villages. Here we assume it to be 55. According to another study focusing on the damage each HWC will cause [4], we can know that damage to agriculture:

$$\boldsymbol{D_A} = L_{Full} \times 0.50 + L_{Half} \times 0.45 + L_{No} \times 0.05 = 0.725\,\text{damage/time} \tag{7}$$

where L_{Full} means losing all agriculture resources, while L_{Half} and L_{No} means losing half and losing none respectively.

According to our simulation, we can know that after 100 iterations (weeks), we will have 19 units of farmlands. Therefore, the HWC will leave the village $19 \times (1 - 0.725) = 5.225$ units of farmlands after 100 weeks, which is a little larger than 5. However, considering the money given to the residents from outside donation, we can conclude that the income of residents won't become less. Therefore, building electric fences around the village is acceptable for residents.

4.7 Model I Conclusion

In this model, we can find that after limiting the area of farmlands, the animals are well protected comparing to the original expanding situation since killing animals in the expanding farmlands and the loss of habitat will both reduce the number of animals. Also, by building the electric fences around the farmlands, the residents will not suffer damage caused by HWC, and we can find that they will not get any less income for limiting the area of farmlands. Therefore, we can conclude that our policies - **build electric fences around the village and restrict the expansion of agricultural land** - are feasible enough.

5 Model II: EPT. Tourism VS Habitat Fragmentation

5.1 Policy II

- **Restrict the width of tourism areas around roads and restrict the plan of roads** to maximize tourism income without reducing wildlife populations.
- **Give part of the tourism income to the surrounding residents** to make up their loss due to our restrictions on tourism and road building.
- **Arrange patrol teams in the reserve regularly** to reduce poaching

5.2 Model Overview

The loss and fragmentation of wildlife habitat caused by tourist routes have posed a great threat to the survival of wild animals. However, banning tourism in order to protect wild animals has bad effects on local economy, as well as causing a great loss to many wildlife lovers. Therefore, we quantify the impact of tourism on animal population growth by building EPT model combining three sub-models: the E sub-model describing the economic effect of tourism within and around Maasai Mara, the P sub-model describing animal life cycles, and the T sub-model quantifying the impact of the movement of animals between different landscapes.

We plan the tourist routes of the nature reserve from two aspects: the width of the tourist areas on both sides of the road and the distribution of the road. We used TOPSIS evaluation model to rank different strategies, exploring under which tourism area width and road distribution the animal population can maintain a proper growth rate while the area can obtain considerable economic benefits at the same time. Finally we can find a solution to guarantee a health level of animal population and develop tourism as much as possible to benefits residents around the reserve.

5.3 Assumptions in this Model

- **The birth rate, mortality rate** of each species for both juveniles and adults remain constant during our simulation.
- **Economic benefits that Tourist area can obtain is proportional to the size of the area.**
- **The boundary length for the Tourist area is 2 times of the total length of the roads.**
- **Juveniles will become adults after one iteration. And after each iteration, all adults will have certain probability to have Juveniles.**

5.4 Model Building

To describe landscapes in Maasai Mara, we distinguish three main landscapes: road (further denoted as $\mathcal{R}$), tourist area ($\mathcal{T}$) and habitat area ($\mathcal{H}$). We use an implicit representation of landscapes to deal with the different behaviours of animals [14], but the information of three landscapes are previously calculated according to the map of Maasai Mara [17] and our six policies of different strictness. We assume that landscape can be described by its total area and perimeter [14] , regardless of its specific shape. We denote the area of three landscapes as $\mathbb{S}_\mathcal{R}$, $\mathbb{S}_\mathcal{T}$ and $\mathbb{S}_\mathcal{H}$.

5.4.1 Economic Effects Sub-model

The E sub-model is used to describe the economic effects brought by tourism development. We assume that the farther away the land is from the road, the less economic value it will produce, since there will be less tourists as the distance from road enlarges. Therefore, we assume that the tourist area will be fully developed after a planned period of time, the economic benefit of one land in the tourist area to the surrounding area should be inversely proportional to its distance from the road.In other words, the whole economic benefit should be:

$$\mathbb{E} \propto \iint_S (\int \frac{1}{x}\, dx) dS \Rightarrow \mathbb{E} = k \cdot \ln(\mathbb{S}_\mathcal{T}) \tag{8}$$

where k is a constant decided by local natural conditions, local economic development level and estimated development speed [12].

5.4.2 Partial Life-cycle Sub-model

The P sub-model is used to quantify the life cycle of animals. We divide the life cycle into two parts: juveniles (further denoted as $\mathcal{J}$) and adults ($\mathcal{A}$). Animals have different survival rates at different physiological stages. Since the young animals are fragile, they will be killed easily. Also, juveniles are infertile, while adult animals have a certain fertility rate. As figure 5 shows, for landscape i, $S_{i,\mathcal{J}}$ denotes the surviving rate of juveniles, $S_{i,\mathcal{A}}$ denotes the surviving rate of adults in landscape, and K_i denotes the fecundity of adults.

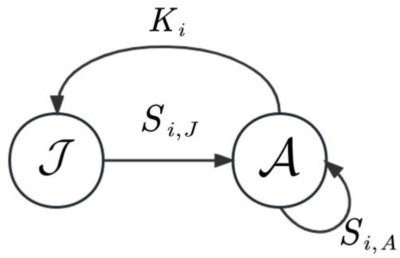


Figure 5: The partial life-cycle of animals, $i \in \{\mathcal{R}, \mathcal{T}, \mathcal{H}\}$[14]

The initial status and iterating parameters when calculating for elephant are measured from experimental data [16] and are given in the table below. Note that J_0 stands for the initial proportion of juveniles, $K_i(i \in \{\mathcal{R}, \mathcal{T}, \mathcal{H}\})$ for reproductive rate, and $S_{i,u}(i \in \{\mathcal{R}, \mathcal{T}, \mathcal{H}\}, u \in \{\mathcal{J}, \mathcal{A}\})$ for survival rate.

Table 2: Initial status and iterating parameters of elephant

Landscape i	K_i	$S_{i,\mathcal{J}}$	$S_{i,\mathcal{A}}$	J_0
$\mathcal{R}$	0.000	0.150	0.600	
$\mathcal{T}$	0.020	0.340	0.850	0.05
$\mathcal{H}$	0.078	0.700	0.950	

The table shows that elephants are hard to survive on the road, $\mathcal{R}$. This may be caused by intentional behaviours such as hunting, or by accidents such as vehicle crashing. Elephants have higher reproductive rate and survival rate in their habitat, $\mathcal{H}$, and can survive steadily in an ideal living habitat, i.e. ignoring the boundary and the needs of transferring.

5.4.3 Transfer and Movement Sub-model

The P sub-model is used to describe animals' transfer and movement. Let P_{ij} be the proportion for a certain kind of animal to transfer from landscape i to landscape j in each iteration. P_{ij} is determined by the moving ability and the different characteristics of different landscapes. Formally:

$$P_{ij} = q_{ij} r_{ij} \tag{9}$$

The parameters q_{ij} refers to the proportion of the animal in landscape i hitting the edge bordering landscape j. The parameters r_{ij} refers to the possibility that the animal decide to cross the boundary, entering landscape j instead of remaining in landscape i. $(i, j \in \{\mathcal{R}, \mathcal{T}, \mathcal{H}\})$.

In a sufficiently small period of time Δt, we distinguish a sufficiently narrow edge-region with width $v\Delta t$, where v is the rate proportional to the speed of the animal. The animals in the edge-region could either leave the boundary or stay in the area, and the proportion is 1/2 each.

Therefore, the area of edge-region $E = C_i v \Delta t$, where C_i is the perimeter of landscape i. For q_{ij} :

$$q_{ij} = \frac{1}{2} \cdot \frac{E}{S_i} = \frac{C_i v \Delta t}{2\mathbb{S}_i} \tag{10}$$

where $\mathbb{S}_i$ is the area of landscape i, $i \in \{\mathcal{R}, \mathcal{T}, \mathcal{H}\}$.

The parameters r_{ij} are measured from experiments and are given below (r_{ij} is the data in row i and column j of the table):

Landscapes	$\mathcal{R}$	$\mathcal{T}$	$\mathcal{H}$
$\mathcal{R}$	1.00	0.90	0.95
$\mathcal{T}$	0.10	1.00	0.80
$\mathcal{H}$	0.05	0.50	1.00

According to the table, elephants have tendency to remain in the same landscape, escape $\mathcal{R}$ and stay in their ideal habitat $\mathcal{H}$, which corresponds with the actual situation.

5.5 Model Calculating

The most decisive indicator for assessing trends in population development of animal over a certain period is the average population growth rate [8]. Put λ to represent this value, i.e. the ratio of final population to the initial populatio. Then our target is to calculate λ.

One significant factor that influences population growth rate is the age composition, which can be represented by the ratio of juvenile individuals to adult individuals [1]. The larger this ratio, the more the future population trend of our animal will grow. Set γ to be the ratio of juvenile individuals to adult individuals. During our iterating process, a rapidly changing γ indicates that the steady state have not been reached. Therefore, we keep iterating until γ remains stable between the last two iterations.

To calculate λ for a given initial state, we will update the initial state by transition matrix U and W to calculate the influence in animal population development [3].

We define the initial state matrix M_{init} to contain the initial population of juvenile and adult animals in each landscape. N_0 refers to the population of animal under natural distribution and behavior, as given in table 1. J_0 is the initial proportion of juveniles given in table 2.

$$\mathbb{S}_{total} = \mathbb{S}_{\mathcal{R}} + \mathbb{S}_{\mathcal{T}} + \mathbb{S}_{\mathcal{H}} \tag{11}$$

$$N_{\mathcal{J}} = J_0 \cdot N_0, \quad N_{\mathcal{A}} = (1 - J_0) \cdot N_0 \tag{12}$$

$$\gamma_0 = \frac{N_{\mathcal{J}}}{N_{\mathcal{A}}} = \frac{J_0}{1 - J_0} \cdot N_0 \tag{13}$$

$$M_{init} = \left[\begin{array}{cccccc} \frac{\mathbb{S}_{\mathcal{R}} N_{\mathcal{J}}}{S_{total}} & \frac{\mathbb{S}_{\mathcal{T}} N_{\mathcal{J}}}{S_{total}} & \frac{\mathbb{S}_{\mathcal{H}} N_{\mathcal{J}}}{S_{total}} & \frac{\mathbb{S}_{\mathcal{R}} N_{\mathcal{A}}}{S_{total}} & \frac{\mathbb{S}_{\mathcal{T}} N_{\mathcal{A}}}{S_{total}} & \frac{\mathbb{S}_{\mathcal{H}} N_{\mathcal{A}}}{S_{total}} \end{array} \right] \tag{14}$$

We define life-status-updating matrix U according to K_i, $S_{i,\mathcal{J}}$ and $S_{i,\mathcal{A}}$, for $i \in \{\mathcal{R}, \mathcal{T}, \mathcal{H}\}$:

$$U = \begin{bmatrix} 0 & 0 & 0 & S_{\mathcal{R},\mathcal{J}} & 0 & 0 \\ 0 & 0 & 0 & 0 & S_{\mathcal{T},\mathcal{J}} & 0 \\ 0 & 0 & 0 & 0 & 0 & S_{\mathcal{H},\mathcal{J}} \\ K_{\mathcal{R}} & 0 & 0 & S_{\mathcal{R},\mathcal{A}} & 0 & 0 \\ 0 & K_{\mathcal{T}} & 0 & 0 & S_{\mathcal{T},\mathcal{A}} & 0 \\ 0 & 0 & K_{\mathcal{H}} & 0 & 0 & S_{\mathcal{H},\mathcal{A}} \end{bmatrix} \tag{15}$$

(If expressed in a separate way, take $\mathcal{R}$ as example, we will multiply $\begin{bmatrix} M_{\mathcal{R},\mathcal{J}} & M_{\mathcal{R},\mathcal{A}} \end{bmatrix}$ with $\begin{bmatrix} 0 & S_{\mathcal{R},\mathcal{J}} \\ K_{\mathcal{R}} & S_{\mathcal{R},\mathcal{A}} \end{bmatrix}$ in each step.)

Then we set moving-and-transferring matrix W according to P. W is a 6×6 matrix to measure the influence of animals' moving and transferring between different landscapes.

$$P^* = \begin{bmatrix} 1 - P_{\mathcal{R}\mathcal{T}} - P_{\mathcal{R}\mathcal{H}} & P_{\mathcal{R}\mathcal{T}} & P_{\mathcal{R}\mathcal{H}} \\ P_{\mathcal{T}\mathcal{R}} & 1 - P_{\mathcal{T}\mathcal{R}} - P_{\mathcal{T}\mathcal{H}} & P_{\mathcal{T}\mathcal{H}} \\ P_{\mathcal{H}\mathcal{R}} & P_{\mathcal{H}\mathcal{T}} & 1 - P_{\mathcal{H}\mathcal{R}} - P_{\mathcal{H}\mathcal{T}} \end{bmatrix} \tag{16}$$

$$W = diag[P^*, P^*]; \tag{17}$$

After calculating transition matrix U and W, we can keep iterating the updating process during our study period. Finally we calculate λ , the ratio of final population to initial population, to quantify the trend of animal population development.

Algorithm 1: Calculate the trend of animal population development

Input: $J_0, N_0, \mathbb{S}_i (i \in \{\mathcal{R}, \mathcal{T}, \mathcal{H}\}), W, U$

Output: λ

Initialize M_{init} with J_0, N_0 and $\mathbb{S}_i (i \in \{\mathcal{R}, \mathcal{T}, \mathcal{H}\})$;

$\gamma \leftarrow \frac{J_0}{1-J_0} \cdot N_0$;

$\gamma^* \leftarrow \infty$;

$M_{cur} \leftarrow M_{init}$ **while** $|\gamma - \gamma^*| > eps$ **do**

  $M_{move} \leftarrow M_{cur} \times W$;

  $M_{survive} \leftarrow M_{move} \times U$;

  $M_{cur} \leftarrow M_{survive}$;

  $N^*_{\mathcal{J}} \leftarrow \Sigma_{i \in \{\mathcal{R},\mathcal{T},\mathcal{H}\}} M_{cur,i,\mathcal{J}}$ `// the population of remaining juvenile animals`;

  $N^*_{\mathcal{A}} \leftarrow \Sigma_{i \in \{\mathcal{R},\mathcal{T},\mathcal{H}\}} M_{cur,i,\mathcal{A}}$ `// the population of remaining adult animals`;

  $\gamma^* \leftarrow \gamma$;

  $\gamma \leftarrow \frac{N^*_{\mathcal{J}}}{N^*_{\mathcal{A}}}$;

end

$N^* \leftarrow N^*_{\mathcal{J}} + N^*_{\mathcal{A}}$;

$\lambda \leftarrow \frac{N^*}{N_0}$;

If $\lambda < 1$, it suggests that after a period of time, the animal population will tend to decline; if $\lambda = 1$, the animal population remains stable; if $\lambda > 1$, the animal population will tend to increase in the long term.

For different λ greater than 1 under different conditions, the meaning of their absolute value is not significant, as when the population grows too large, the environment of the habitat may be destroyed due to the survival needs of animals themselves, which is not well quantified by our model. However, the relative size of λ between different situations is still meaningful, as it can reflect the degree of suitability of the environment for the animal during the study period of time.

In this model, we expect to have $\lambda \geq 1$, but it is still acceptable if λ is slightly smaller than 1 as we can further consider the positive effect of human assistance to animals. However, from the perspective of long-term sustainable development, we expect to keep the animal population stable for a long time with less human assistance, so we did not give more consideration to this factor.

By running the program we gain the animal population with correlating iteration time and tourism area width as follow (see figure 6).

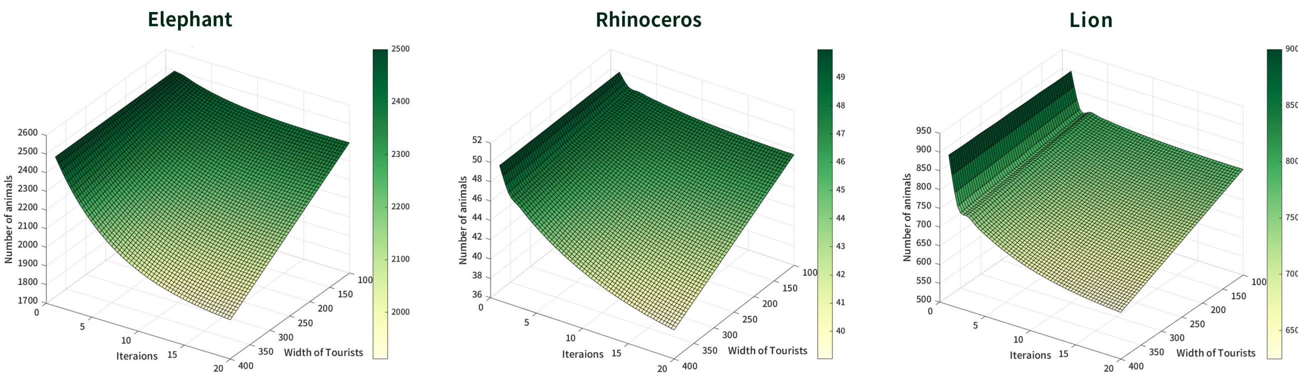


Figure 6: Animal population dynamics with iteration time and tourism area width

5.6 Plans Ranked and Compared by TOPSIS

We designed six plans considering reserve construction. In plan 1 to 4, the road distribution remains unchanged and the tourism area width varies from 1km to 3km, 5km and 10km. Plan 5 and 6 has the same tourism area width as plan 2 (3km) but with different road distributions.

We acquire the raw road network data from open data [11]. Then we extract the infomation of main road by using ArcGIS. To generate plan 5, we iteratively randomly select side nodes that are not on the main road and delete them, and then try to delete roads that are not connected to the outside. The final road network density is reduced to about 75% of the current state. To generate plan 6, we iteratively randomly select two nodes within 10km and connect them with a new road. If two newly-generated roads cross, we create intersection nodes on their cross (as the original representation in ArcGIS).

The schematics of six strategies are given in figure 7. Note that we adjusted the scale when drawing schematics so that the differences between strategies can be easily seen (while still following the original data when calculating).

By the method described in the previous section, we calculate the population growth of three animals, as well as the corresponding economic benefits for each strategy.

We have four values for each of the six strategies (λ for three animals, and $\mathbb{E}$). We form these values into a 6×4 matrix Z. All of our four indicators are "bigger-is-better" indicators, which means we don't need to adjust the direction of the data.

Then we standardize Z according to the formula [2]:

$$Z_{ij}^{*} = \frac{Z_{ij}}{\sqrt{\Sigma_{k=1}^{6} Z_{kj}^{2}}} \quad \text{for } i \in \{1,2,3,4\}, j \in \{1,2,...,6\} \tag{18}$$

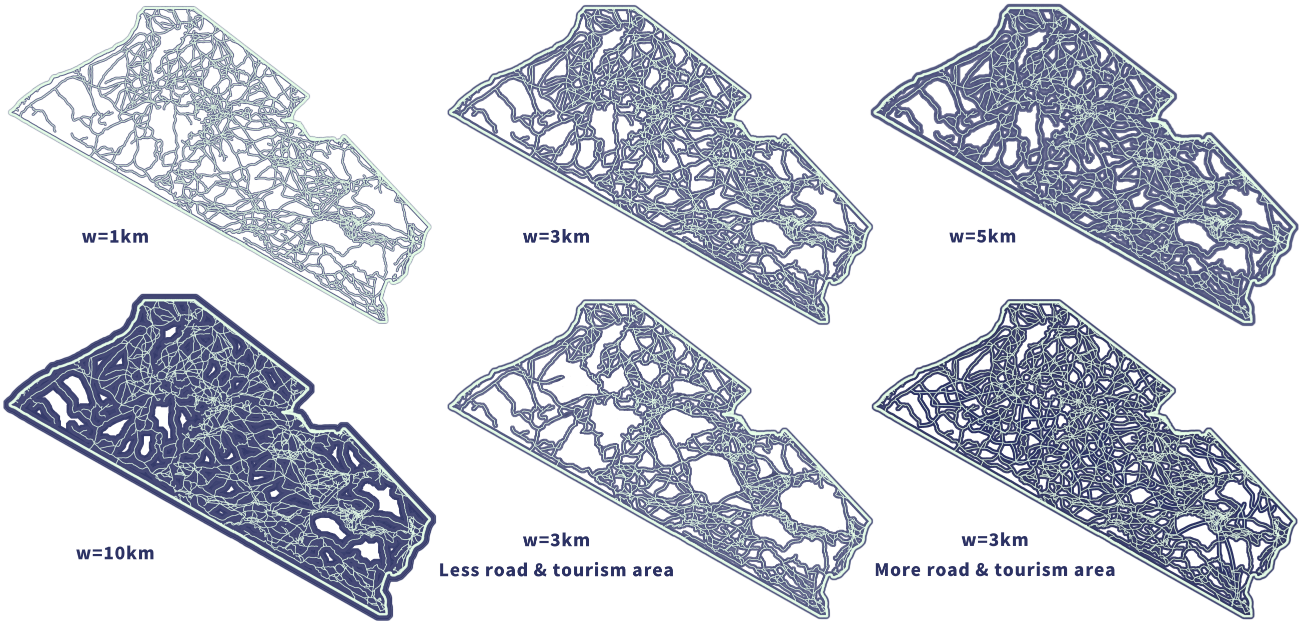


Figure 7: The schematics of six strategies

In order to balance the impact of the two aspects of human-and-wildlife conflict, we give the weight matrix:

$$\omega = \begin{bmatrix} \frac{1}{6} & \frac{1}{6} & \frac{1}{6} & \frac{1}{2} \end{bmatrix} \tag{19}$$

The weight matrix ensures that the total proportion of factors related to animal survival and the proportion of factors related to human economy are both $1/2$.

Determine the best alternative Y^+ and the worst alternative Y^- for each indicator i, $i \in \{1, 2, 3, 4\}$:

$$Y_i^+ = \max_{k \in \{1,2,\ldots,6\}} Z_{ki}^*, \quad Y_i^- = \min_{k \in \{1,2,\ldots,6\}} Z_{ki}^* \tag{20}$$

For each plan j, we calculate its distance measurement V_j to the worst condition, $j \in \{1, 2, ..., 6\}$:

$$T_j^+ = \sqrt{\Sigma_{k=1}^4 (Z_{jk}^* - Y_k^+)^2}, \quad T_j^- = \sqrt{\Sigma_{k=1}^4 (Z_{jk}^* - Y_k^-)^2} \tag{21}$$

$$V_j = \frac{T_j^-}{T_j^+ + T_j^-} \tag{22}$$

The result is shown in the table. The larger the distance measurement, the farther the plan is from the overall-worst alternative and the closer it is to the overall-best alternative, so the plan is better. We rank the six plans by sorting their corresponding similarity.

Plan j	1	2	3	4	5	6
Distance measurement V_j	0.5977	0.6112	0.4788	0.4023	0.5599	0.5968
Rank	2	1	5	6	4	3

According to the results, we decide that plan 2 ($3km$ width of tourism-area), which has the highest evaluation value, should be applied. By remaining current road network and limiting the tourist area, we can achieve a balance between the restrictions for wildlife protection and the economic benefits to surrounding residents.

5.7 Importance of Arranging Patrol Teams

Although poaching has been banned in this nature reserve, the killing of rare wild animals has continued in recent years. For example, according to the Mara Predator Conservation Programme, which is a conservation organization that operates in the Masai Mara ecosystem, six lions were killed by poachers in the reserve in 2020 [15]. In our model, if we reduce the survival rate by $6/900 = 0.067\%$ for each animal to simulate the poaching behavior, we found that the population of every animal was drastically reduced. The number of elephant will decline by 11.8%, rhinoceros will decline by 11.7%, lions will decline by 11.1% than banning the poaching behavior. Therefore, arranging patrol teams to more completely prevent poaching.

5.8 Model II Conclusion

In this EPT model, we take the living conditions of animal population and the economic benefits brought by tourism to the surrounding residents as the main research objects, and explore under which plan the interests of animals and humans can be best balanced. By simulating animal population changes over a period of time, we found that the larger the width of the tourist area or the longer the length of the road, the faster the animal population will decrease from the initial stage. As the number of iterations increases, the reduction rate gradually decreases and the animal population becomes stable. Finally, we comprehensively analyze the factors of animal protection and tourism economy through TOPSIS, and conclude that the optimal scheme was remaining the current state of road network and restricting the tourism area to within 3km from the road. By prohibiting tourists from going too deep into the habitat of animals, we expect to ensure the living space of animals and slow down the fragmentation of habitats, while mitigating the negative economic impacts for residents within and around the preserve.

6 Long-term Model

6.1 Effect of Policy I on a Longer Time Scale

With the application of Policy I, endless reclamation cultivation of new land would be prohibited. We can reduce labour and material wastage while preserving animal habitats and preventing killing much animals. Meanwhile, crop and livestock losses due to animal trampling are also minimized by electric fences. Notably, because during a longer period, the amount of land a person can manage is limited, in reality it's impossible for the land to expand to "Late Stage" extend in Figure 3. According to our estimation in Model I, the income from the initial land with fences is almost equal to that from the expanded land without fences. Therefore, we can conclude that in a long term building a fence guarantees adequate income. The policy is applicable in balancing wildlife protection and human well-being.

6.2 Effect of Policy II on a Longer Time Scale

To verify the efficiency of Policy II, we increase the times of iteration under conditions of plan 2 to gain the population dynamics in a long period (See Figure8). The population of elephant, rhinoceros and lion either remain stable or slowly increases, showing that animals' growth state stable and favorable.

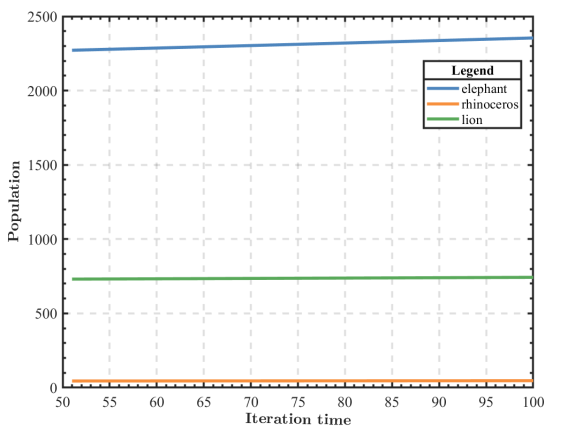


Figure 8: The population dynamics in long term

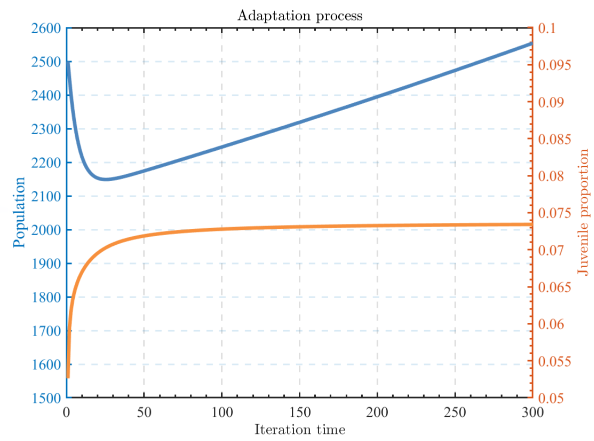


Figure 9: The adaptation process

Also, if we observe the data in detail, we can see that in Figure9, during original state, elephant population (blue line) and juvenile proportion (orange line) both go through a steep alteration. However, after about 30 times of iteration, population stops dropping and the juvenile proportion converges to 0.0734. As the original juvenile proportion is the value in a nature state, when we add human factors to the model, the population can't maintain steady growth. Thus, animals adapt to the change by adjusting juvenile proportion to regain a balance.

7 Feasibility of Approaches in other Preserve

We select two other preserves with different characteristics to verify the universal feasibility of the strategies.

- **Lake Michigan**
  Lake Michigan has a large population settlement and summer resort on its shore. Year-round ferry traffic operates between several ports. Also it is rich in trout and salmon, for which fishing industry thriving. However, the lake itself has not benefited from exploitation. On the contrary, it has been seriously polluted. Therefore, policies are needed to protect fish and other creatures in Lake Michigan.
- **Jilin Hunchun Siberian Tiger National Nature Reserve**
  The landscape of this reserve is mainly mountainous. The reserve contains various precious wildlife including siberian tiger, leopard, original musk deer and sika deer. There are also tourist attractions and farmland in the area.

7.1 CA in Different Terrain Conditions: Feasibility of Model I

We run the CA simulation under the landscape conditions of these two models and get the results in figure 10. The deep orange squares represents the farmland with fences, and the light orange squares represents the expanded area when no fence is applied. In the second figure, the blue area represents the lake where farmland will expand slower. In the third sub-figure of figure 10, the gray areas represent the mountains where farm land can't expand. As the figure shows, the expanded degree of Lake Michigan and Jilin Huichun is even smaller than that of Maasai Mara. Therefore, assuming three preserves have a same severity of human-wildlife conflicts, the fence policy is also efficient in Lake Michigan and Jilin

Hunchun.

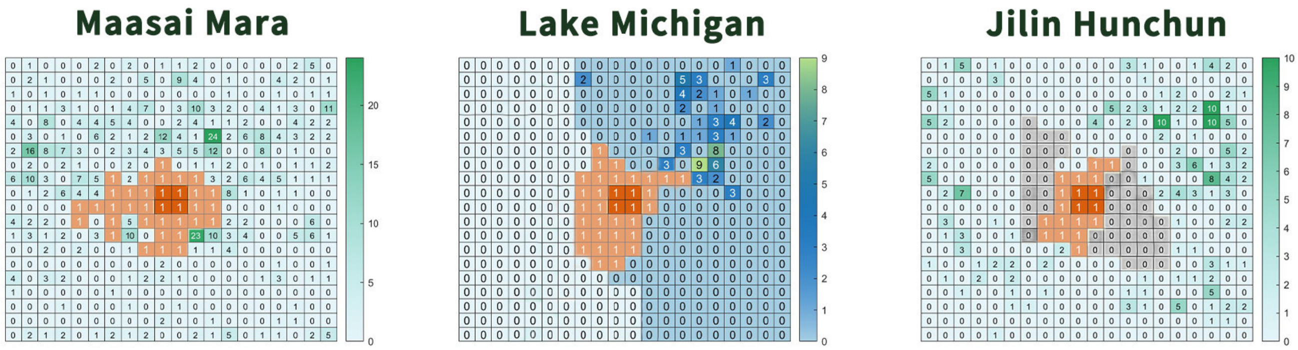


Figure 10: CA simulation for different landscapes

7.2 Updating for Different Species: Feasibility of Model II

Considering the difference in properties and animal species between Lake Michigan and Jilin Hunchun, we adjust the parameters in Model II accordingly. For Lake Mechigan, we select three major fish - Lake Trout, Chinook and Salmon, and change the probability matrix (r_{ij}). For Jinlin Hunchun, we select tiger, leopard and original musk deer. For both of the preserves, We adjust the animal number, mortality rate and birth rate considering the living conditions of selected animals. Then we run the program and gain the following results (see figure11).

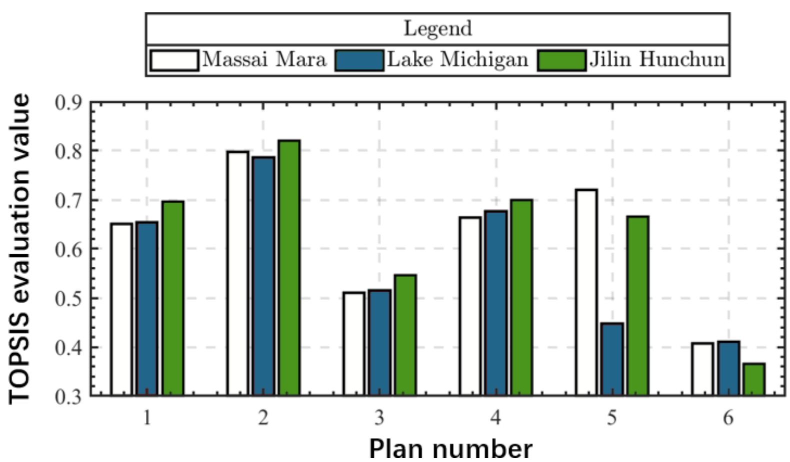


Figure 11: TOPSIS results of different preserves

Although there are differences between preserves, in all three conditions plan 2 stands out. Therefore, it is proved that, by adjusting parameters, our model can be applied to other wildlife management areas to indicate the optimal plan.

8 Sensitivity Analysis

8.1 Sensitivity of the judging matrix of AHP in Model I

In Model I, we use AHP to evaluate the importance of different animals to the whole ecosystem. As an evaluation model, however, the decision of AHP's judgment matrix has some subjective factors, and there might be some changes due to different target animal groups. Re-determining the value of the judgment matrix of AHP within an appropriate range will result in a shift of the evaluation results.

We re-determine the judgment matrix from a sensible but divergent point of view, adjusting the weight of some factors:

Importance	**Elephant**	**Lion**	**Buffalo**	**Hippo**	**Rhinoceros**
Elephant	1	1/5	4	3	1/6
Lion	5	1	9	5	1/3
Buffalo	1/4	1/9	1	1/2	1/9
Hippo	1/3	1/5	2	1	1/8
Rhinoceros	6	3	9	8	1

This new judgment matrix with the consistency ratio $\boldsymbol{CR} = 0.0586 < 0.10$, which is acceptable. With this new judgment matrix, we can calculate the new relative importance matrix for each animal. The result is $RI = \begin{bmatrix}0.1023 & 0.2927 & 0.0333 & 0.0526 & 0.5191\end{bmatrix}^{\dagger}$. Thereafter, we calculate wildlife damage $\boldsymbol{D_W} = 25.3521$, which is 13.99% lower than the original $\boldsymbol{D_W}$ calculated in model I. However, this value is still significantly higher than the damage value with electric fences (0.1047), so it will not influence our policy-making too much.

Therefore, the change in judgment matrix of AHP will result in the evaluation value of wildlife damage changing to some extent, but the difference is acceptable for policy comparison results. The stability and reliability of our model can be ensured.

8.2 Sensitivity of birth rate of animals in Model II

In our MATLAB code, we set some parameters using the data collected from Maasai Mara or other regions in south Africa, such as the birth, survival, mortality rate of three animals at different stages. However, this rate may vary by different regions and animal species, so we need to change this rate a little too prove the stability of our model. For example, we change the birth rate of the three animals by increasing or decreasing 3%, and we find that the final steady number of animals doesn't change much. Take elephant as example, the result, λ, just change by 2.8%, which proves that our model can be applied to different animals in different regions.

Birth Rate	**Birth Rate Change**	λ	λ **Change**
0.07565 (lower)	-3%	0.88082	-2.81%
0.078 (original)	0	0.90633	0
0.08034 (higher)	+3%	0.932254	+2.86%

9 Strengths and Weaknesses

9.1 Strengths

- The use of simulation models, particularly the cellular automata model, can provide a useful tool for evaluating the potential impact of policy interventions. It allows us to test the efficacy of our proposed policy in a controlled environment, without the need for costly and time-consuming field experiments.

- We developed a more comprehensive model (the EPT model) that takes into account of the impact of tourism on local wildlife populations, which is an increasingly important consideration in many other preserves. By doing so, we provide a more comprehensive policy proposal which that keep pace with the times.
- In Model I, we define clear and relevant measures of success for their policy interventions in terms of both ”Wildlife Damage” and ”Economic Damage”. This allows for a all-sided evaluation of the policy, taking into account both ecological and economic impacts.
- In Model II, our multiple sub-models within the EPT model provide a more nuanced and detailed analysis of the potential impacts of various policy interventions. Moreover, the detailed parameters of the plans can be fine-tuned continuously according to different situation. This allows for more informed and precise decision-making.

9.2 Weaknesses

- The study does not provide full details about how some specific parameters used in the simulation model were determined due to the limit of total page number. This might make it difficult for other researchers to replicate the study or for policymakers to evaluate the potential impact of the proposed policy in their own contexts.
- The study focuses on a specific area, which limits the generalizability of the findings to other regions. More research would be needed to evaluate the potential effectiveness of the proposed policy under different conditions.

10 Conclusions

In order to minimize the impact of human-wildlife conflicts on residents as well as animals, we propose policies which prioritizes the implementation of electric fences and prohibits land expansion. To assess the outcomes of our policy, we define two concepts of ”Wildlife Damage,” which captures the impact of biodiversity loss, and ”Economic Damage,” which quantifies the financial costs incurred by human-wildlife conflicts. Through the use of MATLAB software, we conduct simulations with and without the implementation of our policy, and find that the policy was effective in safeguarding local wildlife populations while simultaneously preserving local residents’ incomes. These results indicate that our proposed policy has practical potential for implementation.

In order to present a more comprehensive policy proposal that takes into account the impact of tourism on local wildlife populations, we develop a model named the EPT model. This model includes several sub-models, which evaluate the effects of various policy interventions. Firstly, the economic sub-model illustrates that the overall economic benefit of a given area is logarithmically proportional to its size. Next, the partial life-cycle sub-model is used to determine the impact of tourism on the life cycles of local animal populations. Lastly, the transfer and movement sub-model accounts for the impact of animal migration between different landscapes. Through TOPSIS evaluation process, we identify the most effective policy interventions for promoting sustainable tourism development that minimizes harm to local wildlife populations.

To evaluate the robustness of our model and its potential applications for long-term analysis and other wildlife preserves, we conduct additional simulations with increased iteration counts and parameter adjustments to reflect conditions specific to mountain and lake regions. By using MATLAB to analyze the results, we find that our model and policies remain feasible in alternative settings, which further attests to the model’s robustness and potential for generalization to other contexts.

Report on Policies to Reduce Human-Wildlife Conflict in Maasai Mara Wildlife Preserve

Dear Members of the Kenyan Tourism and Wildlife Committee,

I am pleased to present to you a report on our proposed policies to reduce human-wildlife conflicts in Kenya's Maasai Mara wildlife preserve. Our policies and strategies are based on two major models and have been designed to promote long-term stability and balance between humans and nature.

- **Policy 1**

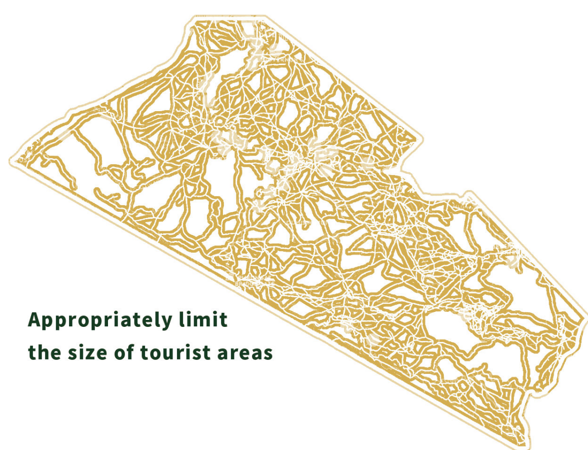
  The first set of policies aims to balance the relationship between residents and wildlife. We propose building electric fences around villages to restrict animal entrance and reduce damage to agricultural land. To make up for the loss of potential farmland, we also suggest financing residents on a regular basis.

- **Policy 2**

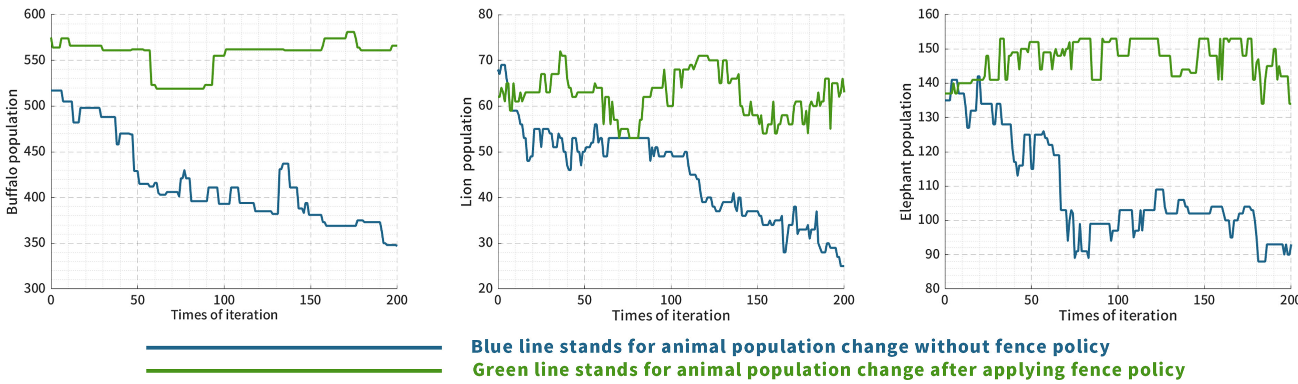
  Our second approach is to plan and arrange the layout of the preserve by restricting tourism areas and the distribution of roads. Under the optimal layout of roads and tourism areas, we maximize the negative economic impacts for residents within and around the preserve under the condition that adequate living space for animals is ensured and the fragmentation of habitats is under control.

- **Policy 3**

  The second set of policies is designed to reduce poaching. We propose arranging patrol teams and toughening penalties for poachers to reduce the threat of poaching on wildlife populations.



Our policies have been evaluated through two models. In Model I, we simulated the interactions between humans and wildlife using cellular automata and analytic hierarchy processes. Our results show that building fences will greatly decrease the damage made to animals, with agricultural income remaining stable. In Model II, we constructed an EPT model based on three sub-models and proposed six different strategies to allocate the land of the preserve. We found that even slight poaching poses a severe threat to wildlife and that arranging patrol teams and toughening penalties for poachers is critical to reducing this threat. By choosing the optimal plan through TOPSIS, we can keep the population of various wildlife species stable or slightly increasing while maintaining considerable tourism income.



We have also conducted long-term analyses to observe the effects of our policies over time. Our findings indicate that the fencing policy is more beneficial to the development of both animals and residents in the long run. Similarly, for Model II, choosing the optimal plan through TOPSIS can maintain long-term stability and balance between humans and nature.

We believe that our proposed policies and strategies will greatly reduce human-wildlife conflicts in Maasai Mara and promote long-term stability and balance between humans and nature. We look forward to your feedback and suggestions on our policies and their implementation.

Sincerely,
Team 2302094

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Appendix

Code for TOPSIS in Model II

```
function S=topsis(l,m,w)
% l(1,:) : Lambda_elephant
% l(2,:) : Lambda_rhinoceros
% l(3,:) : Lambda_lion
% m : economy impact
% w : weight, = [1/6, 1/6, 1/6, 1/2]
    Z=std([l(:,1) l(:,2) l(:,3) m]);% Standardization
    ZMax=max(Z);
    ZMin=min(Z);

    DMax=zeros(6,1); % Distance to ideally best solution
    for ii=1:6
        dist=ZMax-Z(ii,:);
        sqrDist=dist.^2;
        weightedSqrDist=sqrDist.*w;
        DMax(ii)=sqrt(sum(weightedSqrDist));
    end
    DMin=zeros(6,1); % Distance to ideally worst solution
    for ii=1:6
        dist=Z(ii,:)-ZMin;
        sqrDist=dist.^2;
        weightedSqrDist=sqrDist.*w;
        DMin(ii)=sqrt(sum(weightedSqrDist));
    end

    S=DMin./(DMax+DMin); % score
end

function Z=std(X)
    Z=X;
    S=sum(X.*X,1);
    for ii=1:4
        Z(:,ii)=Z(:,ii)./sqrt(S(ii));
    end
end
```

Core code for field expansion in Model I

```
function fieldList=fieldExpansion()
    % ... initialize
    dx=[1,0,-1,0];
    dy=[0,1,0,-1];
    for ii=1:mapSize
        for jj=1:mapSize
            cnt=0;
            for k=1:4
                ni=mod(ii+dx(k)+mapSize-1,mapSize)+1;
                nj=mod(jj+dy(k)+mapSize-1,mapSize)+1;
                if field(ni,nj)==1
                    cnt=cnt+1;
                end
            end
            expandRandNum=rand();
            if(expandRandNum<adjPos(cnt+1))
            % adjPos(cnt+1) is the possibility of filed expansion when
            % adjacent cell number equals cnt
```

```
                field(ii,jj)=1;
            end
        end
    end
    % ... storage
end
```

Core code for animal movement in Model I

```
function mapStat=animalMovement(mapStat,movingAbility,movePos)
    % ... initialize
    dx=[1,0,-1,0];
    dy=[0,1,0,-1];
    mapStat2=mapStat;
    for t2=1:movingAbility
        moveRandNum=rand();
        if moveRandNum>movePos % the possibility of moving
            continue;
        end
        splitRandNum=rand();
        if splitRandNum<splitPos % the possibility of group splitting
            d=randi([1,4]);
            for ii=1:mapSize
                for jj=1:mapSize
                    ni=mod(ii+dx(d)+mapSize-1,mapSize)+1;
                    nj=mod(jj+dy(d)+mapSize-1,mapSize)+1;
                    mapStat2(ni,nj)=mapStat2(ni,nj)+floor(mapStat(ii,jj)/2);
                    mapStat2(ii,jj)=mapStat2(ii,jj)-floor(mapStat(ii,jj)/2);
                end
            end
            d=randi([1,4]);
            for ii=1:mapSize
                for jj=1:mapSize
                    ni=mod(ii+dx(d)+mapSize-1,mapSize)+1;
                    nj=mod(jj+dy(d)+mapSize-1,mapSize)+1;
                    mapStat2(ni,nj)=mapStat2(ni,nj)+ceil(mapStat(ii,jj)/2);
                    mapStat2(ii,jj)=mapStat2(ii,jj)-ceil(mapStat(ii,jj)/2);
                end
            end
        else
            d=randi([1,4]);
            for ii=1:mapSize
                for jj=1:mapSize
                    ni=mod(ii+dx(d)+mapSize-1,mapSize)+1;
                    nj=mod(jj+dy(d)+mapSize-1,mapSize)+1;
                    mapStat2(ni,nj)=mapStat2(ni,nj)+mapStat(ii,jj);
                    mapStat2(ii,jj)=mapStat2(ii,jj)-mapStat(ii,jj);
                end
            end
        end
        mapStat=mapStat2;
    end
    for ii=1:mapSize
        for jj=1:mapSize
            if field(ii,jj)==1
                mapStat2(ii,jj)=0;
            end
        end
    end
    % ... storage
end
```