Problem Chosen	2023 MCM/ICM Summary Sheet	Team Control Number
B		**2316192**

Reshape the Crowning Glory of Maasai Mara

Summary

To call the sprawling savannahs of the Maasai Mara 'breath-taking' would be an understatement of some magnitude. However, recent changes in human society and land resource are jeopardizing the **human-land relationship balance**. This paper aims to propose optimal policies and strategies to achieve the best balance between economy and ecology.

Several models are established: Model I: Human-land Relationship Coupling Analysis; Model II: Multi-objective Strategy Selection Model; Model III: Long-term Trend Prediction Models. Before all the models are proposed, we have comprehensively reviewed the related research and refined our model based on their methodology and experience. Also, data preprocessing is considered to improve the data validity.

For Objective I, our paper translates the conflict between human interests and natural resources into optimizing the human-land **coupling degree**. Inspired by the reference, we utilize the **Rasterized Method** to divide the Big Maasai Mara area into various discrete grid with a width of 8.75km. Through coupling analysis, we classify the grids into four different categories. Finally, we suggest six specific policies and strategies for practical implementation.

For Objective II, we build a **four-layer** strategy evaluation model based on the AHP method to evaluate and rank the policies. The scoring results are shown in Table 4 and Table 5. Then, we present the multi-objective optimization model to quantify the economic and ecological impact. According to the grid data, an underdeveloped grid with a representative coupling degree is selected to test our proposed model. The optimal policies are illustrated in Table 6 and Figure 8.

For Objective III, referring to **Logistic Equation**, we define two predicting factors to project and assess the long-term ecological and economic situation. Then, a systematic Python program is designed for data simulation and trend prediction. Besides, we obtain and present **twelve 100-year prediction scenarios** correspond to twelve sets of parameter configurations to verify the effectiveness and rationality of our model. The results are shown in Figure 9.

Additionally, **sensitivity and robustness analysis** are conducted to help us fine-tune the parameter of our models and improve the performance of long-term prediction. Furthermore, we analyze the strengths and the possible improvements of our model.

Ultimately, for Objective IV, a two-page non-technical report for the Kenyan Tourism and Wildlife Committee will be beautifully and clearly presented at the end of our paper.

Keywords: Human-Land Relationship, Multi-objective Optimization, Trend Prediction Model, Maasai Mara Nation Reserve (MMNR)

CONTENTS

1 Introduction

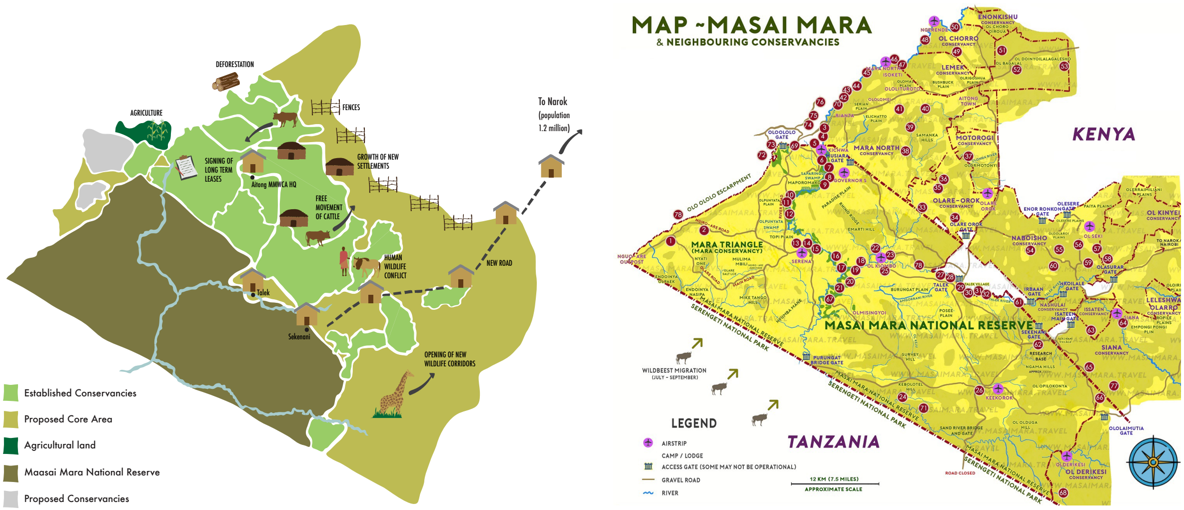
1.1 Problem Background

"If I have ever seen magic, it has been in Africa" said by a famous American author John Hemingway. As a world-renowned wildlife reserve, The Maasai Mara, it has brought crowning glory to Kenya and is a key generator of revenue for the entire Republic of Kenya[1].

However, this fragile environmental resource demands continuous care and attention to safeguard it from irreversible degradation. The loss of biodiversity in this ecosystem would have far-reaching implications, with the potential to significantly impact the region's environment, society, and economy, as well as reverberate globally[2]. To prevent these consequences, immediate steps must be taken to preserve and restore the Maasai Mara's biodiversity.

Therefore, preserving the Maasai Mara as a crucial environmental resource is a collective responsibility that transcends national borders, demanding international support. The survival of this ecosystem hinges on implementing an adaptive and responsive management system that effectively addresses the needs of both human communities and wildlife, while being mindful of Kenya's customs and traditions. Such a system must remain sensitive to changes within and around the Maasai Mara National Reserve (MMNR) and incorporate best practices in parks and protected area management to ensure the long-term viability of this global treasure[3, 4].

By adopting a collaborative, science-based approach, we can improve the economy, biodiversity and ecological integrity of the MMNR and promote sustainable development in the region, benefitting both present and future generations. Based on the background, the following Figure 1 illustrates the current ecological and economic distribution in the MMNR.



(a) Distribution of ecology (b) Distribution of economy

Figure 1 Ecological and economic distribution in the Maasai Mara

In this paper, we focus on the balance between ecological conservation and human interests, so as to minimize negative interactions between animals and humans in protected areas and finally achieve a balanced and sustainable human-land relationship. Furthermore, based on the proposed strategies, we will make a long-term ecological and economic projection for the MMNR, which will provide a scientific basis for the refined management of the nature reserve.

1.2 Restatement of the Problem

Maasai Mara is a world-renowned ecosystem with many complexities. Through in-depth analysis and research on the background of the problem, combined with the specific constraints given, the restate of the objectives can be expressed as follows:

- **Objective 1:** Analyze the specificities of different areas and formulate specific policies and management strategies tailored to the needs of each area.
- **Objective 2:** Develop a comprehensive analytical method to evaluate and rank different policies and strategies, considering the animal-human interactions and economic impacts.
- **Objective 3:** Project and assess the long-term ecological and economic situation in the Maasai Mara by utilizing the proposed optimal management strategies.
- **Objective 4:** Considering the results obtained above, provide a two-page non-technical report for the Kenya Tourism and Wildlife Commission.

1.3 Related Policies and Strategies

In recent years, policymakers and researchers have proposed various policies for managing nature reserves. One of the contributions of our paper is to present a detailed analysis of the four main strategies that have been in place over the past three decades, as shown in Figure 2.

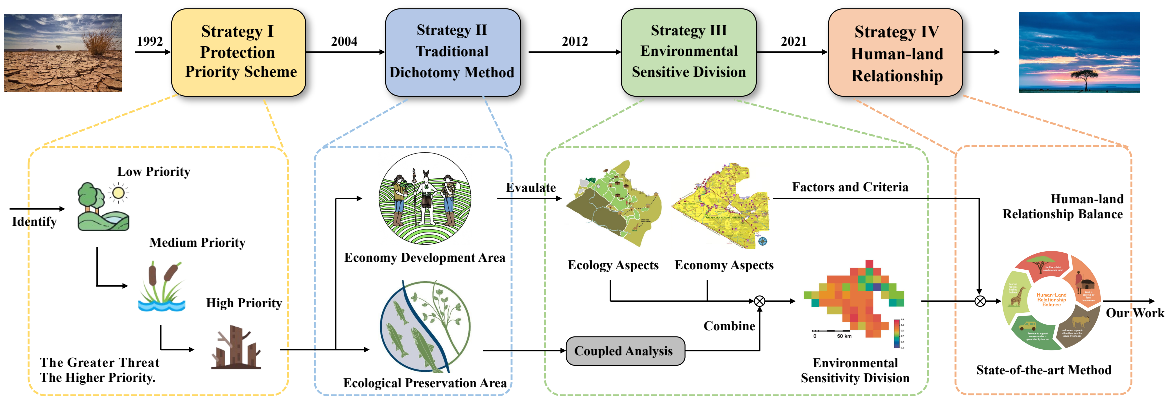


Figure 2 Flowchart of the development of management policies and Strategies

- **Strategy I:** Protection Priority Scheme (PPS, 1992)[5]; Conservation areas that face critical threats are assigned a higher priority than those that are not imperiled. **However**, related studies have shown that unjustified conservation would result in a significant loss of economic value and resource benefits of the nature reserves.

- **Strategy II:** Traditional Dichotomy Method (TDM, 2004)[6]; When nature reserves are clearly zoned, human activities are restricted and controlled to varying degrees according to the nature of the zoning. **However**, due to the complexity of the relationship between people and land in protected areas, the problem of conflicting conservation and use still exists in the practice of zoning management.

- **Strategy III:** Environmental Sensitivity Division (ESD, 2012)[7]; Based on the ecological survey of the nature reserve, different areas are assessed, classified and managed utilizing appropriate evaluation factors and criteria, such as environmental sensitivity and site suitability. **Furthermore**, this method is generally accepted and applied at present.

✧ **Strategy IV:** Human-land Relationship Analysis (HRA, 2021)[3, 8]; Based on the ESD method above, this approach further examines the activity intensity and human-land conflict from a spatially coordinated perspective. **Overall**, this state-of-the-art method can accurately reveal the human-land coupling state of the nature reserve and provides scientific basis for refined management of nature reserves.

1.4 Overview of Our Works

Based on the comprehensive review of the existing policy and strategy, our work mainly includes the following:

- **Model I: Human-land Relationship Coupling Analysis for Objective 1**
  - Coupling analysis model for human-land interaction analysis
  - Rasterized MMNR model for grid classification
- **Model II: Multi-objective Strategy Selection Model for Objective 2**
  - Strategy evaluation model for assessment and ranking
  - Multiple-objective optimization model for specific selection
- **Model III: Long-term Trend Prediction Model for Objective 3**
  - Trend prediction model for quantifying impact of policies and strategies
  - Prediction programs for computing corresponding results
- **A two-page Non-technical Report for Objective 4**

In summary, the whole modeling process can be shown in the following Figure 3.

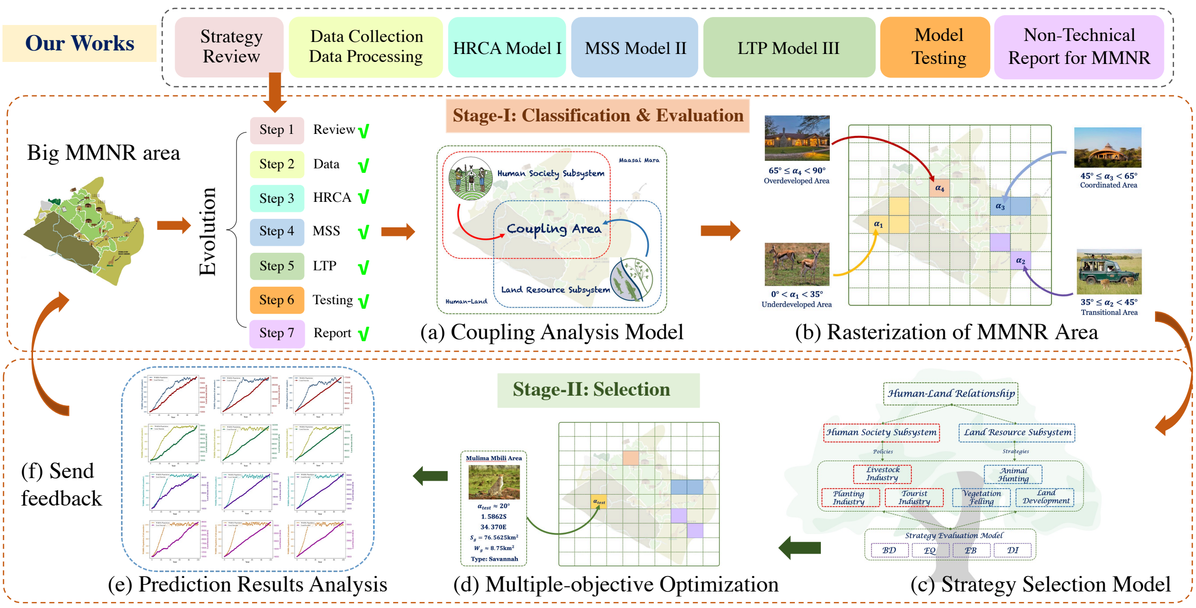


Figure 3 Overview of our works

2 Assumptions and Justifications

Considering the practical situation contains various complex factors, this paper makes reasonable assumptions to simplify the problems. And each hypothesis is closely followed by its corresponding justifications:

- **Assumption 1: Animals naturally increase at the same rate every year.**

⇒ **Justification:** The growth of animals is subject to the natural growth rate and is limited by the maximum capacity of the environment.

- **Assumption 2: The migration of animal populations obeys the laws of nature.**

⇒ **Justification:** Although the migration direction of some individuals may change with the change of local environment, the behavior of groups is subject to the natural laws of animal population migration according to the law of large numbers.

- **Assumption 3: No large-scale natural disasters.**

⇒ **Justification:** Large-scale natural disasters include earthquakes, tsunamis and so on. We assume that there will be no natural disasters within a certain period of time, so that animal and human populations will not change dramatically in a short period of time.

- **Assumption 4: The data collected can be considered reliable and reflect the state of the natural environment in the Masai Mara Nature Reserve.**

⇒ **Justification:** We obtained data from the official website of Masai Mara Nature Reserve and reference books with high accuracy.

3 Notations and Description

The key mathematical notations used in this paper are listed in the following Table 1.

Table 1 Notations used in our paper

Symbol	Description
α	Coupling degree of man-earth system
x_i	A strategy or policy is selected or rejected
V_L	Utility value of the land resource subsystem
V_H	Utility value of the human society subsystem
W	Total utility value of the whole Human-Land System
x	The number of animals
r	Intrinsic rate of natural increase
x_m	Maximum environmental capacity
E	The hunting rate per unit of time
$x_m\ (t)$	The number of animals at the t moment
A	Economic income of local residents

Note: Some variables are not listed here and will be described clearly in each section.

4 Model Preparation

4.1 Data Collection

Since this problem does not directly provide relevant data, finding available data became one of the most critical challenges. Through the pre-requirement analysis of the mathematical model, we needed to gather related information about the Maasai Mara Reserve, such as the geographical characteristic, the distribution of animals, and the income of the local population.

The official website of Maasai Mara National Reserve was queried, and various datasets in the aspect of ecology and economy were obtained. Furthermore, the main data resources including data websites and related references are shown in the following Table 2.

Table 2 Data source collation

Data Description	Data Resources	Types
Area Features	https://earthobservatory.nasa.gov/	Geography
Maasai Travel Data	https://www.maasaimara.com/	Economy
Animal Distribution	Found in the Ref.[1, 9]	Ecology
Population Density	https://data.worldbank.org/	Economy
Map and Image	https://www.mapbox.com/	Image
Other Datasets	https://datasetsearch.research.google.com/	Mixed

4.2 Data Pre-Processing

The data is divided into groups by areas and each set of data is cleaned before being input into the computing matrix. Besides, since the dimensions of the data are non-uniform, we are required to unify the dimensions of the data through standardized processing, so as to eliminate the impact of different dimensions. The original matrix is expressed as $X = [x_1, x_2, x_3, \cdots, x_m]$, utilizing the standardized method as following.

$$Z_i = \frac{x_i}{\sqrt{\sum_{i=1}^{m} x_i^2}} \tag{1}$$

Then, we can obtain the standardize matrix as $Z = [z_1, z_2, z_3, \cdots, z_m]$, which can be used for subsequent calculation. The flowchart of data pre-processing is illustrated in Figure 4.

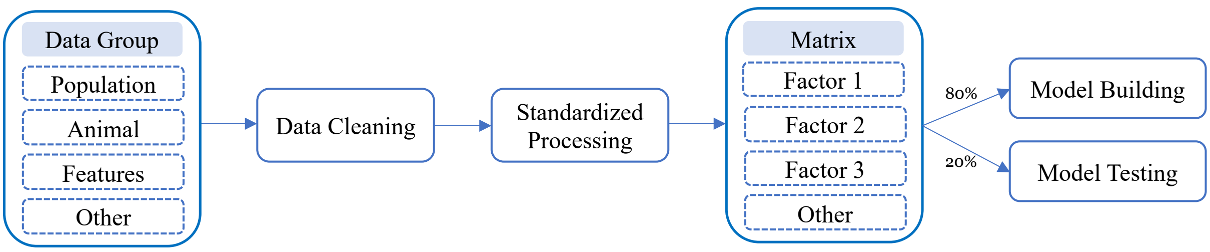


Figure 4 Flowchart of data pre-processing

5 Model I: Human-land Relationship Coupling Analysis

Considering the **Objective I** presented above, this paper translates the conflict between human interests and natural resources into the optimization of the human-land relationship model. **Firstly**, we clearly define and classify the different areas of the Maasai Mara national reserve (MMNR). **Secondly**, to facilitate processing and calculation, the physical space of the MMNR is discretized into many grids through the rasterized method. Then, specific areas are extracted and analyzed based on the relevant data. **Finally**, related policies and management strategies are proposed to address the balance of human-land relationship.

5.1 Coupling Analysis Model

In physics, coupling is the phenomenon whereby two or more systems which affect each other through various interconnections. Coupling is benign when there is a good balance between different systems or different elements within a system, and vice versa. In a word, the coupling analysis aims to obtain the **coupling degree** $\boldsymbol{\alpha}$ between the aspect of ecology and economy, such as environmental features and the intensity of human activities.

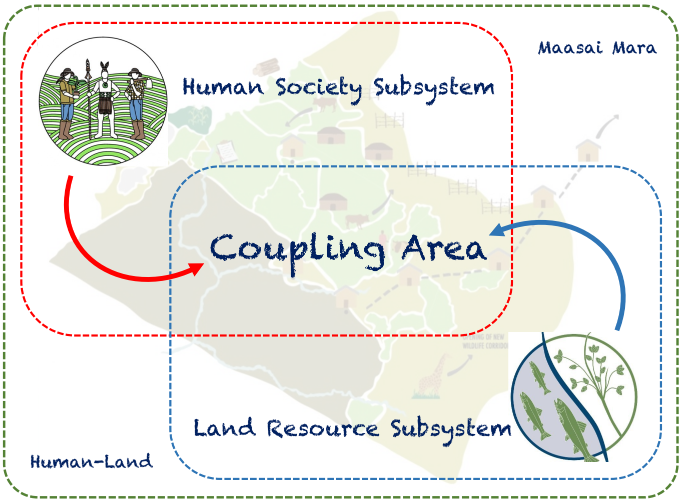


Figure 5 Illustration of the Coupling Model

5.1.1 Entropy Weight Processing

Before coupling analysis, we firstly utilize the entropy weight method to process the relevant data of the specific areas. The specific procedures are shown below:

- Step I: Refer to the formula $P_i = \frac{z_i}{\sum_{i=1}^{m} z_{i=1}}$, calculate the proportion of the sample i, and regard it as the probability used in the calculation of relative entropy.
- Step II: Refer to the formula $e_i = -\sum_{i=1}^{m} P_i \ln P_i$, calculate the information entropy of each indicator.
- Step III: According to the formula $d_i = 1 - e_i$, calculate the information utility value.
- Step IV: According to the formula $w_i = \frac{d_i}{\sum_{i=1}^{m} d_i}$, normalize the information utility value to obtain the entropy weight of each indicator.

The related data and entropy weight results obtained will be shown in the following content.

5.1.2 Definition of Coupling Degree

In the Human-land Relationship System, two subsystems that play a decisive role are the **Human society subsystem (H) and the Land resource subsystem (L)**. Each subsystem possesses many evaluation indicators, such like population density and resident income; number of animal species and annual precipitation. The Relationship Model is defined as follows:

$$\begin{cases} f(H) = \sum_{i=1}^{n} a_i x_i \quad (i = 1,2,3 \dots n) \\ f(L) = \sum_{j=1}^{n} b_j y_j \quad (j = 1,2,3 \dots n) \end{cases} \tag{2}$$

Where a_i and b_i represent the weights of evaluation indexes, while x_i and y_i represent standardized values of evaluation indexes respectively. Finally, based on the Ref.[3], the coupling degree of the Human-land Relationship Model is defined as:

$$\alpha = \arctan \frac{f(H)}{f(L)} \tag{3}$$

Therefore, we can utilize the coupling degree to define and classify the areas of the MMNR.

5.2 Rasterization of MMNR Areas

After defining the coupling degree of human-land system, we can derive the extent of ecological and economic values in different areas of the MMNR and identify the corresponding policies and management strategies. Then, the problem is to propose specific plan from the perspective of spatial coordination. Inspired by the Ref.[10], our paper utilizes the **Rasterized Method** to address this challenge.

Therefore, the physical space within and outside current boundaries of the MMNR is rasterized to a number of grids. Based on the coupling analysis in Section 5.1, each grid possesses different coupling degree. The following Figure 6 shows the grids of MMNR after rasterization.

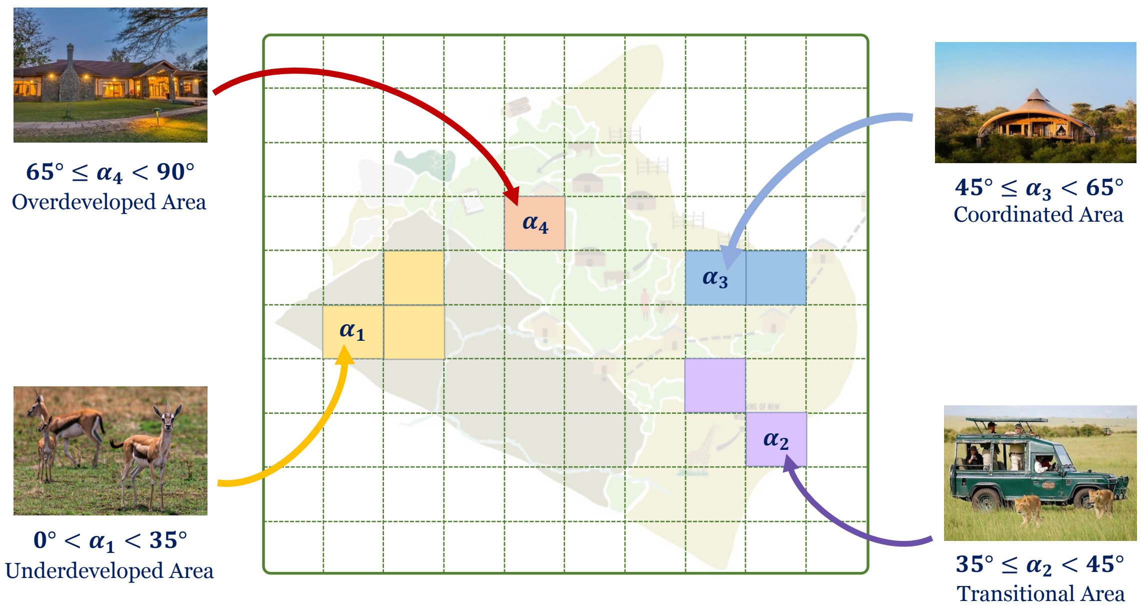


Figure 6 Rasterization of the MMNR grids

5.2.1 Description of MMNR Grids

The key to rasterizing MMNR areas is to determine the relevant geographical features of each grid, such as latitude, longitude, 'area', and geomorphic type. As shown in Figure 6, our paper focus on **the MMNR and its eastern area (0.56264N~2.1124S, 33.919E~36.344E), called Big MMNR area**. The detailed data for this area are shown in the following Table 3.

Table 3: Geographical features of the big MMNR area

Location	Latitude	Longitude	Geomorphic Type
ENONKISHU	0.562648N	35.012663E	Flatlands (Human Area)
OL DERIKESI	-2.112406S	36.002863E	Savannah
LELESHWA	-1.168484S	36.343985E	Mountain
NGUO-ARE	-0.453415S	33.918494E	Savannah
…	…	…	…

Considering the data requirement for further analysis, we require to obtain the area of each grid. Our paper utilizes the Haversine formula to determine the great-circle distance between two points on the earth. According to Haversine formula, the distance D is defined as:

$$D = 2R \times \arcsin\left(\sqrt{\sin^2\left(\frac{\varphi_2 - \varphi_1}{2}\right) + \cos(\varphi_1)\cos(\varphi_2)\sin^2\left(\frac{\lambda_2 - \lambda_1}{2}\right)}\right) \tag{4}$$

Where R represents the radius of the earth, φ_1 and φ_2 correspond to the latitude of the two grids, while λ_1 and λ_2 indicate the longitude respectively. Furthermore, we can obtain the width of each grid using $W_g = D/n$, where n indicates the scale of the rasterized method. As for the convenience of calculation, our paper adopts $n = 10$. Therefore, we can obtain that the width of each grid is approximately $W_g = 8.75\text{km}$ and the area is $S_g = 76.5625\text{km}^2$.

5.2.2 Classification of Grids based on Coupling Analysis Model

After analyzing the geographical features of each grid, we can classify the MMNR grids into four different categories, as shown in Figure 6 above. And the coupling degree scope and specific characteristic of each class are defined as follows:

- ✧ **Underdeveloped Grid:** $0° < \alpha < 35°$. The impact of natural resources on economic development is negligible, the coupling degree of is low. Therefore, the two subsystems are minimally coupled.
- ✧ **Transitional Grid:** $35° \leq \alpha < 45°$. Natural resources are still to be exploited and economic development is still at a backward stage. In this stage, the two subsystems start to interact, but they are not well coupled.
- ✧ **Coordinated Grid:** $45° \leq \alpha < 65°$. The strength of the resource environment provides an excellent basis for good economic development and the two subsystems are satisfactorily coupled at this stage.
- ✧ **Overdeveloped Grid:** $65° \leq \alpha < 90°$.The overuse of natural resources leads to an inability to balance environmental resources and economic growth, at which point the two subsystems become viciously coupled.

5.3 Proposed Policies and Strategies

5.3.1 For Human Society Subsystem

For the economic development of human society, we give the following three policies:

- **Policy 1: Livestock Industry (LI)**

Make full use of the natural resources of the Masai Mara Nature Reserve and the climatic conditions of the savanna to promote the green development of animal husbandry. Optimize the layout of breeding areas, concentrate livestock breeding in less developed areas, and reduce the harm to wild animals as much as possible.

- **Policy 2: Planting Industry (PI)**

The development of planting industry should be regarded as an important part of the economic income source of local residents, and the planting area should be concentrated far away from the wild animal activity area, so as to prevent the destruction of wild animals and cause economic losses.

- **Policy 3: Tourist Industry (TI)**

Masai Mara Nature Reserve has unique wildlife resources, so it is necessary to vigorously develop tourism and plan tourist routes to protect tourists' life safety and wildlife habitat. In addition, the development of tourism facilities such as accommodation, improve the quality of service. Thus driving the local economic growth and awareness of the promotion.

5.3.2 For Land Resource Subsystem

To maximize the protection of wildlife, we propose the following three strategies:

- **Strategy 4: Animal Hunting (AH)**

If human's killing of wild animals exceeds a certain degree, it will affect the natural growth of wild animals, and may lead to the extinction of the population in serious cases. Therefore, people's hunting behavior should be monitored continuously, and excessive hunting should be punished financially, so as to ensure the sustainable reproduction of animals.

- **Strategy 5: Vegetation Felling (VF)**

Excessive deforestation of vegetation will lead to the decline of local environmental quality, but also lead to the destruction of birds and other animals' habitat environment, so people should be within a certain limit for vegetation felling, for excessive deforestation should take financial penalties.

- **Strategy 6: Land Development (LD)**

Overdevelopment of land will lead to a decrease in the maximum environmental tolerance of plant and animal growth. In order to protect the natural environment and species diversity, there should be some planning for land development, and residents should be punished for illegal self-development of land.

6 Model II: Multi-objective Strategy Selection Model

Considering the **Objective II** proposed above, our paper establishes the multi-objective strategy selection model to determine which policies and management strategies will result in the best outcomes. **Firstly**, we build a four-layer strategy evaluation model based on the analytic hierarchy process (AHP) method to evaluate and rank the strategies and policies. **Secondly**, we present the multi-objective optimization model to quantify the economic and ecological impact of the optimal combination of the strategies and policies. **Finally**, we utilized our proposed model to test a representative grid in the MMNR area. The simulation results verify the effectiveness and rationality of our model.

6.1 Strategy Evaluation Model

Given the premise of limited financial resources of local governments, it is not practical to implement all proposed policies and strategies. Besides, as different policies will lead to diverse impacts on the MMNR areas, we need to evaluate and rank each policy or strategy based on the perspective of human-land coordination.

6.1.1 Establishment of Model Structure

Therefore, this paper establishes the strategy evaluation model based on the AHP to tackle this challenge. We have selected four evaluation indicators: Biodiversity **(BD)**, Environmental Quality **(EQ)**, Economic Benefit **(EB)**, and Difficulty of Implementation **(DI)**, to evaluate and make decisions on the human society subsystem and land resource subsystem respectively.

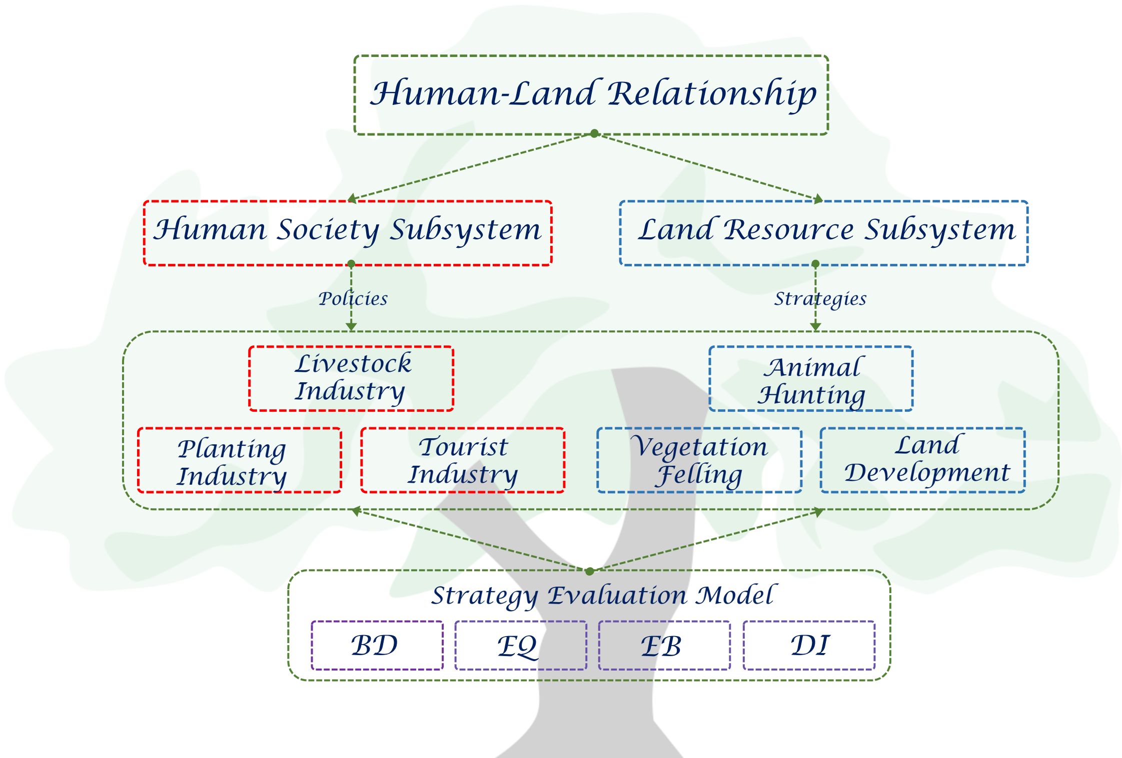


Figure 7 Flowchart of the four-layer strategy evaluation model

Figure 7 illustrates the flowchart of the strategy evaluation model, where the hierarchical structure possesses four layers. And the definitions and interaction between each layer are:

- ✧ **Layer I:** Human-Land Relationship System of the big Maasai Mara area, including the humans, animals, land and all the interactions between subsystems.
- ✧ **Layer II:** Human society subsystem and land resource subsystem, which will be coupled to varying coupling degrees.
- ✧ **Layer III:** Corresponding policies and management strategies, the optimization objectives which would be selected and combined for practical implementation.
- ✧ **Layer IV:** Four evaluation indicators of the AHP method, which are utilized to assess and rank the policies and strategies in the upper layer III.

6.1.2 Calculation for Model Indicators

Starting from the third layer of the hierarchical structure, for each factor belonging to the upper layer, a pair comparison matrix is constructed with a pair comparison method and a 1~9 comparison scale until the lowest level. The pair comparison matrix A is defined as follows:

$$A = \left(a_{ij}\right)_{n\times m}, \quad a_{ij} > 0\,, \quad a_{ji} = \frac{1}{a_{ij}} \tag{5}$$

Through correlation searching for occurrence frequency of four evaluation indicators on the Google Scholar, we have obtained that the keyword 'Biodiversity' possesses around 47.7 million indexes, and 'Environmental Quality' has about 13.1 million, while the data of 'Economic Benefit' and 'Difficulty of Implementation' are 24.45 and 11.9 million respectively. Based on the data, we can estimate the relative weight of each indicator. The detailed results are detailedly presented in the following Table 4 and Table 5.

Table 4 Scoring results for human social subsystem

Index	Weight	Tourist Industry	Planting Industry	Livestock Industry
BD	0.3165	0.1638	0.2973	0.539
EB	0.1423	0.7225	0.1033	0.1741
EQ	0.2597	0.1778	0.6444	0.1778
DI	0.2814	0.1638	0.2973	0.539
Score and Rank		**1.1606739 (rk1)**	**0.9942297 (rk3)**	**1.16067393 (rk2)**

Table 5 Scoring results for land resource subsystem

Index	Weight	Animal Hunting	Land Development	Vegetation Felling
BD	0.3165	0.6	0.2	0.2
EB	0.1423	0.1593	0.5889	0.2519
EQ	0.2597	0.1416	0.3338	0.5247
DI	0.2814	0.539	0.1638	0.2973
Score and Rank		**0.41218651 (rk1)**	**0.40101651 (rk2)**	**0.39466989 (rk3)**

After obtaining the weight of evaluation indicators, we are required to test the consistency of comparison matrices. In this case, the consistency index (CI), random consistency index (RI) and consistency ratio (CR) are introduced and defined as follows:

$$\begin{cases} CI = \dfrac{\lambda - n}{n - 1} \\ CR = \dfrac{CI}{RI} \end{cases} \tag{6}$$

Where n represents the order of the comparison matrix A, λ represents the maximum eigenvalue of A. Besides, RI can be directly found through the comparison scale table. Finally, we utilize MATLAB for calculation, the results show that the final $CR < 0.1$. Therefore, the degree of inconsistency is within the acceptable range and passes the consistency test.

6.2 Multi-objective Optimization Model

As mentioned in the **Objective I** and **Objective II**, we are required to adequately protect wildlife and land resources while minimizing the loss of human interests. Therefore, our paper establishes the multi-objective optimization model to achieve the human-land coordination.

6.2.1 Establishment of Optimization Model

Considering the limited financial resources of local governments, it is unreasonable to implement all management policies and strategies proposed in the Section 5.3. Hence, we need to evaluate the six policies and strategies, and to select the optimal combination based on the specific situation. Based on the proposed strategy evaluation model, our paper further uses the **Zero-one Programming Method** to select the policies and strategies.

In this case, we define the **three strategies** of the land resource subsystem: Animal Hunting, Vegetation Felling, Land Development, as factors x_1 , x_2 , x_3. Similarly, define the **three policies** of the human society subsystem: Livestock Industry, Planting Industry and Tourist Industry, as factors x_4 , x_5 , x_6. Then, organize the definition of zero-one programming method:

$$x_i = \begin{cases} 1, & \text{Select the Policy or Strategy } i \\ 0, & \text{Reject the Policy or Strategy } i \end{cases} \tag{7}$$

Where $i = 1,2,3,4,5,6$, and x_i represents a strategy or policy is selected or rejected.

Now, review the **rasterized MMNR model** we proposed in the Section 5.2 above. The coupling degree α of a grid will be considered as the most important decision variable in the following objective function. The main weight decision method is briefly presented as follows:

- ✧ **Underdeveloped Grid:** When $0° < \alpha < 35°$, weight of $(x_1, x_2, x_3) < (x_4, x_5, x_6)$
- ✧ **Transitional Grid:** When $35° \leq \alpha < 45°$, weight of $(x_1, x_2, x_3) < (x_4, x_5, x_6)$
- ✧ **Coordinated Grid:** When $45° \leq \alpha < 65°$, weight of $(x_1, x_2, x_3) \approx (x_4, x_5, x_6)$
- ✧ **Overdeveloped Grid:** When $65° \leq \alpha < 90°$, weight of $(x_1, x_2, x_3) > (x_4, x_5, x_6)$

Considering the value of coupling degree α ranges from $0°$ to $90°$, so we can obtain that $\boldsymbol{\alpha > \sin\alpha > 1 - \cos\alpha}$, and $\boldsymbol{\cos\alpha > 1 - \sin\alpha > 1 - \alpha}$ within the range. Inspired by the related reference, these two inequation will be utilized to determine the sub-weight of the objective function to make it more balanced and systematic[11].

Based on the rank determined through the strategy evaluation model (Table 4 and Table 5), the objective function of our multi-objective optimization model is defined as follows:

$$\begin{cases} max\ V_L = \alpha x_1 + (\sin\ \alpha)x_2 + (1 - \cos\ \alpha)x_3 \\ \max V_H = (\cos\alpha)x_4 + (1 - \sin\alpha)x_5 + (1 - \alpha)x_6 \end{cases} \tag{8}$$

Where V_L represents the utility value of the land resource subsystem, and V_H represents the utility value of the human society subsystem. The utility value is an economic concept that describes the benefit that relevant policies and strategies bring to the correspond subsystem.

Overall, now the problem of recommending specific policies and management strategies for different areas have been translated to optimize the total utility value W of the whole Human-Land System. So the final objective function can be expressed as:

$$\max W = \max(\mu_L V_L + \mu_H V_H) \tag{9}$$

Where the μ_L and μ_H correspond to the main weight of the two sub-system based on the rasterized MMNR model. Noted that the weight decision method has already been presented above. Ultimately, the constraint conditions are listed below:

- **Constraint I:** Based on the premise of limited financial resources of local governments, the number of the adopted policies and strategies should not exceed four.
- **Constraint II:** On the other hand, to achieve a significant effect, at least two policies or strategies need to be selected for practical implementation.
- **Constraint III:** In order to balance the two subsystems, at least one specific policy or strategy for each subsystem is selected.
- **Lastly**, the expression of the constraint conditions is given as follows:

$$\text{s.t.} \begin{cases} 2 \leq\ x_1 + x_2 + \cdots + x_6 \leq 4 \\ 1 \leq x_1 + x_2 + x_3 \leq 3 \\ 1 \leq x_4 + x_5 + x_6 \leq 3 \\ x_i \in \{0,1\},\ \ i = 1,2,3,4,5,6 \end{cases} \tag{10}$$

Now, we can utilize the multi-objective optimization model to analyze an example grid.

6.2.2 Testing for Optimization Model

Based on the grid data presented in Table 3 of the Section 5.2, we select an underdeveloped grid (Mulima Mbili Area) with a representative coupling degree around $\alpha_{test} = 20°$. The following Figure 8 illustrates the detailed information of the selected grid, where the latitude and longitude are about 1.5862S and 34.370E, the grid width is approximately $W_g = 8.75\text{km}$ while the area is $S_g = 76.5625\text{km}^2$.

Now, utilizing MATLAB program to simulate the multi-objective optimization model, to begin with, we determinate the main weight μ_L and μ_H of final objective function through the weight decision method. According to the related data of this grid, we adopt reasonable weight of $\mu_L = 0.583$ and $\mu_H = 0.417$. Hence, we can get $\max W = 0.583V_L + 0.417V_H$.

Ultimately, the simulation results of the model show that, different combination of policies and strategies would lead to different total utility value W. And the ranking results of simulation are presented in the following Table 6. To conclusion, the optimal combination in this grid is (x_1, x_4, x_5, x_6) and the corresponding total utility value reaches $\max W = 2.597672$.

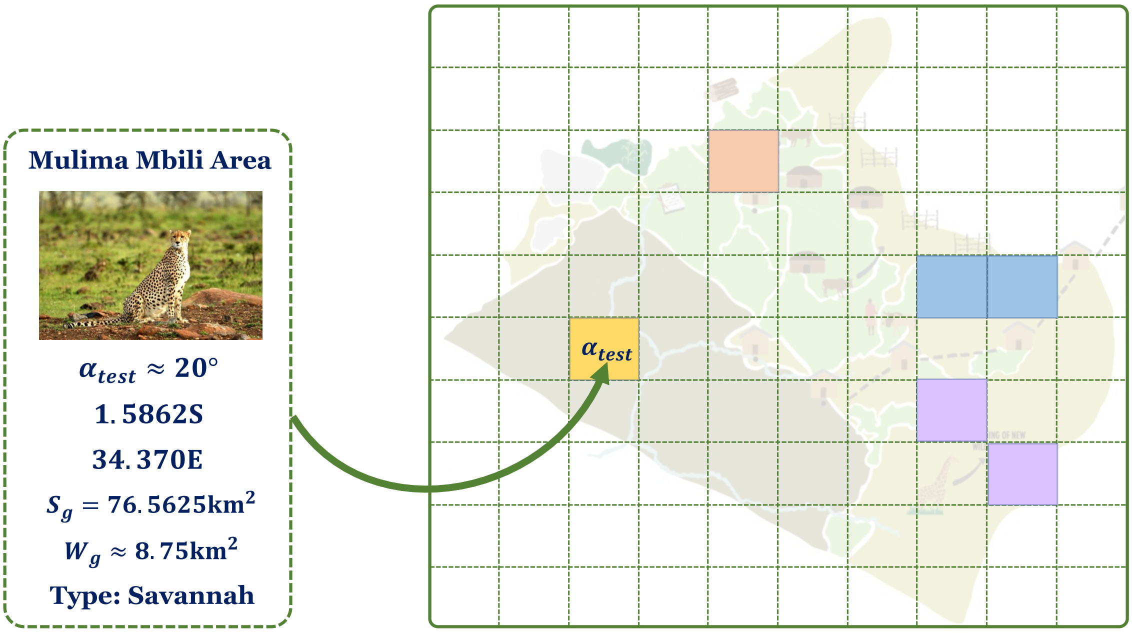


Figure 8 Detailed information of the selected grid

Table 6: Results of the multi-objective optimization model

x_1	x_2	x_3	x_4	x_5	x_6	W	$Rank$
✓			✓	✓	✓	**2.597672433**	1
	✓		✓	✓	✓	2.590626776	2
		✓	✓	✓	✓	2.308914012	3
✓			✓	✓		2.288758421	4
✓	✓		✓		✓	2.281712720	5
✓		✓	✓			2.007045657	6

7 Model III: Long-term Trend Prediction Models

Considering the **Objective III** mentioned above, our paper proposes the long-term trend prediction model to project and assess the long-term ecological and economic situation in the MMNR based on the optimal management strategies. **Firstly**, we quantify the reflection of trend using the change of animal numbers and resident economic incomes. **Secondly**, we propose the specific expression of the Logistic Equation, maximum environmental capacity and resident economic incomes. **Thirdly**, based on mathematical definitions, we design a Python program for our trend prediction models. **Finally**, we obtain and present twelve 100-year prediction results referring to twelve different sets of parameter configurations.

As to the **Objective IV**, a two-page non-technical report for the Kenyan Tourism and Wildlife Committee will be beautifully and clearly presented at the end of our paper.

7.1 Trend Prediction Models

Given the objective to predict the economic and ecological impact of the optimal strategies and policies, it is significant to resolve the statement of influence quantifying. As for the convenience of programming and computing, our paper chooses two predicting factors for the human society subsystem and land recourse subsystem. Then, we use the Python programs to simulate the long-term trend of each predicting factor. The detailed process is given as follows.

7.1.1 Justification for Our Prediction Model

Based on the proposed human-land relationship coupling model and multi-objective strategy selection model, the Big MMNR area is highly coupled by the two subsystems. In this case, we can utilize the change of two subsystems to quantify the trend of the MMNR. The prediction of land recourse subsystem is reflected in **the changes of animal numbers**, and the prediction of human society subsystem is reflected in **the changes of resident economic income**.

Additionally, the interaction between two subsystem is innovatively described according to the comparison of the curve changing rules, which will be presented in the following content. As to the explanation of the area within and around the MMRN, this paper considers the **Big MMRN area** from the beginning to the end, which can be proved by Figure 1 and Table 3.

After the justification, now we will present the establishment of prediction model.

7.1.2 Prediction for Numbers of Animal

Through deep literature reviewing, this paper adopt that the growth of animal follows the **Logistic Equation**, which indicates numbers of animal is affected by natural resources, environmental conditions and other retarding factors. What's more, with the increase of amounts, the retarding effect becomes greater, so the growth rate of animals decreases when the number reaches a certain threshold.

Specially, considering the local conditions of the Big MMRN area, we believe that humans will hunt animals, and the amount of hunting per unit time is proportional to the number of animals, thus affecting the growth rate of animal population to some extent. Based on the above analysis, we established the improved Logistic Equation as follows:

$$\dot{x}(t) = \frac{dx}{dt} = rx\,(1 - \frac{x}{x_m}) - Ex \tag{11}$$

Where x represents the number of animals, t is time and r indicate the intrinsic rate of natural increase, which is the growth rate at $x = 0$. And x_m is the maximum environmental capacity, that is, the maximum number of animals that resources and environment can accommodate. Finally, E corresponds to hunting intensity, which is the hunting rate per unit of time.

Then, considering the policies and strategies proposed by us, while developing human social economy, it will have a certain degree of impact on the habitat environment and natural conditions of animals. The maximum environmental capacity x_m will change with time, so we define the formula as follows:

$$x_m\,(t+1) = x_m(t)\,[1 - (z_1 + z_2 + z_3)] \tag{12}$$

Where $x_m\,(t+1)$ is the number of animals at the $t+1$ moment, $x_m\,(t)$ is the number of animals at the t moment. Besides, z_1, z_2, z_3 represent the intensity of the impact of livestock industry, planting industry and tourist industry.

7.1.3 Prediction for Local Economic Income

Inspired by extensive data and references, we further identified six factors of economic activity: **hunting, land leasing, logging, tourism, crop growing and livestock farming**. Considering the different coupling degree α of human-land system, the selection of policy combination will be greatly influenced. Therefore, to present the influence intuitively, we continue to utilize the weight coefficients of six policies from x_1 to x_6 proposed in the Equation (8).

Besides, considering the three policies of the land resource subsystem contain capital penalties for residents' illegal killing of wild animals, illegal land using and illegal felling. We adopted the method of **Random Simulation** to represent possible situations. The economic income of local residents A is defined as follows:

$$A = \sum_{j=1}^{3} Q_j M_i (1 - R_j) + \sum_{j=4}^{6} Q_j M_i R_j + A_0 \quad (i, j = 1,2,3,\cdots,6) \tag{13}$$

Where i represents the policy and j represents economic activity. Q_j is the baseline economic income for the first type of economic activity. And M_i is the weight coefficient of policy i, which is same as the Equation (8). R_j is a random number with a value interval of $[0,1.5]$, and A_0 is the initial value of residents' economic income when no policy is adopted.

7.2 Prediction Programs and Corresponding Results

7.2.1 Description for Prediction Programs

Based on mathematical definitions above, we have designed a Python program for our trend prediction models as follows:

Algorithm: Simulation and prediction of animal numbers and resident incomes.

Input: i , t , α
Output: A , x
Initialize the desired variables based on i , t and α.
for $t = 1$ to 50 **do**

According to x_m , r , x simulate animal growth in the presence of environmental carrying capacity.

According to m mapped from α, the quantized coefficients of each policy are determined for the next step of calculation.

if the relevant policy in i is selected, **execute** the relevant policy.

When the local people violate the relevant policies implemented, the punishment is imposed on the people, and the effect will react on A and x through the Equation of (11), (12), (13).

When the implementation of relevant policies is conducive to the economic development of local people, the value of x will be calculated through the Equation of (11), (12).

end

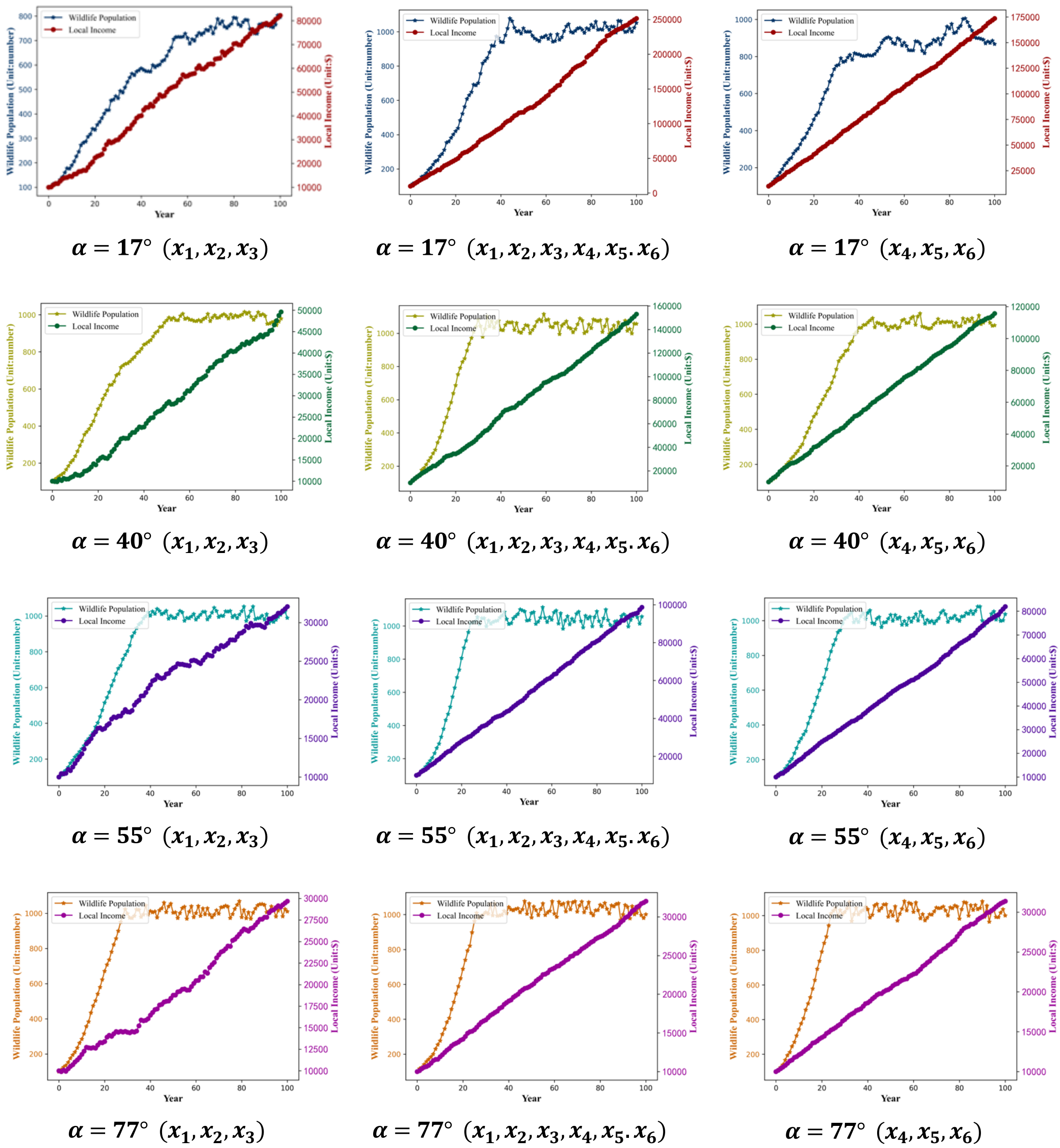
end

Draw statistical graphs according to A, i and x for analysis.

7.2.2 Corresponding Results

Ultimately, we obtain and present twelve 100-year prediction results referring to twelve different sets of parameter configurations, as shown in the following Figure 9, where α is the coupling degree of the human-land relationship model. Besides, (x_1, x_2, x_3) corresponds to the three policies and strategies which were implemented in a specific area.

For instance, $(x_1, x_2, x_3, x_4, x_5, x_6)$ represents a specific area that implements all six policies and strategies, including the Livestock Industry, Planting Industry, Tourist Industry, Animal Hunting, Vegetation Felling and Land Development.



$\alpha = 17°$ (x_1, x_2, x_3) | $\alpha = 17°$ $(x_1, x_2, x_3, x_4, x_5. x_6)$ | $\alpha = 17°$ (x_4, x_5, x_6)

$\alpha = 40°$ (x_1, x_2, x_3) | $\alpha = 40°$ $(x_1, x_2, x_3, x_4, x_5. x_6)$ | $\alpha = 40°$ (x_4, x_5, x_6)

$\alpha = 55°$ (x_1, x_2, x_3) | $\alpha = 55°$ $(x_1, x_2, x_3, x_4, x_5. x_6)$ | $\alpha = 55°$ (x_4, x_5, x_6)

$\alpha = 77°$ (x_1, x_2, x_3) | $\alpha = 77°$ $(x_1, x_2, x_3, x_4, x_5. x_6)$ | $\alpha = 77°$ (x_4, x_5, x_6)

Figure 9 Twelve 100-year prediction results of different parameter configurations

8 Sensitivity and Robustness Analysis

In order to test our proposed model, we conduct the sensitivity and Robustness analysis. Now, we define sensitivity score S_A, S_B, S_C, where S_A corresponds to select the policy $(\boldsymbol{x_1}, \boldsymbol{x_2}, \boldsymbol{x_3})$. And S_B corresponds to select the policy $(\boldsymbol{x_1}, \boldsymbol{x_2}, \boldsymbol{x_3}, \boldsymbol{x_4}, \boldsymbol{x_5}, \boldsymbol{x_6})$. Also, S_C corresponds to select the policy $(\boldsymbol{x_4}, \boldsymbol{x_5}, \boldsymbol{x_6})$. We will test the model under the three conditions of S_A, S_B, S_C. Furthermore, S_A, S_B, S_C will change within $\alpha \in (0,90)$, as shown in Figure 10.

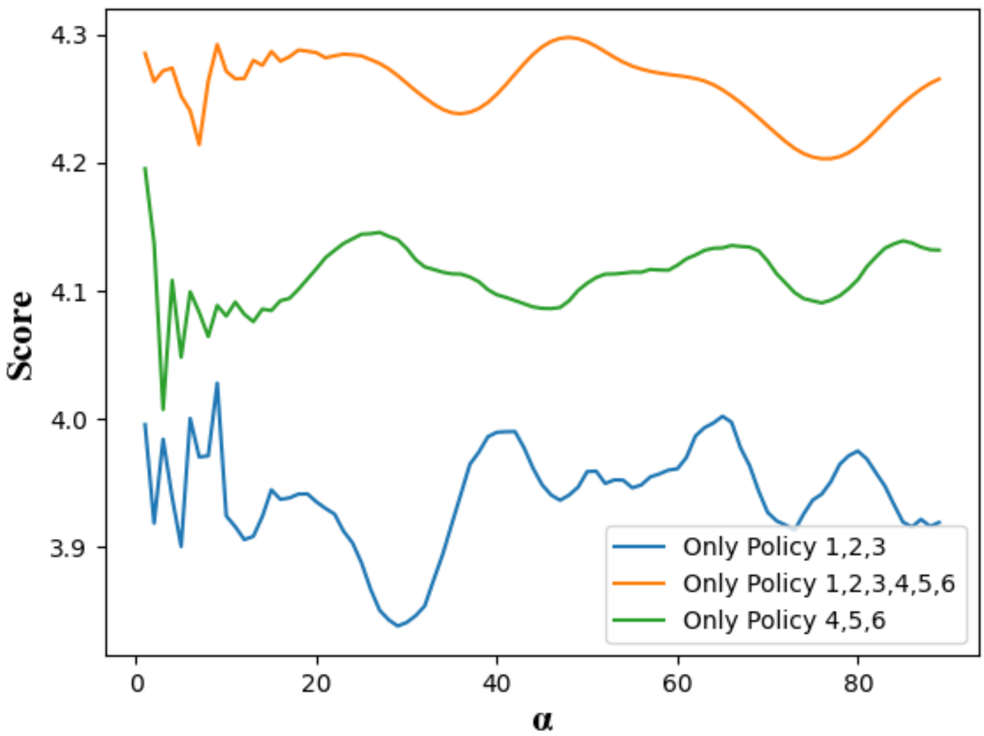


Figure 10 Results of Model Testing

Additionally, we further implement the idea of robustness analysis to the sensitivity analysis and add a small amount of noise when α was too small to observe whether the model system can maintain good performance under the influence of uncertain factors. It was shown that S_A, S_B, S_C would fluctuate in the three cases. Moreover, with the increase of α, The influence of noise on the system in all three cases is gradually decreasing, which indicates that the system is more stable with the increase of α.

In the subsequent sensitivity analysis, we found that under the influence of three different policy combinations, S change of the system reflected the different response degree of the model system to the input under the influence. In the case of S_B, the response degree of the system was the best and its S was the highest, while in the case of S_C, the response degree of the system was slightly worse. Finally, in the case of S_A, the system has the worst response compared with the other two cases.

Ultimately, it comes to a conclusion that under the condition of S_B, when α is not too small, the system performance is better. Under this condition, wild animals can be protected, while the income of local residents can be maximized, thus a win-win situation can be achieved.

9 Model Evaluation

9.1 Strengths

- **Strength 1: Rasterization of MMNR areas.**

⇒ **Explanation:** The method of rasterization analysis is used to collect data in different regions to realize the actual analysis of the development situation of each region.

- **Strength 2: The model is innovative.**

⇒ **Explanation:** A new concept of coupling degree of human-land system is proposed in the model and the calculation method is defined. In addition, we combine the multi-objective programming model with the 0-1 integer programming model, make innovations on the basic mathematical model, and select trigonometric functions to reasonably define the weight of each policy.

- **Strength 3: The model has rationality and integrity.**

⇒ **Explanation:** The model we established is based on the actual situation of the Masai Mara Nature Reserve. For example, the Kenyan government is selective in the implementation of policies. From the analysis of coupling degree of human-land system to the selection of policy combination, the model finally completes the long-term trend prediction, and gradually solves the problem.

- **Strength 4: The model is highly replicable.**

⇒ **Explanation:** The policies and strategies we provide for the Masai Mara reserve, as well as the long-term trends we predict, can also be applied to other wildlife reserves, and even to the interaction between urban and rural areas.

9.2 Weaknesses and Possible Improvements

- **Weakness 1: The number of policies proposed by the model is small.**

⇒ **Improvement:** In order to simplify the model, we consider a small number of policies. Therefore, in the application and promotion of the model, the impact of more policies on the system can be taken into account, such as regional division and prohibition of sewage discharge, so as to make the model more in line with the actual situation.

- **Weakness 2: The effects of different intrinsic growth rates of different animal populations were ignored.**

⇒ **Improvement:** When we forecast the population, we look at the whole Masai Mara as a whole. Therefore, it is better to treat the intrinsic growth rates of different animal populations as a variable when predicting parts of Python code.

10 Conclusion and Further Discussion

10.1 Summary of Results

- **Objective I:** We established the human-land relationship coupling analysis model, processed the data through raster maps and further calculated, and obtained the law of coupling degree. Based on this, we proposed relevant policies:
  - **Underdeveloped Grid:** $0° < \alpha < 35°$
  - **Transitional Grid:** $35° \leq \alpha < 45°$
  - **Coordinated Grid:** $45° \leq \alpha < 65°$
  - **Overdeveloped Grid:** $65° \leq \alpha < 90°$

- **Objective II:** Based on Multi-objective Optimization Model. First, strategies and policies are ranked based on AHP. Multi-objective optimization model is proposed to quantify the economic and ecological impacts of an optimal combination of strategies and policies. Finally, we tested the coupling degree of $20°$ in the MMNR area, and the simulation results showed that when the strategies($\boldsymbol{x_1}$, $\boldsymbol{x_4}$, $\boldsymbol{x_5}$, $\boldsymbol{x_6}$) were selected, the utility value of the whole system reached the maximum, which was 2.5977.

- **Objective III:** A long-term trend prediction model based on the optimal management strategy was proposed. A Python program for the trend prediction model was designed based on the Logistic equation and the specific expression of residents' economic income, and 12 centennial forecast results were obtained. It was found that the proposed policy could protect wildlife and improve residents' economic level.

10.2 Further Discussion

Through the sensitivity and robustness analysis of our model, it is found that when we adopt all the 6 policies, if the local α value is not very small, the model's sensitivity response degree and robustness stability degree are the best compared with the other two cases, but this does not mean that the other two models become useless.

And we found that in our simulation of 12 projections over 100 years, the number of wild animals will continue to increase. Due to the existence of the maximum capacity of the environment, the number of wild animals will fluctuate within a small range and eventually become stable. From the perspective of the income of local residents, the income of local residents will continue to increase with a small fluctuation.

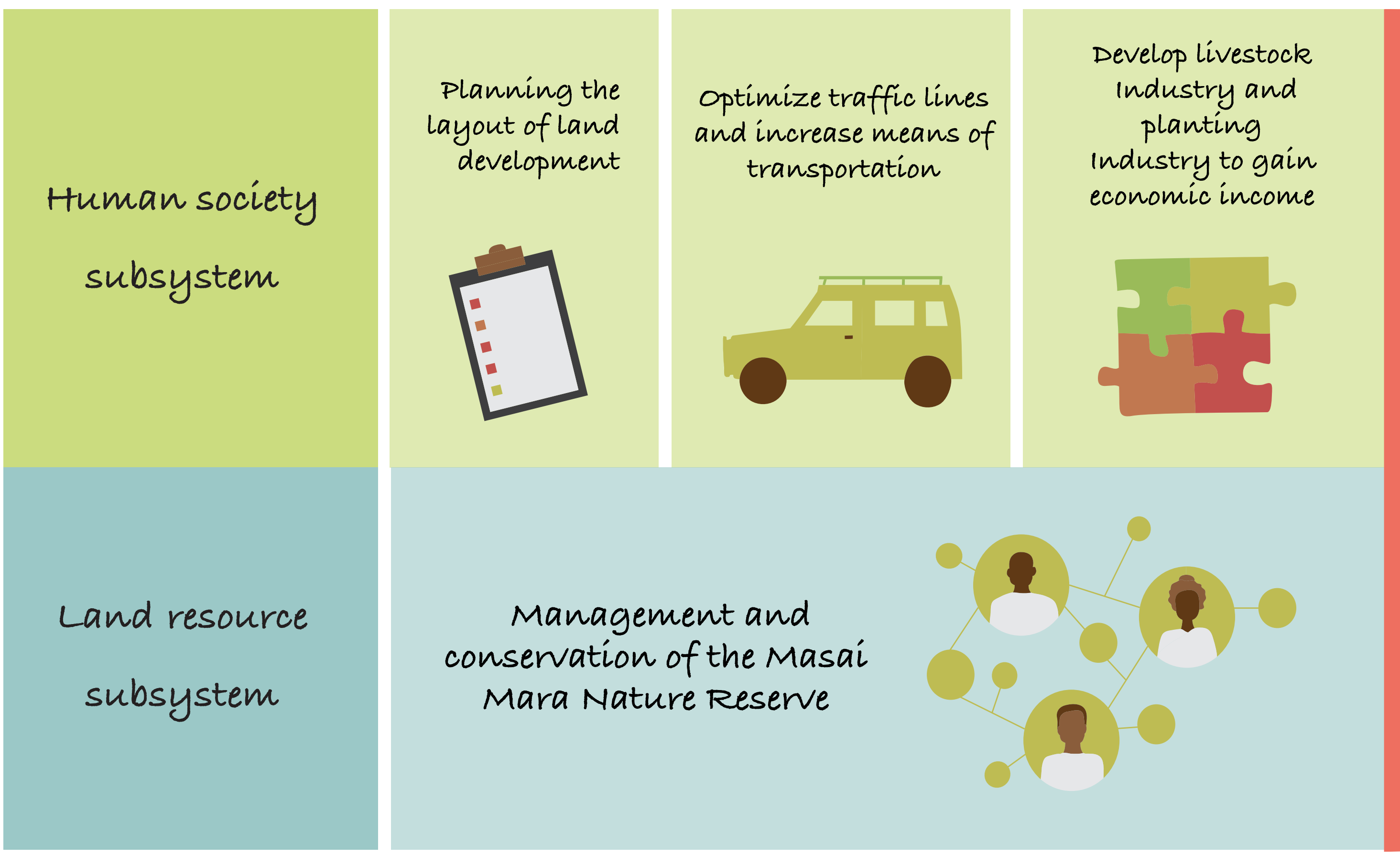
At the moment, we only consider six policies, but from a further perspective, when we extend the model to more places, we need to consider more policies in light of the specific local development situation, in order to achieve a win-win situation of protecting wildlife and generating income for local residents.

Reshape the Crowning Glory of Maasai Mara

This non-technical report is given by MCM Team #2316192

Policy recommendations for the Masai Mara Nature Reserve are as follows:

1. **Policy 1: Livestock Industry.**
   Optimize the layout of breeding areas, concentrate livestock breeding in less developed areas, and reduce the harm to wild animals as much as possible.
2. **Policy 2: Planting Industry.**
   Concentrate crop growing areas far away from wildlife areas to prevent wildlife damage and economic losses.
3. **Policy 3: Tourist Industry.**
   Planning of tourism routes and improving the quality of supporting tourism settings.
4. **Strategy 4: Animal Hunting.**
   Continue to monitor people's hunting behavior and impose fines for excessive hunting to ensure sustainable breeding of animals.
5. **Strategy 5: Vegetation Felling.**
   People for vegetation felling should be in a certain limit, for excessive loggers should take financial penalties, so as to protect the habitat of animals.
6. **Strategy 6: Land Development.**
   In order to protect the natural environment and species diversity, there should be some planning for land development, and penalties should be given to residents who illegally develop their own land.



Develop Tourist Industry

The Masai Mara Nature Reserve has a unique natural environment and wildlife resources, which is suitable for the development of tourist Industry.

Our proposed policies are as follows:

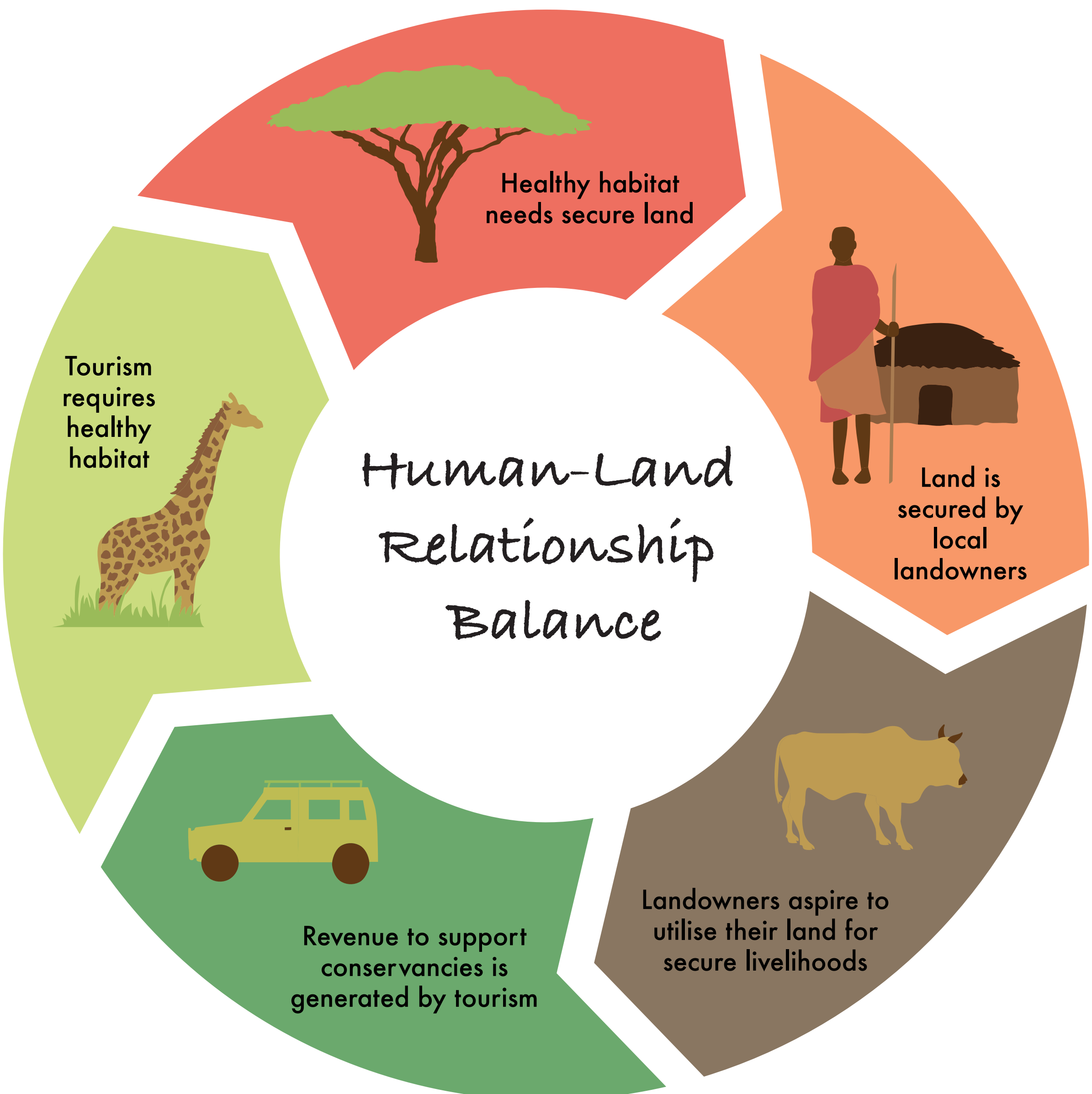
1.Strengthen the management of the Masai Mara conservation area.
As more and more tourists visit, the need for institutionalized management should increase. For example, for garbage cleaning, for the maintenance of facilities and so on. In this way, while ensuring tourists' travel experience, the natural environment can be protected from destruction.

2.Plan multiple travel routes. Tourism along the routes can better appreciate the local natural scenery, but at the same time can minimize the impact on the life of animals.

3.Establish tourism supporting facilities.
Such as hotels, restaurants, shops, public toilets, etc. Overall planning of the layout of each service unit to optimize the tourist experience.

4.Optimize traffic lines and increase means of transportation. Transportation is very important for the development of region tourism, and it can provide convenience and comfort for tourists by optimizing the way they travel.

With the support of relevant policies, Masai Mara's tourism industry will be better developed and its economic level will be greatly improved. At the same time, the development of tourism can make Masai Mara better known and have broader prospects for development.



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