

Orchestrate the Sustainable Forest Future

Summary

Greenhouse gas emissions are a major cause of climate change. Storing CO₂ in the biosphere can sequester it from the atmosphere. Therefore, we develop a carbon sequestration model and a forest evaluation model to propose a timeline for forest management.

First, to calculate carbon sequestration over time, we include canopy plants, undergrowth plants, forest products, soil, and water environments in the analysis. Then, we use a **non-linear optimization model** solved by **Monte Carlo** to determine forest management plans for America, China, Brazil, and Colombia over one hundred years. In this case, the objective function is maximizing carbon sequestration, the decision variables are harvesting rate and harvesting interval, and the constraints are forest area and time. We conclude that Colombian forest managers need to harvest plants at a rate of **0.0213** per **11.67** years. America is similar to Colombia, with a lower harvesting rate and shorter harvesting intervals. China and Brazil, on the other hand, require longer harvest intervals and larger harvest proportions (**Table 4**).

Second, we build a **forest evaluation model** to help forest managers balance the ecological and social benefits of forests. We collect ten indicators of ecology and society from **42** countries. Then we pre-process data by padding and normalization. We employ the **AHP-CRITC** method to obtain the weights (**Figures 6&7**) by the **Lagrange multiplier** and introduce the Ecological Development Index (**EDI**) and Social Development Index (**SDI**). Using k-means++ to calculate thresholds for the EDI and SDI (**Table 8**), we divide the **GE matrix** into nine regions and propose four strategies. For regions I, II, III, IV, and VI, we suggest prohibiting harvesting and establishing protected areas. For regions VII and VIII, where EDI is greater than **0.61** and SDI is less than **0.61**, we suggest harvesting **0.057** plants every **6.46** years to increase the social benefits.

Next, we apply the above two models to five forests in China: Daxinganling, Saihanba, Xishuangbanna, Zhangjiajie, and Jiuzhaigou. Over one hundred years, the carbon sequestration in the coniferous forests, Daxinganling and the Saihanba, will reach **3457.90** and **3196.10** million tons, 10 to 100 times more than the other three broadleaf forests. Among them, Saihanba is located in **Region VII**, which includes harvesting in the management plans. Subsequently, we assume that the harvesting time was **16.46** years and solve the non-linear optimization model. Since the adjusted harvesting rate is **0.085**, we propose a three-stage transition strategy for the Saihanba. Its distances to the optimal point after each stage will be **68.4, 56.1, 37.3**, respectively.

Finally, we analyze the strengths and weaknesses of the models. Sensitivity analysis proves our optimization model and evaluation model are stable when varying constraints and weights, respectively. Additionally, we write a non-technical newspaper article about Saihanba.

Keywords: carbon sequestration; non-linear optimization; AHP-CRITIC; GE matrix

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1 Introduction

1.1 Problem Background

Climate change poses a significant threat to humanity, with greenhouse gases being a primary concern. As shown in **Figure 1**, carbon emissions doubled in 2020 compared to 1980. Reducing carbon emissions can only slow down the rise of carbon dioxide. Storing carbon dioxide in the biosphere can sequester it from the atmosphere. Forests play a central role in this process. **Figure 2** illustrates various forest products, some of which can extend the lifespan of trees and sequester carbon dioxide for a longer time.

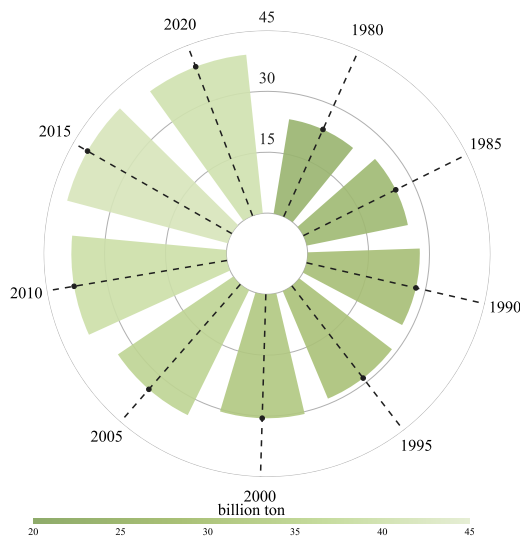


Figure 1: Carbon dioxide emission [1]



Figure 2: Forest products

Changes in carbon sequestration help forest managers to create timely plans. Therefore, we need to develop a carbon sequestration model over time and make forest management decisions based on this to ensure a balance between biodiversity, culture, and other relevant aspects.

1.2 Restatement of the Problem

To understand carbon sequestration and provide suggestions for forest managers, we need to do the following work:

- Calculate the carbon dioxide sequestered by a forest and its product over time and find a plan sequestering most.
- Evaluate forests from the social aspect and utilize their characteristics like location to make management plans.
- Apply previous models to different kinds of forests and select one that is recommended for harvesting for further analysis. Then write a non-technical newspaper article to convince the public of the decision to harvest the selected forest.

1.3 Literature Review

Carbon sequestration is a key focus of research for its capacity to alleviate climate change. Numerous methods exist for evaluating carbon sequestration. Tooichi et al. ^[2] pointed out that the sequestration speed depends on species, wood density, and growth condition of trees. Pukkala et al. ^[3] utilized site fertility and temperature sum to predict Finnish carbon stocks in living tree biomass, dead organic matter, and wood-based products under a forest management scenario. Ying et al. ^[4] employed GM(1,1) and power function to predict the forest carbon sequestration in China, finding an accelerating increase from 2018-2060. Meanwhile, certain scholars suggested management strategies for carbon sequestration and climate mitigation. Profft et al. ^[5] analyzed tree species, timber diameter, and quality concerning carbon storage in wood products. They found forest management concepts and wood processing lead to varying lifespans of the wood products. Bravo et al. ^[6] discovered that the sustainable forest management paradigm in Almazán can increase or maintain forest carbon stocks while ensuring a constant annual yield of goods. Ontl et al. ^[7] introduced the Forest Carbon Management Menu to help forest managers, including increasing the extent of forest ecosystems, and so on.

However, the research on forest management plans best for society is limited. Therefore, it is necessary to develop an easily understandable carbon sequestration model and forest management plans balancing various aspects.

1.4 Our Work

The process of modeling is shown in **Figure 3**. First, we use a non-linear optimization model to maximize carbon sequestration. Second, we apply AHP-CRITIC to calculate EDI and SDI. Then we use k-means++ to determine the thresholds in the GE matrix. Next, we apply our models to five forests, choose Saihanba for further analysis, and write a non-technical newspaper article.

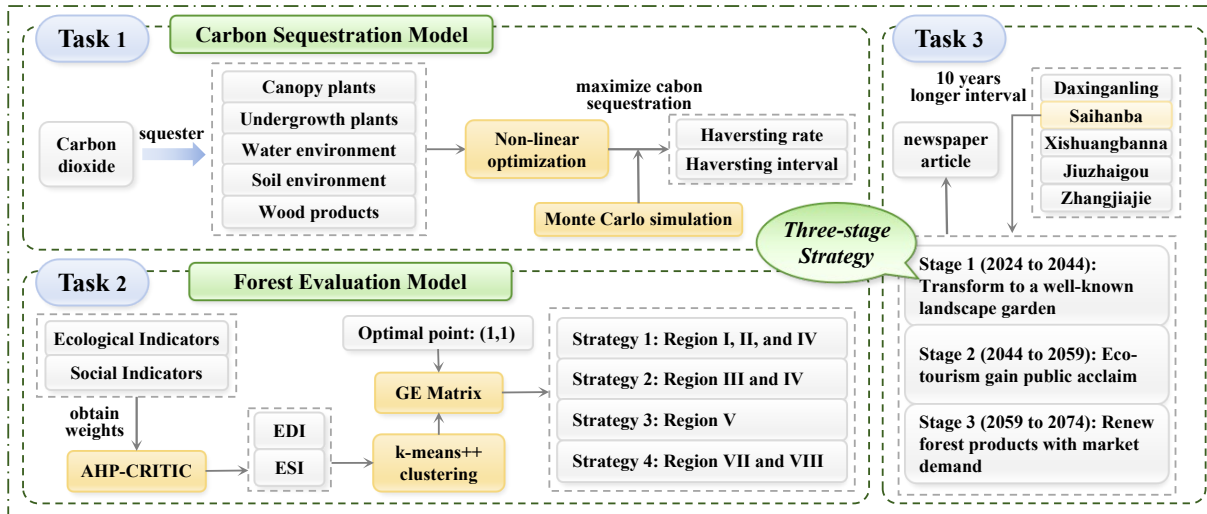


Figure 3: Flowchart of our study

2 Assumptions and Justifications

Carbon sequestration and forest development are complex in reality as they are influenced by many factors. To simplify the models and obtain useful conclusions, we make the following reasonable assumptions:

Assumption 1: The data we obtain from websites is accurate.

Justification: Our data are obtained from official websites and organizations (e.g. FAO and World Bank). It is reasonable to assume the data is of high quality.

Assumption 2: Plant growth and mortality rates follow objective developmental patterns, and the size of forests will not change significantly under natural conditions.

Justification: The probability of chaos, anomalies, and unscientific explanations in nature is very small.

Assumption 3: There will be no sudden global events such as large forest fires in the short term.

Justification: The likelihood of sudden events is low, and the environmental situation is stable enough to assume that occasional localized environmental damage will not affect the whole environment of the forest.

Assumption 4: The correlation between selected indicators is low and can reflect the development of forests.

Justification: The indicators are differentiated and multifaceted. It is reasonable to assume they can reflect the true state of the forest.

3 Notations

Some important mathematical notations used in this paper are listed in **Table 1**.

Table 1: Notations used in this paper

Symbol	Description	Unit
G	Regional carbon sequestration	t
ω_{AHP}	The weight obtained by the AHP method	/
ω_{CRITIC}	The weight obtained by the CRITIC method	/
EDI	Ecological Development Index	/
SDI	Social Development Index	/
θ	Threshold of GE matrix	/
d	Distance score to the optimal point in the GE matrix	/

*Some variables not listed here will be discussed in each section.

4 Carbon Sequestration Calculation and Maximization

4.1 Carbon Sequestration Model

After reviewing various sources, we categorize forest plants by size into three types: **canopy** plants, **undergrowth** plants, and **ground cover** plants. Canopy plants include a variety of common trees such as oak, maple, pine, spruce, fir, beech, birch, and others. Undergrowth plants comprise shrubs, smaller woody plants crucial in many forest ecosystems for carbon dioxide sequestration. Ground cover plants consist of ferns, wildflowers, mosses, and lichens. Ferns typically thrive in moist, shaded forest areas, while mosses and lichens, non-vascular plants, commonly colonize rocks, tree bark, and other forest surfaces. The carbon sequestration by ground cover plants is categorized as soil sequestration.

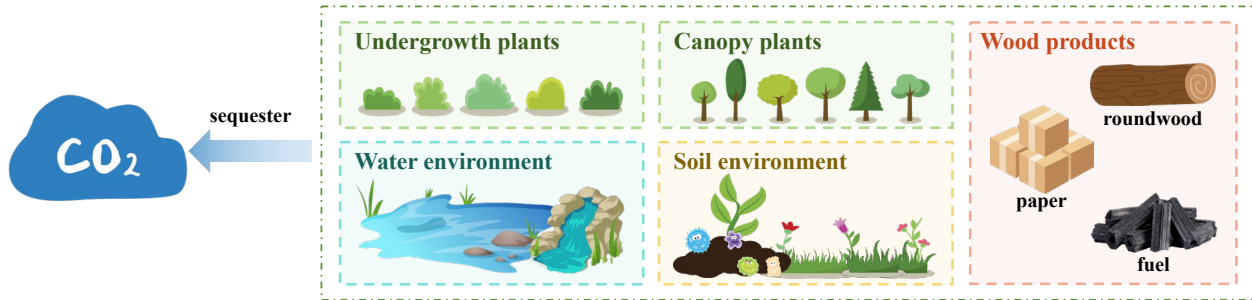


Figure 4: Process of carbon sequestration

Figure 4 shows the process and components of carbon sequestration. Carbon dioxide is absorbed by different plants in the forest and by the soil and water environments. Among them, the soil environment includes soil, ground cover plants, and microorganisms.

Table 2: Notations used in carbon sequestration model

Symbol	Description	Unit
R_C	Amount of carbon in a carbon dioxide molecule (27.27%)	/
S_i	Forest cover area in the i -th year	hm^2
B_y	Net measured forest productivity	$t \cdot hm^{-2}$
F	Forest ecosystem services correction factor (usually 1.01)	/
ε	The ratio of carbon sequestration in undergrowth plants to canopy plants	/
β_i	Carbon sequestration change rate per forest area used for products	/
$f(i)$	Change rate of carbon sequestration of forest products with time	/
A	Carbon sequestration per unit area of soil ^[8]	$t \cdot hm^{-2}$
k_w	Carbon sequestration per unit area of water	$t \cdot km^{-2}$
S_w	Water cover area	km^2

The notations used in the carbon sequestration model are listed in **Table 2**.

Assume a forest cover area is S_0 at the beginning, then the forest cover area in i -th year S_i is calculated by

$$S_i = (1 + \alpha)^{i/\Delta t} S_0 \quad (1)$$

where α is the rate of accumulated change in forest cover area. It is the ratio of forest planted rate minus natural death rate minus harvesting rate λ to total forest area. The number of times this forest has been deforested is calculated by dividing evenly the total years i by the number of years Δt between each harvesting.

We classify wood products into three categories: **Roundwood** products, **paper** products, and **fuel** products. The roundwood products include timber used for construction and manufacturing purposes, such as building materials and furniture production. Paper products include cardboard, plywood, and pulp, among others. Fuel products include wood utilized for energy generation and heating applications.

For fuel and paper products, which are immediately used and eventually discarded as waste, their carbon sequestration decreases more rapidly over time. We have $f(i) = \frac{1}{\sqrt{2\pi}i^2}$. For roundwood products, typically utilized for buildings and furniture, carbon sequestration diminishes slowly over time. We have $f(i) = e^{-t}$.

Regional carbon sequestration encompasses the carbon sequestration of canopy plants G_c , undergrowth plants G_u , forest products G_p , soil G_s and water G_w :

$$\left\{ \begin{array}{l} G = G_c + G_u + G_p + G_s + G_w \\ G_c = \sum_{i=1}^t 1.63 R_C \times S_i \times B_y \times F \\ G_u = \varepsilon G_c \\ G_p = \sum_{n=0}^{i/\Delta t} (-S_{n\Delta t} \times \beta_i) f(i) \\ G_s = \sum_{i=1}^t S_i \times A \times F \\ G_w = k_w \times S_w \end{array} \right. \quad (2)$$

4.2 Result Analysis

We gather data from 217 countries worldwide and compute their carbon sequestration. Due to unavailable data in certain countries, we excluded them from the analysis. We find large differences in carbon sequestration across countries. It is mainly because of differences in forest area and management plans.

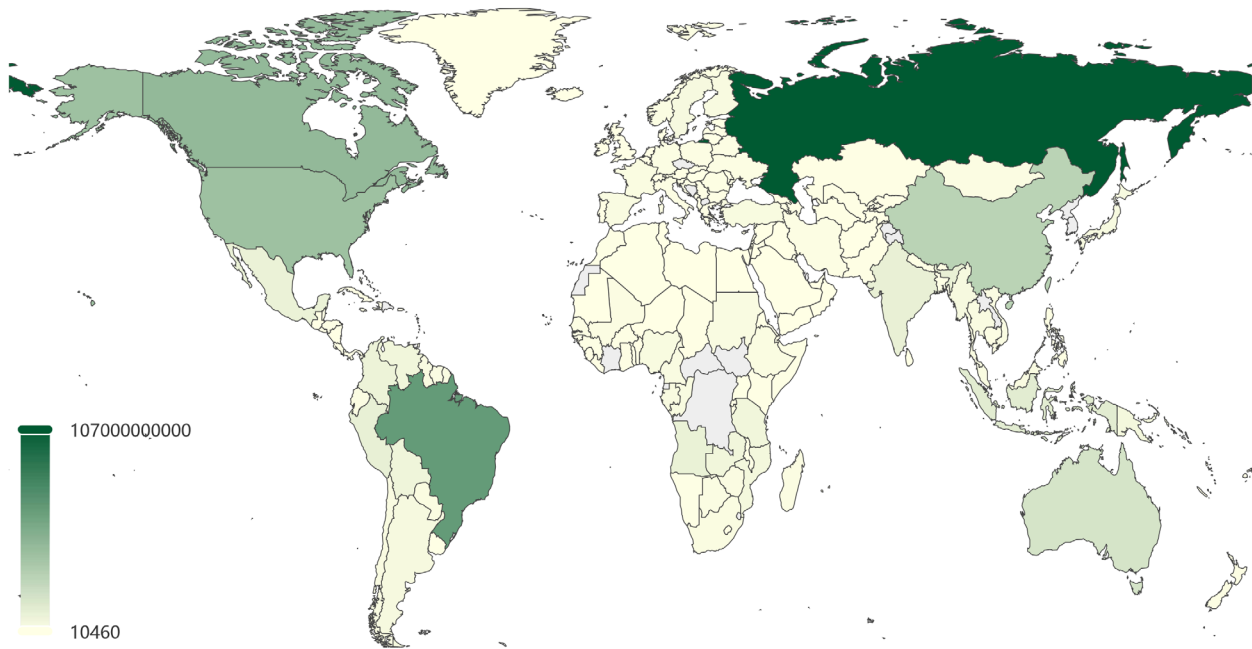


Figure 5: Carbon Sequestration in World

As shown in **Figure 5**, Russia has the largest carbon sequestration of **107** billion tons. This is mainly because Russia has extensive forested areas and low population density, which enable significant carbon storage within its forests. Brazil, Canada, the United States, China, and Australia are also prominent in global carbon sequestration. Specifically, Brazil's substantial carbon sequestration is closely connected to the Amazon rainforest, the largest tropical rainforest in the world. In contrast, countries in Africa and Western Europe display lower carbon sequestration. Sint Maarten (Dutch part), Greenland, and the Faroe Islands have the lowest carbon sequestration, not exceeding 50,000 tons. This is primarily due to limited forest coverage and relatively fewer environmental conservation efforts.

4.3 What is the Most Effective Management Plan?

Based on the data we gathered, forest area is often approximately a hundred times larger than river area, with forest plants being the dominant factor in the carbon sequestration model. To simplify the calculation, we ignore the fluctuation in watershed area over time. The carbon sequestration by canopy plants, undergrowth plants, forest products, and soil is influenced by the forest area.

To develop the most effective forest management plan, we choose harvesting rate λ and interval Δt as two decision variables. Then we develop a non-linear optimization model to maximize the overall carbon sequestration:

$$\begin{aligned} &\text{Maximize } G, \\ &\text{Subject to} \end{aligned} \tag{3}$$

$$\begin{aligned}
0.8S_0 &\leq S_i \leq 1.1S_0, \\
0 &\leq t \leq 100, \\
0 &\leq \lambda \leq 0.1.
\end{aligned} \tag{4}$$

Depending on the actual situation, we give some constraints. First, there is a restricted scope for alterations in forest cover from the original area. Second, we only focus on changes within a 100-year timeframe. Finally, to preserve ecological equilibrium, the rate of deforestation must not surpass 0.1.

Table 3: Data used in carbon sequestration maximization model

Data	America	Brazil	China	Colombia
Forest cover area (km^2)	1713000	496600	219900	59400
Water cover area (km^2)	17200	4900	2300	600
Net measured forest productivity ($t \cdot hm^2$)	6.5	6.4	6.4	6.3

Considering data availability and geographic location, we choose four countries, **America**, **Brazil**, **China**, and **Colombia** for study. The data used in the calculation is in **Table 3**. We then use **Monte Carlo** simulations to obtain λ and Δt that maximize carbon sequestration.

Table 4: Results of four countries

Result	America	Brazil	China	Colombia
Deforestation rate λ	0.0332	0.0519	0.0661	0.0213
Deforestation intervals Δt (year)	11.32	43.45	88.06	11.67

The simulation results are in **Table 4**. To maximize carbon sequestration in Colombian forests, forest managers need to harvest **0.0213** of forest area every **11.67** years. Similarly, American managers need to harvest 0.0332 of forest area every 11.32 years. In addition, Brazilian managers need to harvest 0.0519 of forest every 43.45 years. The harvesting interval is four times higher than those of America and Colombia. Even more, Chinese managers need to harvest 0.0661 of forest every 88.06 years. The harvesting interval is twice that of Brazil.

The most effective management strategies vary widely among the four countries. America has the largest forested areas, where trees grow faster, and net forest productivity is higher. Colombia has abundant tropical rainforest, where plants are more likely to grow quickly and have higher net forest productivity. For both countries, wood needs to be made into forest products promptly to extend carbon sequestration. China and Brazil, with intermediate forest area and net forest productivity, have slower wood growth rates and therefore longer harvest intervals.

In summary, forest managers need to develop management policies based on forest area, tree growth rate, water and soil conditions. Our nonlinear optimization model can derive harvest rates and harvest intervals to maximize total carbon sequestration.

5 Forest Evaluation Model

5.1 Indicators Selection

We should consider not only carbon sequestration but also the social benefits of forests. Therefore, we need to choose indicators to value both the ecological and social development of forests. Then, forest managers can make informed decisions by balancing these factors.

5.1.1 Ecological Development Indicators

Forest cover rate is the share of land area covered by forests and reflects the level of forest development. The greater the forest cover rate, the denser the vegetation. More vegetation can prevent soil erosion and maintain biodiversity. Therefore, it can reflect the level of forest development.

Above-ground biomass is the weight of the total amount of living organisms per square hectare of forest and reflects the forest's biodiversity. A larger above-ground biomass indicates a more complex food chain system with greater regulatory capacity. It therefore reflects the value of the forest in maintaining ecological balance.

A verified forest area is an area of forest that is certified for sustainable use. This indicates the long-term viability of the forest. Healthy and stable forest conditions increase ecological benefits such as soil and water conservation and carbon sequestration.

Air pollution is the sum of emissions of nitrogen dioxide and methane. The higher the emissions of air pollution gases, the lower the level of air purification in that forest. This indicator reflects the ecological effectiveness of the forest in cleaning up the environment.

Carbon sequestration is the mass of carbon elements absorbed by the forests over a given period. The greater the carbon sequestration, the greater the capacity of the forest to absorb carbon dioxide. More carbon sequestration can mitigate global warming, reflecting the ecological value of forests.

The summary of ecological development indicators is in **Table 5**.

Table 5: Forest development indicators description

Indicator	Description	Unit
Forest cover rate	Share of land covered by forest	hm^2
Above-ground biomass	Tones of above-ground forest biomass per hectare	$t \cdot hm^2$
Verified forest area	The area of forest certified for sustainable use	hm^2
Air pollution	The sum of emissions of NOx and methane	ton
Carbon sequestration	Total carbon sequestration	ton

5.1.2 Social Development Indicators

Forest product refers to the weight of wood used to make forest products. The more forest products there are, the greater the social demand and the more value is created. Therefore, the quality of forest products can reflect social development.

Tourism revenue refers to the tourism income generated by forests. The higher the tourism revenue, the more cultural and recreational experiences the forest brings to people. Tourism revenue is therefore a measure of the social benefits of forests.

Life satisfaction refers to how satisfied people are with their lives and is a subjective score on a scale of 0 to 10. The recreational and cultural values that forests bring can enhance the life satisfaction of people.

The forest industry is the share of forestry output. The more developed the forestry industry is, the greater the market share and the greater the social benefits it brings.

The protected forest rate refers to the percentage of forest area that is protected. The higher the protected forest rate, the greater the importance that people attach to it and the higher the cultural value that the forest brings.

The summary of social development indicators is in **Table 6**.

Table 6: Society development indicators description

Indicator	Description	Unit
Forest products	Weight of wood used in the manufacture of forest products	<i>ton</i>
Tourism revenue	Tourism value created by forests	<i>dollar</i>
Life satisfaction	Self-reported Cantril ladder score	/
Forest industry	Share of forestry production	/
Protected forest rate	Share of forest area that is protected	/

5.2 Data Collection and Pre-processing

The data sources are crucial in calculating carbon sequestration and evaluating forests. We collect diverse forest data from 42 countries from reputable databases (listed in **Table 7**) to ensure accuracy and reliability.

Table 7: Data sources used in this paper

Name	Website
Our World in Data	https://ourworldindata.org/
The World Bank	https://data.worldbank.org/
Easy Professional Superior	http://olap.epsnet.com.cn/data-resource.html#
Food and Agriculture Organization	https://www.fao.org/faostat/en/#data/FO

5.2.1 Data Filling

For missing data, we need to fill it in to ensure the availability of the dataset. If there are values before and after the missing value, we use **mean padding**. If only one end has data before and after the missing value, we use **proximity padding**.

5.2.2 Data Normalization

The data in each column will be transformed to a common scale from 0 to 1 after normalization. We adopt different normalization methods after analyzing the data carefully.

For positive indicators, we process them by **min-max normalization**. Each value x_i subtracts the minimum value:

$$\hat{x}_i = \frac{x_i - x_{\min}}{x_{\max} - x_{\min}}, \quad (5)$$

where \hat{x}_i is the normalized value of the data point x_i , x_{\min} is the minimum value of the i -th indicator, and x_{\max} is the maximum value of the i -th indicator.

For negative indicators, we process them by **reverse min-max normalization**. Each value x_i is subtracted from the maximum value:

$$\hat{x}_i = \frac{x_{\max} - x_i}{x_{\max} - x_{\min}}. \quad (6)$$

5.3 AHP-CRITIC for Forest Evaluation

We combine AHP and CRITIC to calculate the weights of forest development indicators. In this case, AHP compares the relative importance of each criterion, and CRITIC takes into account the correlation between the criteria. The combination of subjective factors and data characterization can better evaluate complex issues [9].

5.3.1 AHP

The Analytic Hierarchy Process (AHP) is a decision-making method that measures various criteria. We need to compare the relative importance of each two indicators for forest development.

Step 1: Establish the decision hierarchy. The first step is to determine the extent to which each indicator is impacted by the forest development.

Step 2: Pairwise comparisons. Compare each indicator with every other indicator in terms of their relative importance.

Step 3: Create the pairwise comparison matrix. Construct a matrix representing the pairwise comparisons. The matrix is usually square and symmetric.

Step 4: Calculate the priority weights. Determine the priority weights of indicators by computing the geometric mean or eigenvector method based on the pairwise comparison matrix. The weight of the i -th indicator is

$$\omega_i = \frac{\prod_{j=1}^5 a_{ij}^{1/5}}{\sum_{i=1}^5 \left(\prod_{j=1}^5 a_{ij}^{1/5} \right)}, \quad (7)$$

where ω_i is the priority weight of the indicator i , and a_{ij} is the pairwise comparison value between elements. From this, we obtain five indicators.

Step 5: Check consistency. The consistency ratio (CR) is calculated by comparing the consistency index (CI) with a random index (RI) for the given matrix size. The formula for CR is

$$CR = \frac{CI}{RI}. \quad (8)$$

If CR exceeds 0.1, we need to adjust the comparison matrix. Our CR is **0.0125** and passes the consistency test.

5.3.2 CRITIC

The CRITIC (CRiteria Importance Through Intercriteria Correlation) method is used for multi-criteria decision-making. It considers the inter-criteria correlations rather than relying solely on the decision-maker's subjective judgments. The CRITIC weight is calculated by

$$\omega_i = \frac{1}{5} \frac{\sum_{j=1}^5 r_{ij}}{\sum_{i=1}^5 r_{ij}}, \quad (9)$$

where ω_i is the weight of the indicator, and r_{ij} represents the elements of the normalized correlation matrix. From this, we obtain five indicators.

5.3.3 Weight Combination

We combine two sets of weights that consider both expert knowledge and actual indicators. The final weights will be more reflective of the real situation. Based on Minimum Relative Information Entropy, the objective is minimizing the relative deviation of results under two decision methods ω_{CRITIC} :

$$\text{Minimize } \sum_{i=1}^5 \omega_i (\ln \omega_i - \ln \omega_{AHP}) + \sum_{i=1}^5 \omega_i (\ln \omega_i - \ln \omega_{CRITIC}), \quad (10)$$

Subject to

$$\begin{aligned} \sum_{i=1}^5 \omega_i &= 1, \\ \omega_i &> 0, \\ i &= 1, 2, \dots, 5. \end{aligned} \quad (11)$$

To solve this optimization problem, we construct the **Lagrangian function**:

$$L(\omega, \gamma) = \sum_{i=1}^5 \omega_i (\ln \omega_i - \ln \omega_{AHP}) + \sum_{i=1}^5 \omega_i (\ln \omega_i - \ln \omega_{CRITIC}) + \gamma \left(1 - \sum_{i=1}^5 \omega_i \right), \quad (12)$$

where γ represents the Lagrange multiplier. Then we can obtain the final weight by

$$\omega_i = \frac{(\gamma_i \alpha_i)^{0.5}}{\sum_{i=1}^5 (\gamma_i \alpha_i)^{0.5}}. \quad (13)$$

The weights of ecological development indicators and social development indicators are shown in **Figure 6** and **Figure 7**, respectively.

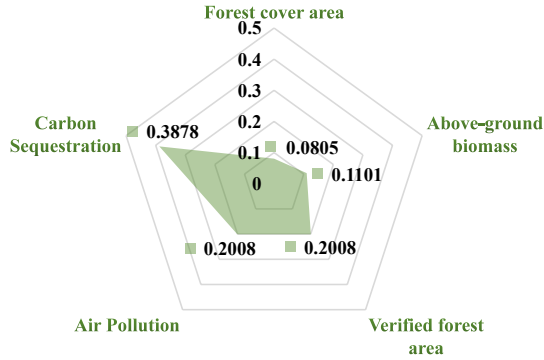


Figure 6: Weights of Ecological Development Indicators

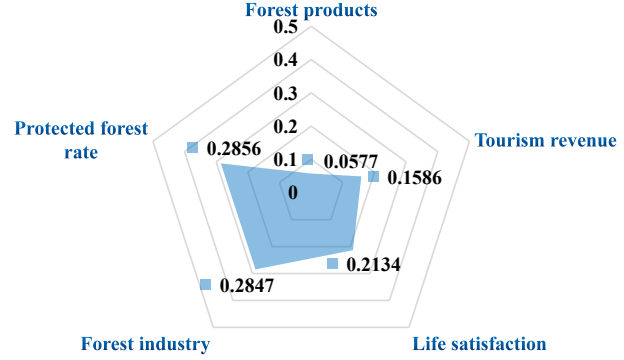


Figure 7: Weights of Social Development Indicators

5.4 Balanced Forest Management

Based on the evaluation above, we introduce the Ecological Development Index (EDI), which is calculated by

$$EDI = \sum_{i=1}^5 \omega_{1i} E_i, \quad (14)$$

where ω_{1i} is the weight of the i -th ecological development indicator, and E_i is the normalized i -th ecological development indicator. Similarly, we introduce the Social Development Index (SDI), which is calculated by

$$SDI = \sum_{j=1}^5 \omega_{2j} S_j, \quad (15)$$

where ω_{2j} is the weight of the j -th social development indicator, and S_j is the normalized j -th social development indicator.

5.4.1 K-means++ Clustering to Determine Thresholds

To distinguish the ecological and social development levels of forests in 42 countries, we put them into classes to find the transition points in forest management plans. First, we use the elbow method to split the 42 countries into three development levels: low, medium, and high. After that, we find the centers for each class using the k-means++ algorithm^[10]. The pseudocode is in **Algorithm 1**.

Algorithm 1: K-means++ Clustering**Input:** The number of clusters k , set of data points X , number of data points n **Output:** k cluster centers $\{c_1, c_2, \dots, c_k\}$

- 1: Randomly select the first cluster center c_1 from X
- 2: **for** i from 2 to k **do**
- 3: Calculate the minimum squared distance $D(x)$ from each data point to the nearest cluster center
- 4: Select the next cluster center c_i with a probability $\frac{D(x)^2}{\sum_{x \in X} D(x)^2}$
- 5: **end for**
- 6: Use $\{c_1, c_2, \dots, c_k\}$ as initial centers
- 7: Assign each data point in set X to the nearest cluster center
- 8: Recompute the cluster centers as the mean of the points assigned to each cluster
- 9: Repeat the above two steps until convergence

Then, we use the mean values between two of the three centers as thresholds θ_1 and θ_2 :

$$\theta_1 = \frac{c_1 + c_2}{2},$$

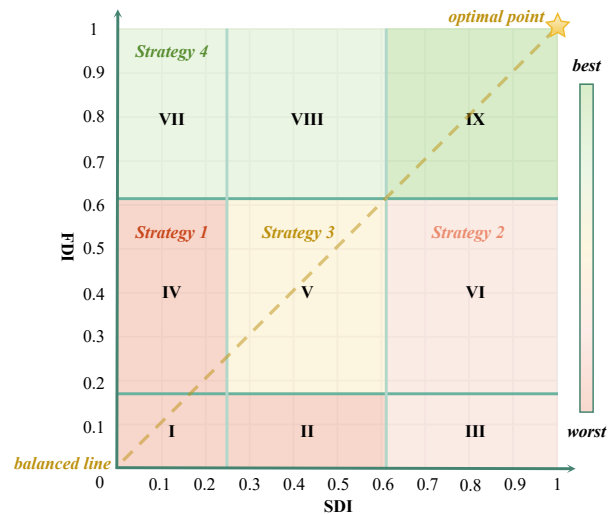
$$\theta_2 = \frac{c_2 + c_3}{2}.$$
(16)

5.4.2 GE Matrix and Transition Points

Using the k-means++ algorithm, we obtain the thresholds for each indicator in the 42 countries and then calculate the corresponding EDI and SDI thresholds, shown in **Table 8**.

Table 8: Threshold of development index

Index	Low	Medium	High
SDI	[0, 0.25)	[0.25, 0.61)	[0.61, 1]
EDI	[0, 0.18)	[0.18, 0.61)	[0.61, 1]

**Figure 8: GE matrix**

We use the **GE matrix** ^[11], also known as the McKinsey matrix, to present the balance between the ecological and social benefits of forest development. As shown in **Figure 8**, the closer the points on the matrix are to (1,1), the more balanced and stable the forest development is. While the closer the points are to (0,0), the less optimistic the outlook for forest development. Additionally, forests that are further away from the **balanced line** are all more unevenly developed. The GE matrix is split into nine regions, and we suggest four forest management plans for these regions.

Strategy 1: For forests in regions **I**, **II**, and **IV**, both SDI and EDI are low or medium level. Forest areas are still in their infancy. We recommend setting up relevant ecological and environmental protection groups, establishing nature reserves, and improve relevant legislation. Forest managers should encourage residents to return to farming, grazing, forests, and lakes, and **prohibit** any commercial forms of logging activities.

Strategy 2: For forests in regions **III** and **VI**, SDI reaches a high level at the cost of EDI. Excessive environmental exploitation led to significant degradation of the forests. Forest managers should take immediate action to **prohibit** harvesting and the destruction of biodiversity. They should improve the legislative mechanism, set up environmental protection groups and nature reserves, and encourage residents to plant trees to conserve water.

Strategy 3: For forests in region **V**, both SDI and EDI are medium level. Forest development is balanced. Forest managers can harvest trees according to the carbon sequestration model and plant trees in time to promote their growth. They can plant trees with short growth cycles and high economic benefits, such as poplar trees. Besides, they can develop eco-tourism. This paradigm can increase economic and social benefits without harming the ecological environment and promote the movement to region **IX**.

Strategy 4: For forests in regions **VII** and **VIII**, the EDI is high level, but the SDI is low or medium level. Forest managers should balance forestry values and social benefits, appropriately **open forest harvesting**, and sell forest products. At the same time, they can combine local characteristics and set up scenic excursion areas to attract foreign tourists and further create social value. We add a constraint $SDI \geq EDI \geq a \cdot SDI$ to the carbon sequestration optimization model, which ranges from 0 to 1 according to needs of forest managers and users. We then conclude that for this type of forest, an average of **6.46** years of harvesting **0.057** of the area can balance development.

5.5 Result Analysis for Locations

Geographical location is often closely related to climate and natural resources of a country. The utilization of natural resources determines the ecological and social development of forests. We ranked the EDIs and SDIs of 42 countries to examine the relationship between their ranking and geographic location.

Table 9: EDI rankings

Rank	Country	EDI
1	Brazil	0.5109
2	Ireland	0.4892
3	Austria	0.4142
...
40	Georgia	0.1493
41	Bangladesh	0.1324
42	Zimbabwe	0.0768

Table 10: SDI rankings

Rank	Country	SDI
1	Brazil	0.8763
2	Indonesia	0.6648
3	Slovenia	0.5944
...
40	Tunisia	0.0544
41	Mauritania	0.0224
42	Algeria	0.0133

In **Table 9**, **Brazil**, **Ireland**, and **Austria** have the highest EDI. These three countries are favorable for vegetation and biological growth because of their climate and topography. Among these, most of Brazil is a tropical climate with rich rainforest resources and biodiversity. Ireland has an oceanic climate conducive to forest growth and ecological stabilization of wetlands. Austria has part of the Alps, a mountainous terrain conducive to the growth of diverse forest vegetation.

Georgia, **Bangladesh**, and **Zimbabwe** have the lowest EDI. These three countries have poor forest development due to climate and natural disasters. Georgia is mostly located in high mountainous terrain and is affected by disasters such as avalanches and landslides. Bangladesh is affected by the monsoon, with heavy rains eroding the soil. The large population also leads to over-cultivation of land. Zimbabwe is in an arid region with insufficient rainfall and land degradation.

In **Table 10**, **Brazil**, **Indonesia**, and **Slovenia** have the highest SDI. These three countries utilize their rich forest resources to generate social benefits. Brazil has the Amazon rainforest, which can bring timber, medicines, and other biological resources to society. Indonesia is the tropical climate that provides abundant timber and attracts a great deal of ecotourism. Slovenia is committed to the sustainable management of its forests and attracts a large number of ecotourists. This generates tourism revenue and ecological benefits.

Tunisia, **Mauritania**, and **Algeria** have the lowest SDI. These three countries have arid climates and forest products are scarce. Tunisia has an arid climate with scarce forests and creates few social benefits. Mauritania is highly desertified and lacks water resources. Algeria also has an arid climate, which affects access to and profitability of forest resources.

6 Model Application and Management Strategies

6.1 Case Study in Chinese Forests

We use the carbon sequestration model and forest evaluation model for five forests in China:

- **Jiuzhaigou:** Jiuzhai National Forest Park is located in Sichuan Province and has a highland humid climate. It has a forest coverage of over 80%, which is a mixed coniferous and

broad-leaved forest, with the main species of oil pine and Huashan pine. There are many species of plants and animals in it, and the dense vegetation provides good living conditions for wild animals. It is also conducive to carbon sequestration and eco-tourism.

- **Saihanba:** The Saihanba National Forest Park is located at the junction of the Inner Mongolian Plateau and the mountains of northern Hebei. It is the largest man-made coniferous forest, known as the "Green Great Wall". Saihanba has various types of vegetation. They can prevent wind and sand, retain soil and water, and sequester carbon.
- **Daxinganling:** The Daxinganling is a vast area located in the northwestern part of Heilongjiang Province and the northeastern part of the Inner Mongolia Autonomous Region. It has more than 60% forest cover, is dominated by coniferous forests, and is rich in wildlife resources. The forest has a strong ability to protect water sources, maintain biodiversity, and sequester carbon.
- **Xishuangbanna:** Xishuangbanna is located in Yunnan Province and is rich in tropical rainforest resources. As a well-preserved primitive forest, Xishuangbanna has tall trees, dense shrubs, and a variety of tropical plants. It is one of the richest biodiversity areas in China.
- **Zhangjiajie:** Zhangjiajie National Forest Park is located in Hunan Province, which belongs to the middle-subtropical climate zone. There are high mountain valleys and dense forests, including all kinds of evergreen trees, deciduous trees, and tropical rainforest plants. It is a famous natural heritage and tourist mecca.

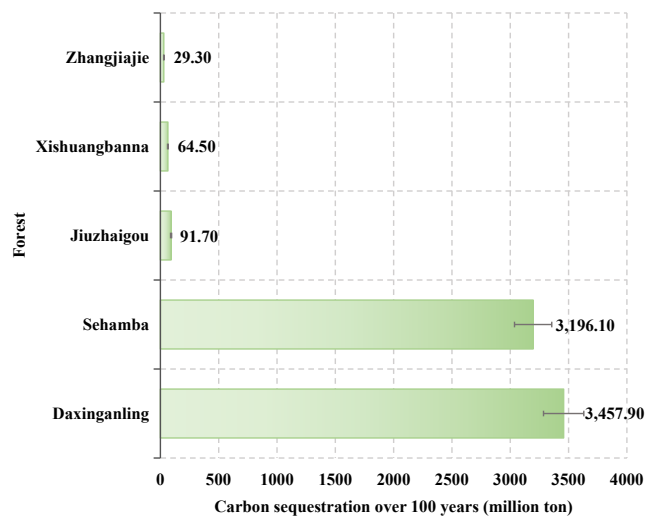


Figure 9: Carbon sequestration

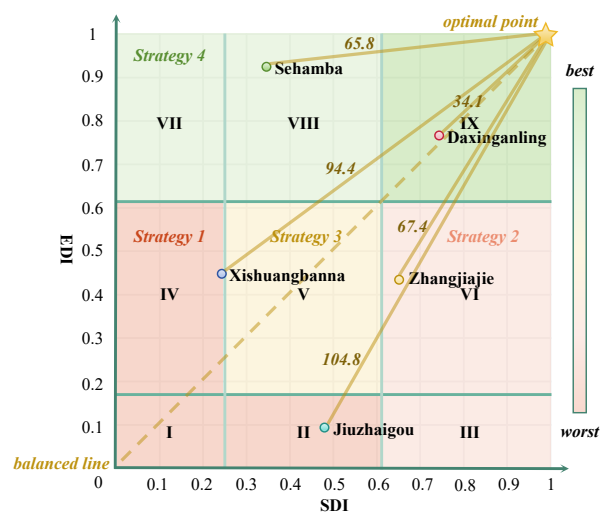


Figure 10: Five forests on the GE matrix

As shown in **Figure 9**, we calculate the carbon sequestration of five forests over 100 years and find huge differences. The Daxinganling has the largest carbon sequestration at **3,457.90** million tonnes. This is followed by the Saihanba, which sequesters **3,196.10** million tonnes of carbon. These two forests sequester ten times more than the other three. Zhangjiajie,

Xishuangbanna, and Jiuzhaigou sequester less than 100 million tonnes of carbon due to the small area of vegetation in these forests. In addition, these three forests are located in the southern part of China and are dominated by **broadleaf** forests. In contrast, Daxinganling and Saihanba are located in northern China and are **coniferous** forests ^[12]. They have acidic soils, cold weather, and slow decomposition of organic matter, which is conducive to organic matter preservation and carbon sequestration.

To compare the development of the five forests, we calculate their distance score d from the optimal point in the GE matrix:

$$d = \sqrt{(1 - EDI)^2 + (1 - SDI)^2} \times 100, \quad (17)$$

where d ranges from 0 to 141, a higher value indicates better development.

Figure 10 shows the location of five forests in the GE matrix and their distance to the optimal point. Daxinganling is in region IX and closest to the optimal point. It has high levels of both EDI and SDI and is very close to the balanced line. This indicates that Daxinganling has achieved balanced sustainable development. Next, Saihanba has the highest EDI, but the SDI is still at a medium level. This indicates that Saihanba overly focuses on forest ecological benefits and should create social benefits appropriately. On the contrary, Zhangjiajie is in region VI and has better social development, and the EDI is at a medium level. It shows that Zhangjiajie focuses more on the social benefits of forests and sacrifices some ecological environment. Finally, Xishuangbanna and Jiuzhaigou are both in the low to medium level and have unbalanced development. These two forest managers should take measures to change the status quo.

Based on our previous models and analysis, the Saihanba is in region VII. It shows that the EDI of Saihanba is high and the SDI is still in the middle level. Forest managers should take **Strategy 4** and open forest harvesting with a harvesting rate of **0.057** and an interval of **6.46** years. In addition, they can utilize forest products for more social benefits.

6.2 Saihanba Three-Stage Strategy Timeline

As shown in **Figure 10**, Saihanba has rich forest resources, but the social benefits are poor. Combined with the forest evaluation model, we calculate that the optimal harvesting rate for Saihanba is **0.085** when the harvest interval increases by ten years to **16.46** years. Therefore, we propose a **transition timeline** for Saihanba, aiming to build Saihanba into an international royal garden with beautiful natural and humanistic landscapes, high social benefits, and satisfaction. The effects of the three stages of our management plan are shown in **Figure 11**. The first stage of the transition will result in a slight decrease in EDI, but as the management strategy continues to advance, Saihanba eventually will reach the optimal region IX.

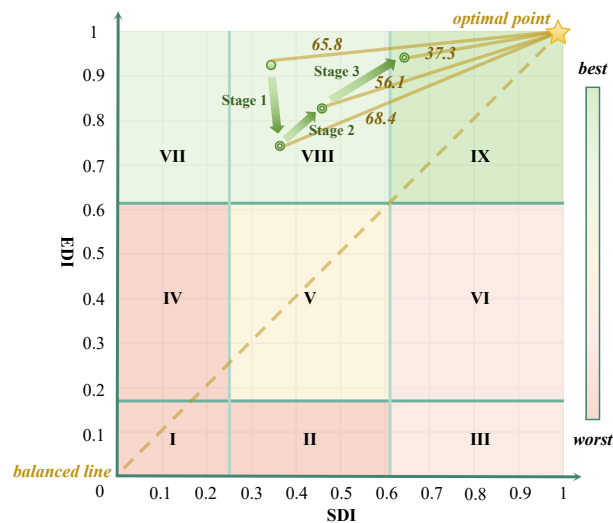


Figure 11: GE matrix of timeline

6.2.1 Stage 1: 2024 to 2044

Saihanba will be transformed from an obscure royal garden to a well-known landscape garden. Forest managers should increase investment in landscape construction. They should increase the harvesting rate to 0.06, the interval to 8 years, and construct a forest product industry chain. Additionally, they should select forests and wetlands to develop eco-tourism without destroying the ecological environment. By 2044, forest products will increase by 1%, tourism revenue will increase by 200%, life satisfaction will increase by 2%, and the forest industry will increase by 1%. The SDI will reach **0.3662**, while the EDI will decrease to **0.7432**.

6.2.2 Stage 2: 2044 to 2059

The area of forests and the popularity of forest products in the Saihanba will increase. Eco-tourism will gain public acclaim. Forest managers should enhance the commercialization of forests and reforestation. In this stage, the harvesting rate will increase to 0.07, an interval of 12 years. Managers should flexibly change the sales strategy according to the market, considering both business and ecology. By the end of 2059, forest products will increase by 100%, tourism income will increase by 200%, life satisfaction will increase by 4%, and the forest industry will increase by 4%. The SDI will reach **0.4658** and EDI will reach **0.8274**.

6.2.3 Stage 3: 2059 to 2074

The forest area and social visibility of the Saihanba will increase significantly. Forest managers should continue to protect ecological diversity and renew forest products with market demand. By the end of 2074, the harvesting rate will be increased to 0.085, the interval will reach the expected 16 years, the forest products will increase by 40%, the tourism revenue will increase by 200%, the life satisfaction will increase by 4%, and the forest industry will be increased by 4%. The SDI will reach **0.6310** and EDI will reach **0.9434**.

7 Sensitivity Analysis

In reality, forest data changes over time and there may be some errors in the data we obtain. Our non-linear optimization model for carbon sequestration may have some bias. Therefore, we change the constraints to observe the changes in the **optimal harvesting rate**.

Additionally, we obtain the weights of indicators and EDI of 42 countries using the AHP-CRITIC method. Since the AHP method has subjective factors, we need to explore the impact of weight changes on the **EDI** results.

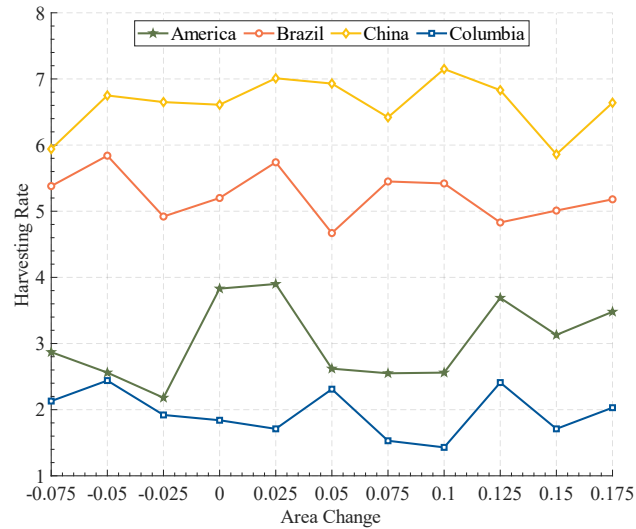


Figure 12: Carbon Emission

For the non-linear optimization model, we change the initial forest cover area from -7.5% to 17.5% in steps of 2.5%, then observe the change in optimal harvesting rate in four countries. As shown in **Figure 12**, the changes in forest cover area influence the optimal harvesting rate. However, the order of harvesting rates remains constant across countries. This shows that our model results are reliable. Our non-linear optimization model can help forest managers determine the optimal harvesting rate for carbon sequestration under uncertain forest areas.

For the AHP-CRITC evaluation model, we calculate the EDI of each country by changing the weights of carbon sequestration, the most important ecological indicator, in steps of 5% from -25% to +25%. In **Figure 13**, the EDI of each country fluctuates as the weight of carbon sequestration changes, and their order changes slightly. Overall, the order of countries remains unchanged as the weight changes. This proves that the results of our AHP-CRITC evaluation model are stable and reliable.

In conclusion, our non-linear optimization model and forest evaluation model are stable. They can provide forest managers with reliable results under input fluctuations. Meanwhile, our models can be **generalized** to climate change, ecological conservation, and other areas of decision-making, providing insights for sustainable resource utilization.

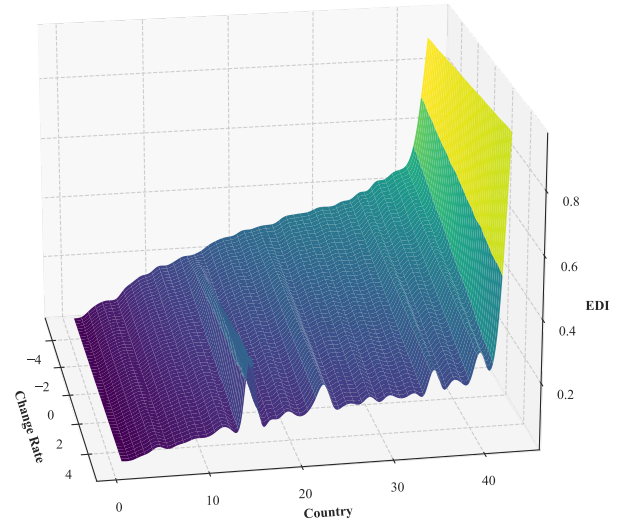


Figure 13: Carbon Emission

8 Model Evaluation and Further Discussion

8.1 Strengths

- In the non-linear optimization model for carbon sequestration, we consider the change in carbon sequestration over time for forest areas and different forest products. The model can give the harvesting rate and the corresponding intervals that maximize the carbon sequestration based on the actual data of the forest.
- The selection of indicators in the forest valuation model is comprehensive. We consider not only ecological indicators such as carbon sequestration and biodiversity but also social indicators such as human well-being and tourism revenue.
- We use the AHP-CRITIC method to calculate the final weights of each indicator by using minimized information entropy and Lagrange multiplier to combine the weights of objective and subjective indicators.

8.2 Weaknesses

- The non-linear optimization model for carbon sequestration is complex and requires a long time to compute the results by Monte Carlo simulations.
- The forest evaluation model contains many indicators, and the accuracy is dependent on the dataset, which may lead to some bias.
- The model does not account for unforeseen events such as hill fires occurring in the forest. Although the effect is small, it may still affect the accuracy of the model calculations.

8.3 Further Discussion

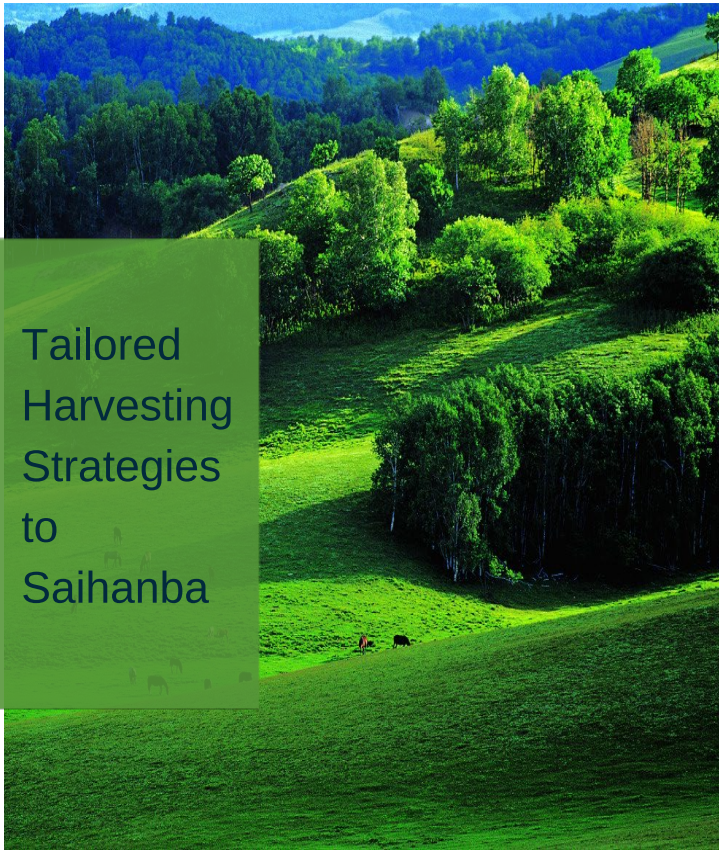
In the non-linear optimization model, we can consider sudden events to make the results more accurate and develop more specific harvesting strategies for different types of plants. In addition, we can apply our models to resource management problems in areas such as climate change and ecological conservation.

9 Conclusion

In this paper, we mainly developed a carbon sequestration model and used nonlinear programming to solve for the optimal harvest rate and harvest interval. Subsequently, we developed a forest evaluation model that considered the ecological and economic benefits brought by forests. We applied models to Daxinganling, Sehanda, Xishuangbanna, Jiuzhaigou, and Zhangjiajie. Then we proposed a three-phase strategy for the Saihanba, with rational harvesting of forests that can bring social benefits. Finally, we wrote a non-technical newspaper article about the Saihanba based on our conclusions.

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Tailored
Harvesting
Strategies
to
Saihanba

OPTIMIZED HARVESTING

By ICM Team #2422579

I. INTRODUCTION

In recent years, the debate around forest management has been polarized, with some advocating for complete preservation, while others promote various levels of deforestation. However, a recent study conducted by Team #2422579 reveals a nuanced approach, where strategic harvesting can enhance a forest's social value and its role in carbon sequestration.

II. UNDERSTANDING THE SCIENCE

Forests are more than just a collection of trees; they are dynamic ecosystems that play a crucial role in our planet's carbon cycle. Trees absorb carbon dioxide, a major greenhouse gas, and store it as carbon in their biomass. This process is known as carbon sequestration and is vital in mitigating climate change.

However, carbon sequestration efficiency and value of a forest do not depend entirely on the trees growing in the forest; Instead, carbon dioxide is sequestered longer when older trees are converted into products. Recent findings show that forests like the Saihanba, where many trees grow relatively quickly and have a small percentage of deforestation can boost the forest's social value by making some forest products as well as improving the carbon sequestration ability. This is because many fast-growing trees capture carbon rapidly but release it into the atmosphere quickly when they die and decompose. Timely harvesting ensures that the wood is used before this carbon is released as well as improving the social value of Saihanba forest.



Balances
Ecological
Needs with
Human
Use

III. THE LOCAL PERSPECTIVE

For local communities, this scientific harvesting approach of Saihanba can offer numerous benefits. Firstly, it supports sustainable forestry practices, ensuring that the forest can continue to provide resources for future generations. Secondly, it can create economic opportunities, such as jobs in sustainable logging and wood processing industries.

IV. BALANCING ECOLOGY AND ECONOMY

The proposed timeline management plans are carefully tailored to the ecological characteristics of Saihanba. In Saihanba, there exists an imbalance between its social and ecological value, the recommended deforestation strategies are tailored through the timeline, aiming to construct Saihanba as an elicit forest with maximum social and ecological value. This strategy ensures that forests continue to thrive and serve their vital role in the global ecosystem.

V. CONCLUSION

The idea of cutting down trees to save a forest might seem counterintuitive at first. However, when viewed through the lens of sustainable management and ecological science, it becomes clear that strategic harvesting is a responsible, beneficial approach. By adopting these plans, we are not just preserving our forests; we are enhancing their ability to combat climate change and sustain our planet for generations to come.

Report on Use of AI

OpenAI *ChatGPT*(Nov 5, 2023 version, ChatGPT-4)

Query1:

I want to search for a dataset containing data for each various forests such as area of that forest, water reserves, biomass, where should I search?

Output:

Food and Agriculture Organization of the United Nations (FAO)'s Global Forest Resources Assessment (GFRA): The FAO's regular GFRA reports contain detailed information on global forest resources, covering forest cover, forest types, biodiversity status, and trends in change.

World Resources Institute's (WRI) Global Forest Watch: This platform provides real-time data and tools on forests around the world, including information on forest cover change, fire monitoring, and forest conservation policies.

National Geographic Information System (GIS) Data Warehouses: Many countries and international organizations have publicly available GIS data warehouses that contain data on forest cover, land use change, etc.

International Union for Conservation of Nature (IUCN) and World Wide Fund for Nature (WWF): These conservation organizations often publish reports and data on globally important forests and ecosystems.

Scientific journals and research institutions: Look for journal articles and reports that publish research on forests, such as specialized publications like Forest Ecology and Management.

To find data directly, I recommend starting with FAO's Global Forest Resources Assessment and WRI's Global Forest Watch websites. These platforms provide easily accessible and usable data for the public, researchers, and policy makers. If you have a specific data need or want to keep up with the latest data, I can help you search online for the most up-to-date information.

Query2:

Does moderate deforestation increase carbon sequestration?

Output:

Whether or not moderate deforestation increases carbon sequestration depends on the management strategy and the recovery of the forest after deforestation. In some cases, moderate deforestation, accompanied by appropriate forest management, can indeed increase the carbon sequestration capacity of a forest, mainly through the following ways:

Improving forest health and productivity: Moderate felling removes diseased and weak trees and reduces in-forest competition, thus providing more space, light and resources for the remaining trees. This helps to improve the overall growth rate and health of the forest, making it more efficient at absorbing carbon dioxide.

Promote the growth of younger stands: Younger trees typically have higher growth rates and

greater carbon sequestration capacity. Through moderate felling and regeneration, forest regeneration can be promoted so that forests maintain a high rate of carbon absorption.

Biodiversity enhancement: Moderate logging can increase the diversity of species within a forest, thereby improving the overall stability of the ecosystem and its carbon sequestration capacity.

Carbon storage in wood: Cut wood can act as a carbon sink to store carbon over time if it is used for long-term purposes such as construction or furniture.

However, these positive impacts depend on the extent of logging, the method, and subsequent forest management practices. Excessive logging or inappropriate forest management can lead to forest degradation, loss of biodiversity and reduction of soil carbon pools, thereby reducing the carbon sequestration capacity of forests. It is therefore critical to balance the economic benefits of logging with ecosystem maintenance and carbon sequestration to ensure long-term sustainable forest management.

Query3:

Which type of forests belong to Xishuangbanna, Zhangjiajie, Daxinganling, Jiuzhaigou, and Sehanba forests?

Output:

Xishuangbanna: Located in the southern part of China's Yunnan Province, it is a tropical and monsoon rainforest. The forests here are characterized by high biodiversity, multi-layered forest structure and evergreen plants. The climatic conditions of Xishuangbanna make the forests here rich in tropical characteristic plants.

Zhangjiajie: Located in the northwestern part of China's Hunan Province, Zhangjiajie is a temperate deciduous broad-leaved forest. The forests of Zhangjiajie are characterized by a combination of peculiar stony landforms and rich vegetation, including many rare plants and wild animals.

Daxinganling: Located in northeastern China, it is a cold temperate coniferous forest. The forests here are dominated by red pine, larch and other coniferous species, making it a typical northern coniferous forest ecosystem.

Jiuzhaigou: Located in the northern part of China's Sichuan Province, Jiuzhaigou is a subtropical to temperate mixed forest. Jiuzhaigou's forests are characterized by colorful lakes, waterfalls and diverse vegetation, including larch and fir.

Sehamba: Located in the northern part of China's Hebei Province, Sehamba belongs to temperate coniferous forests and mixed coniferous and broad forests. The forests of Sehamba are a success story of artificial forestation, dominated by larch and birch species, which have important soil and water conservation and ecological functions.

The forests in these regions differ not only in plant types, but also in their ecological functions, climatic adaptability and biodiversity.