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Computer Decision Model for Maximum Carbon Sequestration Using Analytic Hierarchy Process and Fuzzy Comprehensive Appraisal

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Abstract: *With the advancement of global environmental governance system, the role of forests in carbon sequestration has become a hot topic of current research. We quantitatively analyze the carbon sequestration of selected forests by establishing a model which calculates the maximum carbon sequestration of forests based on age, tree species, geography, topography, the benefits and the longevity of forest products. In order to determine the best use of the forest and help managers to make decisions, we use Analytic Hierarchy Process (AHP) and Fuzzy Comprehensive Appraisal (FCA) to build a decision model that balances multiple values of the forest such as potential carbon sequestration, conservation of biodiversity, recreational use and so on. Clear water and green mountains are as good as mountains of gold and silver. Research shows that appropriate harvesting in forest management is reasonable. We hope to introduce rational harvesting into forest management so as to maximize the use of forests while making a significant contribution to the global environment.*

Keywords: *Carbon Sequestration, Forest Carbon Sequestration Model, Forest Best Use Decision Model, Analytic Hierarchy Process, Fuzzy Comprehensive Appraisal*

1. Introduction

Climate change presents a massive threat to life as we know it. To mitigate the effects of climate change, we need to take drastic action to reduce the amount of greenhouse gases in the atmosphere. We need to make efforts to enhance our stocks of carbon dioxide sequestered out of the atmosphere by the biosphere or by mechanical means. This process is called carbon sequestration. The biosphere sequesters carbon dioxide in plants (especially large plants like trees), soils, and water environments. Thus, forests are integral to any climate change mitigation effort. Forests have a critical effect on carbon storage, but it is worth considering how to improve its efficiency.

On a global scale, forest managers need to make forest management decisions that take into account carbon sequestration, forest outputs, and the multiple ways in which forests are valued. In forest management strategies, appropriate harvesting can be beneficial for carbon sequestration[2]. However, over-harvesting can have the opposite effect of limiting carbon sequestration. Therefore, forest managers must consider all factors to determine the appropriate deforestation plan to find a balance between the economic and ecological benefits of forests.

To further explore the relationship between forest carbon sequestration and forest management, this paper builds a carbon sequestration model and a decision model based on Analytic Hierarchy Process (AHP) and Fuzzy Comprehensive Appraisal (FCA)[1]. The whole modeling process can be shown in the figure 1.

At the same time, these models are used to determine a forest management plan that can balance various ways of forest value (including carbon sequestration), so that forest managers can understand the best use of the forest and better utilize and manage the forest to play its role.

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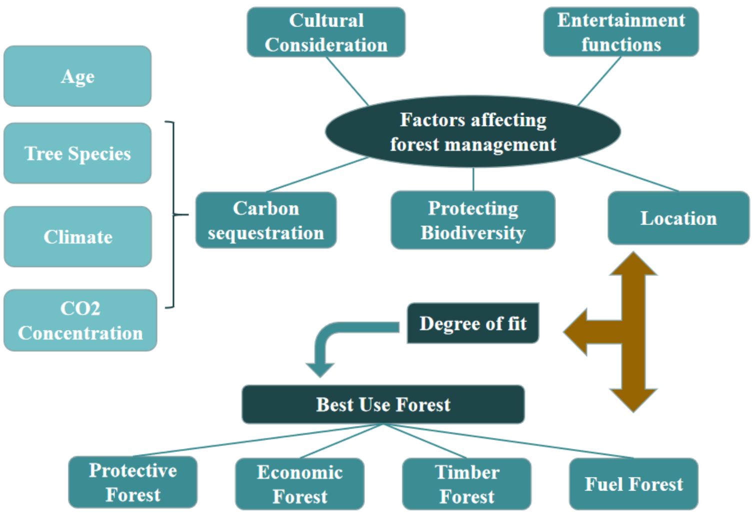

Figure 1: Model Overview

2. Materials and methods

2.1. Assumptions and Justifications

There is a broad and a narrow definition of forest. Forest in a narrow sense refers to tree resources, especially tree resources. In general, trees make up a larger proportion of the forest, compared with other parts, the benefits of trees for carbon sequestration are more obvious. So in our study, to simplify the measurement and calculation of forest carbon sequestration, soils and other biological components of the forest other than trees are not considered for the time being.

2.2. Notations

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

Table 1: Notations used in this paper

Symbol	Description	Unit
h	Years of forest management	year
m	Area of the forest	hm^2
n	The life cycle of forest trees	year
a	Carbon sequestration of young forests	t/hm^2
b	Carbon sequestration of middle-aged forests	t/hm^2
c	Carbon sequestration of mature forests	t/hm^2

2.3. Model I: Forest Carbon Sequestration Model

Based on the age composition of forest trees, people generally classify forests into the same-aged and uneven-aged forests[4]. However, through human management and planned harvesting, same-aged forests will eventually become uneven-aged forests after several years of long-term changes[3].

2.3.1 Premises and assumptions

In order to build models of carbon sequestration and to manage forests more scientifically, we make the following assumptions.

1) Based on the different growth states of trees at different ages, we divided the growth states of trees into three stages, young, middle-aged, and mature forests.

2) To meet market demand and achieve greater economic benefits, we make it a rule to carry out logging once a year.

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3) We specify that the trees to be cut each year are mature forests. Mature forests can be manufactured into a variety of products at the lowest cost and highest quality.

4) To calculate the carbon sequestration of forest products, it is assumed that the efficiency of conversion of forest product wood to products is 100%.

2.3.2 Data in Model

In order to build and apply this model, we need the following forest data.

· Years of forest management: h years in total

· Area of the forest: m acres

· The life cycle of forest trees: n years

· Number of years for each developmental stage: $y=\frac{n}{3}$ years

· The ratio of young, middle-aged, and mature forest: $e:f:g$; $e+f+g=1$

· The average annual carbon sequestration of young, middle-aged, and mature forests are a ton/acre, b ton/acre and c ton/acre

The area of young forest in year i is A_i, the area of middle-aged forest is B_i, and the area of mature forest is C_i.

2.3.3 Model building and solving

The beginning:

$$\text{Starting carbon stocks: } e\times m\times a+f\times m\times b+g\times m\times c \tag{1}$$

$$\text{Young forests: } A_0=e\times m \tag{2}$$

$$\text{Middle-aged forests: } B_0=f\times m \tag{3}$$

$$\text{Mature forests: } C_0=g\times m \tag{4}$$

$$\text{Products: } D_0=C_0\times x \tag{5}$$

In calculating the carbon sequestration of this forest, the starting carbon sequestration of the forest is first calculated as $e\times m\times a+f\times m\times b+g\times m\times c$.

Moreover, the starting area of the young forest is $A_0=e\times m$, the area of the middle-aged forest is $B_0=f\times m$, and the area of the mature forest is $C_0=g\times m$. Harvesting starts at the beginning and the product is $D_0=C_0\times x$.

The first year:

$$\text{Young forests: } A_1=\left(1-\frac{1}{y}\right)\times A_0+D_0 \tag{6}$$

$$\text{Middle-aged forests: } B_1=\frac{1}{y}\times A_0+\left(1-\frac{1}{y}\right)\times B_0 \tag{7}$$

$$\text{Mature forests: } C_1=\frac{1}{y}\times B_0+C_0-D_0 \tag{8}$$

$$\text{Products: } D_1=C_1\times x \tag{9}$$

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By iteration, the nth year:

$$\text{Young forests:} \quad A_n = \left(1 - \frac{1}{y}\right) \times A_{n-1} + D_{n-1} \tag{10}$$

$$\text{Middle-aged forests:} \quad B_n = \frac{1}{y} \times A_{n-1} + \left(1 - \frac{1}{y}\right) \times B_{n-1} \tag{11}$$

$$\text{Mature forests:} \quad C_n = \frac{1}{y} \times B_{n-1} + C_{n-1} - D_{n-1} \tag{12}$$

$$\text{Products:} \quad D_n = C_n \times x \tag{13}$$

Since the age composition of trees varies with time, the number of trees at different growth stages varies for each year of the forest. Since we have assumed that the number of trees of different ages at each growth stage is equally proportional, there will always be $1/y$ trees at each growth stage that will grow into the next growth stage. In addition, the mature forest trees that we cut will be replanted with an equal number of saplings to become trees in the juvenile stage, while the remaining uncut mature forest will remain in the mature stage the following year[5]. So we can calculate the number of young stands in the next year as $(1-1/y)$ the number of young stands in the previous year plus the number of mature stands that were cut in the previous year. The number of middle-aged stands in the following year is $(1-1/y)$ the number of middle-aged stands in the previous year plus $1/y$ the number of young stands in the previous year. The quantity of mature forest in the following year is the remaining quantity of mature forest from the previous year plus $1/y$ the quantity of middle-aged forest from the previous year. In h years, the total carbon sequestration in this forest is the difference between the carbon sequestered in the product obtained each year and the carbon sequestered by the trees in the growing state.

$$Z = \left(\sum D \times c\right) + A_n \times a + B_n \times b + C_n \times c - \left(A_0 \times a + B_0 \times b + C_0 \times c\right) \tag{14}$$

$$0 \le x \le 1$$

Bringing x into Z and taking values for x, we get the following graph of the forest's response to sequestered CO_2, thus giving us the most effective forest management plan for sequestered CO_2.

2.4. Model II: Forest Best Use Decision Model

2.4.1 Model Description

A forest system can contain a variety of forest values, including but not limited to carbon sequestration, biodiversity conservation, recreational use, and cultural impacts of the forest[6].The main values of the forest we judged are different depending on the location, climate, and soil conditions of the forest. The overall process of model building for determining the best use of the forest is shown in figure 2.

Figure 2: Model building flow chart

2.4.2 Model building

Following the principle of comprehensively reflecting the various values of the forest and facilitating the setting of the weights of each indicator, a secondary evaluation index system (figure 3) for evaluating the best use of the forest was constructed.

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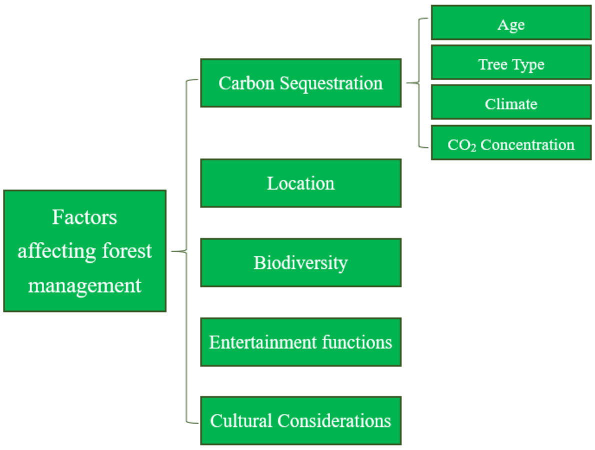

Figure 3: Factors affecting forest management

1) Determine the evaluation index set. As shown in the figure, each layer of evaluation factors for forest use is composed of an evaluation indicator set by its next layer of evaluation indicators. For example, the set of rating indicators for the final target layer is

U = {Carbon Sequestration U_1, Location U_2, Conservation of Biodiversity U_3, Recreational Use U_4, Cultural Consideration U_5 }

For "carbon sequestration U_1", the set of rating indicators is U_1 ={ Forest age U_{11}, Tree species U_{12}, Climate U_{13}, CO_2 Concentration U_{14} }.

2) Construction of judgment matrix. Organize experts to collect data, and discuss to determine the important relationship between the two indicators in each evaluation factor. Let U be the set of evaluation indicators, $U_i \in U$, $i = 1, 2, \cdots, n$. U_{ij} denotes the relative importance scale of factor U_i and factor U_j, and U_{ij} takes the values shown in the table. According to the table, the judgment matrix formed by the discussion is as follows. Where U is the judgment matrix among the five evaluation factors, and U_1 - U_5 is the judgment matrix among the evaluation indexes of each evaluation factor.

$$U = \begin{bmatrix} 1 & 3 & 6 & 6 & 6 \\ \frac{1}{3} & 1 & 2 & 2 & 2 \\ \frac{1}{6} & \frac{1}{2} & 1 & 1 & 1 \\ \frac{1}{6} & \frac{1}{2} & 1 & 1 & 1 \\ \frac{1}{6} & \frac{1}{2} & 1 & 1 & 1 \end{bmatrix} \qquad U_1 = \begin{bmatrix} 1 & \frac{1}{2} & 2 & 3 \\ 2 & 1 & 4 & 6 \\ \frac{1}{2} & \frac{1}{4} & 1 & \frac{3}{2} \\ \frac{1}{3} & \frac{1}{6} & \frac{2}{3} & 1 \end{bmatrix}$$

3) The columns of the judgment matrix are normalized, and the weight vector is finally obtained. That is the weight of each of the 5 evaluation factors.

$$W_u = \begin{bmatrix} 0.5455 \\ 0.1818 \\ 0.0909 \\ 0.0909 \\ 0.0909 \end{bmatrix} \qquad W_{u_1} = \begin{bmatrix} 0.2609 \\ 0.5217 \\ 0.1304 \\ 0.0870 \end{bmatrix}$$

After the evaluation index system is designed and the specific index weights are assigned, the fuzzy comprehensive evaluation method can be used to evaluate the forest use.

From the figure, it can be seen that the forest use evaluation index system consists of two levels:

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factor level and indicator level. Thus a multi-level fuzzy comprehensive evaluation must be used.

2.4.3 Decide the forest management plans

Based on the definition of forest management, we understand that the process of managing a forest should include making plans for cutting down trees and making decisions for regenerating the forest. Suppose a forest is evaluated and its usage is ranked as economic forest, timber forest, charcoal forest, and protection forest. When the local tree species, soil state, carbon sequestration, and social demand all reach saturation, the economic benefits of the output no longer grow continuously and reach a stable state, its advantages as an economic forest are no longer obvious[7]. At this time, we can act to change the type of its usage, such as changing the tree species or the logging plan and so on to make it into a timber forest.

3. Results and discussion

Through our investigation and research, eucalyptus is the most commonly planted tree species in human-managed forests. Therefore, we assume that the forest is a eucalyptus forest with an area of 10000 hm^2. The life cycle of eucalyptus trees is 21 years. We divided the growth state of the trees into three segments according to their life cycle, which are young forest ($0-7$ years old), middle-aged forest ($8-14$ years old), and mature forest ($15-21$ years old), and their ratios are 20%, 50%, and 30%, respectively. According to the dynamics of carbon stock of different forest ages in the figure, we take the average annual carbon stock of young forest as 42.65 (t/ hm^2), middle-aged forest as 78.23 (t/ hm^2), and mature forest as 122.56 (t/ hm^2), as shown in the figure 4.

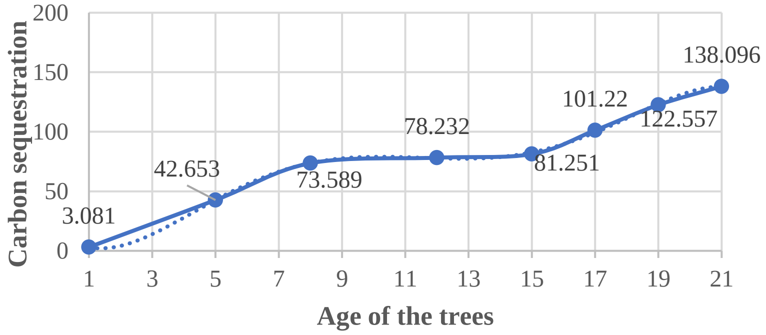

Figure 4: Carbon sequestration in eucalyptus of different forest ages

Assuming a 100-year horizon, with one cut per year and only mature forests cut, the cut rate is set to x $(0 \le x \le 1)$, and the total carbon sequestration is assumed to be z in 100 years.Finally, we get the best value of x is 53.21%.At the same time $Z = 11785000$,as shown in the figure 5.That is, the forest could sequester 11,785,000 tons of CO_2 over 100 years.

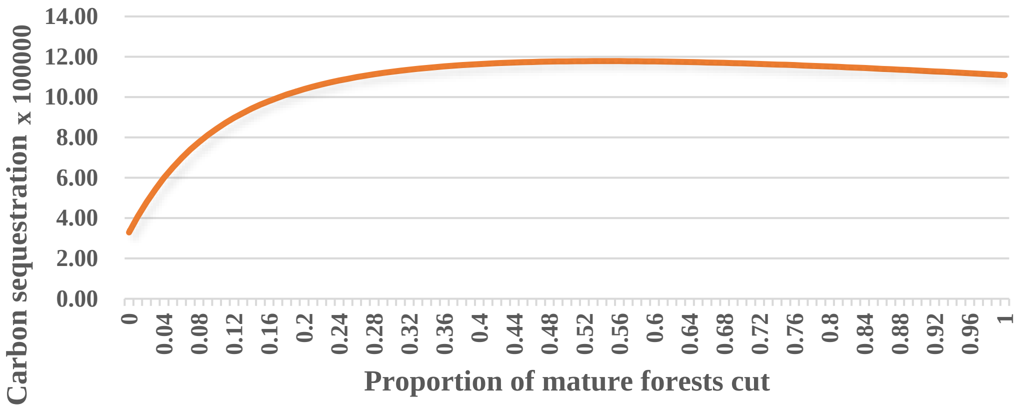

Figure 5: Changes in carbon sequestration in mature forests at different rates of harvesting

In order to determine the best use of this forest, we applied the modelIIto finally determine the type of its usage, the process is as follows.

Comment set A = {Economic forest, Timber forest, Protective forest, Fuel forest}

ISSN 2616-5775 Vol. 6, Issue 4: 77-83, DOI: 10.25236/AJCIS.2023.060410

Indicator set U ={Carbon sequestration U_1, Location U_2, Conservation of biodiversity U_3, Entertainment functions U_4, Cultural consideration U_5 }.

Carbon sequestration secondary evaluation indicator set U_1 = { Age U_{11}, Tree species U_{12}, Climate U_{13}, CO_2 Concentration U_{14} }

By calculating, the first-level indicator affiliation:

$$B_1 = \begin{bmatrix} 0.1917 & 0.2599 & 0.2281 & 0.3204 \end{bmatrix} \tag{15}$$

The second-level indicator affiliation:

$$B = \begin{bmatrix} 0.2304 & 0.3546 & 0.1774 & 0.2376 \end{bmatrix} \tag{16}$$

Based on the results of the above equation, we can get the highest affiliation of 0.3546, which means that the best use of this forest is timber forest.

We know that one growth stage of trees in this forest is 7 years, and when we increase the harvesting interval from 1 year to 11 years, all the middle-aged stands will grow into mature stands at the next harvesting point. Therefore, we can harvest all mature stands at each harvest point, which will allow the forest to maintain the maximum amount of carbon sequestration. In addition, we can expand the production of longer-lived forest products, such as furniture or building materials.

4. Conclusion

With the influence of the world's geography and air environment, people are gradually realizing the importance of reducing carbon emissions and absorbing and sequestering carbon dioxide in the air. On one hand, we promote the concept of green living to control carbon emissions. On the other hand, we absorb and store carbon by planting trees or studying mechanical means. However, some environmentally conscious people tend to believe that any deforestation is harmful to the environment. In fact, our research finds that reasonable deforestation helps increase carbon sequestration and protects the environment more effectively. Therefore, we use the Forest Carbon Sink Model and the Forest Best Use Decision Model to determine the best use of the forest and how to develop a reasonable deforestation plan so that the remaining trees in the forest can absorb carbon more efficiently and sequester more carbon at a certain rate over time. This will maximize the ecological benefits (carbon sequestration benefits) and economic benefits of the forest based on a trade-off between various ways of valuing the forest.

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