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A Forest Steward for Carbon Sequestration and Benefit

Yixuan Zhang[*]

School of Information and Communication Engineering, Beijing University of Posts and Telecommunications, Beijing, 100876, China

*Corresponding author: zhangyixuan0407@163.com

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Abstract: This paper analyzes the change in forest carbon storage over time by constructing a forest carbon storage model. Specifically, we constructed a model for predicting carbon sequestration rates and, based on the Gompertz model, a model capable of solving the annual carbon sequestration value of trees. A cellular automata (CA)-based forest growth simulation system simulates the stand growth and its carbon sequestration process. In addition, a quantitative model is obtained through the quantification of the indicators, and an optimal benefit decision-making model based on a genetic algorithm is constructed with the benefits model as the objective function. Finally, a sensitivity analysis was performed on the considered models.

1. Introduction

Global climatic change, a major scientific issue, presents a huge impact on the development of natural systems and society, affecting the future fate of mankind. In climate change research, the emission and absorption of greenhouse gases are of widespread concern. Fortunately, forests are excellent at sequestrating carbon, with vegetation absorbing carbon dioxide from animals, plants, soil, and water environments during their growth. Forests usually fix carbon in the form of biomass in plants and soil or products made from forest trees. Thus, forests are integral to any climate change mitigation effort. The forest ecosystem is the largest carbon pool in terrestrial ecosystems, which plays an essential role in global carbon ecological balance, mitigating the effects of climate change [1]. However, the excessive deforestation of forest resources emerges in an endless stream, and the loss of forest resources is equivalent to the emission of carbon dioxide, which destroys the ecological environment and the sustainable development of the forest.

An appropriate forest management strategy based on local conditions is essential to maintain biodiversity and long-term carbon balance [2]. In addition, sound forest management plans play a significant role in the sustainable management of forest resources at the regional and national scales, mitigating climate change, and maintaining climate stability.

As a natural carbon pool, forests are significant to the global carbon ecological balance and climate stability [3]. Forest resources continue to be depleted and coupled with the unreasonable felling of trees. Therefore, there is an urgent need to develop forest management strategies based on local differences in forests, climates, and populations worldwide. Through an in-depth analysis of this problem, taking into account the specific constraints that exist in the real world, the problem is reiterated: Developing a carbon sequestration model to determine the amount of carbon dioxide that forests and their products can sequester over time. Developing a decision-making model that considers the value of all aspects of the forest to inform forest managers on how best to use the forest. The model identifies a forest management plan that balances the value of the forest in terms of carbon sequestration capacity, economics, biodiversity, culture, and more.

This paper establishes a forest carbon sink simulation model based on forest carbon sink data. In addition, a decision-making model for maximizing forest value is established with value indicators such as forest carbon sequestration capacity. Finally, based on the above model, the paper evaluates the forest indicators and effectively develops a management plan for appropriate forest harvesting.

2. Carbon Sequestration Simulation Model for Forests

Based on the one-to-many modeling principle, we first simulate the carbon sequestration model of a tree. The sequestration capacity of a tree is influenced by various factors, among which the rate of sequestration is an important consideration. The variation curves of carbon sequestration rate with annual forest growth for different tree types are plotted in Fig.1.

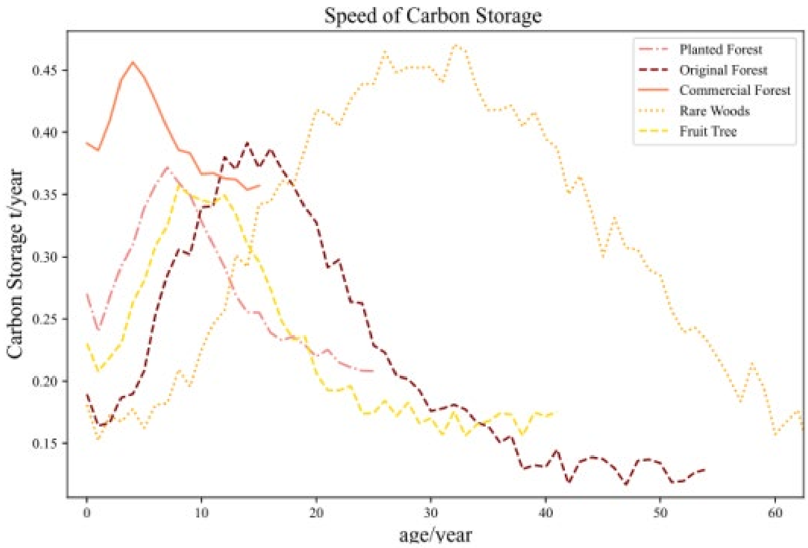


Figure 1 Speed of carbon storage.

From Fig.1, it can be seen that the general trend of carbon sequestration rate changed as trees grew up, with the rate increase and then slowing down, and different types of trees reached the maximum rate at different ages. After reasonable selection, we established the following models:

The height of a tree is described by the correct Weibull model, which can be expressed as:

$$\mathrm{H(T)} = H_0(1 - e^{-k_H T}) \tag{1}$$

where H_0 is the initial height of a single tree, k_H is related to the growth rate (both are greater than 0).

The volume of a tree is described by the Gompertz model, which can be expressed as:

$$\mathrm{V(T)} = V_1 e^{-k_V e^{-bT}} \tag{2}$$

where V_1 is the initial volume of a single tree, k_V is related to the growth rate. b is the shape parameter.

It is assumed that k_C is related to growth rate, carbon sequestration rate (CSR) of a tree is defined as follows:

$$\mathrm{CSR(T)} = \mathrm{B} \times \mathrm{M} \times k_C \times \frac{\mathrm{V(T)} e^{-k_C T}}{H(T)(1+Be^{-k_C T})^2} \tag{3}$$

Where M is related to the original value, k_C, B is connected to the rate of change.

The approach value of volume and height is limited by temperature. The model parameters are modified as follows:

For the height model, $H_0 = temp \times H_{00}$, $k_H = temp \times prec \times k_{H0}$.

For the volume model, $k_V = temp \times k_{V0}$, $\mathrm{b} = temp \times prec \times b$.

For the carbon sequestration rate model, $\mathrm{M} = temp \times prec \times M_0$.

To explore total carbon sequestration, we classify carbon sequestration into three categories, including soil, wood products, and standing forest stock, as shown in Fig.2.

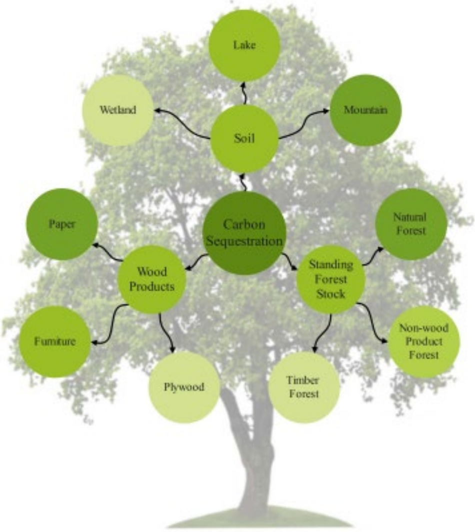


Figure 2 Carbon sequestration classification.

We use number i to describe different products. The probability that wood is used to make different products is $Cate_i$. In a year, wood volume for products is $\Delta \mathrm{Vw}$. Thus, carbon sequestration in products is as follows:

$$\Delta CSP = \Delta \mathrm{Vw} \sum_{i=1}^{N_{product}} Cate_i \times Loss_i \tag{4}$$

where $N_{product}$ for total categories of products, $Loss_i$ for loss during production.

Carbon sequestration in soil per year is defined as ΔCSS, which can be expressed as:

$$\Delta CSS = C_{conv} \times \Delta \mathrm{CSP} \tag{5}$$

Carbon sequestration in living wood per year is defined as ΔCSL, which can be expressed as:

$$\Delta CSL = \sum_{j=1}^{N_{tree}} CSR(T_j) \tag{6}$$

where T_j is the age of tree j, N_{tree} is the number of trees.

Therefore, we can calculate the annual increase of forest carbon sequestration, which can be expressed as:

$$\mathrm{CS} = \Delta CSP + \Delta CSS + \Delta CSL \tag{7}$$

Considering that a forest has different tree species in different growth stages, we design five types of grove models to splice them into a model that is more suitable for the actual forest state. We control the proportion of tree cutting in different groves and the distribution proportion of groves to simulate the model of forest carbon sequestration over time. The structure of our model is shown in Fig.3.

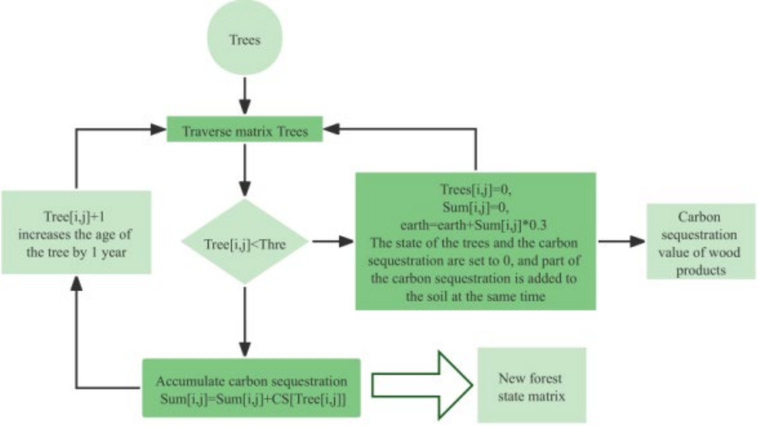


Figure 3 Flow chart of cellular automata.

Through the above model, we simulated the changes in the age composition of trees in the 1st year and the 100th year. We find that trees are, on average, younger in the presence of felling and sequestered carbon faster than mature forests. It also confirms that felling can achieve greater carbon sequestration benefits, as shown in Fig.4.

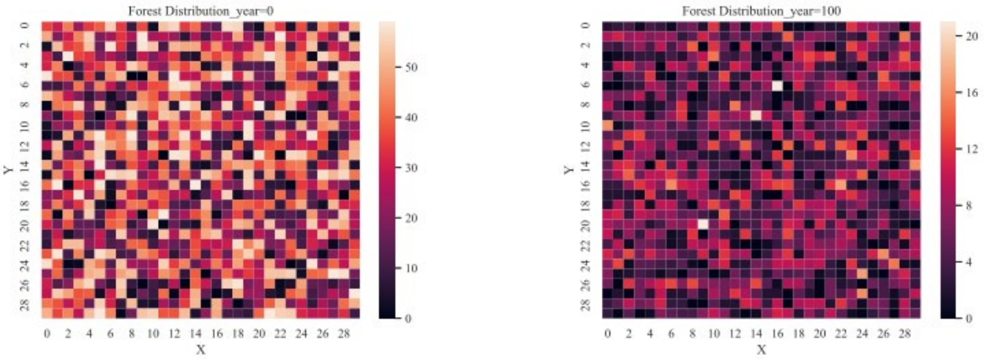


Figure 4 Age composition.

Based on the carbon sequestration model, we obtained the variation curves of forest carbon stock with different cutting times, which are shown in Fig.5.

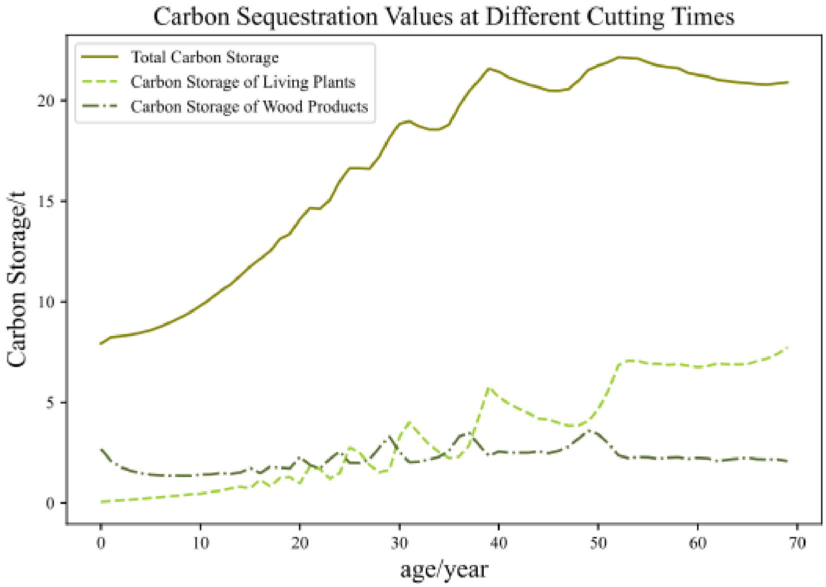


Figure 5 Carbon sequestration values at different cutting times.

From Fig.5, it can be seen that as the logging cycle increases, the carbon sequestration value of the forest fluctuates and tends to level off.

Based on the analysis of the visualization results, we believe that the forest can achieve relatively well carbon sequestration levels with a harvesting cycle of 25 to 45 years and a cutting ratio greater than 50%. To facilitate the analysis of the problem, we assume that a forest consists of three groups of different species (we take five groves) and that the total carbon sequestration value of the forest is the sum of the carbon sequestration values of each component. The change in the carbon stock of the forest over time is shown in Fig.6.

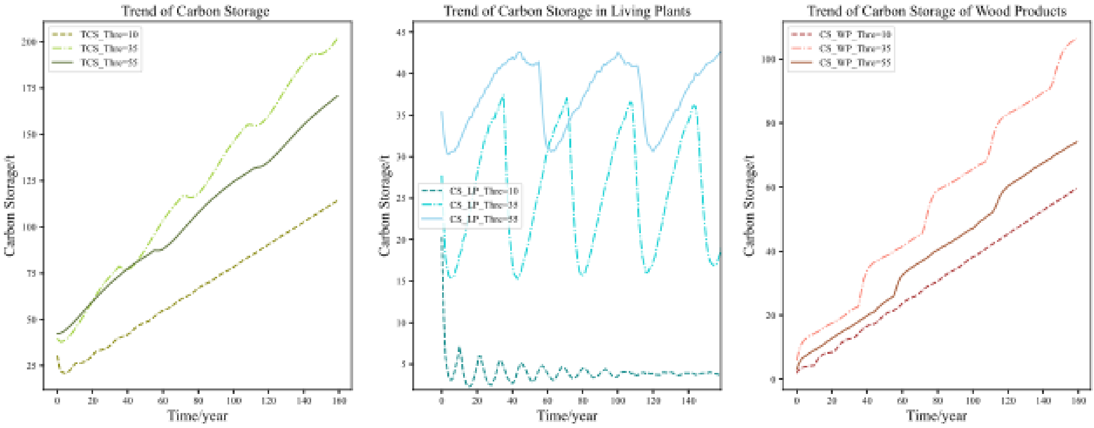


Figure 6 Trend of forest carbon storage.

3. Decision Model of Optimal Benefit

To maximize the value of the forest, we consider multiple aspects to construct a decision model. We consider tree planting and felling strategies and the impact of natural disasters and use economic, ecological, and social benefits as measurement indicators. Then balance the various value indicators of the forest, consider the sustainable development of the forest, and develop a forest management plan.

We use the market price method, shadow project, alternative project method, and the like to analyze the benefits of forest resources comprehensively. The comprehensive benefits of forest resources can be divided into economic, ecological, and social benefits. In each portion, we select specific indicators to analyze its benefits statistically.

The value of carbon fixation can be expressed as:

$$V_1 = CS \times C_{carbon} \tag{8}$$

Where C_{carbon} means carbon sequestration cost. The value can refer to the carbon tax price.

In recent years, with the intensification of global warming, people have used terrestrial ecosystem vegetation and soil to accumulate organic carbon to increase carbon storage in terrestrial ecosystems to slow down the rate of global warming. With the continuous development of the carbon sequestration economy, forest carbon sequestration has become an important assessment of forest value.

The value of oxygen release can be expressed as:

$$V_2 = 1.19C_{oxygen} \times S \times NPP \tag{9}$$

Where S(m^2) for the area of a forest, NPP($t/m^2 \cdot a$) for net primary productivity. Forests are the lungs of the earth and have the function of material transformation. Forest ecosystems release more than half of the oxygen released by terrestrial ecosystems [4].

The value of water conservation can be expressed as follows:

$$V_3 = 9.2C_{water} \times S \times (R - E) \tag{10}$$

Where C_{water}(\$/t) for the price of water, R(mm/a) for rainfall, E(mm/a) for evaporation.

Because of the water conservation function of the forest, 70% of the rainfall can seep into the ground. If there is no forest, there will be floods with rain and drought without rain.

The value of sterilization and purification can be expressed as follows:

$$V_4 = k_4 \times C_{live} \times V_l(\frac{1}{k} - 1) \tag{11}$$

where k_4 for proportion coefficient of sterilization value in the value of living trees, C_{live} (\$/m 3) for the price of living trees.

There are as many as 400 kinds of bactericidal substances such as alcohol, organic acid, and ether released by plant tissues in their natural state.

The value of noise reduction can be expressed as:

$$V_5 = 0.15 \times C_{forest} \times V_l \tag{12}$$

where C_{forest} (\$/m^3) for the average cost of afforestation, V_l (m^3) for tree stock volume.

The leaf structure is fluffy, and its crevices absorb sound energy.

The value of the soil can be expressed as follows:

$$U_1 = D_1 \times S \tag{13}$$

Where D_1(\$/m^2) refers to the annual cost of leasing a unit area of forest land.

The value of forest cultivation can be expressed as follows:

$$U_2 = D_2 \times N_{tree} \tag{14}$$

Where D_2 is the annual price of cultivating a tree, N_{tree} is the number of trees.

The value of timber output can be expressed as:

$$U_3 = D_3 \times V_w \tag{15}$$

Where D_3 (\$/m^3) for timber price, V_w for timber volume.

Forests perform their economic functions primarily by providing wood and other forest products [5]. Using a similar method, we can calculate all indicator values. Together, they constitute our evaluation indicator system.

The importance of each indicator may vary. By consulting expert data, we construct a pairwise comparison matrix. By using part of AHP, we calculate the weights of all our indicators.

Meanwhile, according to the consistency index:

$$\begin{cases} CI = \frac{\lambda_{max} - n}{n-1} \\ CR = \frac{CI}{RI} \end{cases} \tag{16}$$

Our weights pass the consistency test. Moreover, we get the final weights. Some are shown in Table 1.

Table 1. Weights of indicators

Indicator	Weight	Indicator	Weight
Soil	3.1%	Forest Cultivation	5.8%
Forest Output	8.0%	Timber Output	10.9%
Living Trees	10.0%	Carbon fixation	12.6%

NDVI is the abbreviation of Normalized Difference Vegetation Index. To a certain extent, it reflects the composition of plants in the area. Through the relationship graph in Fig.7, we guess that there is a positive correlation between NDVI and altitude.

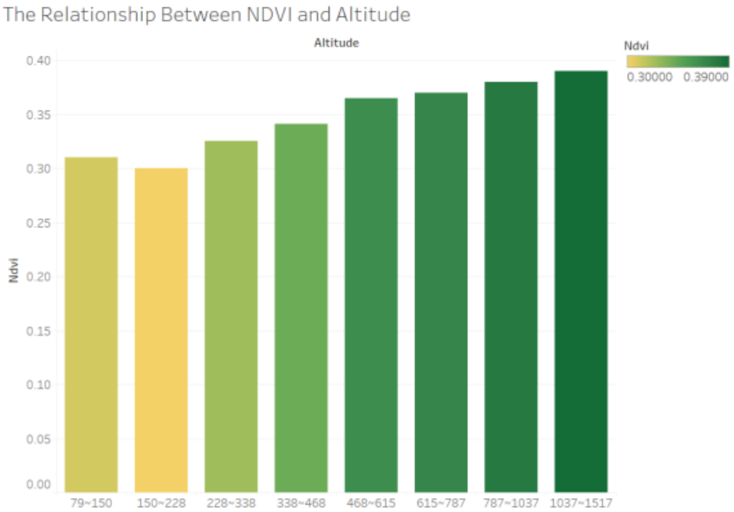


Figure 7 Relationship between NDVI and altitude.

The Pearson correlation test concluded that there is a moderate positive correlation between NDVI and altitude. Altitude changes determine the general terrain within the area.

Currently, based on the geographic location of the forest, we can determine the approximate proportions of its topography and thus the proportion of trees planted. The tree growth parameters are determined from the specific tree species in the forest [6]. Finally, our model can simulate the forest for up to 100 years, and the score over this process can be calculated. The score will serve as our primary basis for making forest management strategies. Therefore, the scope of our management plan mainly includes the composition of tree species in the forest, the proportion of planting during management, and the felling cycle.

We consider the differences between forests in the evaluation-decision model. In areas with harsh climatic conditions (cold and drought), the plants grow slowly, and the volume approach value is low. When acting as an economic forest, the cultivation value is compared with other values, and the loss of economic benefits is serious. For geographically isolated areas, timber prices are reduced by transportation. In desert areas, priority should be given to forests' ecological and social benefits, so it is necessary to reduce the proportion of economic forests and timber forests and increase the area of public welfare forests. Considering what local benefits the forest should play for different landforms, this is the transition point of the management plan. The topographic information of the forest is inquired through satellite, and the approximate vegetation type is obtained through GIS to formulate management plans according to local conditions.

4. Analysis of Forest Management Options

For forest managers, whether reasonable logging can make the forest sustainable is concerned. Therefore, by comparing diverse forests, we will develop a management plan for a forest in Guangxi Province, China, to promote sustainable development while promoting the value of the forest in that area.

Meanwhile, the analysis of the local research papers led to a local ratio of timber forest, economic forest, and natural forest of [3.3: 0.6: 2.4]. Timber forests are generally planted in hills and mountains with relatively high terrain, and their vegetation index (NDVI) is positively correlated with altitude. Economic forests and remarkable forests are generally located in the plains and hills with lower topography. The distribution of natural forests is concentrated in high mountains. In order to rationalize the tree felling cycle of the management program, we separately calculated the age of the most vigorous growth of different types of vegetation in different functional types of forests and averaged them, which is shown in Fig.8.

Figure 8 Age of trees.

We choose a genetic algorithm to search in the feasible domain, which can be expressed as:

$$\Phi = [w_1, w_{2,} w_3] \tag{17}$$

There are three variables to be optimized: the age at which trees in timber forests, economic forests, and natural forests are suitable for harvesting.

To prove that our optimization model can obtain the optimal value, reducing the influence of the instability of GA, we ran our optimization model several times independently and counted the optimal benefits of the optimal solution for each optimization. We put the best management plan obtained into the forest simulator to obtain the change curve of its carbon sequestration value over time, as shown in Fig.9.

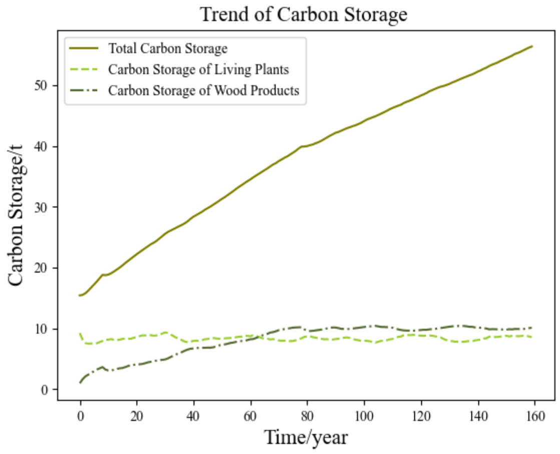
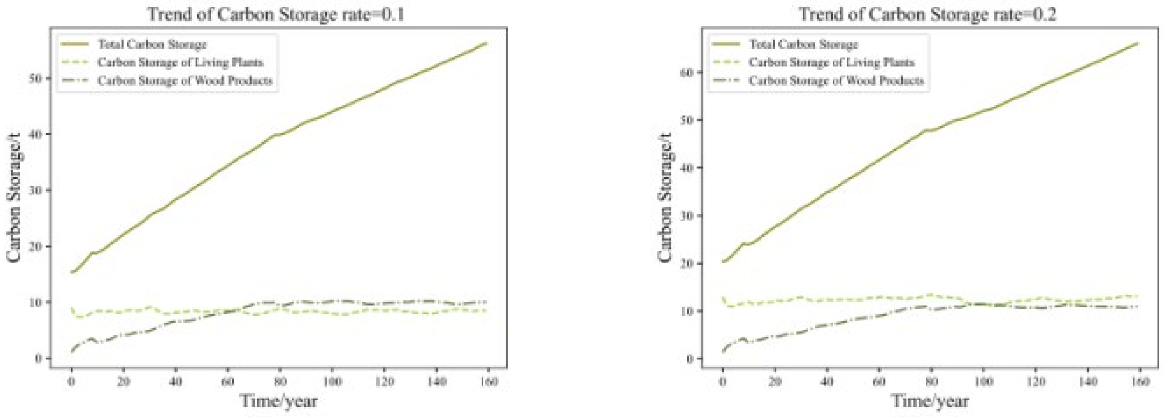


Figure 9 Trend of carbon storage in 100 years.

We test the sensitivity of the model by changing the initial proportion of rare trees in the forest and watching the changes in the amount of carbon sequestered by the forest model. By setting the ratio of rare tree species: 0.1 - 0.2, which is shown in Fig.10.



(a) Proportion: 0.1 (b) Proportion: 0.2

Figure 10 Trend of carbon storage (Proportion: 0.1-0.2).

As shown in Fig.10, the small fluctuation of the proportion of rare trees from 0.1 to 0.2 does not affect our model, and there is robustness.

By setting the ratio of rare tree species: to 0.5, the curves of carbon sequestration in the new forest are shown in Fig.11.

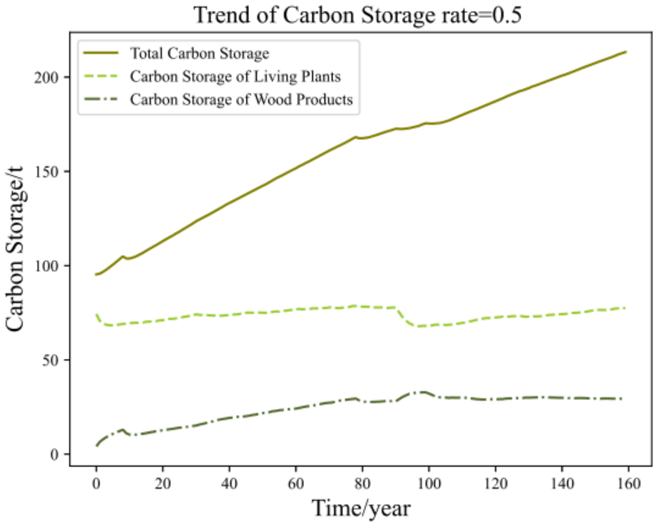


Figure 11 Trend of carbon storage (Proportion: 0.5).

From Fig.11, when we increase the planting ratio to 0.5, the output results produce drastic changes, which shows that the planting ratio of rare forests has an impact on the model.

5. Conclusion

This paper analyzes the change in forest carbon storage over time by constructing a forest carbon storage model. Carbon stocks in the largest forests tend to stabilize around deforestation cycles of 50 years and above. A quantitative model is obtained by quantifying the indicators, and an optimal benefit decision-making model based on a genetic algorithm is constructed with the benefits model as the objective function. Based on our decision-making model, in order to maximize the forest value, we choose the proportion of artificial timber forest and economic forest to be 74% and 26%, respectively, and the harvesting period of timber forest, economic forest, and natural forest are 60 years, 45 years and 113 years, respectively. Finally, a sensitivity analysis was performed on the considered models.

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