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Study on the Effect of Different Crop Rotation Cycles on Forest Carbon Sequestration Capacity Based on Carbon Sequestration Model

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Abstract: *Forests are extremely important ecological reservoirs and contribute significantly to the balance of global carbon cycling and carbon sequestration. In order to fully develop the carbon storage capacity of forests and consider the development of forest social efficiency, it is necessary to establish a reasonable model for the efficiency of forest carbon sequestration. The model should give effective management methods for different types of forests to replace the current widespread practice of over-logging or over-protection. We studied the carbon sequestration of forest vegetation and forest products separately and established a carbon sequestration model based on the effective area of forest. By simulating the effects of different rotation periods on forest carbon sequestration capacity, we conclude that a short rotation of about 10 years is most conducive to carbon sequestration in forests. On top of that, we extend the above evaluation model to the whole world, taking the Malaysian rainforest as an example to explore the best forest management model.*

Keywords: *Carbon sequestration model; Forecast model; Forest Management; The Thornthwaite Memorial model*

1. Introduction

Climate change presents a massive threat to life, and carbon emission greatly accelerate its process. To reduce the amount of greenhouse gases in the atmosphere, simply reducing greenhouse gas emissions is not enough. We need to make efforts to capture the carbon dioxide in the atmosphere by the biosphere or by mechanical means.

This process is called carbon sequestration [1]. The biosphere sequesters carbon dioxide mostly in large plants like trees, as well as soils, and water environments. Forests sequester carbon dioxide in living plants and in the wooden products created from them. These forest products sequester carbon dioxide for their lifespan. Forest managers must consider both environmental and social factors to figure out a management plan includes appropriate harvesting to make more carbon sequestration.

To figure out how to utilize and manage the forests, we are required to develop a carbon sequestration model to determine how much carbon dioxide a forest and its products can be expected to sequester over time. There are several challenges faced when we take details of forest environment and human society into consideration. The spectrum of management plans should be suggested by our decision model, which needs to illustrate that in which condition a forest should be left uncut. Suppose the best management plan includes a time between harvests that is 10 years longer than current practices in the forest, we are required to offer a strategy for transitioning from the existing timeline to the new timeline in a way that is sensitive to the needs of forest managers and all who use the forest.

2. Assumptions and notations

2.1. Assumptions

We use the following assumptions.

Assumption 1: It is considered that the carbon element in the xylem of a big tree comes entirely from the fixation of carbon in the air, and the mass of the xylem can be used to replace the mass of the tree itself.

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Assumption 2: For ease of model analysis, human rotation activity has no additional impact on forest homeostasis.

Assumption 3: The average wood is considered to be composed of 50% cellulose, 30% hemicellulose and 20% lignin.

2.2. Notations

Important notations used in this paper are listed in Table 1.

Table 1: Notations

Symbol	Description	Unit
S_e	Effective forest area	hm^2
S_c	Cutting area	hm^2
S_p	Planting area	hm^2
N	Carbon sequestration benefits	$kg \cdot s$
NPP	Net primary productivity of vegetation	$g \cdot m^{-2} \cdot a^{-1}$
M	Mass of fixed carbon in wood per unit mass	kg/m^2
$M1$	Carbon mass fixed per cubic meter of wood	kg/m^2
CR	consistent ratio	*Null*
C_i	fuzzy evaluation matrix in order of i	*Null*
KMO	Kaiser-Meyer-Olkin	*Null*

3. Carbon sequestration model

We established a carbon sequestration model with forest components and product types as parameters to evaluate the carbon sequestration efficiency of different types of forests.

3.1. Carbon sequestration analysis of forest vegetation

Under certain climatic conditions and human factors, the age structure of trees will change with time, resulting in changes in total productivity [2]. Figure 1 shows the relationship between the carbon sequestration capacity of trees and their age.

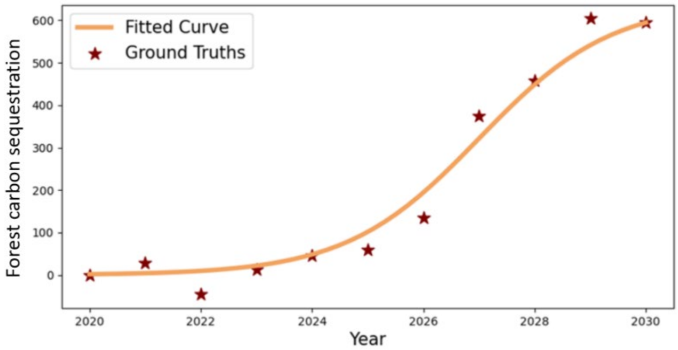

Figure 1: The curve of forest carbon sequestration over time

It can be found that the carbon sequestration rate of a single plant does not increase monotonously in the whole life cycle. It will first increase to a peak and then decrease to a lower level. Based on this, the overall carbon sequestration of the forest was solved.

The total area of the forest is assumed to be S_0, and remain unchanged due to timely reseeding after felling. We assume that in the natural state, the number of trees in different age groups follows a normal distribution, and the proportion of trees in the growing period is U, the following expression can be obtained as follows:

$$U = \int_0^{t1} \frac{1}{\sigma\sqrt{2\pi}} e^{\frac{-(s-\mu)^2}{2\sigma^2}} ds \quad \sigma > 0 \tag{1}$$

In the formula, t_1 is the tree growth cycle, σ is the standard deviation of the tree age, μ is

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approximately the average age of the trees in the forest.

The area occupied by the trees in the growing period in the forest is defined as the effective forest area, recorded as S_e, the effective forest area in the natural state can be calculated as follows:

$$S_e = US_0 = S_0 \int_0^{t1} \frac{1}{\sigma\sqrt{2\pi}} e^{\frac{-(s-\mu)^2}{2\sigma^2}} ds \tag{2}$$

Under natural conditions, the age structure of growing trees remains stable, so a fixed value can be defined as q_0 to characterize the average carbon uptake rate per unit of available forest area.

Then at any time t, the amount of carbon sequestered by growing trees is Q_0, calculated as follows:

$$Q_0 = S_e t q_0 = q_0 S_0 t \int_0^{t1} \frac{1}{\sigma\sqrt{2\pi}} e^{\frac{-(s-\mu)^2}{2\sigma^2}} ds \tag{3}$$

We cannot ignore the role played by mature trees in carbon sequestration and set their average carbon uptake rate as q, which is a relatively small value.

Let the carbon sequestration of a mature tree at time t be Q, calculated as follows:

$$Q = (S_0 - S_e)tq = qS_0 t \int_{t1}^{\infty} \frac{1}{\sigma\sqrt{2\pi}} e^{\frac{-(s-\mu)^2}{2\sigma^2}} ds \tag{4}$$

It is worth noting that there is no infinite tree age in the actual process, so the upper bound is taken as the maximum tree age value.

Define the area of trees felled in period t as ΔS_c, the effective area expansion value of forest caused by reseeding ΔS_e is equal to ΔS_c.

Before and after the implementation of logging, the original effective forest area did not change, and always consumed carbon in the air at a constant rate. After the cutting, the effective area of the newly increased forest immediately began to play a role in carbon fixation.

In practice, tree planting activities are mostly seedling transplanting or seed sowing, so in the newly added effective forest, the age structure of trees is concentrated in the young stage with relatively weak photosynthesis, and the average carbon absorption rate is recorded as a constant value q_1. Generally, there is $q < q_1 < q_0$.

After cutting, in any time of t, the effective forest carbon sequestration is Q_1. There is:

$$Q_1 = Q_0 + \Delta S_c q_1 t \tag{5}$$

During a time of t, the amount of carbon sequestered by mature trees during the period was Q_2, there is:

$$Q_2 = (S_0 - S_e - \Delta S_c)tq = Q - \Delta S_c tq \tag{6}$$

Thus, within a certain time t after each cutting, the total amount of carbon sequestration is:

$$Q_t = Q_1 + Q_2 \tag{7}$$

So, there is:

$$Q_t = Q_0 + Q + \Delta S_c t(q_1 - q) \tag{8}$$

Then the increment of carbon sequestration relative to the natural state is:

$$\Delta Q = Q_t - Q_0 - Q = \Delta S_c t(q_1 - q) \tag{9}$$

When $\Delta Q > 0$, cutting down mature trees and replanting the same amount can improve the carbon sequestration capacity of the whole forest in a period of time. The replanted saplings should be at a stage of growth where their carbon sequestration capacity is greater than that of the felled trees to ensure that $q_1 > q$.

To sum up, the felling methods that can maximize the forest carbon sequestration capacity are rotation felling and reseeding with a fixed cycle. The object of rotation felling should be the mature trees that are close to death, and the cycle is equivalent to the recovery time of the age structure forest. Besides, the reseeding trees should be in the age stage where the individual carbon sequestration capacity is greater than that of the old trees.

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3.2. Carbon sequestration models for forest products

The most important way to use woody plants is to make their xylem into wood. Wood processing waste is generally decomposed or incinerated, which will eventually be converted into carbon emissions, while processed products will continue to store carbon for a long time [3].

In order to evaluate the carbon sequestration capacity of wood processing products and compare it with the condition where trees embrace natural death, we use the product of carbon sequestration quality and sequestration time as the evaluation index N, the larger the value is, the stronger the carbon sequestration capacity of products have.

The average composition of processed wood is 50% cellulose, 30% hemicellulose, and 20% lignin. The molecular formula of the cellulose polymer is $C_6H_{10}O_5$, the molecular formula of hemicellulose is $C_5H_8O_4$, and of lignin is $C_9H_{10}O_3$.

Under ideal conditions, wood does not contain impurities except water, so the carbon content calculated by the relative atomic mass method is 49.155%。 For the convenience of calculation, we take the average carbon content of the anhydrous part of wood as 49%.

Generally speaking, the humidity of wood will be consistent with the ambient humidity, otherwise it will automatically absorb water or dry after a period of time. Define the moisture content of the wood as follows:

$$W = \frac{Gs-Ggo}{Ggo} \times 100\% \tag{10}$$

Gs is the weight of the wet wood and Ggo is the dry weight of the wood.

The average density of the wood is assumed to be ρ kg per cubic meter, the mass of carbon that can be fixed per cubic meter of wood is:

$$M = \frac{0.49\rho}{W+1} \tag{11}$$

For any species of trees, it is approximately considered that the mass m from maturity to death satisfies the following attenuation law with respect to time:

$$\mathrm{m} = a + \frac{1}{n+k(T_0-t)} \tag{12}$$

Among the equation above, T_0 is the remaining life expectancy of the tree, t is the time elapsed from harvesting until the tree dies naturally, a is the initial mass of the tree. n and K are parameters that vary from species to species.

Generally speaking, the part of mature trees that can be processed into wood accounts for about 90% of the total mass, and the water content of this part is about 50%. Assume that the remaining life of a tree is T_0, if the trees are not cut down, the remaining carbon sequestration titer is:

$$N = 0.45\int_0^{T_0} at + \frac{t}{n+k(T_0-t)}dt \tag{13}$$

And if the remaining life of this tree is T_0,when fully processed into a wood product with a service life of T_b, the carbon sequestration titer of the product is:

$$N_0 = 0.2205aT_b \tag{14}$$

At this point, as long as $N_0 > N$ is satisfied，it can be considered that product processing is beneficial to carbon sequestration.

To sum up, it is necessary to harvest older trees whose expected remaining life is below a certain threshold by rotation to produce timber [4]. The use of wood should be inclined to handicrafts and heavy furniture, or building materials, which are used for a long time, while minimizing the production of fast consumables such as paper, matches and disposable entertainment products.

3.3. Testing of carbon sequestration models

The main carbon stores in forests are in the soil and in the branches and leaves of trees. It is generally believed that soil carbon storage cannot be controlled artificially, while the carbon stored in trees can be converted through deforestation and vegetation restoration. Distribution of forest carbon storage is shown in Figure 2.

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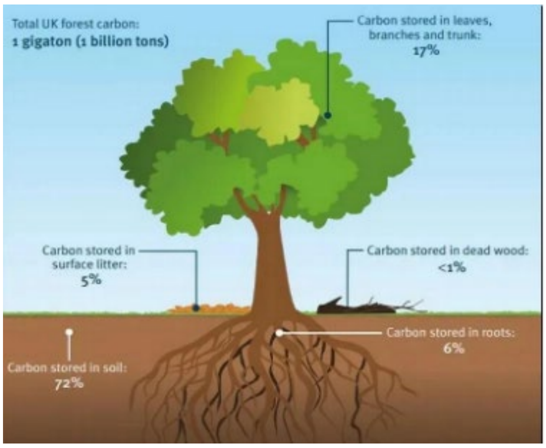

Figure 2: Distribution of forest carbon storage

Forecast model is a stand level model based on the process of forest ecosystem. We use this model to verify the above results. On this basis, the effects of different rotation periods on forest carbon sequestration capacity were simulated.

Data shows that in order to obtain better benefits, the rotation period of forests is generally between 10 and 35 years. To find the best rotation time, we set the rotation as short rotation of 10 years, normal rotation of 20 years, and long rotation of 35 years. The Density of trees is 2000 hm^{-2}, with a time span of 140 years.

According to the statistical results, we artificially set up the age sequence data of Chinese fir plantations under different site conditions. To evaluate the performance of the model, we calculated the model efficiency (ME) of this model:

$$ME = 1 - \frac{\sum D_i^2}{\sum\left(\text{Observed}_i - \overline{\text{predicted}}\right)^2} \quad (15)$$

Among the equation, D_i is the difference between observed value and the predicted value, in order of i.

After calculation, we get $ME = 0.985$, which is close to 1, indicating that the performance of the model is good.

Finally, the critical errors at two different confidence levels are calculated. The results are shown in Table 2.

Table 2: Critical Error

Index	Top height	Dominant DBH	Total tree biomass	Ground cover biomass
Average bias	0.66	-0.37	-6.12	0.02
Pearson's r	0.96	0.97	0.94	0.86
Modeling efficiency	0.95	0.93	0.94	0.87
Relaxed e*(a=0.05)	1.58	1.67	21.45	1.15
Exigent e*(a=0.20)	1.27	1.25	15.80	0.71

By analyzing the changes of different rotation cycles and biological carbon content through MATLAB, the following change law diagram can be obtained.

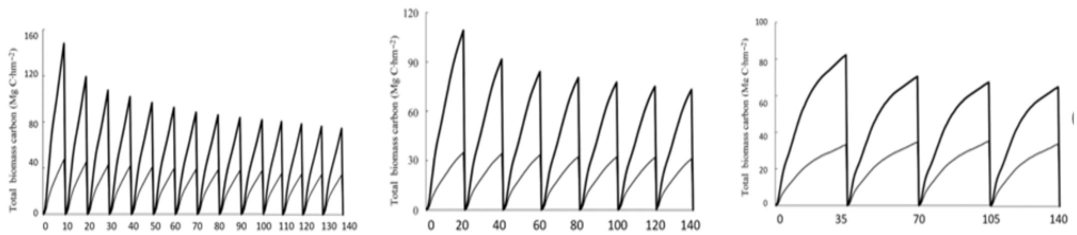

Figure 3: Change of total biomass carbon content in short, normal and long rotation

Change of total biomass carbon content in short, normal and long rotation is shown in Figure 3. It can be seen that in 140 years, the impacts of 10-, 20- and 35-years rotation on the total carbon sequestration were 150. 35 Mg · hm-2, 111. 84 Mg · hm-2 and 82. 76 Mg · hm-2, respectively. The total carbon sequestration of short rotation was 1. 34 times of normal rotation and 1. 82 times of long rotation, respectively.

To sum up, a short rotation of about 10 years is most conducive to carbon sequestration.

4. Extend the model to global forest systems

4.1. Calculation of carbon sequestration in the Malaysian rainforest

To extend the model to a variety of forests, we use the Malaysian rainforest as an example to study the relationship between management practices and carbon sequestration.

Because the forest area determines the amount of carbon sequestration, we can control the forest area and the age of trees by controlling the rotation period, so that it is in the most favorable state for carbon sequestration.

Firstly, the total forest area of Malaysia is 182,700 hectares, and the vegetation Net primary productivity (NPP) of this area is estimated as follows according to the Thornthwaite Memorial model:

$$\begin{aligned} NPP &= 3000\left(1-\mathrm{e}^{-0.0009695(v-20)}\right) \\ v &= \frac{1.05R}{(1+(1+1.05R/L)^2)^{1/2}} \\ L &= 3000+25t+0.05t^3 \end{aligned} \tag{16}$$

In the equations, v is the actual annual evapotranspiration of the area in millimeters; L is the annual evapotranspiration of the area; t is the average annual temperature of the place in degrees Celsius; R is the annual precipitation in this area.

Therefore, it can be calculated that the forest in this area can fix 10.21 billion tons of carbon dioxide in 100 years, which is converted into 2.79 billion tons of carbon sequestration.

4.2. Rainforest Management Strategies in Malaysia

Considering the impact of forests on carbon sequestration and social indicators, combined with the above evaluation system of deforestation cycle, the exploitation cycle of rainforest should be selected as 10 years.

When the external indicators change, it will affect the size of the total index, thus affecting the final management decision. Malaysia has a huge area of rainforest, which is excessive relative to human exploitation needs, so the development of forest products should be oriented to fully meet human needs. On this basis, the ratio of older trees felled each time to the total number of trees is relatively small [5].

The Malaysian rainforest is an evergreen broad-leaved forest with an average net carbon sequestration of 2.89 tonnes per square kilometer per year, while the three-north shelterbelt above is a coniferous forest with a net carbon sequestration of 3.42 $ta^{-1}hm^{-1}$. In contrast, the carbon sequestration capacity of rainforest is 15.5% weaker, which is more suitable for processing into products for carbon sequestration.

To achieve the same carbon sequestration efficiency, the deforestation cycle of the rainforest should be reduced by about 15%, that is, the mining of old trees every 13 years. At the same time, it also increases the economic value of the rainforest and promotes the alternation of the old and new rainforest ecology.

4.3. The transition strategy for growth of rotation period in ten years

If the harvest cycle of the management plan is 10 years longer than the current practice, it will inevitably affect the social benefits. For smoothing the transition from the original timeline to the new timeline, we decided to gradually increase the number of rotation years.

According to the first question, the annual planting amount of the traditional way:

$$S_p = S_0 \int_T^{t1} \frac{1}{\sigma\sqrt{2\pi}} e^{\frac{-(s-\mu)^2}{2\sigma^2}} ds \tag{17}$$

The latest strategy is adopted for planting, and the annual planting area is:

$$S_1 = S_0 \int_T^{t1} \frac{1}{\sigma\sqrt{2\pi}} e^{\frac{-(s-\mu)^2}{2\sigma^2}} ds \quad (18)$$

$$S_2 = S_0(1+V) \int_T^{t1} \frac{1}{\sigma\sqrt{2\pi}} e^{\frac{-(s-\mu)^2}{2\sigma^2}} ds + S_0 \int_T^{t1} \frac{1}{\sigma\sqrt{2\pi}} e^{\frac{-(s-\mu)^2}{2\sigma^2}} ds \quad (19)$$

$$S_{10} = S_0 \sum_{i=0}^{9} (1+V)^i \int_T^{t1} \frac{1}{\sigma\sqrt{2\pi}} e^{\frac{-(s-\mu)^2}{2\sigma^2}} ds \quad (20)$$

Assume that the amount of planting per year using the traditional method is Q, then:

$$S_i = \sum_{p=1}^{i} Q(1+V)^{i-p} \quad (21)$$

In the equation, i indicates a transition from an existing timeline to a new timeline after i years.

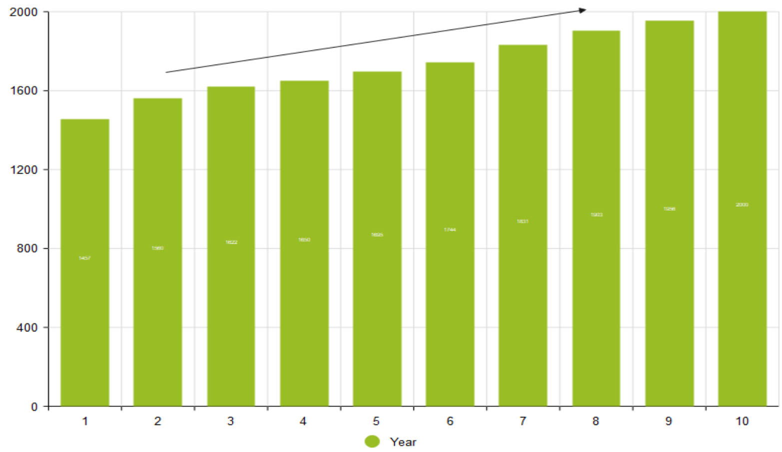

Figure 4: Trend of carbon sequestration over time

Trend of carbon sequestration over time is shown in Figure 4. Based on the above model of increasing rotation years, the annual effective planting area during the time line transition period can be obtained, which can meet the needs of forest managers and users.

5. Conclusion

It has been proved that human intervention can affect the efficiency of carbon sequestration in forests. We analyzed the carbon sequestration capacity of wood products, combined with the growth law of trees, and found that periodically cutting down old trees can effectively prolong the return of fixed carbon to the atmosphere, while creating greater social and environmental value. We propose a transitional strategy to meet the needs of forest managers and users to the greatest extent under the condition that the rotation period is extended by 10 years due to the need to ensure forest restoration.

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