Research on the comprehensive evaluation system of forest carbon sequestration

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ABSTRACT

Carbon sequestration refers to capturing carbon and storing CO_2 safely instead of directly emitting it into the atmosphere. Forests play an integral role in biological carbon sequestration. To quantify the effectiveness of forests in carbon sequestration, this paper develops a complete evaluation model system to design a personalized forest management plan for any forest on Earth. We proposed the Carbon Sequestration Model and the Comprehensive Evaluation Model of Forest. These two models focus on how to calculate the carbon dioxide stored in forests and their forest products. We verify the models with the data of pre-forest resources in Heilongjiang Province of China, and the results show that the model can maximize the comprehensive benefits of forests in carbon sequestration, economic, social, cultural, and ecological aspects.

Keywords: Carbon sequestration, comprehensive evaluation, personalized forest management

1. INTRODUCTION

Effects of climate change have aroused growing attention worldwide. To alleviate the adverse effects of climate change, we need to not only reduce the emission of greenhouse gases, but also make efforts to enhance carbon dioxide sequestration. A large portion of carbon is stored in in living plants and in the products created from their trees. Carbon compounds generated by photosynthesis are mainly in wood stem[1], so forests sequester carbon dioxide in living plants and in the products created from their trees including furniture and other wood products. The forest products have the potential to allow for more carbon sequestration over time.

Stand growth model is the basic means to study the change rule of forest growth and predict carbon accumulation. Petit et al.[2] construct the growth equation of ten native species of Costa Rica using 12-year growth data. Trasobares et al.[3] establish a fixed-density stand growth model of Pinus elliottii in eastern Spain. Mei et al.[4] estimate the forest carbon flux using Biome-BGC model. Sun et al.[5] set up the regression model of forest carbon storage with remote sensing and terrain factors based on geographically Weighted Kriging regression. Zhang[6] analyses the spatial distribution characteristics of urban forest carbon storage and carbon density based on remote sensing estimation. Zhang[7] sets up a forest carbon sink measurement system and put forward countermeasures and suggestions for developing forest carbon sinks.

Human management is the second largest contributor to forests biomass carbon increment. Therefore, a reasonable forest management plan is essential. The basic theory widely used in forest optimal management decision-making is the indefinite discount method of wood production proposed by Faustmann. Riitters et al.[8] use dynamic programming to optimize the thinning and rotation periods of stands. Zhen et al.[9] stimulate the changes in biomass populations and quantitative management through data collected in artificial forests, advocating reduction of the need for more land for forest expansion. Liu[10] puts forward policy suggestions to improve the realization path of forest ecological products value for ecological compensation. By analyzing the amount of carbon sequestration in the ecosystem, Cai et al.[11] propose implementing effective management strategies for existing forests and formulating appropriate afforestation policies. Hu et al.[1] put forward targeted policy suggestions to promote sustainable development of forest carbon sinks. In forest management, some studies also use population algorithms, such as genetic algorithm, simulated annealing, tabu search and so on[12, 13].

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This paper constructs Carbon Sequestration Model and the Comprehensive Evaluation Model of Forest. The two models seek balance points in the fields of carbon sinks, ecology, and economy. After using China's representative Heilongjiang forest carbon sink data and local GDP data, the results show that the model can maximize the overall benefits of the forest.

2. IMPLEMENTATION OF THE CARBON SEQUESTRATION MODEL

2.1 Process thinking of model construction

The development of a carbon sequestration model is to identify changes in the amount of carbon dioxide sequestered by living plants and their forest products in forests over time. We build from the following four steps: First, divide the world's forests into four major types. Because the composition of forests, climate, population, interests, and values vary widely around the world. Different growth environments need to be considered to develop a carbon sequestration model to determine how much carbon dioxide a forest and its products are expected to sequester over time. Second, describe the effective stock volume of different types of forests. Effective stock volume is the bridge between forest management plans and carbon dioxide sequestration. Therefore, we need to fit each typical forest's effective stock volume expression by collecting the relevant data from four typical forests. Third, calculate the amount of carbon dioxide sequestered. The amount of carbon dioxide sequestered in forests is produced by living forest plants and forest products. Finally, determine the optimal forest management plan. Under the condition that only the amount of carbon dioxide sequestration is considered, the forest management scheme that maximizes the amount of carbon dioxide sequestration is the best. We quantify the forest management plan with different parameters.

2.2 Model solving

2.2.1 Four Major Types of the World's Forests. As shown in Global Forest Resources Assessment, 2020 published by Food and Agriculture Organization of the United Nations, the world's forest resources are mainly distributed in the frigid zone, temperate zone, subtropical zone, and tropical zone, as shown in Figure 1. We selected forests in four typical regions of Norway, China's Heilongjiang, China's Fujian, and Brazil as the research objects. Their locations are marked with black boxes in Figure 1.

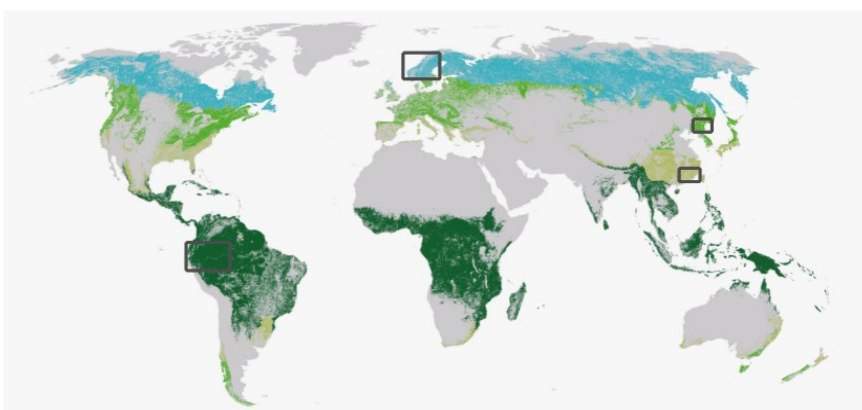

Figure 1. Distribution of global forest area by climatic domain.

To further express the characteristic differences between forests in different temperature zones, we selected typical forest tree species in each temperature zone for research. They are Norwegian larch in the frigid zone, Heilongjiang birch in the temperate zone, Fujian masson pine in the subtropical zone, and Brazilian eucalyptus in the tropical zone. These four typical tree species have obvious differences in the required growth environment, such as temperature, humidity, and light duration. This leads to significant differences in the length of their growth cycles in Table 1.

2.2.2 Effective Stock Volume of Different Types of Forests. The effective stock of a forest can be expressed as the difference between the stock of forest growth and the stock of harvest. Specific to the forest growth stock volume of the four types of typical tree species in the study, we use the volume of the tree species at each forest age in different years to fit the logistic growth curves of these species. The Logistic growth curve formula is as equation (1):

$$V = \frac{a}{1-e^{b-cx}} \tag{1}$$

Next, we describe the stock volume of harvest. Referring to the Faustmann Classic Model, we define the forest stock volume for harvesting as follows, where α is the percentage of harvest. The quantity of harvesting as equations (2) and (3):

Table 1. Growth cycles of the four typical tree species.

	Norwegian larch	**Heilongjiang birch**	**Fujian masson pine**	**Brazilian eucalyptus**
Young forest	≤40	≤30	≤20	≤5
Middle-aged forest	41-80	31-50	21-30	6-10
Near mature forest	81-100	51-60	31-40	11-15
Mature forest	101-140	61-80	41-60	16-25
Overripe forest	≥141	≥81	≥61	≥26

$$V_{harvest} = 0 \ (t \leq T) \tag{2}$$

$$V_{harvest} = \alpha V_{grow} \ (t > T) \tag{3}$$

The difference between the obtained growth curve and the cutting curve can be used to obtain the effective forest stock volume curve. The quantity of effective forest stock volume curve is as follows:

$$V_{efficient} = V_{grow} \ (t \leq T) \tag{4}$$

$$V_{efficient} = (1-\alpha)V_{grow} \ (t > T) \tag{5}$$

Bringing in the growth curves of four typical regional tree species can get their respective effective stock volume curves, and the specific equations are not listed here.

2.2.3. Amount of Carbon Dioxide Sequestered. To obtain the amount of carbon dioxide sequestration, we should first be clear about the relationship between carbon sequestration and forest-effective stock volume. By consulting the IPCC Guidelines, we know the quantitative relationship between the two:

$$C = [V \cdot D \cdot BEF_2] \cdot (1+R) \cdot CF \tag{6}$$

In equation (6), C represents total carbon sequestration in forests, D represents maximum average distance between two repeaters, BEF_2 represents biomass expansion factor, R represents rhizome ratio and CF represents carbon fraction of dry matter.

We have to clarify the main carbon sequestration bodies are forest living plants and forest products. However, there are differences in the way of carbon sequestration between the two. Forest living plants absorb carbon dioxide through photosynthesis and release carbon dioxide through respiration. The difference between the two is carbon sequestration. Forest products sequester carbon by retaining the carbon sequestration of their raw materials from the time they are harvested until the end of the product's life. To simplify the model, we divide the forest products into two types: one is the forest product with a shorter lifespan than the raw material species, which has zero carbon sequestration; the other is the forest product with a longer lifespan than the raw material species, which has a carbon sequestration capacity, the amount of carbon sequestered in raw materials at harvest time, and it will remain there, not dying.

When calculating the carbon sequestration of living forest plants, equation (6) provided by IPCC Guidelines can be used:

$$C_{living} = [V_{grow} \cdot D \cdot BEF_2] \cdot (1+R) \cdot CF \tag{7}$$

When calculating the carbon sequestration of forest products, a parameter β needs to be introduced to represent the ratio between the two forest products, and then into equation (10), we can get:

$$C_{product} = [\beta V_{harvest} \cdot D \cdot BEF_2] \cdot (1+R) \cdot CF \tag{8}$$

Then, the total forest carbon sequestration is the sum of the carbon sequestration of forest living plants and the carbon sequestration of forest products.

Finally, the carbon sequestration amount is multiplied by the ratio of the molecular weight of carbon-to-carbon dioxide to convert the carbon dioxide sequestration amount. The forest management plan includes the following three aspects: when to harvest, which tree species to harvest, and in what proportion. First, determine when to harvest. We decided to select the age of the stand at the peak of the logistic growth curve as the harvest age.

$$S_{Hei} = [1-\alpha(1-\beta)] \times \frac{1.821\times10^4}{1+e^{1.995-3.753t}} \times 0.43095 \tag{9}$$

Once the harvest time is determined, the forest management plan reduces to two questions: which species to harvest and in what proportion. At this point, the forest management plan can be quantified from these two aspects. In the carbon dioxide sequestration equation, α represents the forest harvest stock, which is the harvest ratio in the management plan. β represents the proportion of forest products whose lifespan is longer than that of raw material species. The lifespan of each forest product is fixed, and the change in the proportion comes from the change in the raw material tree species. The β values corresponding to different tree species are different.

3. IMPLEMENTATION OF THE HIERARCHICAL STRUCTURE MODEL

The hierarchy structure of the indicators needs to be determined. It consists of 3 superior indicators and 5 inferior indicators. We take the forest of China as an example to collect relevant data for analysis. The data on wetland area, desertification land area, and rocky desertification land area in China is obtained from the China Forestry Administration. The number of forest tourists and the output value of the forestry industry are obtained from the China Forestry Statistical Yearbook. The national forest stock volume is obtained from the inventory data of China's forest resources. The mind-map of the hierarchy structure is shown in Figure 2.

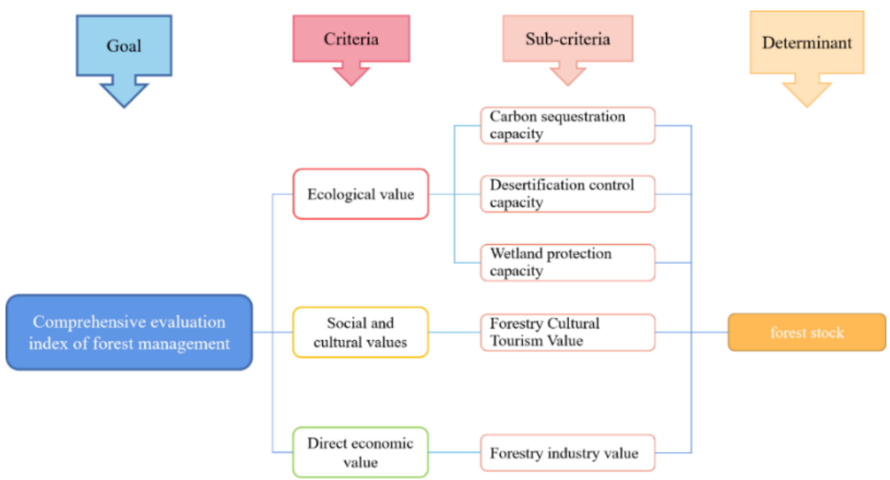

Figure 2. The hierarchy structure of the decision model.

To determine an optimal forest management strategy, we need to link the indicators with the stock volume. Thus, we first calculate the correlation between the indicators and the forest stock. We use SPSS software to calculate the correlation coefficient between each index except carbon sequestration and forest volume. The result is that there is a correlation between desertification control indicators and forest volume, and the other indicators are highly correlated with forest volume. Therefore, in the model, we can perform a univariate regression between each index and the forest volume, and obtain the corresponding relationship between the forest volume and each index. The final forest management model is as equation (10).

$$CEI = q_1GFP + q_2WET + q_3FTT + q_4DLA + q_5RDA + q_6C \tag{10}$$

CEI is comprehensive evaluation index, GFP is gross forestry product, WET is total area of wetland, FIT is forestry tourism, DLA is desertification land area, RDA is rocky desertification land area and q_i is the weight of each index obtained by AHP.

Transition points are variable factors between forest management plans. In this model, one of the transition points between the management plans of all forests is whether to harvest or not, which is determined by the tree species in the forests. The dominant or main tree species of a forest determine the maturity speed, closely related to the temperature zone, the altitude and so on. When the forest matures and starts to be harvested, the amount of harvest is related to the forest age. Whether or not to harvest should take these factors into full consideration. According to the carbon sequestration model, when any forest does not meet the logging standards, the effective forest stock is equal to the total stock. However, it is impossible for any forest with a positive growing forest volume to never meet the logging standards, so the condition that would result in a forest that should be left uncut is that the forest volume is in a downward trend. This is also another transition point.

4. EXPERIMENT AND RESULTS

To test the decision model, we choose Heilongjiang Province as example. Heilongjiang Province is located in the northeast of China. It is not only a major forestry Province in China but also an important natural ecological barrier in northern Asia. However, due to the unreasonable forest management mode, the annual average forest consumption is much higher than the annual cutting quota, and the phenomenon of exceeding the quota is serious. It is suitable to use our decision model to determine a better forest management strategy.

The forest management plan includes the following three aspects: when to harvest, which tree species to harvest, and in what proportion. The effective forest stock volume is still the bridge connecting the forest management plan and the comprehensive index of the forest. where t is the time of harvest, α is the proportion of harvest, and β is the tree species harvested. Due to the obvious dominant tree species in Heilongjiang, to simplify the model, the optimal β value in the Heilongjiang region is selected as the tree species for felling. Once the tree species harvested is determined, the forest management plan reduces to two questions: when to harvest and in what proportion. At the peaks in Figure 3, the corresponding α and t are the optimal forest management plans for the forest. The specific result is shown in Figure 3.

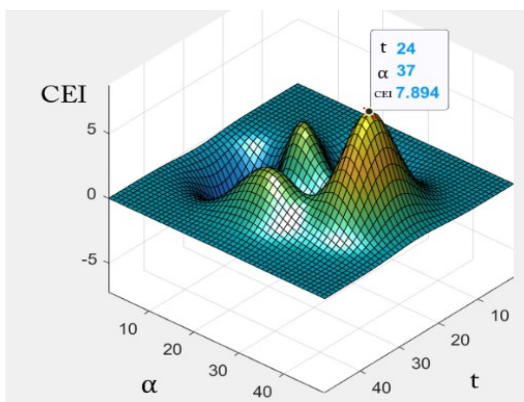

Figure 3. The optimal forest management plan for Heilongjiang Forest.

In the forest, the optimal management plan is to cut down 37% of the forest volume every year starting from the 24th year after tree planting and give priority to tree species whose lifespan is shorter than 70% of the lifespan of forest products. The results above show that for the forest located in Heilongjiang, α that maximizes the total forest value is 37%. Use equation (9) and taking t=100, the carbon dioxide sequestration of this forest and its products within 100 years can be obtained. To sum up, the forest management plan that maximizes the comprehensive value of the forest is used for this forest. This forest and its products will have 29366290.6764 tons of CO_2 sequestered over the next 100 years.

5. CONCLUSION

In this paper, we developed a Carbon Sequestration Model, which focuses on the calculation methods on the carbon dioxide stored in forests and their forest products. In addition, we developed the Comprehensive Evaluation Model of

Forest Management. We used the data from the Greater Khingan Mountains forest in Heilongjiang, China, and determined an optimal harvesting and regeneration scheme, which maximizes the comprehensive benefits of the forest in economic, social, cultural, ecological, and other aspects.

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