

Forest carbon sequestration models under specific forest management strategies

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Abstract: This paper presents a cluster analysis method for carbon sequestration calculations applied to forest product classification. The innovation considers the impact of the final destination (landfill and incineration) of trees and forest products on carbon sequestration. By analyzing the changes of carbon sinks under different management strategies, the forest carbon sink models under specific forest management strategies are finally derived. Combined with the carbon sink model and related research foundations, indicators are constructed from the three traditional dimensions of ecology, society, and economy to reflect the total value of forests. Long-term development is achieved by combining healthy and sustainable socio-economic, natural complex ecosystems.

1. Introduction

1.1. Background

Under the background of global climate change, forest management strategy is an effective way to realize carbon sink and enhance sink. Forests have multiple economic, ecological, and cultural functions and are the critical link between the natural environment and the development of human society. [1] Studying changes in forest carbon sinks makes it possible to infer changes in natural succession and socio-economic conditions, which has important practical significance.

However, most of the previous forest carbon sequestration strategies are based on the forest's carbon sequestration [2, 3], while the carbon sequestration related to forest products is often neglected. Research [4] shows that forest products have significant carbon sequestration capacity and emission reduction potential during their life cycle. Therefore, the carbon sequestration of forest products and regenerated forests from timber harvesting should be included in the forest carbon sequestration system for a comprehensive assessment to formulate more reasonable forest management measures, including the harvesting cycle and harvesting scale.

In addition, the goals of forest management measures should not be limited to ecological and economic goals, nor should the socio-cultural functions of forests be ignored.

Therefore, a general forest assessment system is needed to provide comprehensive assessment and guidance for forest management measures. Meanwhile, it is necessary to popularize this system, improve the public's awareness of the ecological environment, and guide the public to actively participate in forestry and ecological construction with practical actions to form a healthy and sustainable social-economic-natural complex ecosystem, which achieves long-term development.

1.2. Research method

We developed a carbon sequestration model using a biomass approach. We break down the target into two parts: carbon sequestration in forest products and carbon sequestration in forests. Management options, including cutting strategies and product strategies, are introduced into the model as an intermediate link between the two.

We deduce the optimal calculation function of forest biomass by curve fitting and convert biomass to carbon sequestration based on related research. Using cluster analysis to calculate carbon sequestration in forest products, forest products are broadly classified into three categories of raw

materials. Forest carbon sequestration is calculated when combined with the final destination (death, landfill and incineration) of trees and forest products. By analyzing the changes in carbon sinks under different management scenarios, the forest carbon sinks under specific scenarios can be deduced for reference in forest management measures.

2. Specific carbon sequestration model

The carbon sequestration model can be summarized in Figure 1.

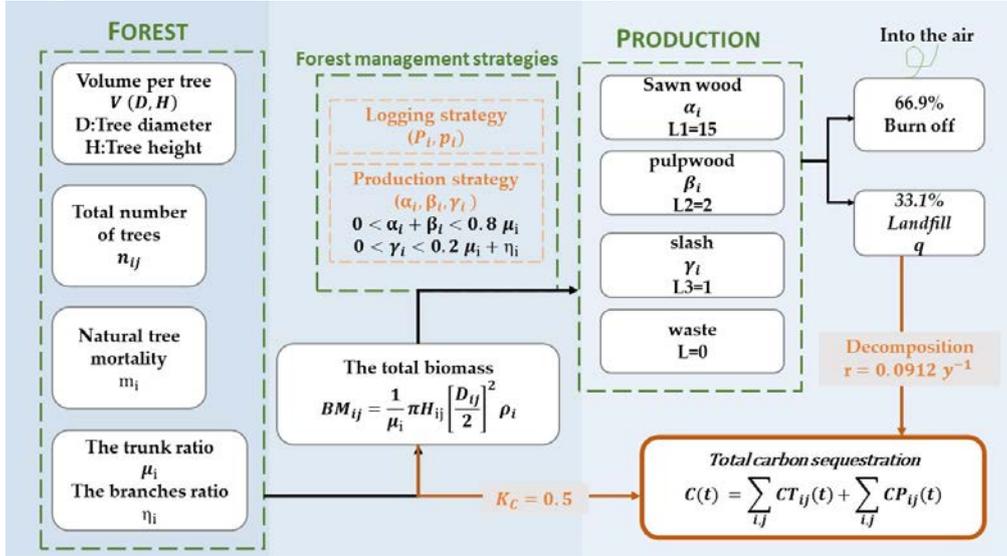


Figure 1. Carbon sequestration model.

2.1. Modelling of carbon sequestration

2.1.1. Biomass function

Based on basic assumptions, we calculated carbon sequestration by converting the volume of trees to biomass. To calculate the biomass BM_{ij} , we first calculate the biomass of the trunk based on the diameter (chest height), height, and density of the tree, and then calculate the total biomass based on the proportion of biomass of the trunk in a single tree.

$$BM_{ij} = \frac{1}{\mu_i} \pi H_{ij} \left[\frac{D_{ij}}{2} \right]^2 \rho_i$$

Data on annual changes in diameter at breast height and height were requested. The data were used to fit the tree diameter, and tree height variation functions D_{ij} and H_{ij} , where i represents species and j represents age. Fit using several sigmoid functions, choosing the one with the best fit to represent the change:

$$\begin{aligned} Y &= Kt^b, \\ Y &= \frac{t}{a + bt}, \\ Y &= \frac{K}{1 + ae^{-bt}}, \\ Y &= Ka^{bt}, \end{aligned}$$

Where K , a , b are undetermined constants. With diameter and height functions obtained, the biomass is calculated via formula.

2.1.2. Tree age distribution and tree mortality

Assuming that the mortality rate m_i of each species is constant and the total number of trees is still N_i , the number of trees of different ages in the current forest can be calculated as follows. Mark the

planting time of afforestation as T_i years ago ($t = -T_i$). Every year, a part of m_i is eliminated due to natural death. Dead trees are replaced by new trees, and the total number is limited to N_i . The ones where $t=0$ are listed below the number of trees.

$$\begin{aligned} n_{i,T_i} &= N_i (1 - m_i)^{T_i-1} \\ n_{ij} &= N_i m_i (1 - m_i)^{j-1}, j = 2, 3, \dots, T_i - 1 \\ n_{i1} &= N_i m_i \end{aligned}$$

Given the average diameter D_i of each tree species, the natural mortality rate m_i of trees under environmental conditions can be obtained by dichotomy. Moreover, by applying m_i , the age distribution of trees when $t=0$ can be obtained using the formula.

$$\overline{D_i} = \frac{\sum_{j=1}^{T_i} D_{ij} n_{ij}}{\sum_{j=1}^{T_i} n_{ij}}$$

2.1.3. Coefficient of biomass conversion to carbon sequestration

The forest carbon sink is mainly calculated by measuring the biomass of forest vegetation and multiplying it by the biomass-carbon conversion coefficient K_c . The 2006 IPCC Guidelines for National Greenhouse Gas Inventories recommend carbon ratios for aboveground forest biomass.

To simplify the model, we take K_c as 0.5, which is the average of empirical data given by IPCC.

2.1.4. Service life of related wood products

Based on the nature of the wood used, we classify forest products into sawn-wood, pulp-wood, and slash. The specific definition is as follows.

Table 1. Classification of forest products

Product	Instance	Service life /year	Disposal mode
sawn-wood	Furniture, building materials	15	Landfill or incineration.
pulp-wood	Plywood, cardboard, paper	10	Landfill or incineration.
Slash	Fuel	1	Burned.

The average product life L_1 of Sawn-wood is assumed to be 15 years, the life L_2 of pulp-wood is assumed to be 10 years, and the life L_3 of slash is assumed to be 1 year. The discarded part has no service life and is not included in the calculation system.

2.1.5. Landfill and decomposition parameters

We classify the final destination of forest products into landfill and incineration. Any treatment other than landfill is considered incineration, which releases carbon dioxide directly into the air and does not count towards carbon sequestration systems.

According to the "2020 Annual Report on the Prevention and Control of Environmental Pollution in Large and Medium Cities" issued by the Ministry of Ecology and Environment of China, the current landfill rate q in China is 33.1%, and the decomposition rate r is 0.0912 per year [3]. The carbon sequestration effect of these forest products is included in the calculation system.

2.2. Calculation of carbon sequestration

2.2.1. Variation of age distribution

The tree age distribution of each year from $t = 0$ is obtained by iteration. The relationship between the age distribution of trees in the two adjacent years is

$$\begin{aligned} n_{i1}(t+1) &= N_i m_i + \sum_{j>P_i} n_{ij} \times (1 - m_i)_i \\ n_{ij}(t+1) &= n_{ij}(t) \times (1 - m_i), 1 < j < P_i \\ n_{ij}(t+1) &= n_{ij}(t) \times (1 - m_i) \times (1 - p_i), j \geq P_i \end{aligned}$$

Formula means that newborn trees would replace trees that were dead or cut down in the next year.

2.2.2. Carbon sequestration in trees

The carbon sequestration in trees can be converted from the biomass of living trees.

$$CT_i(t) = K_C \times \sum_j BM_{ij} \times n_{ij}(t)$$

2.2.3. Carbon sequestration in products

For each year, the biomass of cut-down trees in species i is

$$H_i(t) = \sum_{j>P_i} n_{ij}(t) \times p_{ij}$$

The biomass percentage of trees made into sawn-wood, pulpwood, and slash are respectively α , β , γ their service lives being L_1 , L_2 , L_3 . A proportion of q for sawn-wood and pulpwood ends up in the landfill. The decomposing rate in landfills is r . Therefore, the carbon sequestration in products and their wastes comply with the following relationship:

$$\begin{aligned} \frac{CP_i(t)}{K_C} &= \sum_{\Delta t=0}^{L_1} H_i(t - \Delta t) \times \alpha_i + \sum_{\Delta t=0}^{L_2} H_i(t - \Delta t) \times \beta_i + \sum_{\Delta t=0}^{L_3} H_i(t - \Delta t) \times \gamma_i \\ &+ \sum_{\Delta t=L_1}^{\infty} H_i(t - \Delta t) \times \alpha_i \times e^{-r(\Delta t-L_1)} + \sum_{\Delta t=L_2}^{\infty} H_i(t - \Delta t) \times \beta_i \times e^{-r(\Delta t-L_2)} \end{aligned}$$

2.3. Management strategies

2.3.1. Logging strategy

Harvesting strategy is an important part of forest management strategy, which directly affects the balance between forest and forest products. We introduce a logging strategy (p_i , P_i). It means that for each tree species i , for trees older than the rotation age P_i , a proportion of trees equivalent to p_i should be felled.

By default, p_i varies continuously between 0 and 1. For simplicity, we set the p_i to be the same for each tree species.

Based on actual forest farm data, we tested changes in carbon sequestration resulting from different harvesting strategies.

2.3.2. Production strategy

Forest products are divided into three categories according to their wood properties: sawn-wood, pulp-wood, and slash. They are represented by α , β and γ respectively. Product strategies can be described by number pairs (α, β, γ) . The waste in the production process is treated as a product with a life cycle of 0, which means rapid and complete decomposition within a year.

The biomass of the whole tree trunk is μ_i , and the biomass of the branches is η_i . Assume that 80% of the trunk can be made into sawn timber, and the rest of the trunk and branches can be made into pulp or slash. Everything else is discarded. We derive the following inequality from generalizing the production state.

$$\begin{aligned} 0 &< \alpha_i + \beta_i < 0.8\mu_i \\ 0 &< \gamma_i < \mu_i + \eta_i \end{aligned}$$

To simplify the model, the production strategy takes two extremes:

1. $(\alpha_i, \beta_i, \gamma_i) = (0.8\mu_i, 0.2\mu_i + \eta_i, 0)$
2. $(\alpha_i, \beta_i, \gamma_i) = (0, \mu_i, \eta_i)$

The former is most conducive to the distribution of carbon sequestration, that is, to achieve the longest life of the product. The latter is the least conducive to carbon sequestration. Any other case should be somewhere in between.

2.4. Carbon Sequestration Calculation Formula

In the above carbon sink model, carbon sinks are divided into forest carbon sinks, and forest product carbon sinks. By fitting actual forest farm data, these parameters can be used to calculate the carbon sink for each forest.

$$C(t) = \sum_{i,j} CT_i(t) + \sum_i CP_i(t)$$

3. Multi-aspect Decision Model of Forest Management

Based on the definition of forest value [5], this paper establishes indicators from the three traditional dimensions of ecology, society, and economy, reflects the total value of forests with certain principles and introduces sustainability variables as a reference for forest development potential. Finally, the entropy weight method is used to classify and comprehensively evaluate the forest system's ecological, economic, and social development levels. Based on the evaluation results of specific forests, the model can provide recommendations for forest management.

The Multi-aspect Decision Model of Forest Management can be summarized in Figure 2.

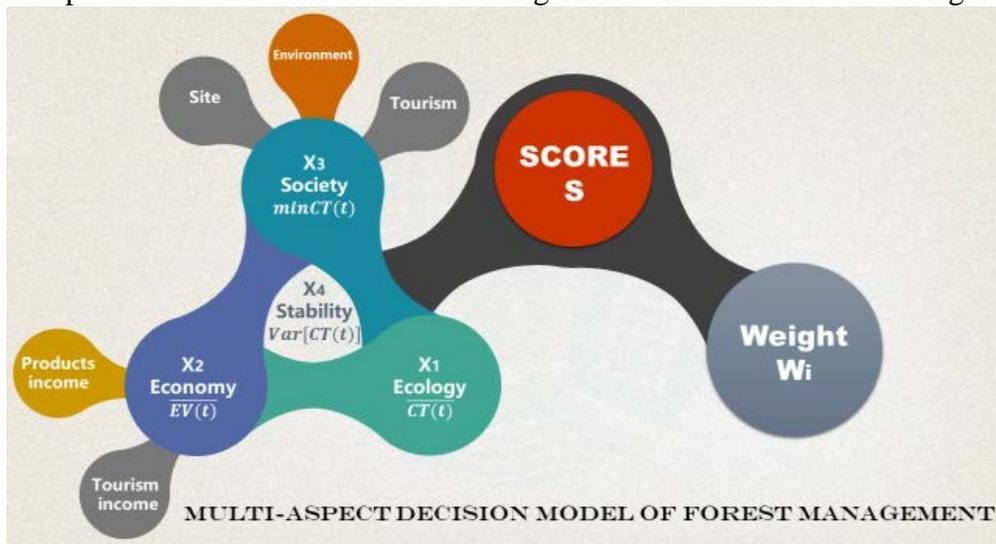


Figure 2. Multi-aspect Decision Model of Forest Management.

3.1. Evaluation dimensions of forest value

3.1.1. Ecological value level

"Canopy density" is considered a classic indicator reflecting the ecological value of forests and can be used to measure the thickness of forests. However, forest data that directly reflect canopy density are difficult to obtain in reality. It can be concluded that canopy density is positively correlated with leaf biomass, so variables directly related to biomass can be used as proxy variables.

In the carbon sequestration model, we conclude that the amount of biological carbon sequestration $C(t)$ is proportional to the biomass to reflect the degree of forest growth. The larger the biomass, the more mature the forest and the more ecological value. Therefore, we derived the following formula to calculate the forest ecological value quantitatively.

Considering the long duration of the ecological effect of the forest, we take the average value of carbon sequestration for 100 years as the ecological indicator.

$$x_1 = \overline{CT(t)}$$

3.1.2. Economic value level

From the perspective of benefit measurement and ecological compensation, the economic value of the forest is often used as the economic benefit of the forest, that is, the monetary expression of forest value in the commodity society. In maintaining the forest's biological characteristics, the forest ecosystem and the forest products or ecological environment produced within its influence range can be used by people. The monetary expression in the commodity economy is the value of the economic benefits of the forest, also known as the total economic value of the forest.

The calculation process of the economic value of forest products is as follows:

Sawn-wood: $r_1=2300$ yuan/cubic meter

Pulp-wood: $Pr_2=5300$ yuan/cubic meter

Slash: $Pr_3=900$ yuan/ton

$$EV(t) = \sum_i H_i(t) \times (\alpha_i Pr_1 + \beta_i Pr_2 + \gamma_i Pr_3)$$

Finally, take the 100-year average of returns as an economic indicator.

$$x_2 = \overline{EV(t)}$$

In the article, the economic value of forest ecosystems was not included in evaluating the economic value of forests for the following reasons.

1) The economic value of the forest's ecological environment is usually reflected in tourism resources. The development of forest tourism is usually affected by cultural factors and local social and economic development, while the ecological environment changes caused by forest management strategies have no significant impact on local social and economic development.

2) The marginal benefit of the forest ecosystem state is low. The high level of forest ecology has little impact on economic benefits. Basically, the economic benefits of the ecological environment can only be qualitative but not quantitative.

Based on the above reasons, this part of the economic income is included in the social value evaluation dimension of the forest in the model rather than the economic value dimension.

4. Model Evaluation

4.1. Sensitivity Analysis

The sensitivity of the carbon sequestration model to the input variables is listed below. Here we use the average carbon sequestration as output. The model was tested under the best management strategies we mentioned above. It can be concluded that the model is more sensitive to changes in the rotation period P_i , but is generally stable at this time.

Table 2. Sensitivity analysis results

Variables	Fluxes	Average C(t)	Output Average CT(t)	Average CP(t)
Felling rate p_i	$\pm 10\%$	$\pm 0.35\%$	$\pm 0.26\%$	$\pm 0.43\%$
Rotation period P_i	$\pm 1\text{yr}$	$\pm 0.23\%$	$\pm 1.74\%$	$\pm 2.99\%$

4.2. Strength and Weaknesses

4.2.1. Strength

1) The tree growth function is fitted according to the characteristics of previous tree growth and reflects the actual situation under local growing conditions.

2) Tree mortality and product disposal after use is considered, so the model reflects the impact of current social dimensions.

3) The selected indicators are easy to obtain, and the model's overall design is relatively simple.

4.2.2. Weaknesses

- 1) Many exceptional cases are ignored for simplicity and easy availability of data and models.
- 2) There are still some problems in setting social indicators, resulting in the indicators being abandoned because their significance in the actual calculation process is not significant.
- 3) The model is only suitable for quantitative analysis of small-scale forest land. Large-scale analysis requires the application of remote sensing models.

4.3. Biochar economic benefits assessment method

According to the production factor estimation method, the evaluation boundary starts from the collection of raw materials, including intermediate links such as transportation, storage, and pyrolysis production, and ends when the product is transported to the application site. For the convenience of calculation, combined with the survey data, a biomass pyrolysis plant is set up, with a typical scale of 8*10⁴t agricultural biomass per year as the processing unit and an operation period of 10a.

The formula for calculating the cost and benefit of biomass pyrolysis is as follows:

$$B = \sum R_i - \sum C_i$$
$$C = \sum (C_p + C_m + C_f + C_o)$$
$$R = \sum (R_{CO_2} + R_{gas} + R_{oil} + R_{BC})$$

In the formula: B is the total benefit of the system; C is the total cost of the system, C., the cost of raw materials C, and the operating cost of the pyrolysis plant C; R is the total revenue of the system, including the value of carbon sequestration and emission reduction R_o, and the value of biogas R_g. Bio-oil (wood tar and wood vinegar) value R_a, biomass char (fertilizer substrate use) value R_{ac}.

5. Conclusion and suggestion

The optimal calculation function of forest biomass was deduced by curve fitting, and the biomass was converted into carbon sequestration based on related research. The optimal calculation function of biomass forest was derived by curve fitting. Using the model in the article based on related research, it is possible to calculate the carbon sink from biomass to forest products and the proportion of carbon sink in the forest. It is provided a technical reference for forestry staff.

The study believes that the "forest carbon sequestration model under specific forest management measures strategy" can be used for regional forest carbon sequestration certificates. However, this study still has insufficient research parameters, such as limited representativeness of research parameters, an insufficient reflection of regional cost-benefit differences and fluctuations, and an analysis of the competitive impact of wood product diversification on benefits. Therefore, the selection of eigenvalues and default values of estimated parameters, the fluctuation of cost-benefit, and the utilization method's influence should be further studied to improve the applicability and accuracy of the method.

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