Research on the optimal forest management strategy aiming at maximum carbon sequestration

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Abstract. In this paper, we use the 3-PG model to establish the relationship between time and carbon sequestration function, further analyze the relationship between forest age and carbon sequestration based on the 3-PG model, and obtain the optimal forest management strategy aiming at the maximum carbon sequestration. In addition, a fuzzy comprehensive evaluation (FCE) model is established to deduce the transition points between optimal forest planning models from the mean values under different conditions. Finally, we use the 3-PG model to estimate the carbon sink values after 100 years. We refer to the 3-PG model and FCE to illustrate the necessity of moderate deforestation, which is beneficial to forest development and carbon sequestration.

Keywords: Carbon sequestration, 3-PG model, fuzzy comprehensive evaluation (FCE).

1. Introduction

With the development of the industrial age, carbon dioxide emissions from various processes have inevitably led to climate changes that are negative for humans who have lived on Earth for billions of years. Forests, which have a huge potential for carbon sequestration, are thus receiving increasing attention as a dual economic and ecological resource [1]. However, it is worth noting that the work of managers is not limited to focusing on the carbon sequestration and oxygen release values of forests but should consider the multiple values that forests have. Therefore, we need to think through and determine a management plan that balances the various values of the forest comprehensively.

Forests are a valuable natural wealth of human beings. Therefore, the ecological conservation and rational use of resources in forests have been the key issues in forest management globally. Traditionally, forests are essential carbon dioxide absorbers for the Earth, contributing to global climate stability, reducing greenhouse benefits, and maintaining ecosystems. We should comprehensively protect forests [2]. However, forest protection is not simply the protection of tree species without any artificial restrictions on the natural growth of forests. Therefore, forest management should involve the appropriate renewal of forest stands and the balance of economic and ecological benefits.

Of course, forest management cannot be based on a single consideration of forest cleanup and carbon sequestration benefits. Forest managers should also balance local ecological health with the economic demand for forests. The ecological health of a forest is a dynamic process, and the ecological stability of a forest depends on the ability of the stand to evolve to local environmental factors [4]. In natural succession, too many old trees in the forest can also affect the normal development of the forest ecology. At the same time, human demand for wood is high, and forest managers can cut down trees that do not fit into the forest's ecological development to supplement human demand for forest products. Deforestation and the subsequent processing of wood materials also generate a sizeable industrial market and many jobs. A balance between economic development and ecological development can be achieved in forest management. Therefore, a more comprehensive approach to forest management is to balance the ecological and economic benefits of cutting "old-growth" trees, considering various factors. It helps to maximize the use of forest values and maintain the vitality of the forest itself. It is the best overall choice for community forest management programs.

In this paper, we develop the 3-PG model to predict the amount of carbon dioxide that forests can sequester over time and obtain forest management plans most conducive to carbon sequestration. In addition, the FCE is established to comprehensively evaluate the forest value and obtain a forest management plan that balances various values of the forest. Applying our model to new forests to predict the amount of carbon dioxide they will be able to absorb over the next 100 years.

2. 3 - PG Model

We use the 3-PG tree growth model to estimate the carbon fixation level of the target forest [1]. The 3-PG model was used to simulate the physiological processes of different stands dynamically through a series of physiological equations on a monthly time scale. This model can be a complete forest carbon balance and water balance model considering the actual environmental conditions and can better explain and simulate the carbon fixation process under the unit photosynthesis of the forest.

Photosynthetic characteristics of forest trunks are not as simple as those of leaves in the canopy. Sunlight decays as it passes through the canopy. According to the law of daylight reduction, the logarithm of the relative light intensity on the horizontal surface of a certain depth of canopy has a roughly linear relationship with the cumulative leaf area index (LAT), so the Beer-Lambert extinction formula is used to describe:

$$\mathrm{I} = I_0 \cdot e^{-k \cdot LAI} \tag{1}$$

Where I_0 is the photosynthetically active radiation intensity (MJ·m -2), k is the extinction coefficient, generally between 0.3 and 1.5. Therefore, it can be concluded that the photosynthetically active radiation ratio (FPAR) of the tree canopy is:

$$\mathrm{FPAR}_{LAI} = 1 - e^{-k \cdot LAI} \tag{2}$$

In the 3-PG model, environmental factors affect tree growth, as shown in Fig.1.

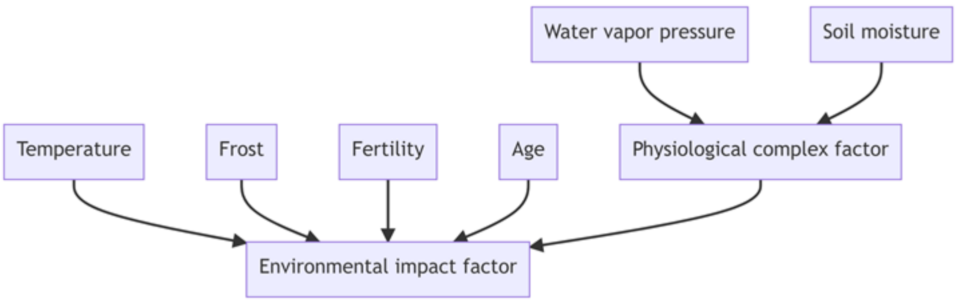

Figure 1 Influencing factors.

Trees need a certain temperature for photosynthesis to work effectively. Both high temperature and low temperature can affect the activity of plant dark reaction enzymes. And then affect the carbon fixation efficiency of vegetation. The enzymatic reaction rate and carbon fixation decreased at a low temperature, lower than the optimum temperature for photosynthesis. When the temperature is higher than the optimum photosynthetic temperature, the enzyme will be passivated, and the photosynthetic rate is lower than the respiration rate, thus reducing the carbon fixation rate. The following parabola can describe the variation of net photosynthesis with temperature:

$$f_T = \frac{(T-T_{min})(T-T_{max})}{(T-T_{min})(T-T_{max})-(T-T_{opt})^2} \tag{3}$$

Where T_{min} , T_{max} , T_{opt} is three base point temperatures of plant photosynthesis, namely minimum temperature, maximum temperature, and optimum temperature, respectively.

In the 3-PG model theory, the cell structure of trees is damaged under frost, and freezing leads to the physiological drought of cells and damage of chloroplasts. Therefore, it is believed that vegetation will stop photosynthesis when the frost comes. The effect of frost on vegetation can be expressed as:

$$f_F = 1 - K_f(d_f/d) \tag{4}$$

Where K_f represents the number of days in the month when growth stopped due to frost, which is non-negative. d_f is the number of frost days in the current month, and d is the number of frost days in the current month. If K_f =0 means that vegetation is not affected by frost.

When the mineral elements in the soil are insufficient, the photosynthesis of plants will be affected to varying degrees. The lack of soil fertility and nutrient components will slow chlorophyll synthesis and the decline of tree photosynthetic intensity. Therefore, the fertility grade (FR) function was introduced into the 3-PG model to describe:

$$f_N = 1-(1-f_{N0})(1-FR)^{nf_N} \quad (5)$$

where f_N is the nutrient correction factor.

The over cooperation intensity of trees is not constant as they grow. Generally, it tends to be stable from weak to strong after reaching the maximum. With the increase of age for a period of time, the intensity of photosynthesis gradually weakened. However, when trees are young, leaves are not fully developed, but respiration is relatively strong, so the intensity of photosynthesis and carbon fixation rate is limited. In forest growth, to meet their development needs, chlorophyll synthesis is accelerated, and carbon fixation intensity increases gradually. With the aging of forest trees, the changes in chlorophyll composition and related reactive enzymes limit photosynthesis. The influencing factors of this growth process of trees on photosynthetic intensity can be described by:

$$f_{age} = \frac{1}{1+(\frac{t/t_x}{r_{age}})^{n_{age}}} \quad (6)$$

Where t_x is the maximum possible growth age of trees, r_{age} for thef_{age} = the relative age of trees at 0.5, n_{age} is relative index of influence of stand age.

In the 3-PG model, the vapor pressure difference change factor can be expressed as:

$$e_s(T) = 0.61078 \cdot e^{\frac{17.269T}{T+273.3}} \quad (7)$$

$$\mathrm{D} = 0.6 \cdot \left(e_s(T_{max}) - e_s(T_{min})\right) \quad (8)$$

$$f_D = e^{-K_D \cdot D} \quad (9)$$

Where e_s is the saturated vapor pressure, D is the environmental vapor pressure of the stand. K_D is the regulating factor of stomatal response to environmental vapor pressure in the stand.

In the 3-PG carbon production model, the influence of different soil water content changes on photosynthetic intensity can be expressed as:

$$f_\theta = \frac{1}{1+\left(\frac{1-\frac{\theta_s}{\theta_{sx}}}{C_\theta}\right)^{n_\theta}} \quad (10)$$

where θ_s is soil water content, θ_{sx} is the maximum soil water content, C_θ is soil water holding capacity, n θ Index of soil water holding capacity. C_θ and n_θ are different in different types of soils. The value ranges from 0,4 to 0.8 and 3 to 9.

The 3-PG carbon production model defines them as comprehensive physiological factors (φ), including water vapor pressure difference, soil water content, and forest age, which can be expressed as:

$$\varphi = f_{age} min\{f_D, f_\theta\} \quad (11)$$

In photosynthesis, we can measure the utilization rate of light energy in the stand, which can be expressed as:

$$\alpha_c = \alpha_{cx} \varphi f_T f_F f_N \quad (12)$$

Where α_{cx} is the maximum utilization efficiency of light energy.

In this study, the total photosynthetic efficiency is mainly stimulated. In the model, the total photosynthetic productivity can be expressed as:

$$\mathrm{GPP} = 0.0183\alpha_c \times FPAR \times PAR \quad (13)$$

where the unit of GPP is molC·m-2 ·month-1, 0.22 is the conversion of total radiation to photosynthetically active radiation and gC to molC (0.083). The comprehensive coefficient is 0.0183.

PAR is the total amount of photosynthetic radiation within a specific time (MJ·m-2 ·s-1), usually used as the radiation average in a practical application model.

In the calculation, the average is 28.6 mol·m-2 ·d-1.As a reference point [3]. According to the energy conversion rules, the average daily adequate light and radiation is 28.6 MJ·m-2·s -1. According to the formula, it can be obtained:

$$\mathrm{N} * \mathrm{GPP} = \mathrm{N} \times 0.0183 \times \alpha_c \times FPAR \times PAR \tag{14}$$

According to the 2019 China Forest Resources Census report, China's forest carbon sequestration is about 1.2 billion tons of carbon dioxide per year. That translates to about 2.7 trillion moles of C. According to the above formula and 365 days in a single year, the annual carbon sequestration of China's forests is about 2.4 trillion mol C. The error with standard statistics is about 9%.

According to the optimized 3-PG carbon fixation model, we can calculate the carbon sequestration amount of forest trees and their products by the time parameter, which can be expressed as:

$$\mathrm{Total} = \mathrm{N} \times 0.0183 \times \alpha_c \times FPAR_T \times PAR_T \times T \tag{15}$$

Where PAR_T is the effective photosynthetic radiation in the T time zone, $FPAR_T$ is the proportion of effective photosynthetic absorption in the same time segment.

According to the 3-PG model, forest productivity was related to stand age, external environmental factors, and photosynthetic radiation absorption capacity. Sensitivity analysis was carried out after model optimization. It is concluded that the modified model has model sensitivity to parameters in the research range.

In summary, from the 3-PG carbon production model, we conclude that the management plan to maximize carbon sequestration is: appropriately cut down older trees in the existing forest to carry out iterative stand renewal.

3. Fuzzy Comprehensive Evaluation Model

3.1. Indicator Description

Carbon storage: The drafting or signing of a series of international climate change documents such as the "Bali roadmap," "Copenhagen agreement," and "Paris agreement" and the advent of the post-Kyoto era make the role of forests in reducing carbon dioxide level more and more attention, and carbon storage is an important standard to quantify the absorption of carbon dioxide by forests. Therefore, we use carbon storage to reflect the green ecological value of forests.

Water and soil conservation: Forest has irreplaceable importance in water conservation and soil fertilizer conservation. We introduce the concept of soil and water conservation to evaluate the ecological value of the forest.

The number of persons is employed in forestry and logging. Because of their vast area, forests provide many employment opportunities for labor, including logging, manufacturing of forest products, and service industries selling forest products.

Log output. Abundant forest resources produce countless and diverse forest products. We use log output to replace the total output of forest products, ignore some additional forest products that are difficult to measure, and the problem of loss in production.

Social service value. As a unique tourism resource, and its cultural connotation gradually derived with the development of history, the forest is an indispensable part of the evaluation of forest value. We introduce the concept of social services to evaluate the social value of forests.

3.2. Weight of Indicators

After determining the evaluation indicators, we further determined the weight of the five indicators. Since the value of the index differs greatly and can separate the management plans of each country, the index should be given considerable weight, so we choose the coefficient of variation method to determine the weight of the index. Firstly, the fuzzy vector $\mathrm{A} = (a_1, a_2, a_3, \dots, a_i)$ is introduced and set as the weight vector of the index, where a_i is the weight of the index.

Let's figure out the mean and variance of the i term:

$$\overline{x_i} = \frac{1}{n}\sum_{j=1}^{n} a_{ij} \tag{16}$$

$$s_i^2 = \frac{1}{n-1}\sum_{j=1}^{n}(a_{ij} - \overline{x_i})^2 \tag{17}$$

Define the resolution of indicators:

$$v_i = s_i/|\overline{x_i}| \tag{18}$$

Normalize:

$$a_i = \frac{v_i}{\sum v_i} \tag{19}$$

Because there is much information about evaluation indicators, in order to avoid information loss, we choose a weighted average type to obtain evaluation results, which can be expressed as:

$$F_j = \sum_{i=1}^{m} a_i r_{ij} (j = 1,2, \dots, n) \tag{20}$$

According to the definition of value F_j, the smaller the value F_j is, the more important the corresponding evaluation index is. Therefore, the order of importance is soil and water conservation > social service > staff service > carbon storage > economic benefit. In other words, soil and water conservation is the most important for selecting the most socially beneficial forest management options, and we also found that the evaluation results of these indicators are not much different, around 0.1.

Normalized each column of data representing different country models in the obtained fuzzy comprehensive evaluation matrix R and arranged the values in rows from small to large, which is shown in table 1.

Table 1. Data normalization

Carbon storage	0	0.164	0.1868	0.2513	0.3823
	Brazil	Canada	USA	Turkey	China
Number of people employed in forestry and logging	0	0.0793	0.2327	0.2464	0.4166
	Turkey	China	Canada	USA	Brazil
Log production	0	0.1164	0.1798	0.1866	0.2513
	USA	China	Canada	Brazil	Turkey
Social service area	0	0.223	0.2513	0.2815	0.422
	Brazil	Canada	Turkey	USA	China
Soil and water conservation area	0	0.2004	0.246	0.2852	0.3968
	China	Canada	Turkey	USA	Brazil

The values in the list are the proportions of each factor in different country models. Then, the transition point can be obtained by averaging the values between neighboring countries, which is shown in Table 2.

Table 2. The average value of the data

Carbon storage	Brazil	0.082	Canada	0.1754	USA	0.21905	Turkey	0.3168	China
Number of people employed in forestry and logging	Turkey	0.03965	China	0.156	Canada	0.23955	USA	0.3315	Brazil
Log production	USA	0.0582	China	0.1481	Canada	0.1832	Brazil	0.21895	Turkey
Social service area	Brazil	0.1115	Canada	0.23715	Turkey	0.2664	USA	0.35175	Turkey
Soil and water conservation area	China	0.1002	Canada	0.2232	Turkey	0.2606	USA	0.341	Brazil

Countries are measured values in the statistical data, and it is concluded that the fuzzy comprehensive evaluation value. The normalized after each numerical compared with transition point, choose the corresponding to the different numerical model, through the value will belong to corresponding to each country model together, it is concluded that the highest value model, and shows the countries with the selected model is most close to, The country's forest planning scheme is optimal.

4. Model Application

We adopt the 3-PG carbon production model. Norway is located in the western part of Scandinavia. Despite its proximity to the Arctic, Norway has long winters and short summers. However, due to the influence of the North Atlantic Current, most coastal areas belong to the temperate maritime climate, and in the mountainous areas of the interior is the lower temperature of the sub cold zone coniferous climate. Norway's forest stands are composed of fir and birch, and their photosynthetic efficiency is close to the average value of broadleaf pine forest. Therefore, some values of broadleaf pine forest are considered substitutes.

According to the Norwegian Forest Resource Data website, Norway has 93,870 square kilometers of forest. The annual photosynthetically active radiation in Norway at the average latitude is 161880K·cm2, PAR=6.77605×10 3 MJ·m-2 ·Year-1. According to the study of Zhang Leiming et al., the photosynthetic efficiency of broad-leaved pine forest is (0.040±0.002) μmolCO2·μmol photon-1.

Norway's forests sequester 250 billion moles of carbon in a single year. After 100 years, Norway's forests are expected to sequester 2.5×10 13 Mole carbon. It should be noted that the photosynthetic efficiency of broadleaf pine forest has been taken into account by environmental factors.

We can get the values of the models of the United States, Brazil, and Canada as 0.1595 0.2317 0.7173. Norway's national model for best forest management is that of Canada. By integrating Canada's national model and Norway's actual situation, it can be concluded that Norway's best forest management scheme is shown in Fig.3.

From Fig.3, we know 0.2% of the production area, 49% of the soil and water conservation area, and 3% of the social service area.

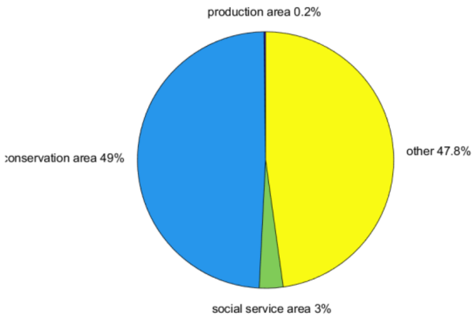

Figure 3 Forest management scheme.

5. Conclusion

In this paper, we rely on the ability of forests to absorb carbon, taking into account multiple value factors, to develop a clear, individualized forest management strategy. By establishing the 3-PG model, the optimal forest management strategy for maximum carbon sequestration is obtained. In addition, the carbon stocks of 5 countries were analyzed using FCE. Finally, taking the Norwegian National Forest as an example, the 3-PG model is used to estimate the carbon sink after 100 years. Using FCE and Norwegian National Forest data, Norway's optimal forest planning model is 0.2% production area, 49% soil and water conservation area, and 3% social service area.

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