Research on Forest Utility for Maximizing Forest Value

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Abstract. In order to measure forest carbon sequestration and make decisions on forest management, three models were established in this paper. Firstly, in Model I, we use ARIMA model and CBEF model to obtain the total biomass stored in the forest area and annual carbon sequestration of different dominant species in the same year. Then in Model II, the study classifies the value of forest ecosystem into carbon sink value, economic value and ecological benefit value. Then determine the weight of different forest values to obtain total forest value. Ultimately, In Model III, this paper defines the forms of economic benefits after tree harvesting based on economic principles, Tietenberg model and empirical equation, so as to obtain the optimal harvesting intensity and cycle of different tree species. So the optimal forest management plan can be determined. In this paper, the optimal management plan for forest value maximization in Palau within a certain period is given based on the above multidimensional measurement of forest value. Sensitivity analysis was also carried out, which shows there was little difference in the total value of forests calculated by the model when average log prices remained stable.

Keywords: Biomass; Carbon sequestration; Value assessment; Manage decisions.

1. Introduction

In recent years, extreme climate change has brought disaster as the level of greenhouse gases in the air rises. The key to dealing with this series of climate changes is to reduce the amount of carbon dioxide in the air. And forests can fix it in plants and wood products. Due to the products created by trees are different from the life cycle of trees, cutting down trees properly can achieve more carbon sequestration, while excessive logging can increase carbon dioxide levels, so cutting down what kinds of trees at what time is a key question. Forest managers need to consider the economic and ecological benefits of forests and their products while considering how to cut down forests to achieve higher carbon sink value.

For a long time in the past, many forest managers did not know how to use and manage their forests, which caused a certain loss of funds for forest managers, but also brought pressure to the ecological environment. More critically, there is also a lack of existing research on how to make optimal forest management decisions.

To fill a gap in the field, this paper evaluates the forest value and benefit in different forest management plans and gives scientific and reasonable suggestions for forest managers in making forest management plan decisions.

2. Data and Notations

The data sources are summarized in Table 1.

Table 1. Data and Database Websites

Database Names	Database Websites
FRA	https://fra-data.fao.org/PLW/fra2020/home/
Global Forest Watch	https://globalforestwatch.org/dashboards/country/PLW/
FAOSTAT	https://www.fao.org/faostat/zh/data/FO
The World Bank	https://data.worldbank.org.cn/
ADB	https://www.adb.org/
IPCC	https://www.ipcc.ch/
Google Scholar	https://scholar.google.com/

Since the data of forest area and carbon storage published by THE Food and Agriculture Organization of the United Nations (FAO) are not annual statistics, we grouped the data by year. For the years with missing data, we supplemented the data by linear interpolation along time.

Some important mathematical notations used in this paper are listed in Table 2.

Table 2. Notations used in this paper

Symbol	Description	Unit
BEF	Biomass expansion factor	—
B(t)	Biomass stored in year t	tonne
C(t)	Carbon dioxide sequestration in year t	tonne
L(t)	Carbon dioxide uptake in year t	tonne
S(t, i)	The area of the i-th tree in year t	ha
ρ(t,i)	Density of trees of the i-th species in year t	tree/ha
h(t,i)	Cutting intensity of the i-th species trees in t year	—
M_i	Average trunk weight of the i-th species tree population	tonne
δ	Coefficient of global ecosystem ecosystem service value to world GDP	—
φ	The weight coefficient of forest ecosystem to global ecosystem	—

3. Methodology

3.1 Model I: Biomass-carbon Sequestration Model

Forests can sequester carbon dioxide from the atmosphere in living plants and wood products created by plants. The plants and products of these forests sequester a certain amount of carbon dioxide over their life cycle. If the life cycle of forest products exceeds the life of the trees that produced them, there will be additional carbon sequestration effect, achieving more carbon sequestration within a certain period of time. A carbon sequestration model was established to determine the total carbon sequestration of forests and their products.

The tree population in the selected forest is divided, and it is assumed that the selected forest contains n types of trees. The following area of n tree populations per year is expressed as: S(t), Where t represents time, which means the next t year. Due to the difference of tree population, different areas of forest will show different ecological characteristics and value characteristics. The average life span of each tree population contained in a forest can be expressed as:T(n). Considering that the forest ecosystem itself can constantly expand its area due to the natural growth of trees in the forest, and combined with the characteristics of the growth cycle of trees, we calculated the average life span of each tree population in the forest T(i) (i=1,2,3...,n) as the research period of each tree, the forest area data of the first 30 years are fitted by ARIMA model, and the forest area S(t) of each year in T(i) (i=1,2,3...,n) period was predicted. Since the forest area data used in the fitting are actual data, the impact of human activities on forest area change has been included. The projected data also take into account human activities, so the previous year's forest area is used in the following calculation of felled area.

Combined with the natural growth law of forest trees, that is, the volume growth rate of trees in different periods is different, we defined the growth coefficient function of species i tree population as follows according to sigmoid function and empirical equation

$$f(t, i) = \frac{1}{1 + e^{-t+T(i)/2}} \tag{1}$$

Where T(i) is the average life span of each tree population in the forest (i=1,2,3...,n). Suppose that the average life of a certain tree is 12 years, T(i)=12, draw the function graph of f(t)at this time, as shown in Figure 1.

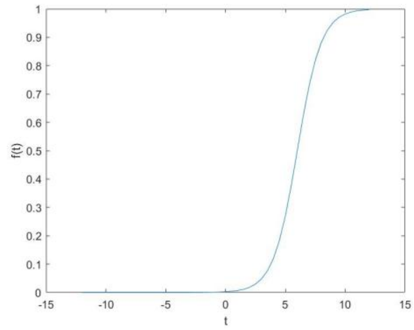

Figure 1. The function graph of f(t)

First, the accumulation density of each stand type and age class was calculated according to the total volume and total area, and then the mean biomass density of each stand type and age class was estimated by using the continuous biomass expansion factor method. The equation is as follows:

$$\mathrm{BEF} = \mathrm{a} + \frac{\mathrm{b}}{\mathrm{x}} \quad (2)$$

$$\mathrm{B} = \mathrm{BEF} \cdot \mathrm{x} \quad (3)$$

Where, x is the quantity of wood per unit area, a and b are constants of a specific forest type, B is biomass density, and BEF is biomass expansion factor. According to the biomass conversion and expansion factor, the biomass of the trees and their dimensions in the year t within the average life T(n) of i−th species is

$$b_1(t,i) = S(t,i) \cdot \rho(t,i) \cdot BEF \cdot f(t,i) \cdot M_i \quad (4)$$

If there is felling in year t, the biomass of the products made from the felled part of the tree species is

$$b_2(t,i) = S(t-1,i) \cdot h(t,i) \cdot \rho(t,i) \cdot \alpha_i \cdot M_i \quad (5)$$

If the products before t−k are eliminated in t year, the biomass released after the elimination of the products is

$$b_3(t,i) = S(t-k,i) \cdot h(t-k,i) \cdot \rho(t,i) \cdot \alpha_i \cdot M_i \quad (6)$$

In equations (4)-(6) above, B(t,i) represents the stored biomass.BEF is a biomass expansion factor, and continuous biomass expansion factor (CBEF) is recommended in practical application. However, due to the lack of field exploration conditions, BEF data provided by IPPC is used for estimation. H(t,i) is the felling intensity of each type of trees in the forest at t, that is, the proportion of felled trees to the total number of tree population; t is the time variable; M_i is the average trunk weight of the i−th species tree population; ρ (t,i) is the density at t year; α_i is the volume loss rate of tree of species i, including the loss during machining and cutting. k is the service life of the main product made from trees of species i.

In conclusion, if felling and product elimination exist in year t, the total biomass of species i tree population and its products stored is

$$B_1(t,i) = S(t,i) \cdot \rho(t,i) \cdot BEF \cdot f(t,i) \cdot M + S(t-1,i) \cdot h(t,i) \cdot \rho(t,i) \cdot \alpha_i \cdot M - S(t-k,i) \cdot h(t-k,i) \cdot \rho(t,i) \cdot \alpha_i \cdot M_i \quad (7)$$

If only felling existed, the total biomass of species i population and its products is

$$B_2(t,i) = S(t,i) \cdot \rho(t,i) \cdot BEF \cdot f(t,i) \cdot M + S(t-1,i) \cdot h(t,i) \cdot \rho(t,i) \cdot \alpha_i \cdot M_i \quad (8)$$

If only elimination existed, the total biomass of species i population and its products is

$$B_3(t,i) = S(t,i) \cdot \rho(t,i) \cdot BEF \cdot f(t,i) \cdot M - S(t-k,i) \cdot h(t-k,i) \cdot \rho(t,i) \cdot \alpha_i \cdot M_i \quad (9)$$

If neither felling nor elimination exists, the total biomass of species i tree population and its products is

$$B_4(t,i) = S(t,i) \cdot \rho(t,i) \cdot BEF \cdot f(t,i) \cdot M_i \quad (10)$$

The total sequestered biomass of the forest system and its products by year t is summed over the total sequestered biomass of all species of trees contained in the forest ecosystem:$B(t) = \sum_{i=1}^{n} B_i$;At this time, the total biomass is obtained. According to the conversion coefficient between biomass and carbon sequestration, the total carbon sequestration of the forest system in year t is:$C(t) = B(t) \cdot \beta$,In the formula, β is the conversion coefficient of carbon storage, which needs to be determined by local field exploration, usually between 0.4 and 0.5. In this paper, 0.5 was selected.

The annual total carbon storage is obtained, and the difference of the annual total carbon storage is the total carbon fixed by the forest system in this year, which can be expressed by the formula

$$\triangle C(t) = C(t) - C(t-1) \tag{11}$$

Where △C(t) is the difference of carbon sequestration in the interval years, that is, the total amount of carbon sequestration in the t year. According to the relationship between the molecular weight of total carbon and total carbon dioxide, the amount of carbon dioxide absorbed by the forest each year can be obtained.

$$L(t)=\frac{M(CO_2)}{Ar(c)}\triangle C(t) \tag{12}$$

Where L(t) is the amount of carbon dioxide absorbed by the forest every year; Ar(c) is the relative atomic mass of carbon; $M(CO_2)$ is the relative molecular mass of carbon dioxide. After the biomass-carbon sequestration model was established, we selected the forests of Palau to predict the amount of carbon sequestration, and compared the actual amount of carbon sequestration to confirm the rationality of the model.

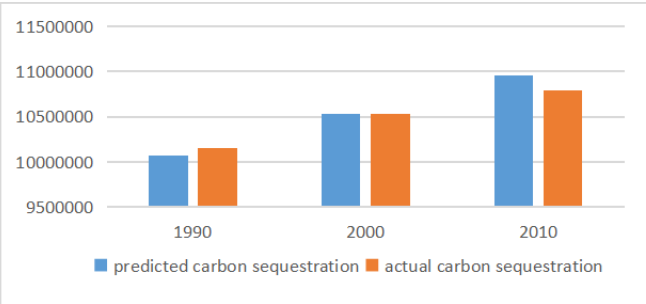

Figure 2. Comparison between actual and predicted carbon sequestration in 1990/2000/2010

After establishing the carbon sequestration model, this study calculated the theoretically predicted value and compared it with the actual value. It can be seen from Figure 2 that the error is within a reasonable range, and the preliminary conclusion of the model is scientific to a certain extent.

3.2 Model II: Forest Valuation Model

Forests not only reflect the value of carbon sequestration in the aspect of carbon sequestration, but also play a huge role in other aspects. This paper will establish an evaluation model of forest value to systematically evaluate the value of forests in various aspects among different forests and under different forest management plans of the same forest.

3.2.1 Value of Carbon Sequestration

Since forest ecosystem has the functions of carbon storage and carbon fixation, this paper divides the carbon sink value of forest into carbon storage value and carbon fixation value and calculates them respectively.

Carbon fixation value refers to the benefits of the process of permanently fixing a unit of carbon dioxide in the atmosphere. This paper adopts the cost method of artificially fixed carbon dioxide to calculate the fixed value of carbon, and estimates the price of forest carbon sequestration based on the average forestation cost. The process is as follows:

$$V_c=\sum_t^T \triangle C(t) \cdot \overline{cost} \cdot e^{-r_t \cdot t} \tag{13}$$

Where, C(t) is the carbon fixed value, $\overline{cost}$ is the average afforestation cost, and r_t is the discount rate in the t year.

The value of carbon storage can be estimated by the following methods

$$V_s=P_0 + \sum_t^T \triangle C(t) \cdot P_S \cdot e^{-r_t \cdot t} \tag{14}$$

Where V_s is carbon storage value; P_0 is the initial carbon storage reference value (constant); P_S is the value of carbon dioxide unit stock.

3.2.2 The Economic Value of Forests

The trees in the forest that are cut down (unprocessed) are sold as timber resources. Subsequently processing production for a variety of forest products, such as furniture, plywood and other wood products, and produce a certain economic value. The economic value of forests can be measured by the following formula:

$$V_t=\sum_{i}^{n}\sum_{t}^{T} S_{t-1,i} \cdot h_{t,i} \cdot \rho_{t,i} \cdot v_i \cdot P_{t,i} \cdot e^{-r_t \cdot t} \tag{15}$$

Where V_t is the timber value of the forest, v_i is the average volume of actual commercial rate of trees of type i, $P_{t,i}$ is the average price of wood of type i in year t.

Forest resources are also important local medical resources, and play a special role in the development of modern drugs by using modern technology. Therefore, we include the medicinal value of forests into the accounting scope, and the calculation formula is as follows

$$V_d=\sum_{j}^{m}\sum_{t}^{T} S_{t-1,j} \cdot h_{t,j} \cdot \rho_{t,j} \cdot v_j \cdot P_{t,j} \cdot e^{-r_t \cdot t} \tag{16}$$

Where V_d is the medicinal value of forests, v_j is the average volume of the actual commercial rate ofthe species of j medicinal trees in the t-1 year, $P_{t,j}$ is the average price of finished products of the species j medicinal trees in the t-1 year.

3.2.3 The Ecological Value of Forest

There is a great deal of species diversity and genetic diversity in different ecosystems. Forest biodiversity can also be used as a resource for value accounting. This paper mainly uses opportunity cost method to calculate the value of forest biodiversity. Assuming that all forest resources are exploited without considering forest biodiversity conservation, the income from all forest products is the opportunity cost of forest biodiversity.

$$V_b=\sum_{i}^{n}\sum_{t}^{T} S_{t-1,i} \cdot \rho_{t,i} \cdot V_i \cdot P_{t,i} \cdot e^{-r_t \cdot t} \tag{17}$$

The ecological service value of forest is embodied in the aspects of water conservation, wind prevention and sand fixation. Using GUMBO (Global Unified Metamodel of the Bio-Sphere) model, researcher Boumans estimated the global ecosystem on a global scale, based on long-term modeling work and rapidly expanding global databases. It is concluded that there is a proportional coefficient between the value of global ecosystem ecosystem services and world GDP.

$$V_e=\epsilon \cdot \delta \cdot \varphi \cdot \mathrm{DP} \quad \cdot \sum_{i}^{n} \frac{S_{t-1,i} \cdot \rho_{t,i} \cdot m}{\sum_{i}^{n} S_{t-1,i} \cdot \rho_{t,i} \cdot m}(1-h_{t,i}) \tag{18}$$

Where, V_e is the ecological service value of forest; GDP is the annual GDP of the place; ϵ is the correction coefficient; δ is the proportional coefficient between the value of global ecosystem ecological services and the world GDP, 4.5 is selected here. φ is the weight coefficient of forest Ridge ecosystem in the global ecosystem(0.4).

3.2.4 Total Value of Forests

The sum of these six values is weighted to give the total value of the forest. The formula for calculating the total value of forests is as follows:

$$V=\sum_{i}^{n} \omega_i \cdot V_i \tag{19}$$

Where, V is the total value of forests; ω_i(i=1,2,3,4,5,6) is the weight of various values of the forest. For forests of different types, terrain, latitude and longitude, climate and policies, the weight of each forest value will be different. Therefore, it is reasonable to have different weights ω_i(i=1,2,3,4,5,6) in the process of measuring the total value of forests. For example, the number of tree types is used to judge whether it is virgin forest or artificial forest. For virgin forest, we give higher ecological benefit value; For plantation forests, we assign higher economic value.

Below, we determine the weight of various values of different forests by DARE sequential scoring method, and prove the feasibility of initial assignment through subsequent tests.

3.3 Model III: Forest Management Decision Model

3.3.1 Determination of Harvesting Intensity in Forest Management Plans

According to the carbon sink value, economic value and ecological benefit value considered in the above value model, the optimal cutting intensity of selected forests was determined on the basis of the above forest value evaluation model. The cutting rate was used to represent the cutting intensity, and △V was set to represent the total value change of forests caused by increasing the cutting intensity.

$$\triangle V=\sum_i^n \omega_i \cdot \triangle V_i \quad (20)$$

If only the carbon sink value and ecological benefits are considered, the smaller the cutting intensity, the least damage to the forest ecosystem, is the most appropriate. On the other hand, just for economic reasons, we might choose to harvest more intensely so that we can get more wood for demand. The benchmark cutting intensity we selected was 0, and the relationship between △V and H was showed in Figure 3.

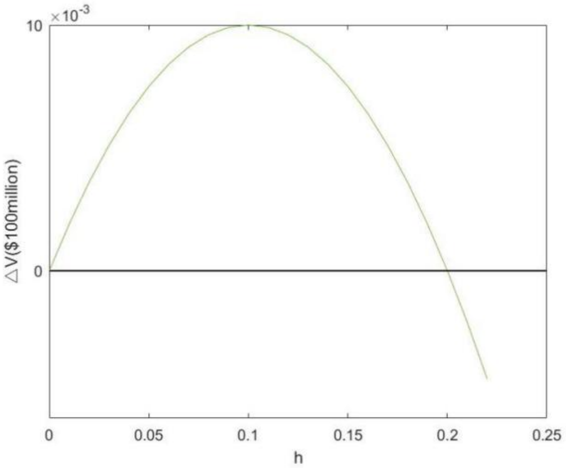

Figure 3. The relationship between △V and H

According to the principle of Inter-Generational Equity, in the selected analysis period, we can get the cutting rate h^* at the critical condition △V=0 as the optimal cutting intensity.

3.3.2 Harvesting Cycle Decision Making

The optimal cutting intensity in the management plan has been identified in model II. On this basis, we can continue to solve the optimal cutting cycle.Based on the Tietenberg model and empirical equation, we express the economic benefits of tree harvesting as follows

$$R=(P_{t,i}-VC_{t,i})\cdot f(t,i)\cdot V_i \cdot e^{-r_t \cdot t} \quad (21)$$

Where R is the net present value of the income of a single wood; $P_{t,i}$ is the price of wood per unit volume; $VC_{t,i}$ is the cost of logging per unit volume; f(t,i) is the growth coefficient function; V_i is the average volume of the tree; r_t is the discount rate; t is time in years.

$$\frac{df(t^*)}{dt\cdot f(t^*)}=r_t \quad (22)$$

The maximum value of equation (20) can be obtained: when and is unequal, there is an optimal cutting cycle, so the maximum harvesting period of each tree species is taken as the analysis period, and the optimal harvesting period can be calculated from Equation (21), so as to obtain the total forest income within the optimal harvesting period under the optimal harvesting intensity, and continue to the next tree growth cycle until the maximum harvesting period of each tree species ends. If the analysis period is extended, the growth coefficient of forest area after the cutting cycle can be adjusted according to the change of the cutting intensity, and the forest area in the next growth cycle can be predicted by rolling into the ARIMA model until the end of the analysis period, so that the cutting cycle and the cutting intensity table with the maximum total income in the analysis period can be obtained.

4. An Optimal Management Plan for Palau Forests

In order to make the model fitting more accurate, we chose the forest of Palau, a Pacific island country, as the object of analysis. Figure 4 shows the composition of Palau's forests. Except for the Marine economic zone, most of its territory is covered by tropical rain forest. Its small scope, prominent dominant tree species and obvious forest ecological characteristics are helpful for our analysis.Palau’s domestic forests are mainly divided into volcanic forests and limestone forests, which have obvious differences in ecological characteristics.

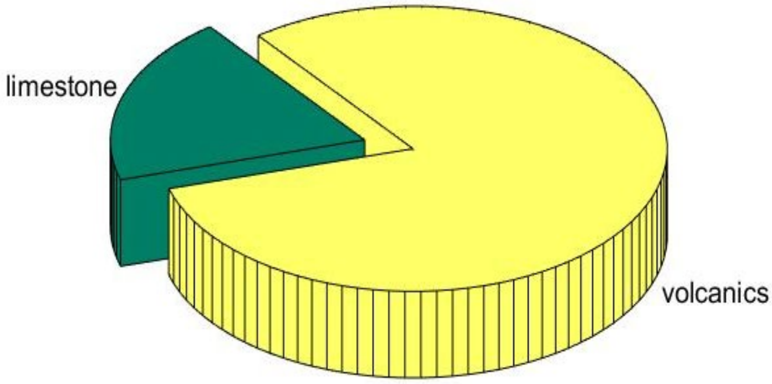

Figure 4. Pie chart of the forests that make up Palau

By fitting various data and exogenous variables of Palau’s forests with the model, the management plan for palau’s forests in the next 12 years is shown in Table 3(where we calculate that the optimal harvesting period of limestone forest is 5 years and that of volcanic forest is 14 years. It is assumed that the two types of forest have already been felled once in 2020.)

Table 3. Management schedule for Palau’s forests, 2021-2034

	Annual Carbon Sequestration (tonne)	Forest Value ($100 million)	Limestone Forest Cutting Intensity (%)	Volcanic Forest Cutting Intensity (%)
2021A	22152.0294	3.6955		
2022E	21611.7362	3.7008		
2023E	21071.4426	3.7059		
2024E	20801.2959	3.7109		
2025E	33984.5991	3.7170	6.74	
2026E	19450.5123	3.7205		
2027E	9175.5635	3.7232		
2028E	18640.0746	3.7298		
2029E	18099.7823	3.7342		
2030E	28771.3038	3.7402		
2031E	17565.9735	3.7427	5.33	
2032E	17117.5311	3.7467		
2033E	18244.5802	3.7507		
2034E	93658.4612	3.7665		10.81

The carbon sequestration and forest values predicted for Palau forests in each year before and after the implementation of the management plan are shown in Figure 5. As can be seen from the figure, after the implementation of the management plan, the carbon sequestration of Palau’s forests increased by 94,521.2191 metric tons and the forest value increased by us $1074.8 million.

(a) (b)

Figure 5. (a) Carbon sequestration in the years before and after optimal forest management plan, (b) Forest values in the years before and after the implementation of the forest management plan

5. Sensitivity Analysis

In section 3.2.3, the average price of wood, as an exogenous factor, is introduced to estimate the value of a forest: the average price of wood. According to the formula in 3.2.4, the total value of forests and the average price of wood are first-order relations. Thus, the relationship between the total value of forests and the average price of timber is approximated by a first-order difference

$$\frac{\partial V}{\partial P} \approx \frac{V(P+\Delta P)-V(P)}{\Delta P} \tag{23}$$

The calculation results are shown in Figure 6. And the study shows that the total value of forests in the analysis period T increases with the increase of the average price of wood, reflecting that the total value of forests also increases with the increase of the average price of wood. The trend of the model obtained by sensitivity test is consistent with the actual situation, which also proves the rationality and robustness of the forest value assessment model.

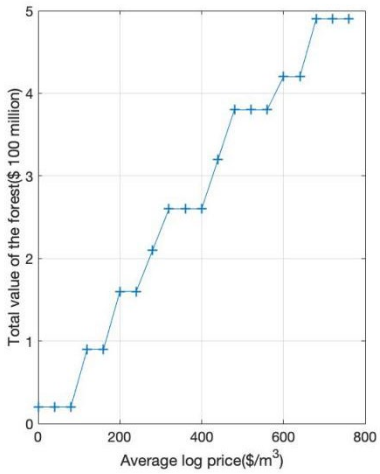

Figure 6. Sensitivity analysis of p

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