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Dynamic Forest & Brighter Future

Summary

In recent years, with global warming and other climate changes, the concept of "carbon" has attracted widespread public attention. Low-carbon-emission products such as clear energy has prevailed a lot. However, in addition to reducing carbon emissions, carbon sequestration is also a powerful way to mitigate carbon dioxide. With an attempt to effectively increase the amount of carbon sequestration and provide possible strategies for forest managers, our work is proceeded as follows.

First of all, we establish a dynamic **SHG model** to simulate Sequestering-Harvesting-Growing carbon cycle of a forest ecosystem. A forest is divided into three parts: **product**, **mature** and **immature** area. They appear to be independent but influence each other. The model takes fixed parameters of the forest (area, tree species, region, etc.) as input and outputs the total amount of carbon sequestered over a period of time. By the Monte Carlo method, we obtain a haversting rate of **3% to 5%** that maximizes carbon sequestration.

Secondly, we devise a comprehensive and practical indicator system, on which the **ECC model** is based. ECC model provides a value quantitative method in which we divide the values of forests into three categories: **ecological**, **economic** and **cultural** values. Among these, ecological value depends on the result of SHG model.

Thirdly, according to the result of ECC model, we develop Target Oriented Forest Management Strategy by adopting **decision tree algorithm**. With 2,214 forest samples, we calculate the percentage of different values and put them as features into the algorithm, which automatically generates a decision tree with threshold. The final decision threshold value is **10.8%** of economic value percentage and **69.5%** of ecological value percentage. They can be viewed as a transition point in forest management. Forest managers can assess the current state of forest by calculating the combination of different values and compare it with the threshold to determine the future development directions.

Finally, we apply our models in Heolongjiang Province of China and obtain the total 100-year carbon sequestration of $\mathbf{7.599 \times 10^9}$ tonnes. During 2010 to 2018, the total value of it reaches to **92.2249** billion dollars in 2018 where ecological, economic and cultural value account for **81.64%**, **12.68%** and **5.67%** respectively. According to our strategy, forests of Heilongjiang are in intermediate stage and they should adopt a culture-oriented strategy to develop tourism and enhance the input of scientific research. The transition point of management emerged in **2014-2015**.

Keywords: Carbon Sequestration; SHG; Value Quantification; Decision-making

Contents

1 Introduction

1.1 Problem Background

As one of the oldest ecosystems on earth, forest ecosystems have played an integral role in the evolution process of the planet's ecology. They have potent ecological functions such as maintaining water and soil, protecting biodiversity and regulating climate, which reflect great ecological values. Among them, the function of carbon sequestration is the most prominent. Carbon sequestration refers to a process where forests sequester carbon dioxide out of the atmosphere, which plays an essential part in the biosphere cycle. However, the development of the forest is twisting. Due to the lack of environmental awareness and effective management, the earth's forests have been destroyed on a large scale over the past few centuries. Ecology and economy seem to be on opposite sides when both are considered. Therefore, economic and ecological forest management plans are urgently needed.

1.2 Restatement of the Problem

- **Problem 1:** Establish a carbon sequestration model to calculate how much carbon dioxide a forest system and its products can sequester, and choose the most efficient forest management plan for carbon dioxide sequestration based on the model.
- **Problem 2:** Build a decision model to balance the diverse values of forests so that forest managers can make the best use of forest resources.
- **Problem 3:** Take consideration of harvesting in the management plan and observe the model results by applying the model to specific forests.

1.3 Our Work

Firstly, we devise Dynamic **SHG** (Sequestering-Harvesting-Growing) Simulation Model to calculate the total carbon sequestration over time period of ΔT. By adjusting the variable parameters, the model can reach the maximum of carbon sequestration.

Secondly, we establish a comprehensive indicator system including **ecological**, **economic** and **cultural** values. Based on the indicator system, we build the **EEC** (Ecological-Economic-Cultural) Model to quantify various values of a forest ecosystem.

Thirdly, we adopt the **decision tree** algorithm to predict the development stage of the forest and develop **Target Oriented Forest Management Strategy** to assist managers or landowners to make wise decisions. In this way, they can perceive the current stage of the forest and adjust development strategies in future.

Finally, we apply our three models to the specific forest, conduct a case study, calculate the 100-year carbon sequestration and give the possible forest management plan.

The whole framework of our essay is shown in Fig. [1].

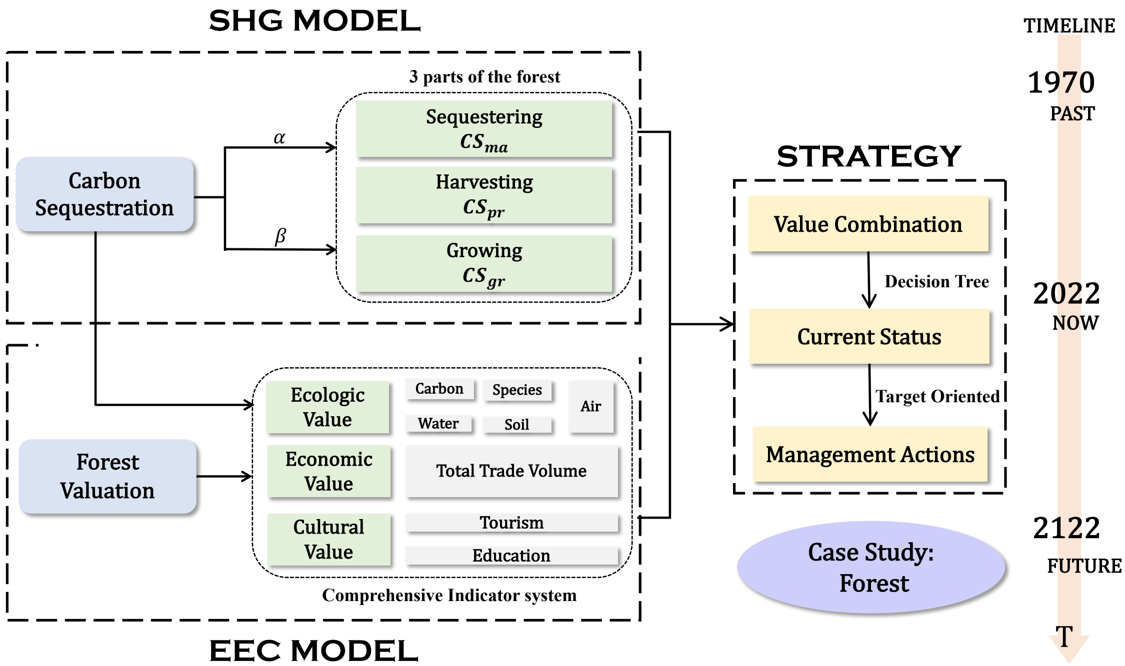

Figure 1: The whole framework of our essay

2 Assumptions and Justifications

- **Assumption 1:** The statistical data obtained are reliable and accurate.
  - ↪ **Justification:** Most data are collected from authoritative websites and papers, under which our model is operational and practical.
- **Assumption 2:** The forest ecosystem is the smallest unit we consider.
  - ↪ **Justification:** Forest ecosystems are incredibly complicated. To preserve the macroscopic nature of the model, all data are collected on the principle that we view the forest as a whole.
- **Assumption 3:** No massive unlawful logging activity will be carried out during the managing process, and the timber harvesting processes are all within control.
  - ↪ **Justification:** During the regulating process, the executors will strictly stick to the plan, and the security of the forest resources can be guaranteed, which means there will not be any massive illegal timber harvesting process.
- **Assumption 4:** Extreme events are ignored, which means fixed parameters are stable, such as the area of the forest, the structure of forest product, etc.
  - ↪ **Justification:** Since the forest is stationary, we assume the biosphere is stable and developing. The force majeure will not be considered.

3 Notations

Table 1: Notations used in this essay

Symbol	Description	Unit
T	time	year
S	the area of the forest	ha
ω_i	the weight of wood per area of the forest type i	tonne/ha
α	the proportion of tree harvest	Unitless
β	harvested area ratio compared to the exact amount of area	Unitless
$pp_{i,j}$	the proportion of timber product i in forest j	Unitless
als_i	the average lifespan of timber product i	year
c_i	the time for a land turning into forest type i	year
$v_{t,i}$	the carbon sequestering speed of forest type i in time t	tonne/year · ha
TCS	total carbon sequestration	tonne
CS_{ma}	carbon sequestered by mature forest area	tonne
CS_{pr}	carbon sequestered by timber product	tonne
CS_{gr}	carbon sequestered by growing forest area	tonne
TV	the total value of the forest	dollar
V_{ec}	ecological value of the forest	dollar
V_{pr}	economic value of the forest	dollar
V_{cu}	cultural value of the forest	dollar

4 TASK I: Dynamic SHG(Sequestering-Harvesting-Growing) Simulation Model

4.1 Model Overview

To better use the resources in the forest, the schedule of forest managing will contain the timber harvesting processes of tree cutting. After harvesting the log from the wood, the log will be made into different kinds of wood products. And apart from generating economic value, the harvesting activities will also speed up the carbon sequestering process.

To quantify the carbon sequestered by the forest, we categorize the amount of the total carbon sequestration (TCS) into three sections, which come from the mature forest area (CS_{ma}), the growing forest area (CS_{gr}), and the product produced from the log in the forest(CS_{pr}).

$$TCS = CS_{ma} + CS_{pr} + CS_{gr} \tag{1}$$

The dynamic process of sequestering, harvesting and growing is shown in Fig. [2]. After the categorization, we will give the definitions of the three parts.

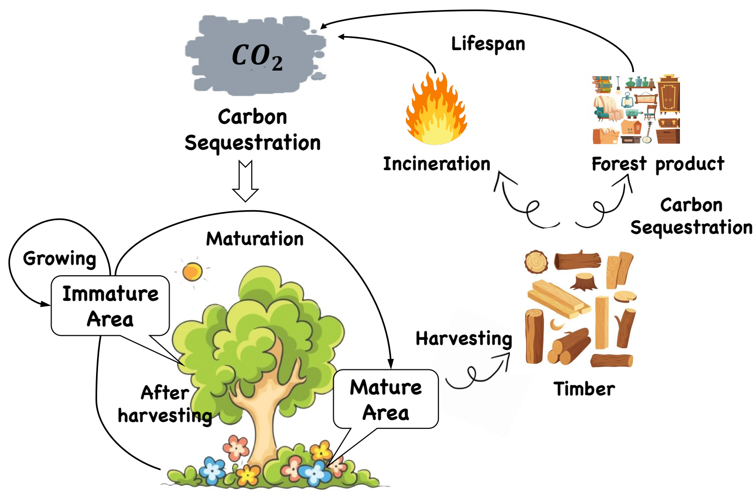

Figure 2: Dynamic process of sequestering, harvesting and growing

4.2 Dynamic Carbon Cycle Simulation

4.2.1 Sequestering: The Mature Area

Forest is the central part of the global carbon cycle. During its growth, land plants in the forest can synthesize organic matter by absorbing CO_2 within a specific concentration range, thus saving the cost of carbon sequestration by some technologies like separation and purification.

Because the annual carbon conversion rate of different types of trees per square hectare can be obtained in previous studies, the carbon sequestration stock of mature forest can be calculated directly by using the following formula where the ΔT is the period of time. For $v_{t,i}$ may varies in different years, we use summation sign to express the accumulation in ΔT, the same as below.

$$S_{ma} = S - \sum_{growing} S_{area} + \sum_{\substack{finish \\ growing}} S_{area} \tag{2}$$

$$CS_{ma} = S_{ma} \sum_{t=1}^{\Delta T} v_{t,i} \tag{3}$$

The expression shows the mature part's area is dynamic annually in our model, for we've considered the growing process of the previously harvested area. When the growing process is completed, the land will be recalculated as a part of the mature area.

4.2.2 Harvesting: The Forest Products

Harvested trees can be used for various purposes, including wood fuel, industrial roundwood, plywood, paper, and more. Among these, the carbon in wood fuel is incinerated and returns to the atmosphere. This process cannot be classified as carbon sequestration so we define the lifetime of wood fuel is 0. On the contrary, other forest products can complete carbon sequestration during their lifespan and return to nature as inorganic carbon once their lifespan ends. The lifespans of forest products are shown in Tab. [2].

Table 2: Average lifespan of different forest products [2]

i	*Item*	als_i
1	Industrial roundwood	15.3
2	Wood pellets and other agglomerates	4.1
3	Sawnwood	21.0
4	Wood-based panel	7.5
5	Papers	29.8

We assume that the carbon sequestrated in product i released at a constant speed and the forest products structure in the specific region is stable. When region j is determined, the formula below can give the carbon sequestration of products. $pp_{i,j}$ denotes the product i's ratio of all the wood product in region j. The data of $pp_{i,j}$ can be obtained in Brunet-Navarro et al, 2017 [2].

$$CS_{pr} = \sum_{t=1}^{\Delta T} S\alpha\omega \sum_{i=1}^{5} \frac{pp_{i,j}}{als_i} \tag{4}$$

4.2.3 Growing: The Growing Area

In this part, we will give the definition of the amount of carbon that sequestrated by the growing area of the forest.

For the trees in a particular area in the forest, the growth rate for the trees will gradually slow down as the maturity of this block of forest increases. By now, the tree will not have sufficient space to grow any further. And if the land is completely wiped out, the process for the bare ground transforming into the forest will be extremely long, and to fully restore may take over a century [3]. So, drawing the inspiration from Pierre-Franois Verhulst's mathematical model, we formulate the growing area i's full rate $fr_{area,i}$ in total using the logistic model to calculate the initial time t_{ini} after one area's harvest.

$$\frac{dfr_{area,i}}{dt} = C_0 fr_{area,i}(1 - \frac{fr_{area,i}}{1}) \tag{5}$$

In the logistic model, C_0 is called the growth rate, which negatively correlates to c_i. i refers to different types of forest or trees and S_{area} denotes the area of the harvested land i. For this model, when $t = \frac{c_i}{2}$, the $fr_{area,i}$ will equal to 0.5. So t can be expressed as:

$$fr_{area,i}(t) = \frac{1}{e^{-\frac{C_0 t}{c_i} + \frac{C_0}{2}} + 1} \tag{6}$$

According to different types of forests, C_0 may be different. Considering the time, we expect that when $t = c_i$, the $fr_{area,i}$ will reach approximately 1. So we give that:

$$fr_{area,i}(c_i) = \frac{1}{e^{-\frac{C_0}{2}} + 1} \geq 0.95 \Rightarrow C_0 \geq 2ln19 = 5.88 \tag{7}$$

After harvesting, the mature area becomes an immature area, and the corresponding growth time t_{ini} can be calculated via $fr_{area,i}$. In the formula, we round down t_{ini} to simplify the calculation.

$$fr_{area,i} = \frac{1}{e^{-\frac{8t_{ini}}{c_i}+4} + 1} \to t_{ini} = \left\lfloor \frac{c_i}{C_0}(ln(\frac{fr_{area,i}}{1 - fr_{area,i}}) + \frac{C_0}{2}) \right\rfloor \tag{8}$$

As the tree continues to grow, the area's density is getting closer to saturated status, so the pace of growth is slowing in the meantime. As Fig. [3] from the FAO shows that the speed of carbon sequestrating rises rapidly and felling down slowly with the bare area as the initial state.

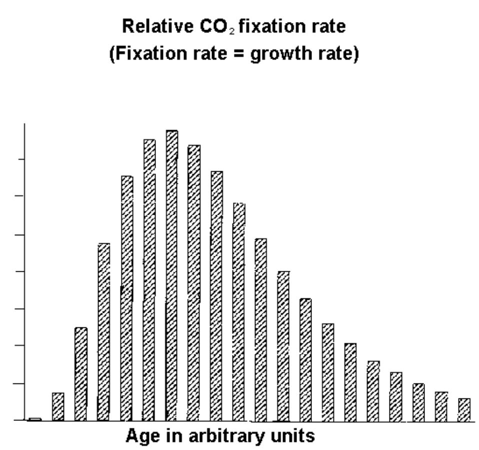

Figure 3: Typical carbon dioxide fixation rate of a tree as a function of its age [4]

To simplify the model, we use logarithmic functions to construct expressions $v_i'(t)$ to fit data above in the shape of skewed distributions.

$$v_i'(t) = q_i \frac{ln(p_i t + 1)}{p_i t + 1} \tag{9}$$

Where p_i and q_i denote two coefficients of different forests or trees. By adjusting these two coefficients, the curve can change into various shapes, which can fit the discrete data in Fig. [3].

Charlotte E. Wheeler et al. [5] find that the biomass accumulation increased fourfold to 3.9 Mg ha^{-1}y^{-1} between 10 and 18 years. And two graphs in Kotaro Iizuka's re-

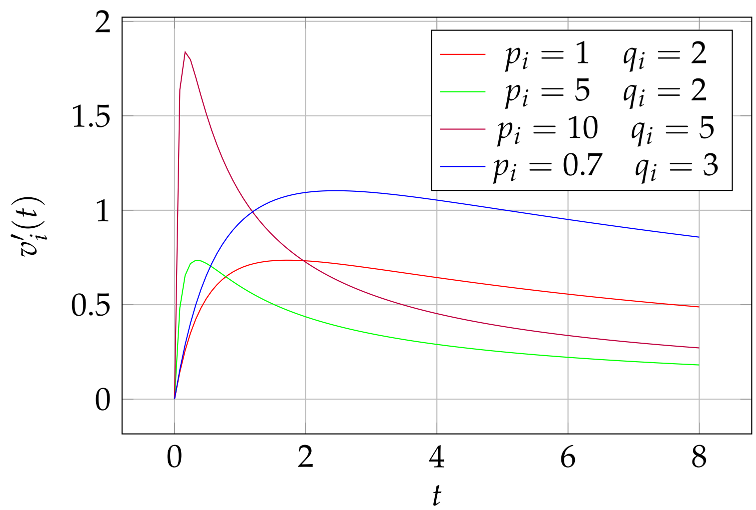

Figure 4: Speed fitting curve with different p_i and q_i

search [6] also show that the highest rate of carbon sequestration of coniferous forest, deciduous broadleaf forest and evergreen broadleaf forest all occur in the group of 15-20 years, whose results are consistent with FAO's graph of Fig [3].

We can figure out that when $t = \frac{e-1}{b}$, $v_i'(t)$ will reach its maximum level $\frac{a}{e}$. So, we can define that:

$$\begin{cases} \dfrac{e-1}{p_i} = t_{i,max} \\ \dfrac{q_i}{e} = v_{i,max} \end{cases} \Rightarrow \begin{cases} p_i = \dfrac{e-1}{t_{i,max}} \\ q_i = ev_{i,max} \end{cases} \tag{10}$$

Where $v_{i,max}$ denotes the max carbon sequestrating speed of different kinds of forests or trees, $t_{i,max}$ denotes the age of reaching $v_{i,max}$. Based on the data of Kotaro Iizuka, et al. [6], Meenakshi Kaul, et al. [7], the carbon sequestrating speed calculating sheet are as follows:

Table 3: Carbon sequestrating speed calculating sheet

i	$tree/forest\ type$	p_i	q_i	$v_{i,max}$	$t_{i,max}$
1	Eucalyptus	0.430	72.034	26.5	4
2	Poplar	0.430	75.242	27.68	4
3	Sal	0.022	26.367	9.7	75
4	Teak	0.115	28.542	10.5	15
5	Coniferous	0.115	43.792	16.11	15
6	Deciduous Broadleaf	0.115	18.729	6.89	15
7	Evergreen Broadleaf	0.115	18.83	6.93	15

After finishing $v_i'(t)$ speed function, we can now give the definition of CS_{gr}. It reflects the amount of the carbon sequestrated by the growing area in the time period ΔT after the harvesting process of rate α.

$$CS_{gr} = \sum_{area} \sum_{t=t_{ini}}^{t_{ini}+\Delta T} S_{area,i} v_{area_i} \quad = \sum_{area} \sum_{t=t_{ini}}^{t_{ini}+\Delta T} \alpha\beta S v_{area,i} \tag{11}$$

Here, $v_{area,i}$ is the speed of carbon sequestrating of one growing area of forest kind i, which can be calculated through Tab. [2].

4.3 Results

To conclude our model by adding three parts up, the amount of carbon sequestrating of a year can be calculated as follow:

$$\begin{aligned} TCS &= CS_{ma} + CS_{pr} + CS_{gr} \\ &= \Big(S - \sum_{growing} S_{area} + \sum_{\substack{finish \\ growing}} S_{area}\Big) \sum_{t=1}^{\Delta T} v_{t,i} + \sum_{t=1}^{\Delta T} S\alpha\omega \sum_{i=1}^{5} \frac{pp_{i,j}}{als_i} + \sum_{area} \sum_{t=t_{ini}}^{t_{ini}+\Delta T} \alpha\beta S v_{area,i} \end{aligned} \tag{12}$$

4.3.1 Reaching the maximum of carbon sequestration with fixed α

Using the model in equation (12), we can measure the total carbon sequestration of the forest. In this section, we use related data of evergreen broadleaf forests to test our model in a relatively short period of time. Given that the duration is short, we assume that all the data above will retain, and we will use the different time period to test the given forest model. Retrieved from FAO's website [8] and lIGN [9], the related figure and parameters are as follows:

Table 4: Related parameters of evergreen broad-leaf forests

variables	values	function
S	5000 ha	The total forset area of this case
c_{eb}	50 year	The average life span of the trees
$v_{t,eb}$	5.3 tonne/year·ha	The carbon sequestration rate of the mature area
ρ_{eb}	0.54 tonne/m^3	The average density of the live wood
ω_{eb}	112m$^3/ha$	the average growing stock
C_0	8	The coefficient used to express $t_i ni$
p_{eb}	0.115	Two coefficient used to calculate the restoration
q_{eb}	18.83	rate of the growing part

We run our model under period of 5 years and 15 years, and we set $\beta \in [1, 10]$, and $\alpha \in (0, 1)$, and use Monte Carlo method 10^4 times per test. Setting the maximum carbon sequestration of the target, in the 5-year model, the result gives that when $\alpha = 0.0770$ and $\beta = 2.62$, the maximum level of carbon sequestration in total will be 139523.604 tonne in 5 years. And in the 15-year model, the simulation shows that when $\alpha = 0.0381$ and $\beta = 5.73$, the maximum level of carbon sequestration in total will be 415367.965 tonne in 15 years.

When just considering a very short period of time, the best harvest rate is around 8% of the total living stock of the forest, and $\beta = 2.62$ points out that harvest activities must be concentrated into a smaller area in order not to damage the large mature area. And when considering the longer period, the model's result shows that the best harvest rate is around 3.8% of the total living stock of the forest, and $\beta = 5.73$ points out that harvest activities must be separated into a larger area of 5.7 times rather than totally wiping out a tiny amount of area. The instruction given by this model is consistent with the universal knowledge of distributed harvesting.

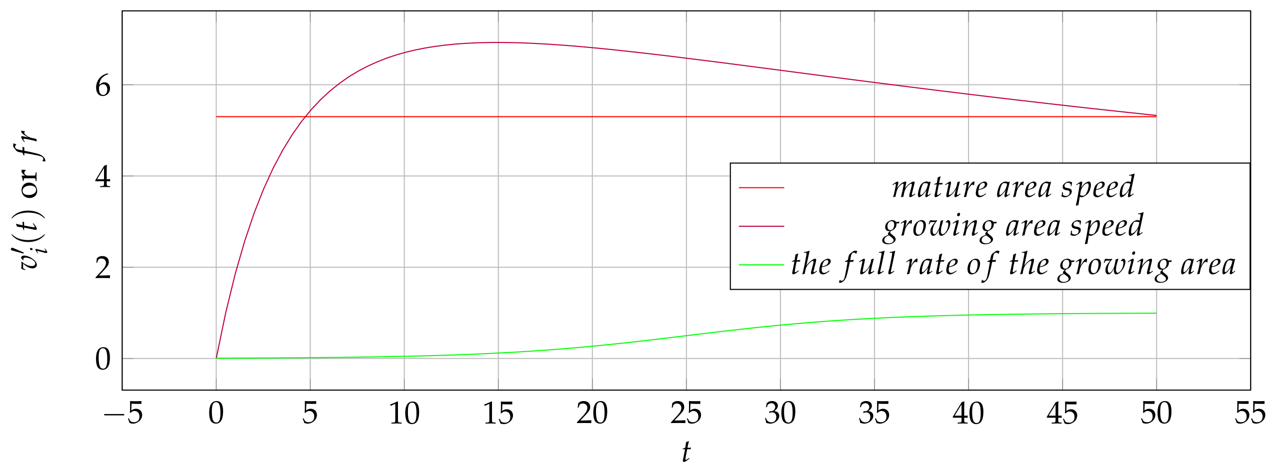

Figure 5: Curves used in the test

4.3.2 Reaching the maximum of carbon sequestration with dynamic α

Last test, we made the proportion of tree harvest α to be fixed in during the test. But in the reality, our managers have to adjust the coefficient α to change the total amount of harvesting logs. One effective way of adjusting α is using the negative feedback mode. When the total amount of wood in the forest is decreasing compared to the last year, the manager will lower α to reduce the log production activities this year to restore the level of ecology. And after the restoration, the total amount of wood in the forest will return to the higher level. So the manager can adjust α higher to increase the timber production. In a long time, the forest will reach a stable fluctuating state.

The definition of how α change chronologically is listed as the formula below.

$$\alpha_{this\ year} = \alpha_{last\ year} \times \frac{TA_{last\ year} - Sw\rho\alpha_{last\ year} + CS_{gr,last\ year}}{TA_{last\ year}} \tag{13}$$

Where TA_i denotes the total amount of wood in the forest in year i.

We apply this method in the forest model in section 4.3.1. From the result, we can plot the changes of α and the TCS thorough 15 years of the simulation. The results shows that the initial $\alpha = 0.0407$, and it begins to fall to about 0.38. Then as the immature area sequesters faster than the mature area, the TCS ratio begin to rise, so does the α. Finally, the TCS is higher than the one under the fixed α by 5‰. Meanwhile, α can finally rise to around 0.05, meaning more logs can be produced in this forest than the fixed α situation.

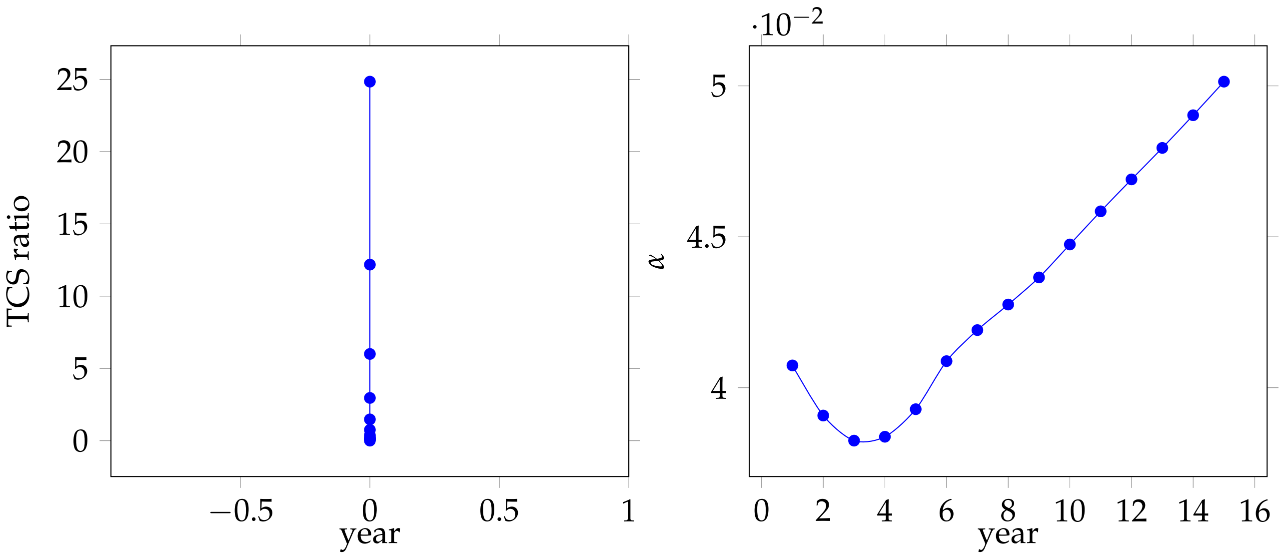

Figure 6: Left: TCS ratio of dynamic and fixed α Right: Dynamic change of α in 15 years

5 TASK II: EEC(Ecological-Economic-Cultural) Value Model

5.1 Model Overview

Forest resources can have a far-reaching impact on human society. The value of forests is often not only reected in the function of carbon sequestration. To assess the value of forests concisely and comprehensively so that facilitate forest managers can be informed of the best use of forests, we divide the total value of forests(TV) into three categories: ecologic values(V_{ec}), economic values(V_{pro}) and cultural values(V_{cu}). [19] [20]

$$TV = V_{ec} + V_{pr} + V_{cu} \tag{14}$$

5.2 Forest Value Quantification System

5.2.1 Ecological Value

The ecologic values of forests can be categorized into the value of carbon sequestration (V_{carbon}), water conservation(V_{water}), soil consolidation(V_{soil}),air purification(V_{air}) and specise protection($V_{species}$).

$$V_{ec} = V_{carbon} + V_{water} + V_{soil} + V_{air} + V_{species} \tag{15}$$

Value of Carbon Sequestration

Using the model in Task I, equation (12), we can calculate the TLS of the forest. So the value of carbon sequestration can be easily calculated using the unit price of carbon(C_{carbon}).

$$V_{carbon} = TCS \times C_{carbon} \tag{16}$$

Value of Water Conservation

Forest can intercept and absorb most of the precipitation to conserve water sources. We choose two indicators: water storage and purified water quality to reflect the water conservation value of forests. First, we calculate the annual increase of accumulated precipitation in the forest ecosystem in the study area(Q) by the following formula where P_t is the amount of the annual rainfall,R is the amount of the annual surface runoff and EF is the evaporation capacity.

$$Q = S_{ma} \times (P_t - R - EF) \tag{17}$$

Storage function and purifying function of forest can be evaluated by the alternative engineering method and restoration cost method respectively where C_{res} is the unit cost of reservoir construction, and K_{pure} is the local tap water purification cost.

$$V_{water} = Q \times (C_{res} + K_{pure}) \tag{18}$$

Value of Soil Consolidation

Forests have the value of soil consolidation.The annual soil quality of forest conservation (G_{soil}) can be calculated in the following equation where X_1 is the actual annual soil erosion modulus of forest land and X_2 is the potential annual soil erosion modulus of forest land.

$$G_{soil} = S_{ma} \times (X_2 - X_1) \tag{19}$$

We use opportunity cost method to calculate value and the indicators include average annual income of forestry(P),annual soil quality of forest conservation, soil thickness(H) and average bulk density of soil(ρ) to calculate the value of soil consolidation.

$$V_{soil} = P \times \frac{G_{soil}}{\rho \times H} \tag{20}$$

Value of Air Purification

Forest can absorb and decompose air pollutants. The value of forest purifying air pollutants includes the value of absorbing sulfur dioxide, fluoride and nitrogen oxides. The recovery cost method can be used for evaluation where K_{SO_2},K_{NO_x} and $K_{dust}$are the cost reduction for sulfur dioxide, fluoride and nitrogen oxides and W_{SO_2},W_{NO_x} and W_{dust} are the annual absorption of sulfur dioxide, fluoride and nitrogen oxides by forests.

$$V_{air} = S_{ma} \times (K_{SO_2} W_{SO_2} + K_{NO_x} W_{NO_x} + K_{dust} W_{dust}) \tag{21}$$

Value of Species Protection

As the main habitat of natural biological species, the forest ecosystem is an important place for the survival and reproduction of valuable germplasm. We use the achievement reference method to evaluate this kind of value.V_s is the annual conservation value of forest species per unit area.

$$V_{species} = S_{ma} \times V_s \tag{22}$$

5.2.2 Economic Value

The forest products provided by wood in the forest for human beings are its direct economic value, which can be obtained by calculating the final profit of the trade. Where j is the region of the forest, p_i is the average price per tonne of Tab. [2]'s different products.

$$V_{pr} = S\alpha\omega \sum_{i=1}^{5} pp_{i,j} p_i \tag{23}$$

5.2.3 Cultural Value

The cultural value of the forest ecosystem is to provide human development cognition and help people gain pleasant experiences in the process of interaction between humans and the forest. So we categorize cultural value of the forest into recreation value and scientific research value.

$$V_{cu} = V_{rec} + V_{sci} \tag{24}$$

The travel cost method is a widely used method in evaluating forest recreation value in the world. We use the annual recreation value per unit area of forest (P_{to}) and the proportion of forest tourism area in the total area(σ) to calculate the recreation value.

$$V_{rec} = P_{to} \times (S_{ma} \times \sigma) \tag{25}$$

Forests are an important base for scientific research so the value of forestry science and technology can be reflected through the calculation of its output and the contribution rate where P_o is the annual output value of forestry and E_a is the contribution rate of the forestry science and technology.

$$V_{sci} = P_o \times E_a \tag{26}$$

6 TASK III: Target Oriented Forest Management Strategy

6.1 Overview

Forest management strategies outline the managers' or landowners' target for their forests, describe the status quo of the forests, and give a plan of actions to accomplish management targets [21]. To help forest managers or landowners make proper and efficient forest management, according to the EEC model, we divide forest development directions into three categories: ecological orientation ,economic orientation and cultural orientation, which correspond to the three development stages of the forest ecosystem: elementary, intermediate and advanced.

6.2 Stage and Strategy

6.2.1 Elementary Stage: Ecologically Orientated Strategy

This kind of forest management strategy is suitable for forests with sparse vegetation or damaged forests, which are vulnerable and poorly self-regulated. In this stage, managers or landowners should put the target of forest ecological protection in the first place by intervening in the forest to help forests restore growth quickly. Alternative decisions are listed below.

- **Protect soil and water**. Soil and water are vital to maintain the healthy operation of the forest ecosystem. For instance, managers can substitute native plants for invasive canary grass along the creek, which is harmful to water quality.
- **Enhance wildlife habitat**. Species richness is an essential measure of forest health that we cannot ignore. Managers can improve the habitat for birds and other wildlife in the forest.
- **Plant trees and afforest**. As the most significant contributor to carbon sequestration, trees play an indispensable role in the healthy functioning of forests, and planting trees properly will improve forest carbon sequestration.

6.2.2 Intermediate Stage: Economically Orientated Strategy

The intermediate stage is transitional in forest management. With the accumulation of forests' ecological value, we can turn the main target from ecological value to economic value. Specifically, the production and trade of forest products. In this process, the area's harvesting volume and product structure are the key factors. When the ecological value reaches a certain value, managers or landowners can change the development direction in time.

- **Conduct forest thinning regularly**. According to the SHG model, it is reasonable to say that for a healthy forest system, harvesting must be incorporated into the forest management plan to realize its comprehensive value. The optimal deforestation rate will be given by the SHG model.

- **Adjust product structure**. Forest products are the main source of forest economic value. Different forest products have different profits. Managers can properly adjust the product structure to obtain greater benefits.

6.2.3 Advanced Stage: Culturally Orientated Strategy

This is the most advanced stage of forest management. At this stage, the forest has not only a rich ecological value and a stable economic value, but also the ability to create a cultural value. The most important source of a forest's cultural value is tourism and scientific research activities. Low-level forests are either unable to regulate themselves or lack sufficient economic support to carry too many tourists, and naturally cannot develop their cultural value. This is where culture-oriented forest management is advanced.

- **Develop tourism**. For high-level forests, the appropriate opening of tourism policies can improve the local spiritual and cultural level, and profit-making tourist attractions can also gain benefits and achieve a win-win situation.

- **Establish research bases**. Due to the complex community structures and biological species, advanced forests have great potential research value.

6.3 Implement of Forest Management Strategies by Decision Tree

In decision analysis, a decision tree can be used to visually and explicitly represent decisions and decision making. As the name goes, it uses a tree-like model of decisions [22]. As one of machine learning algorithms, it takes features and targets as input, trains through a certain algorithm and builds a branched tree to make classification.

6.3.1 Data Distribution

In this section, we use the ecological, economic and cultural values percentage of different forests as features and three development stages of forests as targets for training. We selected 2,214 forests [23], according to the ECC model, calculating the percentage of their ecological, economic and cultural values as feature input. Distribution of data is shown in Fig. [7].

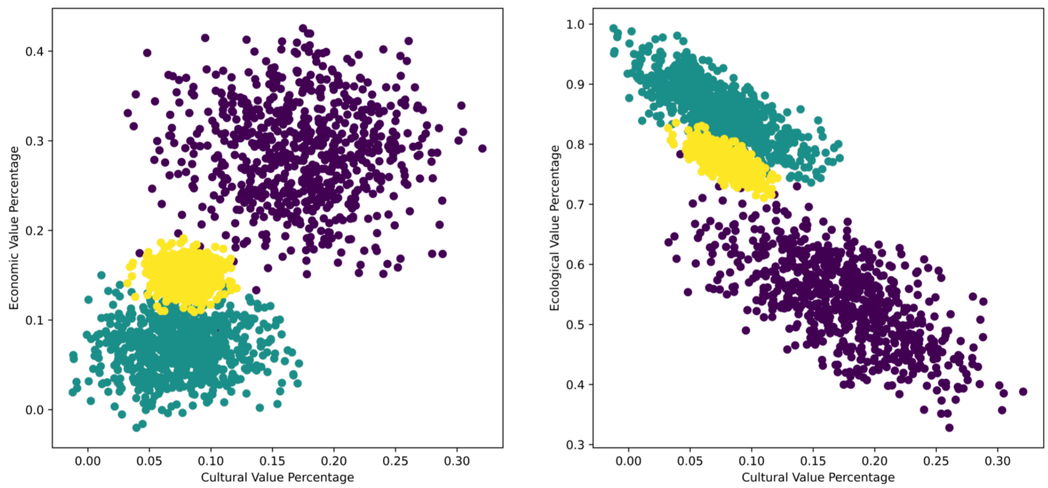

Figure 7: Data distribution in different dimensions

6.3.2 Adjust the Parameters

Among the total data, the training set accounts for 70% of the total data, and the rest is used for testing. By decision tree algorithm, we can obtain the ideal classification plan of forest stage. Here, we set the count of random state as i and depth of the decision tree as j. By loop iteration of i and j, we finally determine the most suitable random state as 190 and the max depth of the decision tree as 2. Then we choose the cross-validation method to test our model. The final accuracy reaches 96.54%. The process of finding random state and max depth are shown in the following figures.

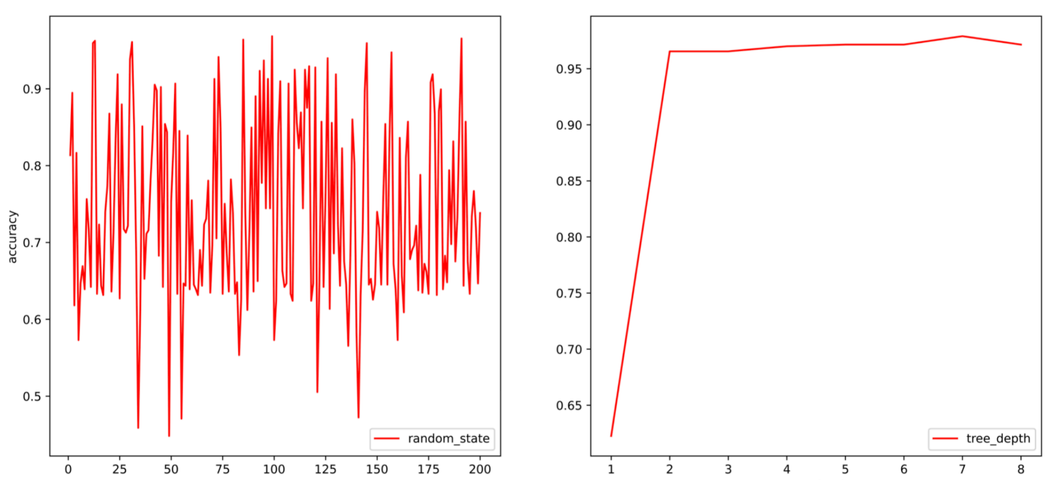

Figure 8: Process of finding the best random state and tree depth

6.3.3 Strategies and Threshold Analysis

Finally,we can draw the following decisions from our decision tree:

- When the economic value ratio is greater than **10.8%** and the ecological value is less than or equal to **69.5%**, the forest is in the **primary stage**, where an **ecological-oriented** management strategy should be adopted.

- When the economic value ratio is greater than **10.8%** and the ecological value is greater than **69.5%**, the forest is at an **advanced stage**, and the development direction should be adjusted to a **culture-oriented** strategy.
- In other cases, the forest is at an **intermediate stage** and an **economic-oriented** management strategy should be adopted.

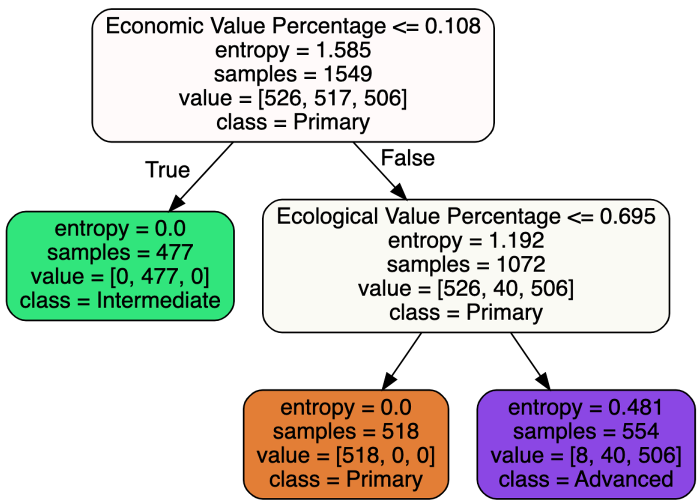

Figure 9: Decision tree graph

Target Oriented Forest Management Strategy is the right handle for forest managers or landowners. They just need the forest parameter table for one year, use the SHG and ECC models to calculate the composition of the total valu. Then, by referring to the strategies, they can easily determine the stage of the forest and the future direction of development. The transition management plan appear near 10.8% of economic value, which reminds forest managers and landowners not to harvest too much. Keeping the economic value near 10% may be the best option.

7 Case Study

Since we are required to provide forest managers with reasonable forest management plans to understand the best use of forests, we combine **SHG Simulation Model** and **EEC Value Model** with specific examples to comprehensively consider and calculate the ecological, economic and social values of forests. Then, we use the **Target Oriented Forest Management Strategy** to make sure harvest is included in the forest management plan and determine the future management plan most suitable for the current forest development.

7.1 Forests of Heilongjiang Province,China

Heilongjiang is located in Northeast China with vast forests which can bring huge benefits for local people.

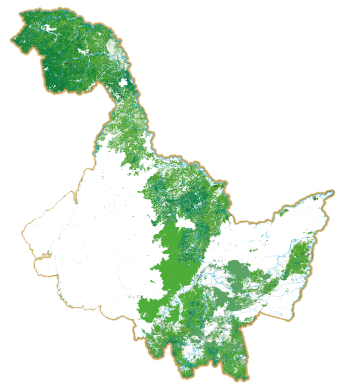

Figure 10: Forest distribution map of Heilongjiang Province

We log on the official websites of China Meteorological Administration and Forestry Administration to obtain the data required in EEC Value Model from 2010 to 2018, and quantify the forest value of Heilongjiang according to its formula. As shown in the table below.

Table 5: Quantitative forest value in Heilongjiang from 2014 to 2016(billion dollars)

year	ecologic value	economic value	cultural value
2010	55.9578	6.9057	3.47850
2011	57.2133	7.3199	3.7113
2012	59.7257	7.6231	3.9765
2013	61.7045	7.8787	4.3097
2014	62.8302	8.0561	4.54694
2015	67.7652	9.6319	4.5624
2016	73.0542	11.1379	4.5402
2017	74.2948	11.5136	4.9423
2018	75.3012	11.6933	5.2304

7.1.1 Carbon sequestration stock in the next 100 years

According to the SHG Simulation Model, we get the maximum annual carbon dioxide storage under the optimal proportion of forest harvest. After accumulation, the total amount of carbon dioxide that can be stored in Heilongjiang forest within 100 years can be obtained. The annual TCS and α is plotted in Fig. [11].

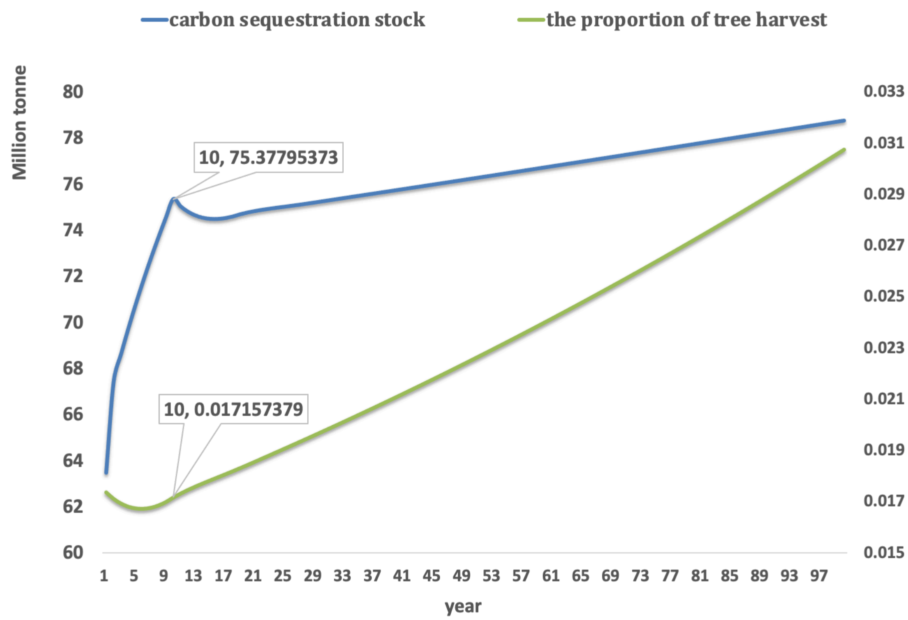

Figure 11: Forecast line chart of carbon sequestration and proportion of tree harvest

According to our model, when the initial $\alpha = 0.01767$ and $\beta = 2.286$,the total amount of the carbon sequestration over 100 years will reach its maximum of 7.599×10^9 tonnes, 15.6 % more than carbon sequestration taken by untouched forest. So the harvest should be considered in the management plan to maximize the amount of annual carbon sequestration.

7.1.2 Forest Management Plan in Heilongjiang Forest

Based on the data in Tab. [5], we can calculate the proportion of different forest values in Heilongjiang from 2010 to 2018. We apply the decision tree algorithm to make the analysis about Tab. [6] below, and use the Target Oriented Forest Management Strategy to

Table 6: the proportion of different forest values in Heilongjiang from 2010 to 2018

year	ecologic value	economic value	cultural value
2010	84.34%	10.41%	5.24%
2011	83.83%	10.72%	5.43%
2012	83.73%	10.68%	5.58%
2013	83.50%	10.66%	5.83%
2014	83.76%	10.67%	6.03%
2015	82.68%	11.75%	5.57%
2016	82.33%	12.55%	5.11%
2017	81.87%	12.68%	5.45%
2018	81.64%	12.68%	5.67%

give proper suggestion on the future direction of forest development.All the conclusions and advice are stated below.

- **Conclusion 1:** Heilongjiang forest has been in the intermediate stage since 2010 according to the decision tree algorithm. The economic value ratio was stable at around 10.5% and the ecological value ratio was above 80% for 4 years which indicates that Heilongjiang forest was protected well at that time without deforestation or overuse.
- **Conclusion 2:** The transition point during 2010 to 2018 in Heilongjiang forest is 2015 when the economic value ratio was more than 10.8% and the ecological value ratio was still above 80%, a symbol of an advanced stage in decision tree algorithm.
- **Suggestion:** Heilongjiang forest can be seen as a stable and advanced forest since 2014 with few possibility that the proportion may change accidently, so the development strategy can be directly into culture-oriented one. Government should explore the underlying value of the forest in cultural layer such education, tourism and scientific research.

8 Strength and Possible Improvement

8.1 Strength

- **Comprehensive consideration:** Our model considers comprehensive aspects of the developing process and management aspects. Not only simulates the natural carbon sequestration, out model also takes economical value and cultural value into the consideration to fully maximize the forests' value in various aspects, and using money to give the final quantitative indicators.
- **Well-Simulated, complete parameter system:** Supported by multidimensional parameters, our **SHG** model and **EEC** model are capable of simulating complicated cases with multi parameters.
- **Self-adjustment:** Harvest will reduce the living stock in the forest, but will enhance the carbon sequestration rate. With the negative feedback considered in the model, our model can make self-adjustment by comparing the history data to make decision of adjusting the coefficient in the system. This advantage can give important instruction to the forest managers.

8.2 Possible Improvements

- **Short-period prediction:** In our model and collected data, the minimum time units are all measured in year. Besides, it's difficult to obtain the monthly data from the authority. Thus, the short-period prediction is still need to be developed.

- **Average harvest:** In the carbon sequestration model, we assume that the timber product companies will make average harvest of the selected area. However, when the area given by the schedule is too large to fully cover, the worker may choose to harvest in an smaller area to save time and gasoline, which may led to the deviation of the predicted values from the actual data.
- **Dataset dependency**: This shortcoming comes from the decision tree model. Due to the complexity of our indicators and the limited amount of data, only 1,550 forest samples are finally trained, and the threshold for decision-making may be biased.

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Appendices

Appendix A First appendix: Article for newspaper

Why Harvesting?

Team 2213962 *International Carbon Management Collaboration*

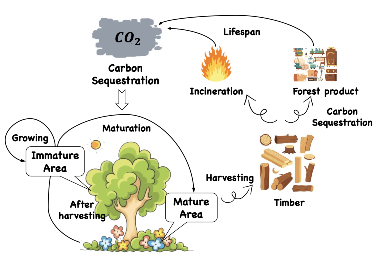
Forest management plans have been attracting people's attention. Why harvesting? What are the benefits of harvesting? This article will take you to uncover the mysteries of forest management.

1 The Dilemma We Face

Forests have an irreplaceable position in the biosphere and are a valuable asset of society that must be cherished and cared for by all humankind. However, due to the lack of awareness of environmental conservation and the excessive pursuit of economic benefits, the vast forest resources have rapidly declined in recent centuries. The protection of forests has not been slow in coming, and forest management plans have adapted to the needs of the times. Economic and ecological dilemmas come into focus.

2 Misunderstandings

Since the introduction of the concept of forest management plans, the debate on this issue has not ceased. Influenced by environmental organizations, a voice has been raised in society in recent years: When formulating forest management plans for all different regions, we should leave the forest untouched so that it is not affected by human factors. They believe that deforestation destroys the balance of the ecosystem and causes the forest to lose its original benefits and functions.

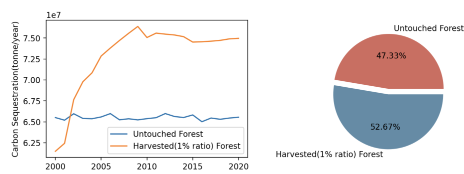


This view can actually be challenged. Attitudes toward deforestation should not be limited to the potential damage to ecosystems, but should also consider the benefits. Properly harvesting can yield a tremendous amount of wood resources, and this processing can produce a large number of forest by-products such as paper and furniture that is needed in people's daily lives. The production and trade of forest products greatly enhance the opportunity of employment and promote local economic development. Most importantly, the carbon can be sequestered in the product and will not be released when the wood is burned. A balanced harvesting plan is a win-win situation.

3 Why Harvesting?

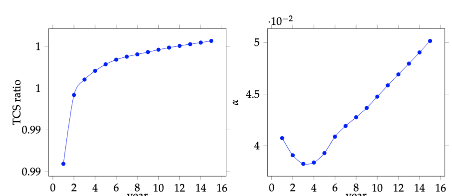
In response to this problem, our collaborating organization developed a dynamic forest value estimation model. This model will dynamically monitor the value composition of forests according to different regions, different forest types and other parameters, which is a powerful tool for the forest managers to obtain the current state of the forest and the future developmet direction in time.

Each forest system must plan future forest management plans in detail in conjunction with the development goals of the various regions, but it is clear from the model that each forest management plan must incorporate deforestation into the respective plan. We monitored local forest data over 20 years, including forest tree species, forest area, carbon sequestration rate, forest product structure, etc. Using our carbon sequestration model, we arrived at the following results. The following figure shows a comparison of carbon sequestration in local forests in untouched condition and maintaining a 1% per year deforestation rate.



The above picture shows us that although untouched forests sequester more carbon than deforested forests in the first few years, deforested forests grow faster over time, and some of the carbon is stably sequestered. In the case of forestry products, the whole system will absorb more carbon than the original one, which is why we recommend that local forest managers to harvest properly.

To assist local forest managers in their decision-making, the picture below shows the maximum harvesting rate for each year that maximizes the value of the forest. According to this chart, adjusting the area harvested will help provide greater economic benefit while maintaining ecological value. We recommend that the maximum deforestation rate can be set to around 5%



The harmonious and balanced development of man and ecology is the theme of future environmental protection. Let us work together in environmental protection to share a better and brighter future.