Problem Chosen	2022	Team Control Number
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Forestry for Carbon Sequestration

Summary

Forest carbon sequestration plays an important role in mitigating the effects of climate change. There are two types of forest carbon sequestration: plant carbon sequestration and forest products carbon sequestration. For forest managers, it becomes a challenge to develop optimal forest management plans based on these two aspects. This report aims at developing a model to calculate the carbon sequestration of forests and forest products over time and assessing the integrated level of forests. We are expected to consider the benefits derived from forests in as many ways as possible and provide forest managers with the best forest management plan for certain forest.

For problem 1, we are primarily concerned with two aspects. The first is the dynamic calculation of carbon sequestration of plants and their products.And the second is the impact of harvesting management on the dynamic calculation. We use a logistic regression model. In model 1: **Dynamic Carbon Sequestration Model**, we set time as the independent variable and carbon sequestration as the dependent variable to solve the problem of carbon sequestration. After that, we design a reasonable harvesting management and calculate the time distribution of carbon sequestration in forests and their products. Our model can provide forest managers with optimized harvesting density and rotation.

For question 2, we need to further consider various ways of realizing forest value based on forest carbon sequestration, and then evaluate the comprehensive forest value. In model 2: **SEE model**,we first determine the evaluation indexes, then calculate their weights by AHP and EWM and then combine the data with expert opinions to establish the scoring system of decision variable matrix. Next, according to the indicators we determined, we carry out multi-objective programming with a total of three indicators ,including ecological , economic and social benefits as decision variables and carbon sequestration as the objective function .After solving Pareto Optimality,the final optimal forest management plan is obtained.

In the case study, we investigate forest carbon sequestration in the Mohe forest area in northern Greater Khingan Mountains, China. According to model 1, based on the forestry data of Greater Khingan Mountains, we calculate the carbon sequestration in Mohe forest area of Greater Khingan Mountains in the next 100 years using matlab. According to model 2, we designe a reasonable and optimized forest management plan. Finally, we extended the 10-year rotation period and explored the timeline transition strategy.

At the end of the article, we perform a sensitivity analysis, analyze the strengths and weaknesses of the model, and consider directions for further improving.

Keywords: forest sequestration; Logistic regression; AHP&EWM; Dynamic Carbon Sequestration Model; SEE model;

Contents

1 Introduction

1.1 Problem Background

When studying climate change, we should consider carbon sequestration as one of its influencing factors. Forests, as an organic and complex system, are capable of converting greenhouse gases into organic matter we can find in plants, water sources, etc. Also, forest products, like hardwoods and paper products have carbon sequestration capacity. Considering the decay of carbon, they have a longer carbon sequestration effect.

Properly balanced harvesting and conservation can be beneficial for carbon sequestration and mitigation of climate change impacts. However, there is still widespread over-harvesting globally, while some argue that we should not harvest any trees.

In response to ICM's challenge, we decided to develop models to allow forests to absorb as many greenhouse gases as possible, and to optimize forest management by combining multiple forest values in order to further highlight the role of forests in climate change, see Figure 1[1].

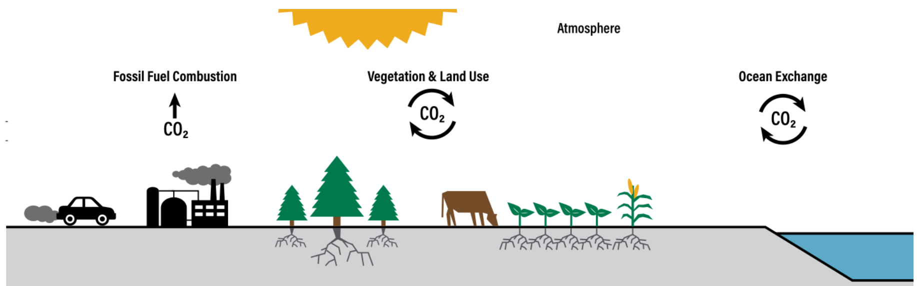


Figure 1: Carbon Cycle and Sequestration

1.2 Restatement

Based on a full understanding of the problem, we're required to complete the following tasks:

- **Develop a model of carbon sequestration and determine the capacity of a forest and its products to sequester** CO_2 , and then determine an optimal forest management plan which is effective and reasonable.
- **Develop a model that balances multiple forest values not limited to carbon sequestration.** We will consider the spectrum of management plans, factors that might make a forest left uncut and the transtion point between differeent forests.
- **Apply our developed models to a specific forest to predict its carbon sequestration over 100 years and determine an optimal forest management plan,** and further consider a demand-sensitive harvesting strategy over timelines.
- **Make further exploration of the sensitivity of our models, and determine the strengths and weaknesses.**

[1]Source: Adapted from U.S. DOE NETL 2018.

1.3 Our Work

To solve the first problem, we developed a Dynamic Carbon Sequestration Model to calculate the carbon sequestration of forest and its products, where rotation and the percentage of trees to be harvested dominate the outcome. For forest, we consider trees as the most important factor affecting the carbon content of the forest and build the logistic regression model to predict the carbon in trees. For forest products, we classify them into paper products and hardwoods, using difference eqution to solve the recursive question.

To solve the second problem, we build our SEE model using analytical hierarchy process(AHP) and entropy method to determine alternative ways of realizing forest values beyond the amount of carbon sequestered, combined with the optimization model to determine the scope of forest management and the transition point of forest management methods.

To solve the third problem, for the Mohe forest area in the northern part of the Greater Khingan Mountains, we first collected some forestry data and historical overview, calculated the amount of carbon sequestered in this forest area after 100 years using Dynamic Carbon Sequestration Model, evaluated forestry development using SEE model, determined a reasonable forestry management plan, and determined a new forest management plan after the rotation period was extended by ten years.

Next, we analyzed the sensitivity of the model and assessed its stability. Finally, we wrote a non-technical newspaper for the community in conjunction with the model and conclusions to convince the community to accept moderate exploitation of the forest.

Our work can be summarized by Figure 2.

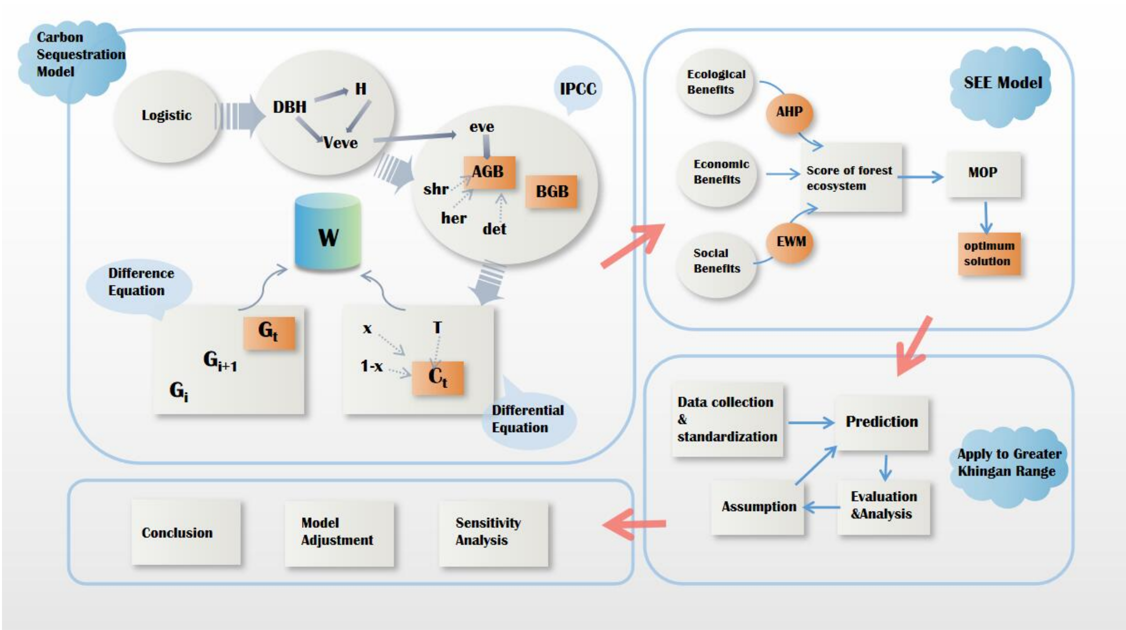


Figure 2: Our Work

2 Assumptions and Notations

2.1 Assumptions

We make the following fundamental assumptions to simplify the problem, each of which is properly justified.

- **Assumptions 1:Vertical stratification of plants dominates the model**

  Justification: Because of the similarity of different areas of the same biotope, we consider vertical stratification within a given area to be our first priority in classifying vegetation rather than horizontal stratification, which is realistic and reasonable.

- **Assumptions 2:Animal activities have a negligible influence on forest carbon sequestration**

  Justification: Although animal activities are important, we ended up ignoring animal carbon sequestration, such as mammals, insects, microorganisms, etc., for the sake of model simplification compared to the large base of plants[10].

- **Assumptions 3:The forest is at the stage where mature trees dominate initally**

  Justification: According to biotrophic science, for a naturally occurring jungle, there tend to be far more mature trees than seedling trees, unless the forest was planted by hand and has not had sufficient time to evolve.

- **Assumptions 4:Hardwood and paper are the main forest products**

  Justification: Hardwood products and paper products are ubiquitous in our lives. It is hard to find forest products other than these two products. Therefore, it is reasonable to consider only these two types of products when analyzing the carbon sequestration of forest products.

2.2 Notations

We've included some notations below for your convenience, see Table 1. Other specific notations, if necessary, will be demonstrated and illustrated when we build models.

3 Model I : Dynamic Carbon Sequestration Model

3.1 Carbon Sequestration of Forest

We need to understand the sources of carbon in forestry ecosystems, or the carbon pools before we predict carbon sequestration, see Figure 3. According to IPCC[1], carbon sources mainly include **above-ground biomass, below-ground biomass**. There are also other special terrains that are not easily calculated in this way and should be considered separately[1].

In our model, we will define the total amount of carbon sequestration in carbon pools by calculating carbon stock in divided area, which are defined as follows:

$$c_i = (AGB_i + BGB_i) \times s_i \tag{1}$$

[1]Abbreviation for **Intergovernmental Panel on Climate Change**

Table 1: Notations

Symbol	Description
c_i	all carbon sequestration in region i
$c_{species}$	carbon sequestration of the species in region i
C_n	carbon sequestration in in the whole area
$C_{n,t}$	carbon sequestration in in the whole area at time t
G_t	carbon sequestration in forest production at time t
AGB_i	above-ground biomass in region i
BGB_i	below-ground biomass in region i
eve	carbon sequestration of trees in region i
D_t	the diameter at breast height(DBH) of a tree
H_t	the height of a tree
W_f	the total carbon sequestration of the forest in one rotation
W_p	the total carbon sequestration of forest production in one rotation
$A(t)$	the minimum forest resource accumulation required for stable social development
H'	Shannon-Wiener index
PV	the total cost of wood processing
T	Length of the rotation
$x\%$	Harvesting Intensity: the percentage of trees to be harvested

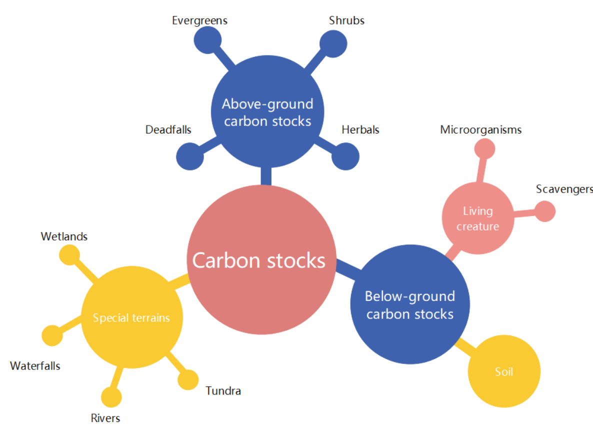


Figure 3: Forestry Carbon Pools

$$C_n = \sum_{i=1}^{n} c_i \tag{2}$$

where

- s_i represents the area of region i
- n represents the total number of regions divided in the area

3.1.1 Above-ground Biomass

In forests, a wide variety of plants occupy a prime position in the carbon cycle. In order to make full use of solar light, plants are vertically stratified and horizontally stratified. Vertical stratification refers to the vertical structure of the community. Horizontal stratification refers to plants that grow differently in different geographical locations.

In our model, we ignore the vegetation differences due to horizontal stratification and divide the vegetation into trees, shrubs, herbs, and deadfalls.

$$c_{species} = \begin{cases} (V_{species} \cdot BCEF_{species})\,(1+R)CF_{species}, & \text{if} \quad species = eve \\ (V_{species} \cdot BCEF_{species})\,CF_{species}, & \text{if} \quad species = shr, her, def \end{cases} \tag{3}$$

and

$$AGB_i = c_{eve} + c_{shr} + c_{her} + c_{def} \tag{4}$$

where

- eve represents carbon sequestration of trees in region i
- shr represents carbon sequestration of shrubs in region i
- her represents carbon sequestration of herbals in region i
- def represents carbon sequestration of deadfalls in region i
- $V_{species}$ represents the species accumulation in region i
- $BCEF_{species}$ represents basic forest density of the species
- $CF_{species}$ represents biomass expansion factor of the species
- R represents rootstock ratio of trees

3.1.2 Below-ground Biomass

Carbon enters the soil in the form of plant and animal residues, which are decomposed and transformed by complex microbial processes, mostly into CO2 and released into the atmosphere. In the end, only a very small amount of carbon enters the soil organic matter and is retained for a long time. However, due to the huge amount of soil, the total amount of carbon in it should not be underestimated.

The total amount of carbon stored in soil[4]:

$$BGB_i = \rho \cdot SC \cdot D \cdot E \cdot K \tag{5}$$

where

- SC represents soil organic matter content
- D represents soil carbon capacity
- E represents soil thickness

- K represents soil looseness
- ρ represents soil average carbon content

The carbon content of forest land resources has generally remained stable over a longer period of time. In exploring the carbon sequestration capacity of forests, for simplicity, the carbon content of land can be treated as a constant,i.e.

$$\sum_{i=1}^{n} BGB_i = Constant \tag{6}$$

3.1.3 DBH Logistic Regression

We have developed a dynamic carbon sequestration model that links the amount of species accumulation to the amount of carbon sequestration, but we need to further model the species accumulation over time, which is important for us to understand carbon sinks in time.

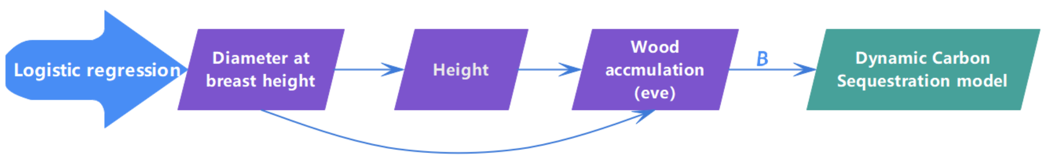


Figure 4: DBH Logistic Regression

As we can see from Figure 4, we calculate the diameter at breast height through logistic regression:

$$D_t = \frac{k}{1 + m \cdot \exp(-rt)} \tag{7}$$

then we build model for Diameter at breast height(DBH) and get the value of height:

$$\frac{1}{H_t} = \frac{1}{a \cdot D_t^d} + \frac{1}{H_{\max}} \tag{8}$$

Afterwards, we calculate the tree accumulation by combining the tree height and diameter at breast height. It is noted that the carbon sequestration of trees is one hundred times more than that of shrubs[3], [9], while the carbon content of herbals and deadfall will be much smaller than that of shrubs. Therefore, we specifically build model for trees:

$$\ln B_t = a + b \ln D_t \cdot H_t \tag{9}$$

$$V_{eve} = B_t \cdot \rho' \tag{10}$$

where

- ρ' represents number of trees in the chosen region
- B_t represents the carbon stock of one tree over time

- H_{max} represents the maximum growth height of tree in the area

and the whole carbon stock of the forest:

$$C_n = \sum_{i=1}^{n} \left[(V_{eve} \times BCEF_{eve})(1+R)CF_{eve} + \sum_{k=shr,her,def}^{n} (V_k \times BCEF_k) CF_k + \rho \cdot SC \cdot D \cdot E \cdot K \right] \cdot s_i \tag{11}$$

when ignoring the difference among various regions and above-ground biomass except for evergreens, we can get

$$C_{n,t} \approx n \cdot s \left[(B_t \cdot \rho' \cdot BCEF_{eve})(1+R)CF_{eve} \right] + Constant \tag{12}$$

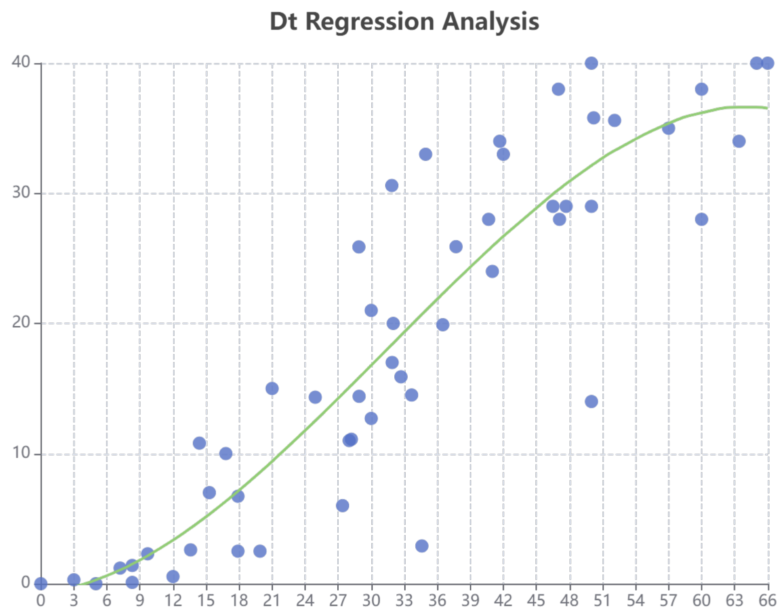


Figure 5: Regression Analysis

As we can see in Figure 5, the results of the regression analysis are consistent with our daily life experience, where the growth of trees has a similar s-shaped curve. During a period of tree growth, the carbon content of the tree increases rapidly. When trees grow long enough to reach the maturity stage, their diameter at breast height grows slowly.

Note that we ignore BGB here because BGB is a large constant and has no effect on the shape of our graph,and because the difference of regions is hard to measure, for simplicity we can assume that the forest area is of the same nature and therefore ignore the parameter i.

3.2 Carbon Sequestration of Forest Production

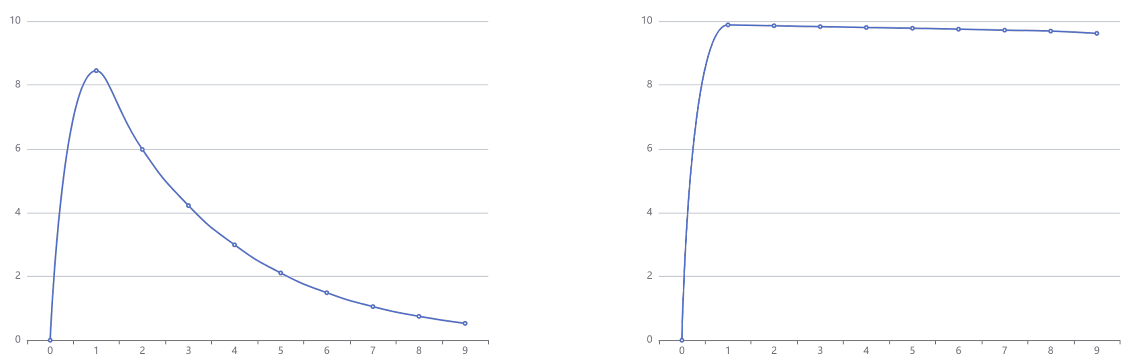
The Harvested Wood Products(HWP) is an extension of forest resource use and is part of the overall forest carbon cycle management, transferring carbon sequestered in the forest to products through forest harvesting and product use. The rate of carbon release depends on the production process of the products and the end use of these products[6]. Here we give our **HWP Difference Equation**, whose input is the P_t and the output is G_t:

$$G_{t+1} - \mathrm{e}^{-k} G_t = \left[\frac{\left(1 - \mathrm{e}^{-k}\right)}{k} \right] \cdot P_t \tag{13}$$

where

- k represents the the first-order decay variation per year amount, and $k = \ln 2/halflife$
- P_t represents the amount of carbon in products newly produced in the year t

For hardwoods, $halflife$ = 30 years; for paper products, $halflife$ = 2 years[6]. Consider the performance of forest products over 10 years: In the first year, we cut a certain number of trees, for example $P_{t=0} = 10$. We also assume $G_{t=0} = 0$. In the following 9 years, we do not cut the forest, which means $G_t = 0, t = 1, 2, 3...9$. We can obtain single curves for the decay of the carbon sequestration, see Figure 6:



(a) HWP model of paper products

(b) HWP model of hardwoods

Figure 6: HWP model

To sum up 3.1 and 3.2, we have built two models of carbon sequestration in forest and its productions, which are ingenious and reasonable. Next, we are going to study the harvesting machanism and eventually decide our carbon sequestration over time.

3.3 Model Analysis and Forest Management

We have modeled carbon sequestration on forests and forest products separately, and to determine our ultimate carbon sequestration benefits, we also need a rational harvesting mechanism, which is shown in the figure below.

In Figure 7, the horizontal coordinate represents the time of tree growth and the vertical coordinate represents the total amount of carbon sequestered by trees of the same age that make up the forest. Where A_0 represents the age of newly planted saplings after each cutting; the maturity point is the point we specified after which the tree growth trend converges, or the amount of carbon sequestered almost ceases to change over time. This gives the sapling maturity period as T_0.

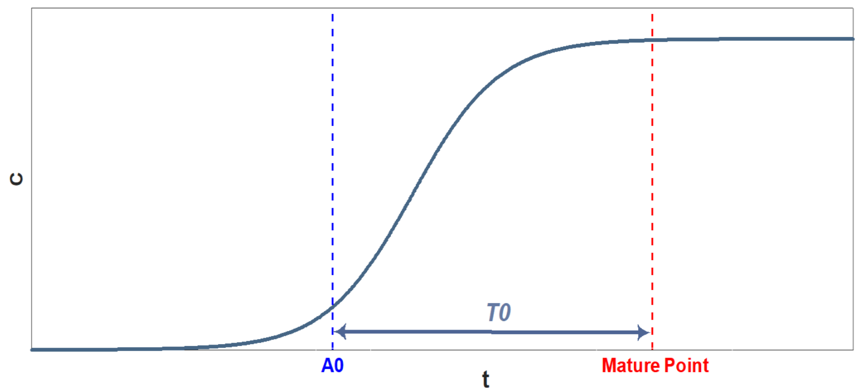


Figure 7: Time curve of carbon sequestration

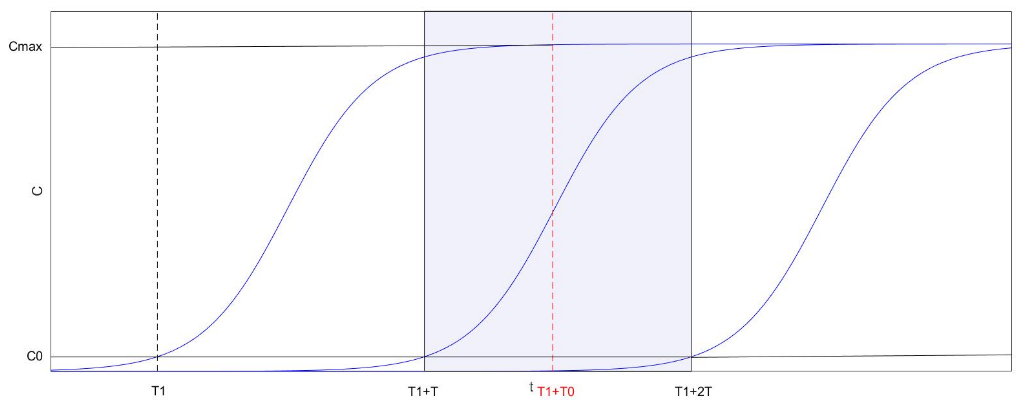


Figure 8: Time curve of carbon sequestration considering rotation

We simplify the forest carbon sequestration to the sum of carbon sequestration of all trees. Then, we model the amount of forest carbon sequestration with harvesting intensity $x\%$ and rotation period T. This model is based on the idea of integration. The rotation period and harvesting intensity are both certain, which means that they will not change over a considerable period of time.

We only need to consider the change of total carbon sequestration in the forest with the change of harvesting intensity and rotation period in any logging period after the start of the rotation.

$$T_1 + T \to T_1 + T_0 : C_1 = x\%C_{t-T_1+A_0} + (1 - 2x\%)C_t + x\%C_{t-T_1-T+A_0} \tag{14}$$

We divide the rotation into two periods: the first period is from $T_1 + T$ to $T_1 + T_0$, where the young trees planted after the previous round of harvesting are not yet mature and the value of carbon sequestration is Eq. 14, see Figure 8.

$$T_1 + T_0 \to T_1 + 2T : C_2 = x\% C_{t-T_1-T+A_0} + (1 - x\%)\, C_t \tag{15}$$

The second period is from $T_1 + T_0$ to $T_1 + 2T$, where the young trees planted after the previous round of harvesting are already mature and the value of carbon sequestration is Eq. 15, see Figure 8.

$$W_f = \int_{T_1+T}^{T_1+T_0} C_1 dt + \int_{T_1+T_0}^{T_1+2T} C_2 dt \tag{16}$$

These two periods of carbon sequestration functions are integrated over time and then The summation gives the equation of forest carbon sequestration with respect to the rotation period and harvesting intensity Eq. 16

$$W_p = 2x\% \cdot V \cdot (\lambda G_{paper,t} + (1 - \lambda) G_{hardwood,t}) \tag{17}$$

where

- T_1 represents the year we harvest trees at first time
- C_1 represents the carbon remain during the time between planting and cutting of the previous batch
- C_2 represents the carbon remain during the time from maturity of the previous batch to the cutting of this batch
- W_f represents the carbon stock in forest
- W_p represents the carbon remain in forest production
- V represents the wood accumulation of the total area
- λ represents conversion rate of paper products(from wood)

Our goal:

$$max(W_f + W_p) \tag{18}$$

which means the best carbon sequestration.

4 Model II :SEE (Social-Ecological-Economic) Model

Although Dynamic Carbon Sequestration Model is able to determine the most effective forest management in terms of sequestering carbon dioxide. However, from the standpoint of improving the overall development of forests, it is unrealistic to use the amount of carbon sequestration as the only indicator. Because other values of the forest are evaluated by society, Model 2 will combine other aspects of forest values to develop an evaluation-decision model that will show forest managers the best use of the forest.

4.1 Decision Model

When we build the decision model, we use multi-objective programming as our method that can combine ecological, social, and economic benefits with carbon sequestration as four objective functions.They also represent the spectrum of management plans that our decision model suggests.To solve the model, we use the ε-constraint method. In this case, the main reference objective of interest is carbon sequestration, and the other three objective functions become as constraint conditions of the model.

Specifically, Objective function:

$$max(W_f + W_p) \tag{19}$$

Decision Metrics:

$$\boldsymbol{x} = [x\%, T]^T \tag{20}$$

$$\begin{aligned} & max\,(W_f + W_p) \\ \text{s.t.} & \begin{cases} R(t) - h(t) \geq A(t) \\ H' \geq 5 \\ p(t) * x\% * F_{sum} \leq MP_{\min} \\ \boldsymbol{x} \in X \end{cases} \end{aligned} \tag{21}$$

The parameters $A(t)$ function and MP_{min} are supposed to be given by the forest manager after investigating the actual situation of the forest.In the section below, we will explain Eq 21 in detail.

4.1.1 Social Benefits

A(t) is used to denote the minimum forest resource stock required to sustain the needs of society. In the model, it is mainly determined by social demand, and its magnitude does not change with the overall forest resource stock. Due to the social development, population size, human-land conflict, and environmental pollution will bring many social problems, therefore, the minimum amount of forest resources reserved for social development is to alleviate some of the social problems[7].

The minimum forest resource accumulation A(t) required for stable social development changes with time, while the factors affecting A(t) change in a short period but basically are not very variable, and in a short period,it can be considered as a fixed constant.

$$A(t) = \alpha\rho(t) + \beta\phi(t) \tag{22}$$

- α represents the demand for forest resources per unit of population density
- β represents the demand for forest resources to improve each unit of environmental quality
- $\phi(t)$ represents the environmental quality factor of the studied region
- $\rho(t)$ represents the population density of the studied region

Constraint for A(t):

The forest resource stock $R(t)$ (post-harvest stock $R(t) - H(t)$) at any moment t must be greater than or at least equal to the minimum forest stock required to provide ecological goods to society at that moment, i.e.:

$$R(t) - h(t) \geq A(t) \tag{23}$$

4.1.2 Ecological Benefits

We focus on biodiversity as the main object of study and quantify biodiversity through the Shannon-Wiener index. The Shannon-Wiener index is a standard diversity index, which can indicate both the species richness of a community and the evenness of species distribution within a community[8].

$$H' = -\sum_{i=1}^{s} p_i \log p_i \tag{24}$$

where

- p_i represents the percentage species i take up in all species
- s represents the number of species

If $H' \geq 5$, the conservation value of species diversity per unit area is good enough, see Table 2. Our model chooses $H' \geq 5$ as the constraint for optimization.

Table 2: Grade partition and values of Shannon-Wiener index

Level	Shannon-Wiener Index	Values / $\left(\text{yuan} \cdot \mathrm{hm}^{-2} \cdot \mathrm{a}^{-1}\right)$
1	Index $\geqslant 6$	50000
2	$5 \leqslant$ Index < 6	40000
3	$4 \leqslant$ Index < 5	30000
4	$3 \leqslant$ Index < 4	20000
5	$2 \leqslant$ Index < 3	10000
6	$1 \leqslant$ Index < 2	5000
7	Index < 1	3000

4.1.3 Economic Benefits

It is vital for forest operators to make the forest profitable. When analyzing economic benefits, we use the commercial use of the harvested timber as its main criterion and combine cost, pricing, and exploitation to determine the constraints.

$$PV = p(t) * x\% * F_{\text{sum}} \leq MP_{\text{min}} \tag{25}$$

where

- PV represents the total cost of wood processing
- $p_t\%$ represents the cost of wood processing per unit
- F represents the overall trees accumulation
- MP_{min} represents the minimum market price of wood

4.2 Evaluation Model

Forests are not only responsible for carbon sequestration, but also provide ecological products, cultural products, and economic benefits to society. For forest resource operators, the main consideration is forest stock, which is related to economic benefits. For society, we want to maximize the economic and cultural benefits of forest resources, etc., while ensuring the amount of forest carbon storage.

The location, climate, surrounding population around the forest, and the condition of local economic development all have an impact on the level of forest integration. The optimal solution in the decision model is known to be within an ensemble. In order to extend the use of the decision model and give more accurate forest management plans for different types of forests, an evaluation model was developed to assess the current situation of the forest.

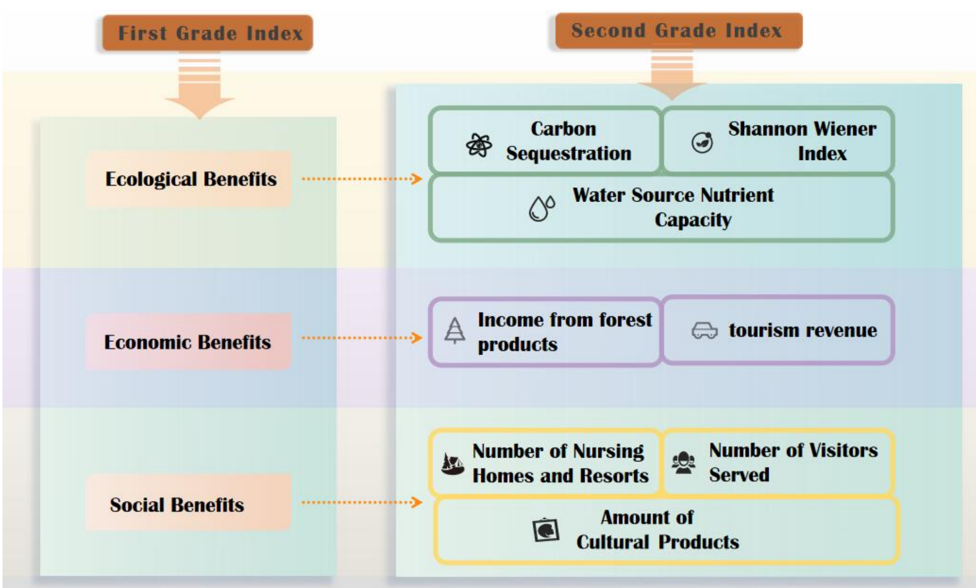


Figure 9: Indicator System

4.2.1 First Grade Indicators

As we can see in Figure 9, a comprehensive forest evaluation system contains three first grade indicators: social, ecological, economic benefits.We will assess the forest in these three main aspects.

4.2.2 Second Grade Indicators

After that, we subdivided the three first grade indicators into several secondary indicators to improve the evaluation system.

When we could not directly quantify the impact of geographic location on the forest, we also restricted the selection of indicators in order to include as large a range of forests as possible in our model, e.g. when selecting the secondary indicators for social benefits, we considered one of the aspects of the differences in the amount of forest visitors by geographic location.

Similarly, the biodiversity index is strongly related to the geographical location of the forest. Following this method, we achieved an indirect process of quantifying the geographical location of the forest. The weights were determined by combining the hierarchical analysis and entropy weighting methods and by referring to expert opinions, see Table 3 and its visualization Figure 10.

Table 3: Indicators and weights[1]

Symbolic Notation	Weights	Second Grade Index	Symbolic Notation	Weights
X_1	0.5250	Carbon sequestration	x_{11}	0.7306
		Biodiversity Index	x_{12}	0.1884
		Water source nutrient	x_{13}	0.0810
X_2	0.3385	Forest products income	x_{21}	0.8333
		Tourism income	x_{22}	0.1667
X_3	0.1365	Number of resorts	x_{31}	0.1245
		Visitor Services	x_{32}	0.8662
		Cultural Products	x_{33}	0.0092

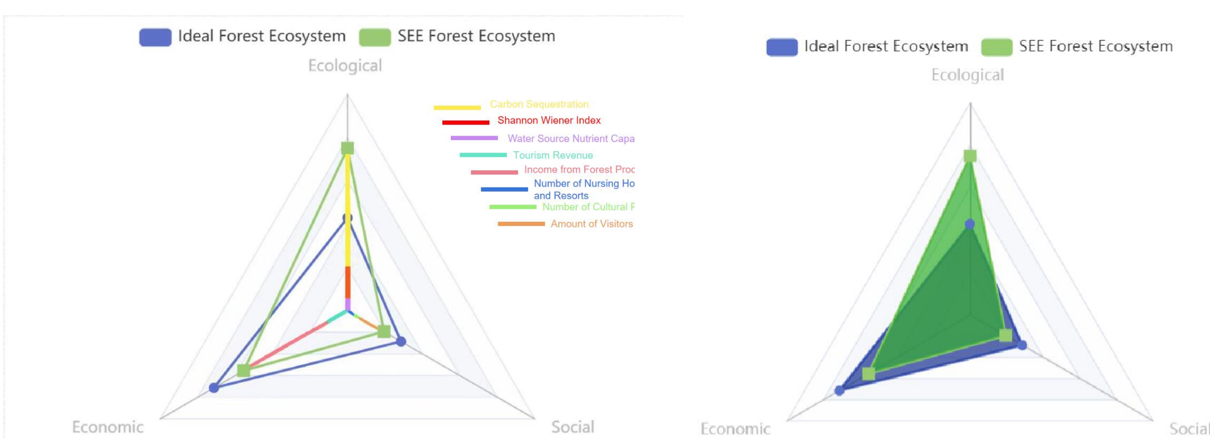


Figure 10: Weights visualization

Then, the scoring of the overall level of the forest can be expressed as:

$$\begin{gathered} S_1 = 0.7306 \times S_{11} + 0.1884 \times S_{12} + 0.0810 \times S_{13} \\ S_2 = 0.8333 \times S_{21} + 0.1667 \times S_{22} \\ S_3 = 0.1245 \times S_{31} + 0.8662 \times S_{32} + 0.0092 \times S_{33} \\ S_{sum} = 0.5250 \times S_1 + 0.3385 \times S_2 + 0.1365 \times S_3 \end{gathered} \tag{26}$$

4.3 Model Analysis

In Model 2, we have built a decision model and an evaluation model successively. To determine the most effective and comprehensive forest management plan, we combine these two models in the following analysis.

4.3.1 Extreme conditions

In the set of optimal solutions of the decision model, we consider that there is a very small probability that both $x\%$ and T will be equal to 0. The explanation is as follows:

If there are no trees to be cut, both $x\%$ and T in the model are zero, and the carbon sequestration formula only includes the carbon sequestration of the forest $f(t)$, with no carbon sequestration of wood products, resulting in a total carbon sequestration that is obviously lower than the forest with $x\%$ and T.

Consider an extreme case in which the percentage of forest trees is low enough to have an impact on biodiversity and social benefits, preventing the optimization model's constraints from being satisfied and the model's forest management approach from being applied to this extreme situation. As a result, in that case, precautions should be taken to avoid deforestation to the greatest extent possible.

4.3.2 Grading of scoring results

Based on this evaluation system, the existing forests with access to relevant data were evaluated, in which the overall condition of the forest was divided into three stages by scoring results, namely $0 \sim 31.7$ as **weak**, 31.8$\sim$ 64.3 as **good**, and $\geq$64.4 as **excellent**. We define the forest composite condition with scores of 31.7 and 64.4 as the transition point of the forest management approach, according to which three forest management approaches with different $x\%$ and T can be adopted for the three stages, see Table 4.

4.3.3 Determination of forest management

According to the assessment system, the calculated rotation periods are divided into three types, i.e. short rotation, normal rotation and long rotation, for 15a, 25a and 50a, respectively. When the total number of years of harvesting is fixed, shorter rotation periods should be used for forests in the weaker category duration of the evaluation system. At the same time, the harvesting intensity should be reduced to 10% to 20%. In this case, the short harvesting period and high harvesting frequency can increase the total carbon sequestration of the forest a nd its products in the total harvesting years in a short period of time.

Table 4: Grading scale for forest management plans

Level	Scores	$x\%$	T
Weak	$0 \sim 31.7$	$10 \sim 20\%$	$15a$
good	$31.7 \sim 64.3$	$25 \sim 35\%$	$25a$
Excellent	$\geqslant 64.3$	$\geqslant 35\%$	$30a$

However, the high harvesting frequency will lead to a part of soil nutrients being depleted after harvesting, which makes the forest land's nutrient capacity decrease and is not conducive to the sustainable development of forest land. Therefore, it is recommended that forests with weak comprehensive evaluation adopt harvesting approaches with time intervals, such as no harvesting for 5 years after experiencing a short rotation period, to restore soil nutrients through the forest's self-adjustment ability.

Manual intervention is recommended to plant new trees at 50% of the cut to ensure the forest's stand stock Forests located in the good assessment criterion can use a normal rotation period, with a harvesting intensity $x\%$ also using an average harvesting intensity of 25-35%, while ensuring that the soil nutrients are within a reasonable fluctuation range.

Among them, the harvesting intensity can be adjusted according to specific forest types, and a larger harvesting intensity can be adopted for faster-growing species, such as spruce trees, which are shallow-rooted and shade-tolerant, and the stand growth is greatly influenced by the geographical location when harvesting, and trees growing on shady slopes grow faster than those growing on sunny slopes, which should be focused on harvesting spruce trees and reducing the main harvesting age. Therefore, the appropriate harvesting intensity in terms of growth rate is within 60%[9].

For forests at the excellent stage in the evaluation system, the rotation period can be appropriately extended to 50a, and the species with faster growth rate can be selected according to the species diversity of the forest itself, and the intensity can be increased by 5% to 10% based on the normal harvesting intensity, so as to compensate for the loss of carbon sequestration in wood products due to the low number of harvests.

4.3.4 Determination of forest management

Below is a schematic of our model after determining the parameters. It can be seen that the model has an extreme value point, which corresponds to the point where x and T are the optimal solutions without constraints, i.e., the transition point between forest management plans. When economic and social constraints are taken into account, the extreme value point may not always be reached, so whether the transition point actually exists or not depends on the actual situation of the particular forest, see Figure 11.

5 Case study:Forests of Greater Khingan Mountains

The Mohe forest area in the northern part of Greater Khingan Mountains was chosen as the case of our model based on the collected data. Because the northern Greater Khingan Mountains

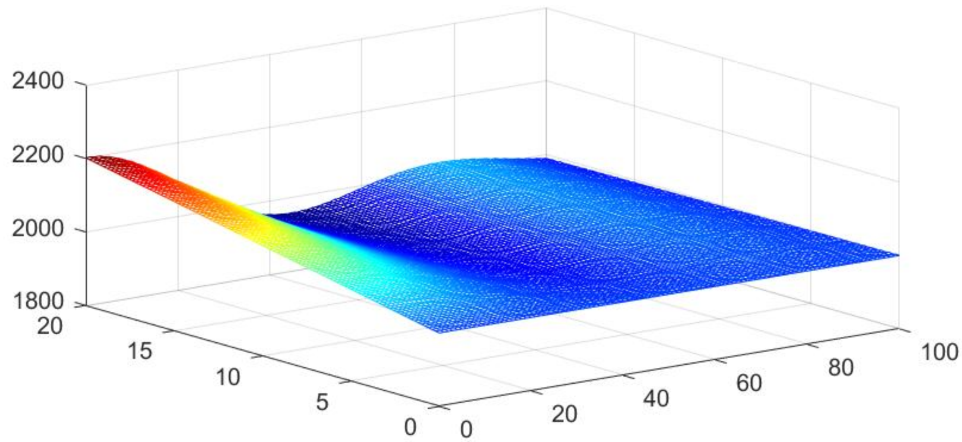


Figure 11: Carbon sequestration model under unconstrained conditions

forest has the coldest climate due to the highest latitude, a study of forest carbon sequestration in this region is quite interesting. Timber forests, protection forests, special forests, and fuel carbon forests are the four types of forests found in the northern area. Timber forests account for a bigger share of these, and the economic value provided by the other three types is lower, hence the model application only considers the section of timber forests[10].

Table 5: Data list[9]

Tree species	Accumulation percentage	R	$BCEF$	m	k	r	ρ'	T_0
Larch	64%	0.23	0.7	0.135	0.9	0.209	0.2377	15
Sphagnum pine	4.1%	0.23	0.7	0.12	0.8	0.241	0.073	15
White birch	24.8%	0.26	0.9	0.075	0.5	0.255	0.3075	13
Others	3.7%	–	–	–	–	–	–	–

5.1 Caculating the amount of CO2 sequestered:

In Dynamic Carbon Sequestration Model we have built model for the change of carbon sequestration in forests and their products over time, and collect the latest carbon sequestration-related data into Model 1 to obtain the change of carbon sequestration in the next 100 years (at the node of each decade) as shown in Figure 11.

- The Mohe forest area in the northern part of Greater Khingan Mountains and its products will sequester about **9384** t/hm^2 100 years later.

5.2 Developing the best solutions for managing forests:

By analyzing the searched data, we can get some values of the parameters to be determined for the model built above (Fig.), so that we get the model that can be solved after refinement. By

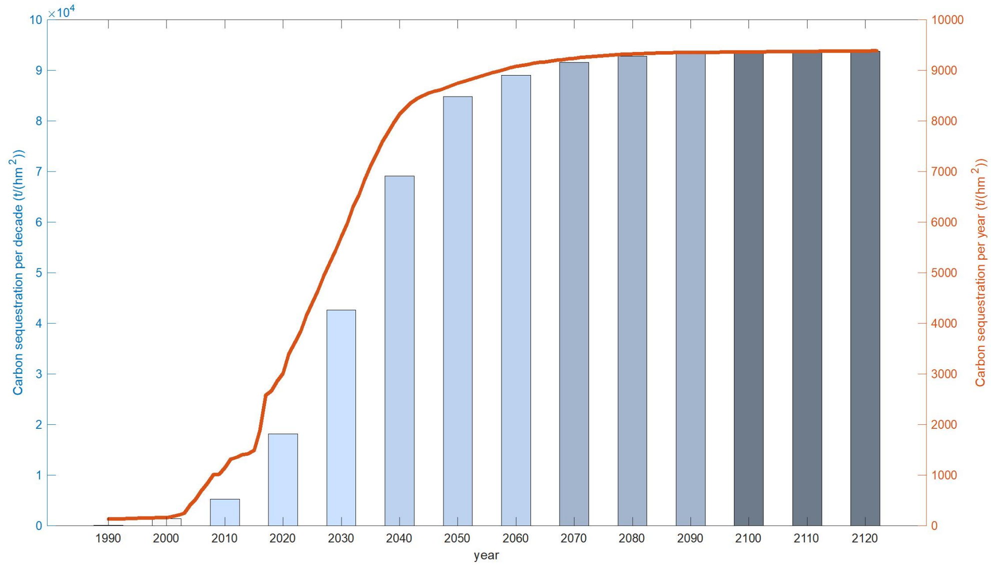


Figure 12: Carbon sequestration over 100 years

scoring the current forest area with the evaluation model we have built, we can evaluate the forest area to be in this stage of our evaluation system as good. We also use our decision model to solve for x and T, and give the management approach (forest management) accordingly.

The harvesting intensity is $11.83 \sim 25.96\%$ for mature and over-mature forests, and we take 20%. Moreover, according to the local government policy, for forest areas that need natural regeneration or artificial regeneration to promote natural regeneration, a certain number of mature trees should be retained when harvesting, and seedlings should be planted before harvesting to protect the young trees. In order to prevent forest erosion, logging should be carried out in strips, and block logging should be used for forest strips that are vulnerable to pests and other serious natural disasters. The most appropriate rotation period for all-woods harvesting is 19.77 to 26.12 years, and we have determined that it is 22 years.

Special note: In 1987, a major fire occurred in the northern Daxinganling primary forest area, resulting in a large area of forest being burned and a sharp decrease in forest cover. Therefore, considering the impact of natural disaster factors on forest carbon sequestration, forest management in the Mohe forest area should also consider the self-restoration capacity of forest ecosystems. Due to the problem of different forest types and differences in growth rates in the forest area, it is recommended to appropriately reduce the harvesting intensity of the forest types with high fire impacts, setting the intensity at $10 \sim 15\%$.

5.3 Strategy for timeline transition:

The rotation period will be changed when increasing the rotation period from 25 years to 35 years. The decision factor in Model 2 is only x%, and calculating the model yields x% after the adjustment.

When the rotation period increases, it leads to a lower growth rate of carbon sequestration in the forest. When the year of sequestration statistics is fixed, the frequency of harvesting decreases compared to 25 years, then the total sequestration of forest products decreases. In order to ensure that the new plan is as close as possible to the value of carbon sequestration of the original optimal harvesting plan, based on the purpose of not changing too much of the forest management plan, we only modify the harvesting intensity to (x+5)% to meet the needs of forest managers.

6 Model Evaluation

6.1 Sensitivity analysis

We carry out sensitivity analysis in two parameters:$x\%$ and T. First, we changed the value of $x\%$ in the range of -10% to 10%. The results are shown in the figure, which shows that the trend of carbon sequestration is less different in the first 30 years, but there is a larger difference after thirty years.This variation is reasonable because in our model more trees are converted to forest products in forests with high harvesting intensity as time increases, making the carbon sequestration increase steadily over the lifetime of forest products.

After harvesting, the carbon sequestration capacity of regenerating young trees is greater than that of the original mature trees, which is also the reason for such a change in the curve. Therefore, $x\%$ is an essential parameter that should be decided carefully.

Similarly, we varied T in the range of -10% to 10% and found that its sensitivity was not significant. In summary, $x\%$ is tested to be a sensitive parameter. Our model is also robust.

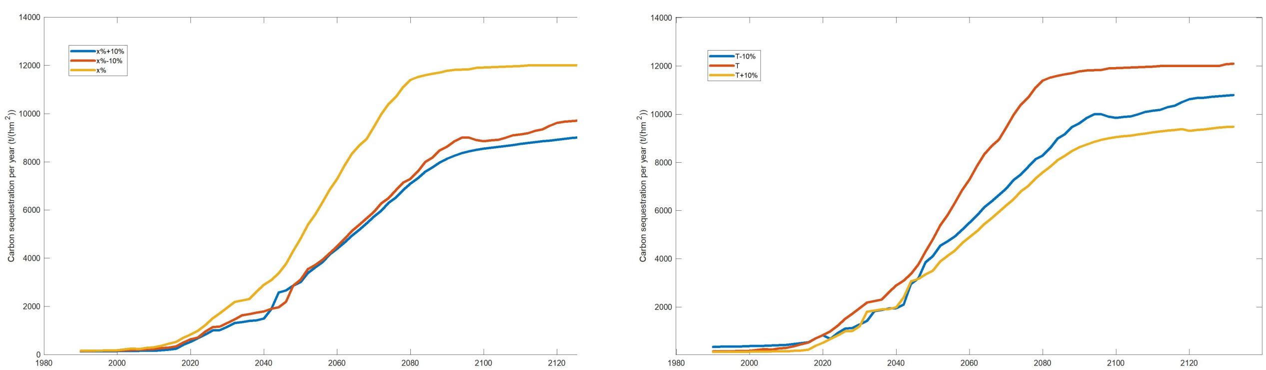


Figure 13: Sensitivity analysis

6.2 Strengths

- **Comprehensive scope of the model**
  In addition to carbon sequestration, ecological, economic and social benefits are combined to enhance the rationality of forest management plans
- **Extensive evaluation index system**
  A rich and comprehensive index is used to assess the comprehensive condition of the forest, which provides a sufficient basis for the formulation of forest management plans.

- **Proper integration with government policies**
  In the case study for the forests of Greater Khingan Mountains,we not only consider harvesting intensity and rotation , but also collect specific policies set by the local forestry bureau which provides forest managers with more realistic plans.

6.3 Weaknesses

- **Ignorance of the impact of carbon emissions**
  When we calculate carbon sequestration , we only took into account the accumulation over time and did not subtract consumption to calculate the net carbon conten

- **Limitations of our data collection**
  Due to the limited availability of data, we did not find quantifiable indicators related to climate and geographic location, but chose to use other indirect relationships as their substitutes, leading to the omission of information.

- **No consideration of the impact of other factors within the forest ecosystem**
  Factors such as water, soil and microorganisms in the ecosystem of the forest all play an important role in carbon sequestration and the level of forest synthesis, but we did not include them in our model.

6.4 Possible Improvments

When considering the effect of rotation period and harvesting intensity on forest carbon sequestration, we only calculate the carbon sequestration in one rotation period to judge and solve the model. Although our model is reasonable with the rotation period as the cycle, the time of one rotation period is relatively short and the model discard more unexpected factors, which may make our model more unstable, so it can be extended to more rotation periods and consider as many unexpected factors as possible.

The constraints in the decision model are the results of our simplification, while the real ecological, economic and social benefits do not only depend on the parameters we have given, and we will add the more objective functions appropriately in the later model.

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"Achieving Sustainable Forest Management on a Global Scale"

Community News

MCM/ICM Contest

VOL.I. . . No.1 | *FEBRUARY 20, 2022* | 0 DOLLARS

Harvesting is necessary for forests

By TEAM #2221177

Forests account for a little over one-third (38%) of habitable land area. They are among the most bio-diverse environments on the planet, and play an important role in climate regulation by absorbing CO2 from the atmosphere.

Forests, as we can see from Figure 1, undoubtedly play an extremely important role in the carbon cycle. According to the forest carbon flux map currently available on Global Forest Watch, Forests emitted an average of 8.1 billion metric tonnes of carbon dioxide per year from deforestation and other disturbances between 2001 and 2019, but they absorbed 16 billion metric tonnes of CO2 each year at the same time.

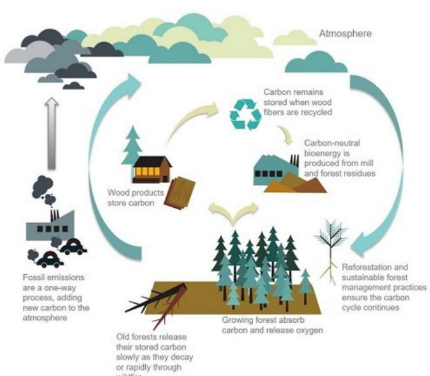

Figure 1: Carbon Cycle

Yes, as expected, we demand that forests, some of which are being destroyed, be protected. However, we would want to emphasize that the essential forest harvesting in forest management is beneficial to carbon capture, from which our people can obtain high-quality wood and wealth.

Abandoning Stereotypes: the Necessity for Logging

Figure 2: Forest

Greetings, friends! We are happy to share with you some of the forest development and conservation ideas we have discovered. We arrived at the following conclusions after a thorough examination of worldwide forest cover and forest exploitation.

First, environmental conservation and rigorous forest protection are not inextricably related. According to the results of Nature journal, 8% of the carbon stored in forests is stored in dead trees rather than living trees. Each year, dead wood emits around 115 percent of the carbon produced by humans. As a result, allowing forests to grow at their own pace will limit their carbon-capture capacity.

Second, the biodiversity of the forest is very stable and will not be reduced by moderate deforestation.We may have heard stories of deforestation resulting in massive habitat loss for Amazonian creatures, but moderate deforestation results in much less tree loss than brutal deforestation, and can often be restored within 10 years.

Third, sawmills bring jobs to communities, and processed trees make fine furniture and paper, all of which can bring considerable wealth.

Why Logging is Good for Carbon Sequestration?

There's increasing recognition of how nature can help tackle the climate crisis. Forests offer significant climate mitigation benefits. Now, new research shows that letting forests regrow on their own could be a secret weapon to fighting climate change.

Harvesting trees is able to better the carbon capacity of forest. When forest trees are cut down, the carbon that these trees collected from the atmosphere is sequestered in products like wooden furniture, avoiding the creation of dead wood and, to some extent, promoting forest development by allowing younger trees to better sequester carbon as they grow. The carbon in wooden furniture is hard to decay, which needs over 20 years to be reduced to half.

Figure 2: Axe