Problem Chosen	2022 MCM/ICM Summary Sheet	Team Control Number
E		2212916

Start with Carbon Sequestration, Maximize the Value of Forests

Summary

Climate change is now a serious threat to life. We can mitigate the effects of climate change by sequestering carbon from the atmosphere. Such process is called carbon sequestration. Among all the roles contributing to carbon sequestration, forest accounts for the vast majority. In this paper, we will focus on forest carbon sequestration and develop a model that gives out a management plan to maximize the use of forests.

Focusing on carbon sequestration, we initially develop a model that is capable to work out a harvesting plan that maximizing carbon sequestration. Firstly, we need to measure carbon sequestration of a forest. After rejecting the use of evaluation model, we turn to the data based method of **multiple regression analysis**, by which we obtain an equation that estimates all the marginal effect of some most related features which are air temperature, relative humidity, CO2 absorbing ability, soil depth, soil bulk density and soil organic matter content. To obtain the appropriate harvesting plan, our model compares the total carbon sequestration among different felling age, with considering effect of forest products. The specific algorithm of our model is **Monte Carlo**.

However, the value of forest is far more than carbon sequestration only. In order to give out the plan that really maximizes the use of forest, we then improve our initial model by increasing the spectrums of value created by forest. Through literature review, our improved model now is capable to measure values of seven aspects: carbon sequestration of trees, protecting soil, oxygen emission, carbon sequestration of forest products, transaction value of forest product, bio-diversity, water conservation. In order to obtain the best management plan, our improved model compares the total value of forest. Based on the unadditivity of different units, we transform value of all aspects into economic value. Slightly different from the initial model, since computational complexity rises exponentially as more aspects are considered, **genetic algorithm** would be the better method to solve such optimization problem.

Finally, we perform a sensitivity analysis on the model. By **visualizing** the impact of changes of each parameter on cutting age of trees, we can directly find the transition point through observation because outcome fluctuates wildly round the transition point.

To put our model into practice, we chose Changbai Mountain Dabiangou Forest. Using the regression equation, the carbon sequestration of the forest in 100 years is 191816403.9 ton. Through the genetic algorithm in our model, we obtain the best management plan, by which the forest is able to create a total value of $6839165853.1. Perhaps taking the value of labor and time into account, the best cutting interval is changed to 10 years by some theories. To work out a transition strategy that is sensitive to the needs of forest managers and all who use the forest, we conduct the sensitivity analysis on cutting interval and find the **transition point** which is 4 years. To reduce the impact of changing the cutting interval, we recommend that the cutting age should be the optimal age (figure out through the sensitivity analysis) with the interval of four years.

Keywords: Multiple Regression Analysis, Monte Carlo, Genetic Algorithm, Visualization

Contents

1 Introduction

1.1 Background

At present, life on earth is severely threatened by climate change. Rising levels of greenhouse gases in the atmosphere may take the most responsibility for climate change. Rather than reducing greenhouse gas emissions, enhancing our stocks of carbon dioxide sequestered out of atmosphere could be the most critical means of mitigating the effect of climate change, which is called carbon sequestration.

Forests are integral to any climate change mitigation effort for the crucial role they are playing in carbon sequestration. Not only plants and soils in forests sequester carbon dioxide, forest products like furniture also are part of carbon sequestration. Considering lifespan, producing forest products can sometimes contribute more carbon sequestration than not cutting forest at all because of regrowth of young forests.

In order to figure out how to utilize and manage forests, it is momentous to develop a relatively universal model, which should be able to measure carbon sequestration of forests and determine a manage plan of appropriate harvesting.

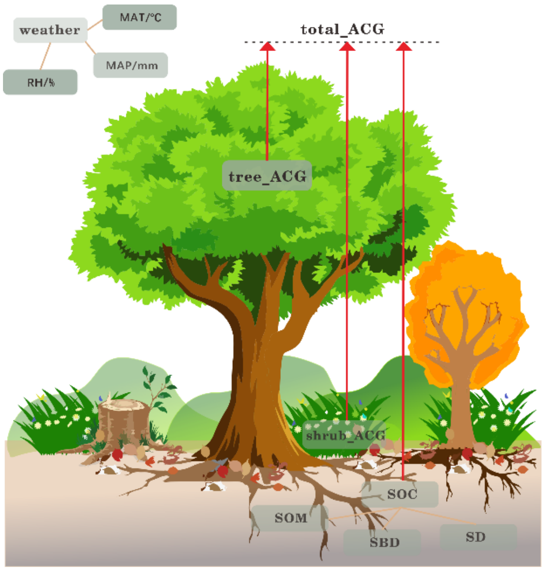


fig 1Carbon sequestration

1.2 Restatement of problems

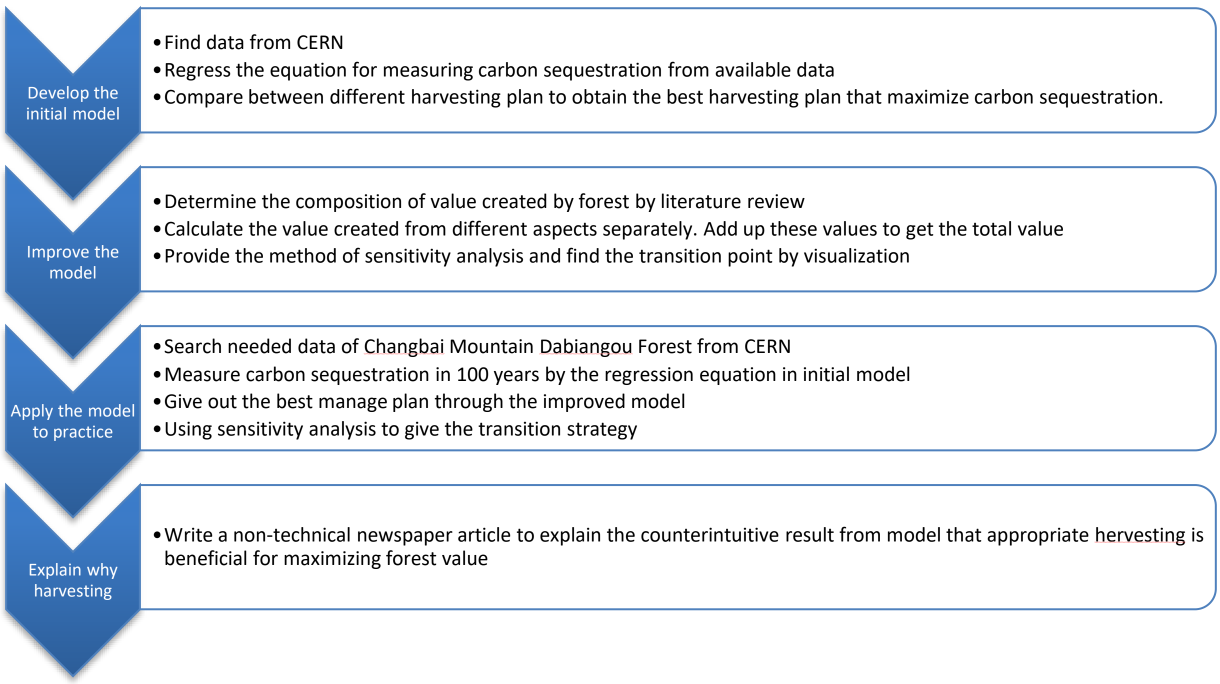
Based on the background information, the main tasks of this paper are as follow:

✧ Develop the initial model. The model should be able to measures carbon sequestration of a particular forest by some features of itself and subsequently, give out an appropriate harvesting plan that maximizes the carbon sequestration through trade-offs between positive effect of producing products and negative effect of harvesting.

- ✧ Improve the model by expanding the spectrum of management plans. Use the improved model to find the manage plan which is the best use of a forest considering its various values.
- ✧ Apply our model to the real case (data from a real forest). First measure carbon sequestration over 100 years of the forest. Decide the appropriate harvesting then. Come out a transition strategy when unusual outcome occurs.
- ✧ Convince the local community that appropriate harvesting included in the best manage plan is the best decision for their forest.

1.3 Overview of our work

Generally speaking, our work is divided into four steps:



2 General Assumptions and Notation Description

2.1 Assumptions

1. Unmanaged forests are in a stable state. (Features of a forest vary little over time)
2. After cutting down a tree, plant the same species of tree in situ immediately.
3. *The life of a tree is divided into five periods: young, middle age, near mature, mature and over mature. Carbon sequestration of a tree varies with different life period, low on both sides and high in the middle.*[1] Carbon sequestration of a species of tree is same in a period.
4. Proportion of itself's amount of different period is same in all species.

[1] Wang xiao-ke & Liu Wei-wei.(2021). Factors influencing forest carbon sequestration. *Forestry and Ecology* (03),40-41. doi:10.13552/j.cnki.lyyst.2021.03.022.

5. Carbon sequestration of forest products is the ratio of its own carbon reserves and its lifespan.
6. Proportion of lifespan of different period is same among species.
7. All the wood made from trees completely converts to forest products.
8. Trees growth in a forest are in dynamic balance which indicates that the proportion of each life period would not change

2.2 Notation

Symbol	Description
Ta_i	Average air temperature of forest i (°C)
RH_i	Average relative humidity of forest i (%)
AP_i	Average precipitation of forest i (mm)
TCs_i	Carbon sequestration every year of trees in forest i (g*cm^{-2})
SCs_i	Carbon sequestration every year of soil in forest i (g*cm^{-2})
FCs_i	Carbon sequestration every year of forest I (g*cm^{-2})
Cst_i	Carbon sequestration every year of trees of species i (g*cm^{-2})
Cr_t	Carbon reserves in year t (g)
Ca_i	Average CO_2 absorbing ability of specie i (g*cm^{-2})
NPR_i	Average net photosynthetic rate of species i (g*tree^{-1})
D_i	Trees density of species i (tree*cm^{-2})
Sbd_i	Average soil bulk density of forest i (g*cm^{-3})
Dpt_i	Average soil depth of forest i (cm)
SOM_i	Average soil organic matter content every kilogram(g)
P_i	Proportion of each life period of a tree (No unit)
A_{ij}	CO_2 absorbing ability of species i in their period j (g*cm^{-2})
X_i	Ratio of the age that trees cut and their lifespan[2] (No unit)
t	Service time of products made from forest
Age_i	Age at which trees of species i should be cut (yr)
Lfs_i	Average lifespan of species i (yr)

3 Model Establishment

3.1 Initial Model: Carbon Sequestration Measurement and Harvesting guidance Model

To measure carbon sequestration, the first thought that came to our minds was to use the evaluation model. Giving weight to each feature of the forest, we can easily measure its carbon

[2] $X_i = \frac{Age_i}{Lfs_i}$

sequestration. However, in forestry study, those weights should be given by field investigation cautiously[3]. Meanwhile, those weights are time sensitive. Hence, developing evaluation model directly from the existing literature is likely to be outdated and subjective.

3.1.1 Finding Data

All of our data is applied from CERN [4](Chinese Ecosystem Research Network).

We download related data from 10 CERN observation stations (CBF, BJF, MXF, SNF, HTF, QYF, ALF, DHF, HSF, BNF).

Features of forest we found from CERN are as follow:

Air temperature (°C)
Precipitation (mm)
Relative humidity (%)
Forest age (yr)
Soil bulk density ($g*cm^{-3}$)
Soil organic matter content ($g*kg^{-1}$)
Soil depth (cm)
Soil organic carbon density ($g*cm^{-2}$)
Tree carbon density ($g*cm^{-2}$)
Total ecosystem carbon density ($g*cm^{-2}$)
Tree species proportion (%)
Net photosynthetic rate (g/tree)
Tree density ($trees/cm^{-2}$)
Mass of trees in different age (g)

3.1.2 Measure Carbon Sequestration

Based on data above, we can calculate the total forest ecosystem carbon sequestration of the year by figuring out the difference of this year and next year:

$$FCs = Cr_{t+1} - Cr_t \tag{1}$$

By equation(1) and time series data of Tree carbon density and time series data of soil organic density, we can calculate carbon sequestration of trees and soils of each forest.

Meanwhile, total carbon sequestration of forest ecosystem equals the sum of soil carbon sequestration and tree carbon sequestration. Thus, in order the measure the total carbon sequestration, we firstly measure carbon sequestration of trees and soils separately.

Chinese Society of Forestry (CSF) had put forward a measure theory that[5]:

- Carbon sequestration every hm^2 of trees is the product of tree density, ability of absorbing CO_2 (Net photosynthetic rate) and conversion coefficient.

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3 Zhang Wenqin (2020). A summary of Chinese modern forestry research in the past 40 years of reform and opening up *Agricultural Archaeology* (03),257-264. doi:

4 Chinese Ecosystem Research Network. http://www.cern.ac.cn/0index/index.asp

5 He, Y. (2005). A review of methods for estimating forest carbon sequestration. *World Forestry Research* (01),22-27. doi:10.13348/j.cnki.sjlyyj.2005.01.005.

- Carbon reserves every hm^2 of soils is the product of soil depth, soil bulk density, soil organic matter content and conversion coefficient.

i. Carbon sequestration of trees in a forest

According to the theory of CSF, CO_2 absorbing ability is a necessary indicator to measure carbon sequestration. Also in the theory, CO_2 absorbing ability is equivalent to the product of net photosynthetic rate and tree density. Therefore, we calculate CO_2 absorbing ability in terms of net photosynthetic rate multiply by tree density.

$$Ca_i = NPR_i * D \tag{2}$$

CO_2 absorbing ability varies from species to species. We take the average of CO_2 absorbing ability of different species in the forest, weighted by the number of species in the forest. We define such average of CO_2 absorbing ability to be the CO_2 absorbing ability of the forest. Simplifying calculation, we have generalized the tree species in a forest into three groups: arbor, shrub and others. In this way, CO2 absorbing ability of forest varies from forest to forest only relied on the different groups (arbor, shrub and others) composition. CO_2 absorbing ability of forest i is noted $\overline{Ca}_i$:

$$\overline{Ca}_i = \sum_{k=1}^{3} Ca_k * weight_k \qquad (3)^6$$

Since the CO_2 absorbing ability is a theoretical indicator which only relied on species, we should consider the absorbing ability of trees in a forest in practice when we need to measure the trees carbon sequestration in a forest. Based on the great correlation between photosynthesis (process that trees absorb CO2) and climate[7], we take some climate indicators into consider. Consequently, we put out an opinion that carbon sequestration of trees in a forest is related to climate and absorbing ability.

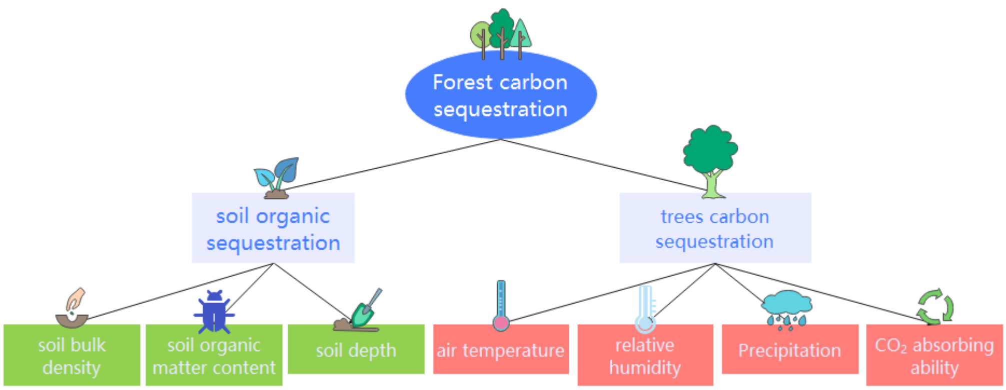

fig 2Composition of forest carbon sequestration

Thus, we put out an equation:

$$TCs_i = \beta 0 + \beta 1 * Ta_i + \beta 2 * RH_i + \beta 3 * AP_i + \beta 4 * \overline{Ca}_i \tag{4}$$

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[6] Three groups of trees in a forest. they are arbor, shrub and others.

[7] Cai Yongzhan, Zhou Puxiong, Zhang Liu, Wang Zheng, Xu Qionghua, Yang Huanwen & MAO Zichao.(2015). Effects of different climatic conditions on photosynthetic rate and protein expression in Leaves of *Yunyan 87* during flourishing period. *Acta Tabacaria Sinica* (01),39-48. doi:10.16472/j.chinatobacco.2013.420.

Based on assumption 1, features in the equation above of a forest vary little over time. In order to solve the coefficient in equation(2), we use cross-sectional data to regress (data from 8 different forest: CBF, BJF, MXF, SNF, HTF, ALF, DHF, HSF).

According to the above theoretical equations, SPSS is used to find the best function by minimizing the sum of squares of errors. Using this method, the parameter data are simply analyzed to keep the minimum sum of squares of error between the obtained data and the actual data. Through calculation, the equation of the model is obtained[8]:

$$\widehat{TCs_i} = -238.937 + 16.853 * Ta_i + 3.487 * RH_i + 0.147 * AP_i + 1.361 * \overline{Ca}_i \tag{5}$$

R^2 (Goodness of fit) is 0.927, adjusted R^2 is 0.83. Obviously, our regression model can well explain the dependent variable (carbon sequestration of trees in a forest). However, P value of RH_i is greater than 0.1, which indicates that the marginal effect of RH_i on dependent variable is not significant at 90% confidence level. (P values of other features are less than 0.1) Hence, we did another regression after removing RH_i. Outcome is:

$$\widehat{TCs_i} = -240.179 + 20.331 * Ta_i + 0.141 * AP_i + 1.372\overline{Ca}_i \tag{6}$$

R^2 and adjusted R^2 is 0.91 and 0.843, respectively. P values of all features are less than 0.1.

ii. Carbon sequestration of soils in a forest

Unlike trees, soils' features are mainly determined by its own chemical properties. It is less affected by climate. Therefore, there's no need to add climate indicators into the equation. Yet, we can't simply make use of the equation descripted in the theory of CSF because our target is carbon sequestration rather than carbon reserves in soils. CSF's theory tells us that carbon reserves is highly related to soil depth, soil bulk density and soil organic matter content. To figure out the marginal effect of three soil indicators mentioned on carbon sequestration, it is reasonable to use multiple regression analysis. The equation is:

$$SCs_i = \beta 0 + \beta 1 * Sbd_i + \beta 2 * Dpt_i + \beta 3 * SOM_i \tag{7}$$

Same as above, we use cross-sectional data to regress (data from 8 different forest: CBF, BJF, MXF, SNF, HTF, ALF, DHF, HSF).

Using SPSS, the equation of the model is obtained:

$$\widehat{Scs_i} = -362.874 + 682.677 * Sbd_i - 4.695 * Dpt_i + 4.198 * SOM_i \tag{8}$$

R^2 and adjusted R^2 is 0.883 and 0.795, respectively which infers that our regression model has relatively good effect. The P values of all features is less than 0.05 which indicates that the marginal effects of all features are significant at 95% confidence level.

iii. Carbon sequestration of a forest (total)

$$\widehat{FCs_i} = \widehat{TCs_i} + \widehat{SCs_i} \tag{9}$$

[8] Detailed regression results are in the appendices

3.1.3 Maximize Carbon Sequestration

Second part of the model is to determine the way of felling which maximize carbon sequestration. According to assumption 3, trees of a kind have different carbon sequestration in different life period, and carbon sequestration goes down as those trees become older and older after the peak period. Besides, products made from forest contribute to carbon sequestration.

Hence, when carbon sequestration of cutting trees over a certain age is larger than not cutting at all, cutting all the trees over the certain age is a better way of cutting than not cutting at all (noted that carbon sequestration compared here include those from forest products).

To calculate the carbon sequestration of trees of one kind, we define A_{ij} and X. A_{ij} refers to CO_2 absorbing ability of trees of species i in period j (5 periods according to assumption 3, and name them 1 to 5). Unlike measuring forest carbon sequestration, CO_2 absorbing ability of exactly species is needed here instead of CO2 absorbing ability of the three groups.

X_i is the ratio of the age when trees of species i are cut and their lifespan.

For X_i between period j and period j+1, average CO_2 absorbing ability of trees of species i is:

$$Ca_i = \frac{A_{i1}P_1 + \cdots + A_{ij-1}P_{ij-1} + A_{ij}\left(X_i - P_1 - P_2 - \cdots - P_j\right)}{X_i} \tag{10}$$

By bringing Ca_i into variable $\overline{Ca_i}$ of equation(6), we got the carbon sequestration of trees of a species : Cst_i. To add up the carbon sequestration of all species in a forest, we have the total carbon sequestration of trees after cutting down trees over a certain age (varies from species).

Besides living trees in the forest, products made from forest contribute carbon sequestration because they would not give out CO_2 or be decomposed to be CO_2 in their service time. We can simply divide the carbon reserves of their own by their service time as their carbon sequestration.

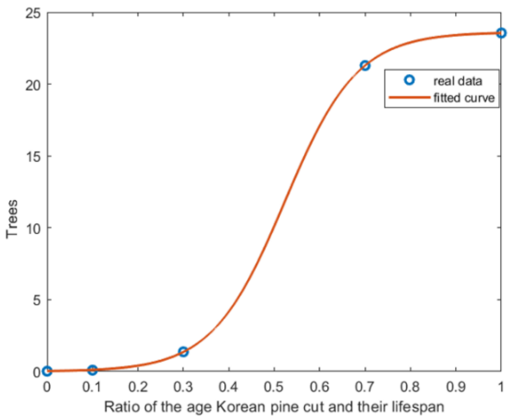
It is not easy to know the carbon reserves of products. Based on existed theory, carbon reserves of trees is half of their mass[9]. Meanwhile, mass of trees is related to their age. By regressing data (carbon reserves and X_i) from different species, we come out with a function form that suit all species[10] ($f(X_i)$ is carbon reserves of trees at their X_i):

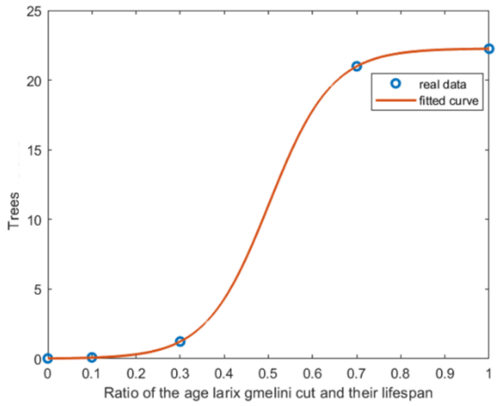
$$f(X_i) = \frac{con1}{1 + e^{con2 - con3 * X_i}} \tag{11}$$ [11]

[9] André Lacointe, Abdellah Kajji, François-Alain Daudet, Philippe Archer, Jean-Sylvain Frossard, Brigitte Saint-Joanis & Marc Vandame (1993) Mobilization of carbon reserves in young walnut trees, *Acta Botanica Gallica*, 140:4, 435-441, DOI: 10.1080/12538078.1993.10515618

[10] Zhang, C.Q. (2007). Study on the dynamics of plant growth during the growing season of Typical Steppe in Inner Mongolia (ph. D. Dissertation, Inner Mongolia University) .https://kns.cnki.net/KCMS/detail/detail.aspx?dbname=CDFD0911&filename=2008174059.nh

[11] Con1,2,3 are constant that varies from species.





Trees would be cut down and be made to be products at their X_i. According to assumption 7, carbon reserves of products made from one tree is $f(X_i)$. Meanwhile, in dynamic balance, based on assumption 2, 6, average of trees cut is $\frac{D}{Age_i}$.

Carbon sequestration of products is $\frac{f(X_i)}{t} * \frac{D}{Age_i}$.

Carbon sequestration of performing harvesting at X_i is:

$$Carbon\ sequestration = Cst_i + \frac{f(X_i)}{t} * D \tag{12}$$

To maximize carbon sequestration descripted above, we use Monte Carlo to get near to the optimal X_i.

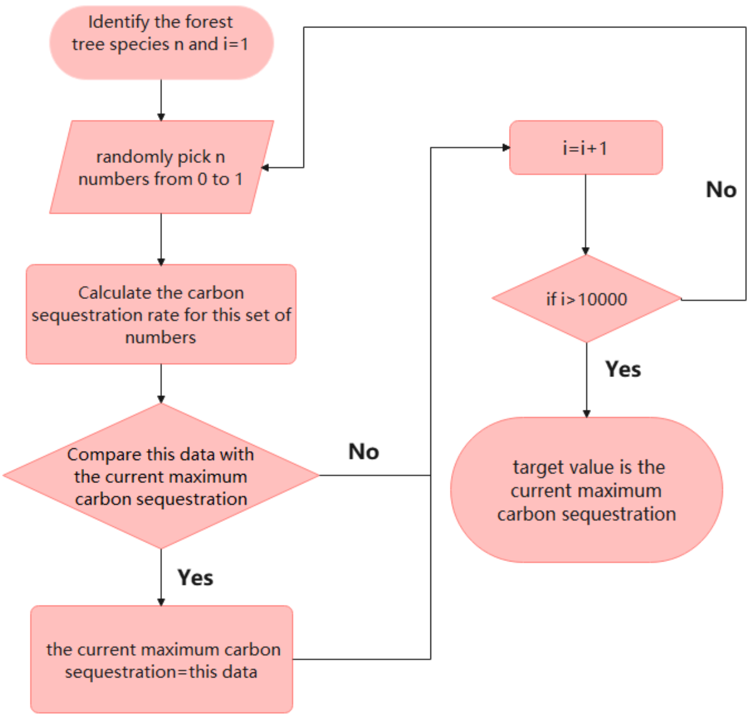


fig 3Flow chart of Monte Carlo

3.2 Improved Model: Optimal forest management model with comprehensive consideration

So far, we've developed a model that gives out a manage plan which maximize carbon sequestration. However, when talking about value to society, forest can create more value than just carbon sequestration in many aspects. According to the MEA classification of ecosystem services[12], forests create value in several aspects:

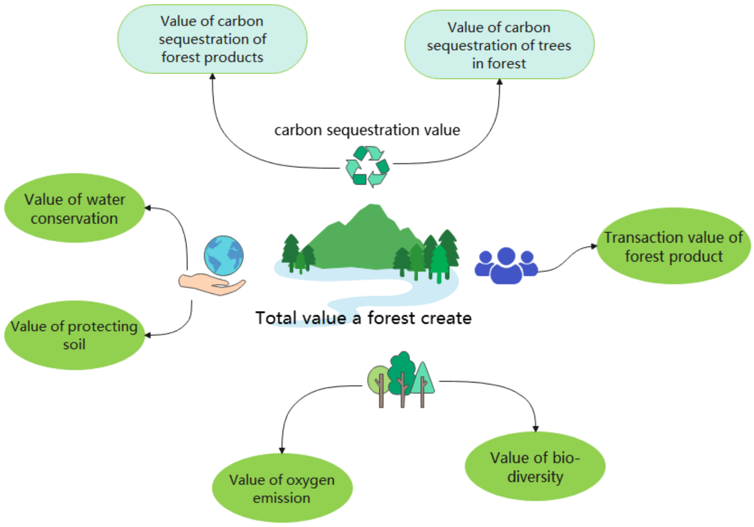


fig 4Composition of Value created by forest

New problem has arisen that it is difficult to add up value from different aspects because of different units and difficulty to quantifying. Follow the current method of ecosystem value accounting, we measure value of different aspects in money terms[13]. In other words, we transform all the value of different aspects created by forest into economic value. Hence, to inform forest managers of best use of a forest is equivalent to work out the plan that maximize the total, transformed economic value. Our initial model would be improved to a model with comprehensive consideration, instead of considering carbon sequestration only.

3.2.1 Measuring Value of Forest

Some new variables are used in this section, following is the explanation.

Symbol (in this section (3.2))	**Explanation**
Ψ	Total value created by forest (unit: \$)
α	Value of carbon sequestration of trees in forest (unit: \$)
β	Value of protecting soil (unit: \$)

[12] Zhao, SHidong & Zhang, Yongmin.(2006). Ecosystem and human well-being: Achievements, contributions and prospects of the Millennium Ecosystem Assessment. *Advances in Earth Science* (09),895-902. doi:

[13]Geng jianxin & Liang Chengzhi.(2020). Practical application analysis of forest ecosystem value estimation -- based on comparison with SNA and SEEA. *Future and Development* (12),43-54. doi:

γ	Value of oxygen emission (unit: $)
δ	Value of carbon sequestration of forest products (unit: $)
ε	Transaction value of forest product (unit: $)
ζ	Value of bio-diversity (unit: $)
η	Value of water conservation (unit: $)
VCs	Value of every gram of carbon sequestration (unit: $)
$SLRc$	The amount of soil erosion denuded and displaced per unit area and per unit time ($g*cm^{-3}*yr^{-1}$)
cc	Proportion vegetation coverage on soil surface (no unit)
Gr	Growth of trees, related to age, an abstract indicator (no unit)
LCP	Land conservation price every gram (unit: $)
Q_i	Price of forest products per gram (unit: $)
SLC	Species loss cost per cm^2 (unit: $)
FSA	Forest structure area (unit: cm^2)
OP	Precipitation outside the forest (mm)
FSE	Forest structure evapotranspiration (mm)
RSR	Rapid surface runoff (mm)
μ	Forest ecosystem service correction coefficient (no unit)
SCR	Storage cost of reservoir project every mL (unit: $)

After transforming all the value into economic value, total value a forest create would be:

$$\Psi = \alpha + \beta + \gamma + \delta + \varepsilon + \zeta + \eta \tag{13}$$

Goal of our improved model is to maximize the total value of a forest:

$$Max\ \Psi \tag{14}$$

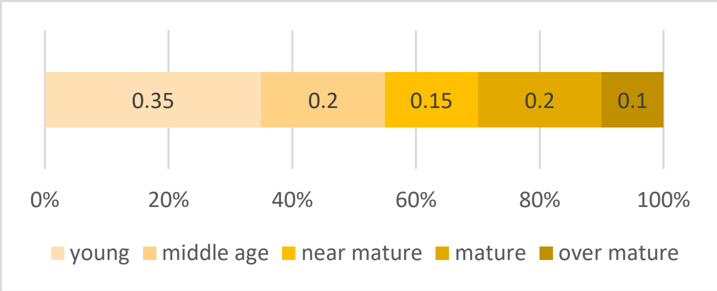
Calculating the value of each aspect require input data of different kind. Therefore, we will calculate the value of each aspect separately.

i. α : Value of carbon sequestration of trees in forest

The core of measuring value of carbon sequestration of trees in forest has been given in equation(6). Three climate indicators and $\overline{Ca_i}$ (CO_2 absorbing ability of forest i) are needed. Unlike what we have done in establishing the model, we can calculate $\overline{Ca_i}$ more accurately by calculate the weighted average of Ca_i of all species in the forest.

Considering harvesting, Ca_i of a species would be different if they would be cut at different age (In section 3.1.2, no any cutting behavior is considered). Based on assumption 6, proportion of lifespan of all species[14] is:

[14] Yao, L., Kang, W., Zhao, Z., & He, J. (2015). Plant carbon sequestration in a Chinese fir plantation at different growth stages. *Acta ecologica sinica* (04),1187-1197. doi:



The calculation formula of Ca_i is equation(10).

Bringing $\overline{Ca_i}$ into equation(6), we have Cst_i (Carbon sequestration every year of trees of species i ($g*cm^{-2}$)). Knowing the density of each species of trees in the forest D_i and the price of carbon sequestration[15] VCs, it is possible to measure the value of carbon sequestration of trees in the forest:

$$\alpha = VCs * \sum (Cst_i * D_i) \tag{15}$$

ii. β :Value of protecting soil

Using a logic similar to opportunity cost, we get the soil protected when trees are not cut down by calculating the soil loss when these trees are cut down, and calculate its (soil) value.

According to ***Technical guide for the accounting of gross terrestrial ecosystem product (GEP) in China*** , relation between $SLRc$ and cc is:

$$\mathrm{SLRc} = -5.614(\mathrm{cc}^{0.7366}) \tag{16}$$

Knowing that trees of species i would be cut at their X_i of their lifespan, their Gr and cc are:

$$\mathrm{Gr} = \mathrm{con} * \mathrm{f}(\mathrm{X_i}) \tag{17}$$
[16]

$$\mathrm{cc} = \sum (\mathrm{X_i} * \mathrm{D} * \mathrm{Gr}) \tag{18}$$

Also in GEP, we know the land conservation price LCP. And value of protecting soil is:

$$\beta = \mathrm{LCP} * \mathrm{SLRc} * \sum (\mathrm{X_i} * \mathrm{D} * \mathrm{Gr}) \tag{19}$$

iii. γ : Value of oxygen emission

Oxygen emission or oxygen release is another massive value that forest creates. Knowing carbon sequestration of the forest, calculating oxygen release is simple because they are linearly correlated[17].

For each ton of dry matter formed by plant growth, it needs to absorb 1.63 tons of CO_2 and release 1.19 tons of O_2, and the carbon content in CO_2 is 27.27%, so the ratio of oxygen release to carbon sequestration can be calculated as 1.19/0.4445.

Price of releasing oxygen is \$0.1581 per gram according to *National Health Commission of the People's Republic of China.* So, value of oxygen emission is measured:

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[15] Wu wenting, Xia Guoyuan & Bao Zhiyi.(2016). Evaluation of carbon sequestration and oxygen release value of urban green space in Hangzhou city. *Chinese garden* (03),117-121. doi:

[16] con is a constant which descripts the relation between Gr and volume of trees.

[17] Carbon and Plants 1 . *Nature* 66, 620–622 (1902). https://doi.org/10.1038/066620a0

$$\gamma = \sum (Cst_i * D_i) * \frac{1.19}{0.4445} * 0.1581 \tag{20}$$

iv. $\boldsymbol{\delta}$: Value of carbon sequestration of forest products

Section 3.1.3 has already mentioned the method of measuring carbon sequestration of forest products: $\frac{f(X_i)}{t} * \frac{D}{Age_i}$. So, the value can be measured as:

$$\delta = VCs * \frac{f(X_i)}{t} * \frac{D}{Age_i} \tag{21}$$

v. $\boldsymbol{\varepsilon}$: Transaction value of forest product

Mass of wood is double as its carbon reserves.[18]

Therefore, mass of products can be calculated as $2 * \frac{f(X_i)}{t} * \frac{D}{Age_i}$. And transaction value is:

$$\boldsymbol{\varepsilon} = \boldsymbol{Q_i} * 2 * \frac{f(X_i)}{t} * \frac{D}{Age_i} \tag{22}$$

vi. $\boldsymbol{\zeta}$: Value of bio-diversity

The increase of proportion vegetation coverage on soil surface (cc) will lead to the increase of bio-diversity. Again, using a logic similar to opportunity cost, we measure the cost of decreasing bio-diversity as the value of bio-diversity created by forests. The formula[19] is:

$$\boldsymbol{\zeta = SLC * cc} \tag{23}$$

vii. $\boldsymbol{\eta}$: Value of water conservation

We measure the value of water conservation by using the method of shadow project[20]: the value of water conservation of forest is equivalent to the cost of building a reservoir with the same storage capacity[21]:

$$\eta = 10 * cc * (OP - FSE - RSR) * \mu * SCR \tag{24}$$

[18] André Lacointe, Abdellah Kajji, François-Alain Daudet, Philippe Archer, Jean-Sylvain Frossard, Brigitte Saint-Joanis & Marc Vandame (1993) Mobilization of carbon reserves in young walnut trees, Acta Botanica Gallica, 140:4, 435-441, DOI: 10.1080/12538078.1993.10515618

[19] Geng jianxin & Liang Chengzhi.(2020). Practical application analysis of forest ecosystem value estimation -- based on comparison with SNA and SEEA. *Future and Development* (12),43-54. doi:

[20] Han meiqing, Wang Luguang, Han Lingling & Yan Donghua.(2009). Economic loss of water pollution in Hebei Province based on shadow engineering method and shadow price method. *China Water Transport (second half)*,2009,9(02):76-78.

[21] CAEP, & CAS. (2020). The Technical Guideline on Gross Ecosystem Product (GEP) (1.0 Version)

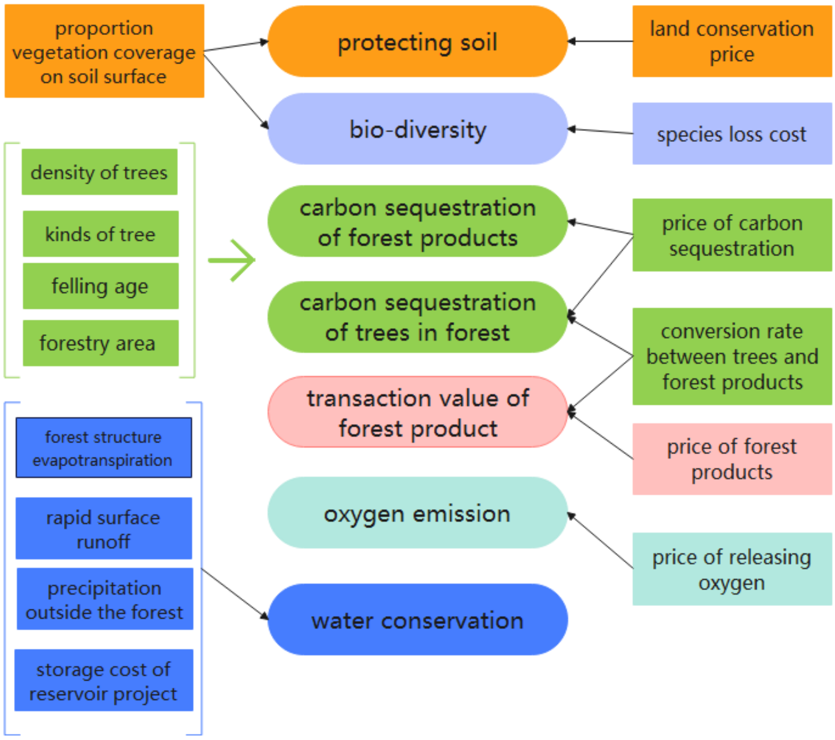


fig 5Variables needed

3.2.2 Maximize Value

Use the same basic logic of section 3.1.3, our model give out a comprehensive value-maximized manage plan through trade-offs between positive effect of producing products and negative effect of harvesting according to total value that the forest creates in each status (different species and their cutting age).

To solve for the optimal Age_i, the basic logic is to figure out the value of each Age_i and compare these values to find the Age_i that corresponds to the maximum value. However, direct traversal is very computationally expensive. Thus, we use genetic algorithm (GA) to simplify the calculation.

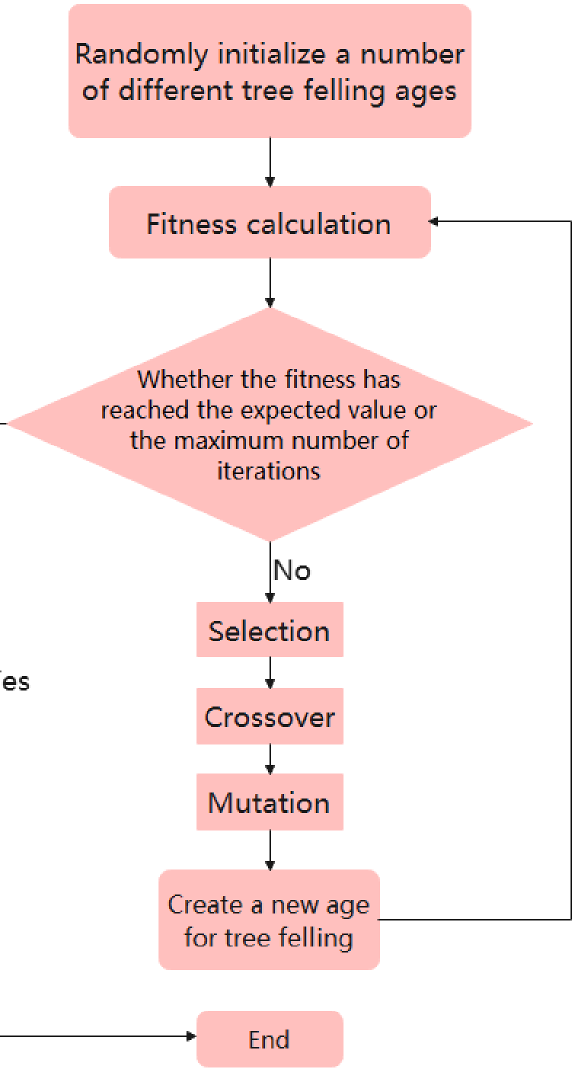
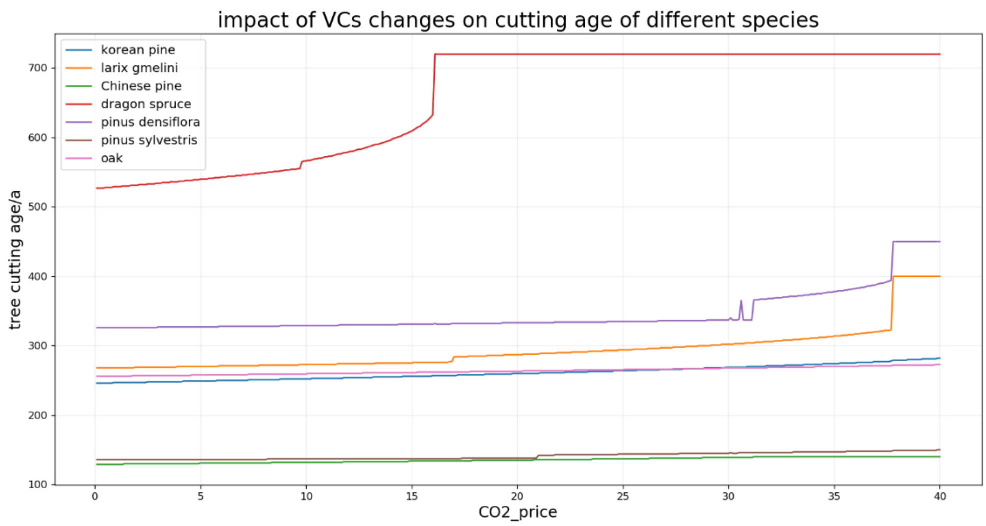


fig 6Flow chart of genetic algorithm

3.2.3 Method of Sensitivity Analysis

Holding all the input constant, change each parameter. We then measure the impact of changes of each parameter on cutting age of trees. To visualize the impact, we will plot the figure that the change of parameter is on the horizon axis and total value on vertical axis. For instance[22]:

[22] One of the figures of sensitivity analysis in section 4.



Transition point would be the parameter corresponding to sudden change of tree cutting age.

4 Apply the Model to Practice

Up to now, the principle of our model has been introduced completely. We then bring data from a real forest into our model in this section. We download necessary data of Changbai Mountain Dabiangou Forest from CERN.

i. Carbon Sequestration of the Forest in 100 Years without Harvesting

We used the seven most numerous tree species to represent all the trees in the forest. Following data is needed for calculation in equation(6), (8):

Ta_i	5 °C
AP_i	750 mm
Sbd_i	1.53 g*cm^{-3}
Dpt_i	50 cm
SOM_i	15.66 kg

A_{ij} (kg*m^2)	Young	Middle age	Near mature	Mature	Over mature
korean pine	0.5328	2.0013	2.8291	2.7291	1.493
larix gmelini	0.8328	1.4123	1.922	2.312	2.444
Chinese pine	1.0328	2.4123	2.9419	2.731	2.569
dragon spruce	0.9328	1.538	2.626	2.8419	1.454
pinus densiflora	0.4328	0.8495	1.232	1.902	1.555
pinus sylvestris	0.6328	0.8842	1.2332	1.848	2.222
oak	0.6722	1.294	2.375	2.919	2.877

Multiplied by the total area of forest, carbon sequestration every year of Changbai Mountain Dabiangou Forest is measured to be 1918164.039 ton. Thus, carbon sequestration in 100 years is 191816403.9 ton.

ii. Get the Value-Maximized Manage Plan

To measure value of Changbai Mountain Dabiangou Forest, our model need numerous types of data. For reasons of length, specific data will be presented in the appendices.

After using genetic algorithm (GA), we give out the manage plan that makes best use of the forest.

Age_i of each species is shown in the chart below:

	korean pine	larix gmelini	Chinese pine	dragon spruce	pinus densiflora	pinus sylvestris	oak
Age_i	247	268	129	529	326	136	256

To compare the difference of manage plan between carbon-sequestration-maximized and total-value-maximized, we give out a radar diagram as follow:

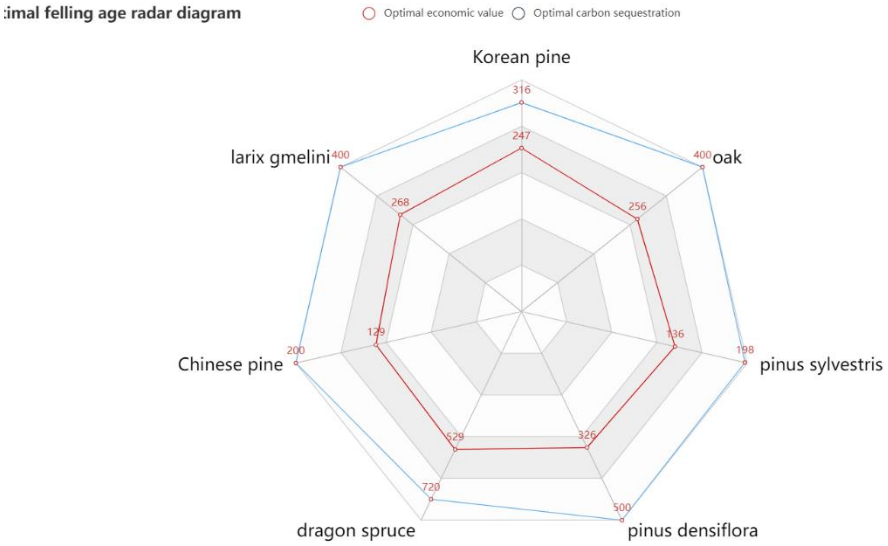
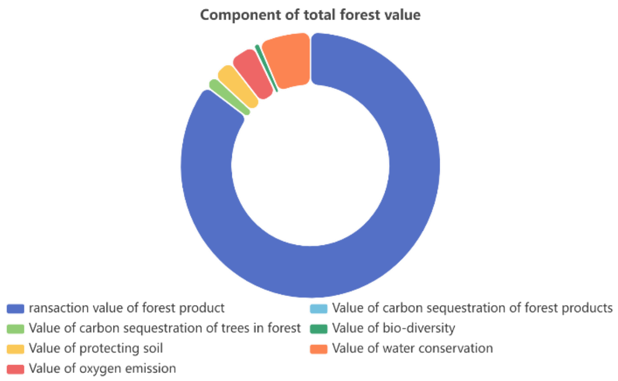


fig 7Radar of cutting age

Values of different aspects in the best manage plan are calculated:



α	\$106286734
β	\$175877853.1
γ	\$237122635
δ	\$1745611.972
ε	\$5824350283.2
ζ	\$49378273.58
η	\$444404462.3

And total value Ψ is \$6839165853.1.

To explore the impact of trade-offs between different aspects of value, we made the following radar diagram. The vertices of each corner represent the economic value that can be achieved by maximizing this aspect of value.

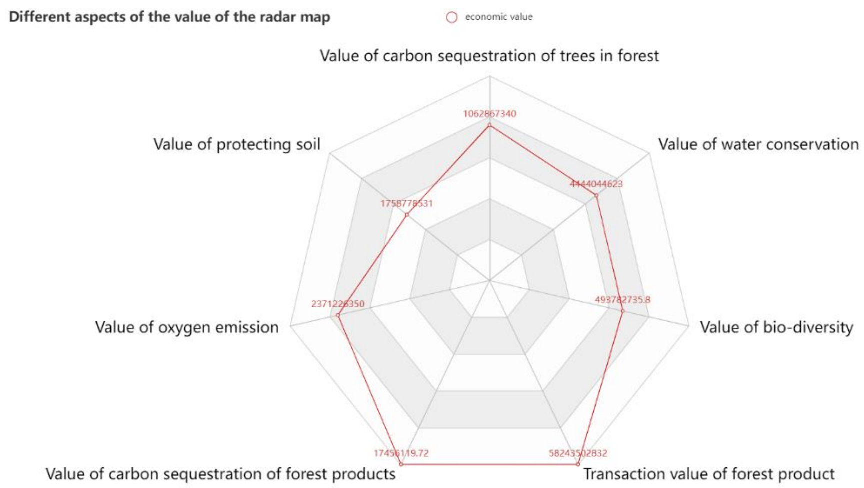


fig 8Radar of value

iii. Sensitivity Analysis

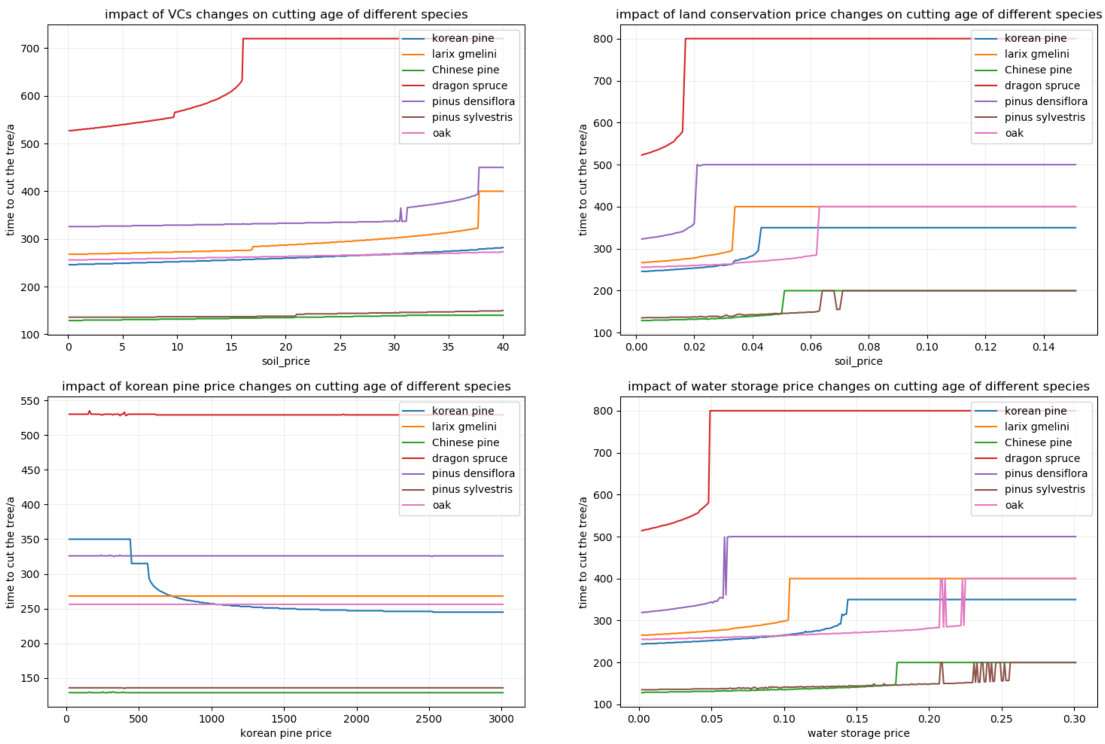


fig 9Result of sensitivity analysis on four different parameters

Figure above has shown the impact of changing each parameter (VCs, land conservation price, Korean pine price, water storage price for instance) on cutting age of different species.

Transition point is the parameter corresponding to the sudden change of tree cutting age. We can find the transition point simply by observing the visualization figure above.

iv. Transition Strategy

At present, we consider only the net benefits of cutting down and replanting forests every year, and do not take into account the human resources and time costs of cutting down trees.

Therefore, we guess that the best management strategy in the title takes into account more factors of forest management costs. Using the most management strategy given in the title, we will present a transition method from the current annual felling to felling once a decade.

By using the same algorithm we coding mentioned, we calculate the value of different time interval that creates:

Time interval of cutting (yr)	Value ($)	korean pine	larix gmelini	Chinese pine	dragon spruce	pinus densiflora	pinus sylvestris	oak
1	4327824152	247	268	129	529	326	136	256
2	4024512275	120	132	64	254	158	68	126
3	3957323897	81	87	42	168	105	45	84
4	3921205189	60	64	32	124	80	32	64
5	3888789018	50	50	25	100	65	25	50
6	3870982593	42	42	24	84	54	24	42
7	3837817940	35	35	21	70	42	21	35
8	3868102300	32	32	16	64	40	16	32
9	3798981652	27	27	18	54	36	18	27
10	3586095615	30	30	10	50	30	20	30

It can be seen that with the increase of tree cutting time interval, the net income of the forest decreases, but at the same time, it can be speculated that the management cost of the forest decreases, making the total income rise, so that the optimal management strategy can reach the peak. The peak time is the position where the interval of cutting trees is 10. However, in our model, in order to achieve the maximum benefit, the age of each tree will decrease one by one as the interval of tree cutting increases, and this way of tree cutting will definitely lead to the decrease of forest density cc, thus increasing the greenhouse effect and affecting all people who need forest resources. Performing sensitivity analysis on time interval of cutting, we made the diagram as follow:

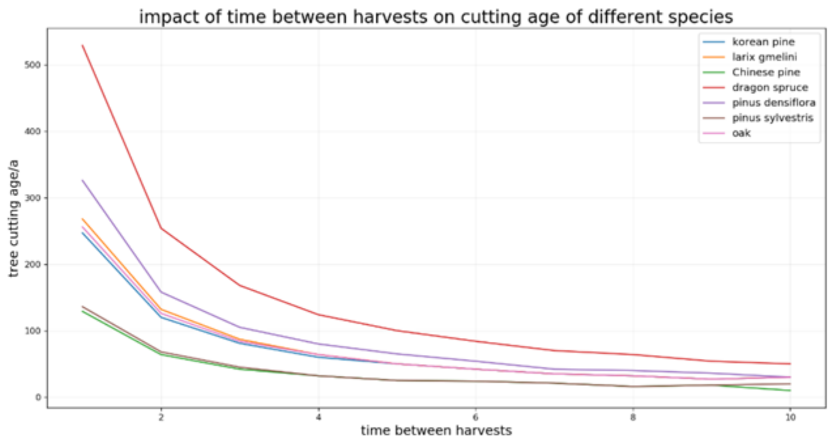


fig 10Sensitivity analysis on cutting interval

From the picture, we can also see that the fluctuation of tree cutting age is the largest at the interval of 1-4 years, and the forest density reduced at this time will be the largest, which will have a greater impact on people and other forest income personnel. In order to reduce the impact of forest resources on people, We recommend that the cutting age should be the optimal age with an interval of four years (optimal ages of different interval are shown above)

Yet, we do not recommend a 10 years interval between harvests to reach maximum value. It may greatly increase the impact of forests on land, water sources, bio-diversity, etc. Although the direct benefits are good, long-term forest protection should also be paid attention to, and the frequency of forest management should be improved.

5 Evaluation of our Model

5.1 Strengths

1. We're collecting official, up-to-date data, so the source of data has some reliability. In the meantime, we consider the problem in its entirety by Considering various factors. Therefore, our results have high credibility and reference value.
2. Algorithm advantage. We used Genetic Algorithm which can get the optimal value rapidly and accurately. At the same time, the sensitivity analysis proves that the model has high anti-interference ability.
3. Generalizability of the model. There are not just eight species of trees in different forests, but thousands. However, the model and algorithm also support the calculation of optimal cutting time for thousands of trees. Thus it can bring better reference to forest management.

5.2 Weaknesses

1. The value of forests is inconsiderate. There are still many parameters that have not been taken into account. The value of forest is not only in the seven aspects shown in the article, but also in the value of windbreak and sand fixation, the value of climate regulation and other additional values.
2. Labor and time costs are not taken into account in forest management, so the cost of cutting down trees and growing them is ignored. We can also further enhance the credibility and reference value of forest management.

6 Explanation Why Harvesting (newspaper article)

Appropriate Harvesting Brings Massive Harvest

Through our model, the manage plan for Changbai Mountain Dabiangou Forest we give out should include some degree of harvesting, which is counterintuitive to many locals. However, to be frank, appropriate harvesting included in the manage plan is the best decision for their forest, for which increases the total value of the forest.

T o obtain the best manage plan, our model compare the total value created by the forest among different way of harvesting (includes no cutting at all). The reasons that appropriate harvesting is concluded in the plan are as follow:

First of all, the average price of forest products is much higher than the value created by the forest in other aspects. Take the value of water conservation for example. Changbai Mountain Dabiangou Forest creates a value of \$444404462.3 in the aspect of water conservation. In a same area, multiplied by a same constant in other words, value of transaction of forest products is appalling \$5824350283.2. One major difference between them is price (SCR, Q_i).

Moreover, harvesting is beneficial to increase the average efficient of carbon sequestration. Harvesting plan guides managers to cut down all the trees that is over Age_i. Trees that is over Age_i are generally in the decline of their life. The existence of these old trees will occupy the land while sequester little carbon. So, to maximize carbon sequestration which is also maximizing the value of the forest, cutting down these trees and plant the new trees would be a better decision.

Value of oxygen emission is also benefited by appropriate harvesting. In equation (20), value of oxygen release is positive related to carbon sequestration. The internal mechanism is obvious: Trees release oxygen through photosynthesis which absorb CO_2 in the meantime. Thus, once the efficient of carbon sequestration decreases, oxygen emission also goes down, which reduce the value of oxygen emission.

By the trade-off between the positive effect of harvesting (mentioned above and some other effect on other aspects of value) and the negative effect of harvesting (lower total carbon sequestration for instance), our model gives out an manage plan that appropriate harvesting is included which brings massive harvest.

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8 Appendices

1. Detailed regression result of equation (5):

the results of regression (n=8)

	Non standardized coefficient		standardized coefficient	t	p	VIF	R^2	adjusted R^2	F
	B	standard error	$Beta$						

constant	-238.937	81.994	-	-2.914	0.062	-			
Tai/° C	16.853	6.174	0.968	2.73	0.072	5.183			
APi/mm	0.147	0.035	1.021	4.227	0.024*	2.408	0.927	0.83	$F(4,3)=9.563, p=0.047$
RHi/%	3.487	4.191	0.263	0.832	0.466	4.126			
Cai	1.361	0.304	0.853	4.471	0.021*	1.5			

* $p<0.05$ ** $p<0.01$

2. Detailed regression result of equation (8):

the results of regression(n=8)

	Non standardized coefficient		standardized coefficient	t	p	VIF	R^2	adjusted R^2	F
	B	standard error	$Beta$						
constant	-362.874	125.283	-	-2.896	0.044*	-			
Sbdi	682.677	130.525	1.932	5.23	0.006**	4.655	0.883	0.795	$F(3,4)=10.035, p=0.025$
SOMi	4.198	0.96	1.556	4.372	0.012*	4.32			
Dpti	-4.695	1.715	-0.711	-2.738	0.052	2.299			

* $p<0.05$ ** $p<0.01$

3. Detailed data of Changbai Mountain Dabiangou Forest:

unity m3							
forestry area	high-forest	proportion	shrubwood	proportion	other	proportion	
2.2 billion hm2	179888.5million	82.43%	3192.04 billion hm2	14.63%	641.16 billion hm2	2.94%	
Dominant species of arber							
korean pine	larch	Chinese pine	dragon spruce	pinus densiflora	pinus sylvestris	oak	
Changbai Mountain big edge ditch forest farm							
total area	korean pine	larch	Chinese pine	dragon spruce	pinus densiflora	pinus sylvestris	oak
4677.4hm2	547.7hm2	2788.9hm2	238.9hm2	174.5hm2	37.7hm2	52.7hm2	659.4hm2
life span	350	400	200	800	500	200	400
carbon sequestration (kg/m3/a)							
	Young	Middle age	Near mature	Mature	Over mature		
korean pine	0.5328	2.0013	2.8291	2.7291	1.493		
larch	0.8328	1.4123	1.922	2.312	2.444		
Chinese pine	1.0328	2.4123	2.9419	2.731	2.569		
dragon spruce	0.9328	1.538	2.626	2.8419	1.454		
pinus densiflora	0.4328	0.8495	1.232	1.902	1.555		
pinus sylvestris	0.6328	0.8842	1.2332	1.848	2.222		
oak	0.6722	1.294	2.375	2.919	2.877		
LCP dollar/m3	0.58/6.324						
Oxygen price (dollar/kg)							
	1/6.324						
Efficiency of wood formationβ							
0.5							
CO2price (dollar/kg)							
Opportunity cost of species loss 10000/6.324 dollar/hm2/a							
	1.2/6.324						
The price of each type of wood							
	korean pine	larch	Chinese pine	dragon spruce	pinus densiflora	pinus sylvestris	oak
dollar/6.324/m3	2130	1750	1330	1700	1200	2150	3400
Species loss cost (dollar/m2/a)							
	1/6.324						
total area	46774000m2						
precipitation (mm/yr/m3)							
	750						
Stand evaporation (mm/yr/m3)							
	150						
Rapid surface runoff (mm/yr/m3)							
	300						
Correction coefficient of forest ecological function							
	1						
Storage cost of reservoir project (dollar/m3)							
	0.5/6.324						
gdp (dollar)							
	2000						
	height	DBH	volume				
korean pine	30	1	23.55				
larch	35	0.9	22.25475				
Chinese pine	25	1	19.625				
dragon spruce	45	1	35.325				
pinus densiflora	30	1.5	52.9875				
pinus sylvestris	25	0.8	12.56				
oak	30	1	23.55				