Selection harvesting-to live or to destroy?

Xuan Qiao, Xinyu Pan, Ke Wang*

Engineering Institute, Beijing Forestry University, Beijing, 100091

*Corresponding author. Email: wangke220314@163.com

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Abstract: In this paper, we develop a carbon sequestration model. The model was applied to Pinus koraiensis, the dominant tree species in Mengjiagang forest, to further explore the influence of forest product life cycle, climate, topography and geographical location, and social and economic factors on carbon storage in the forest ecosystem. In addition, the entropy weight method (EWM) and the coefficient of variation method (CVM) are used to determine the weights of the three aspects of the seven indicators, and use the weights to construct a forest value evaluation model.

1. Introduction

Nowadays, the greenhouse effect problem has attracted more and more attention. You may have heard that the annual carbon fixation of the forest ecosystem accounts for about two-thirds of the whole terrestrial ecosystem, but do you know that wood products made into furniture, houses and so on can still have the ability of carbon sequestration. The life cycle of some of them will be much longer than that of living trees. As long as their carbon sequestration efficiency is higher than that of harvested wood, wood harvesting and wood forest products will improve the total carbon storage of the forest ecosystem and wood forest products carbon pool. Wood is a renewable natural resource, providing an edge over any other raw material. The harvesting and processing of wood products also incur the least amount of negative environmental impact, by any measure. In addition, the direct substitution of wood for fossil fuels can reduce the carbon emissions from the combustion of fossil fuels and slow down climate warming.

In 2021, the latest report of the United Nations Intergovernmental Panel on climate change (IPCC) clearly showed that climate change is a crisis that has come [1]. At present, efforts are mainly made in the following two aspects to control the continuous rise of greenhouse gas concentrations such as CO2 in the atmosphere: reducing greenhouse gas emissions and sequestrating carbon through biological measures [2].

Among various methods, the goal is to maximize the sum of forest carbon reserves and forest product carbon reserves. Therefore, according to the specific forest conditions and the needs of managers, through the monetization of the value of forest resources, dynamic multi-objective and reasonable forest management planning is an important requirement for the realization of high-efficiency and sustainable development forests. Therefore, in this work, we develop a forest carbon sequestration model to determine the carbon sequestration of forests and forest products that change at any time, and the most effective cutting time for carbon dioxide storage.

2. Ty Model

2.1. Model Establishment

The biomass conversion factor method based on forest stock volume has been widely used in the calculation of carbon storage [3]. The formula for carbon storage of forest trees can be expressed as

$$C_t = CF \times M_t \times BEF \times WD \times (1 + R) \tag{1}$$

where C_t is the carbon storage of standing trees in t year, CF is the carbon content of forest biomass, BEF is the conversion coefficient of forest biomass, WD is the wood density, and$R$is the uforest's underground biomass/above-ground biomass.

For the forest soil carbon storage, the soil carbon pool can be calculated as:

$$SOC = 0.58 \cdot C \cdot D \cdot E \cdot \frac{(1-G)}{100} \quad (2)$$

where SOC is the carbon density of the soil, C is the soil organic matter content, D is the soil bulk density, E is the soil thickness, and G is the volume percentage of gravels with a diameter of ≥ 2 mm.

The organic carbon storage of the regional soil can be calculated as:

$$\mathrm{TOC} = \sum_{i=1}^{n} A_i \cdot SOC_i \quad (3)$$

where *i* and *n* represent the soil type code and number, respectively.

TY is defined as a forest weekly carbon benefit evaluation index that comprehensively considers the amount and carbon sequestration time of the forest. However, it should be noted that there are also differences in the carbon sequestration time of the growth amount corresponding to each growth period of the forest. It is the accumulation of the annual carbon sequestration of the forest multiplied by the number of years of carbon sequestration in each part, which is calculated as follows:

$$TY_n = \sum_{i=1}^{n} t_n C_n \quad (4)$$

where TY_n is the annual unit of the n-year-old stand is t·a, C_n is the net carbon sequestration of the stand in the nth year, the unit is t, t_n is the time that the growth of the stand in the nth year has fixed carbon until now, the unit is a.

TY_n can further expressed as:

$$TY_n = \sum_{i=1}^{n} t_n C_n = nC_1 + (n-1)C_2 + \cdots + 2C_{n-1} + C_n \quad (5)$$

The TY value of forest products is related to their life cycle. The specific calculation formula is as follows:

$$TY_m = CF * \alpha * (1-\beta) * V_t * BEF * WD * (1+R) * A \quad (6)$$

where α is the yield of wood, which is 0.7, β is the loss of wood during processing, and A is the life cycle of wood forest products.

2.2. Carbon Sequestration in Forests and Wood Products

2.2.1. Establishment of the accumulation and growth model of Korean pine

Taking the dominant tree species Korean pine in mengjiagang forest Farm as an example, with the support of the standard ground data of this tree species, the fitting results of the four common growth equations of this tree species are shown in Table 1.

Table.1. Growth equation fitting results of Pinus koraiensis

Species	Model	Parameter Estimation			R2 Coefficient of Determination	MSE Mean-square Error
		a	b	K		
Pinus koraien sis	Richards	263.29	0.033	0.527	0.796	126.38
	Kolf	342.164	1.392	0.251	0.873	114.392
	Logistic	137.902	3.308	0.139	0.987	78.1572
	Gompertz	142.58	2.214	0.465	0.8911	116.986

This study adopted the principle of maximum determination coefficient R2 and minimum mean square residual error MSE, and the optimal accumulation and growth equations of Chinese fir were screened out as logistic models.

The selected models were tested for independence using the remaining 20% of the test samples, and the results are shown in Table 2.

Table.2. Test results of the prediction model of Pinus koraiensis

Species	The optional model	ME	MAE	MPE	P
Pinus koraiensis	Logistic	5.891	5.891	4.313	95.686

It can be seen from Table 2 that the average absolute error MAE of the two prediction models is 5.89133, the average relative error MPE shows that the overall prediction results are within ±4.3%, and the prediction accuracy P is above 95%. The model prediction accuracy meets the requirements and can be used.

2.2.2. Annual budget results of stand tons

The wood forest is divided into an example, as shown in Table 3. From Table 3, it can be known that the representative is under the 100-year forest product life cycle level, with the increase of Chinese fir forest age. The value of TY per hectare of forest stand for total carbon sequestration efficiency shows an increasing trend, while the average TY of stand represents carbon sequestration efficiency. The average TY of living wood per hectare showed a trend of first increasing and then decreasing, peaked in 47 years. At this point, the 100-year forest product life cycle is determined. The maximum average TY value per hectare of Chinese fir stands at the period level is 54.01 t·a, and the corresponding annual average ton value of forest products. It is 37.97t·a, and the maturity age of carbon sink is 47 years.

Table.3. Determine the maturity age of carbon storage

Ages	Average TY of living wood per hectare	Average TY per hectare of wood forest products	Average tons per hectare stand
20	55.4	12.68256557	35.51
30	99.8	22.84693219	42.64
40	125.6	28.75325334	40.254
47	139.2	31.86666294	37.968
48	138.1	31.61484305	36.884
50	140.9	32.25583914	18.063
60	141.2	32.32451729	15.084

As shown in the Fig.1, changing the life cycle of wood products will significantly impact the maturity age of carbon storage and the carbon storage capacity of forest trees. With the extension of the life cycle of wood products, the numerical turning point of the stand's annual average TY representing carbon sequestration efficiency will shift significantly to the left, and the maturity age of carbon storage will be significantly smaller. This suggests that the longer the life cycle of the resulting wood products, the sooner forest managers need to harvest the wood, and the higher the overall carbon storage capacity as both standing wood and wood products.

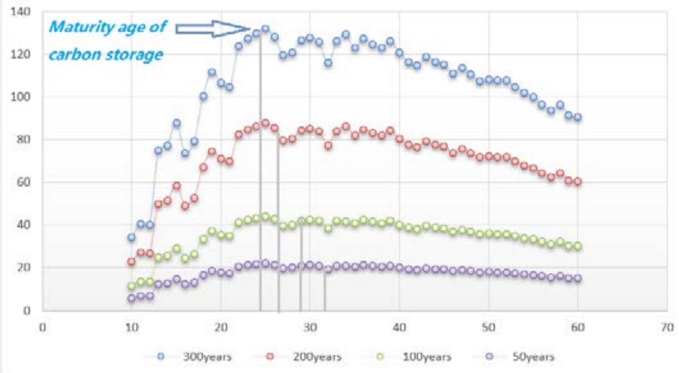

Figure 1. Life cycle impacts of wood products.

3. Decision Model

Wood production benefit is the main economic benefit of forest ecosystem, and the wood price usually reflects its value. The timber harvest value can be expressed as:

$$U_w = G \cdot (T \cdot P_w - C) \tag{7}$$

where G is the net growth of forest, P_w is the timber price of different forest types, T is the timber output of trees, and C is the various expenses.

The value of non-timber forest products can be expressed as:

$$U_{nw} = P_{nw} \times Y_2 \tag{8}$$

However, the value of carbon sequestration can be expressed as:

$$C_t \times P = CF \times M_t \times BEF \times WD \times (1 + R) \times P \tag{9}$$

In our study, the goal of water conservation mainly refers to the role of forests in regulating water volume, and its calculation formula is:

$$\mathrm{GW} = 10\mathrm{S} \times (\mathrm{P} - \mathrm{E} - \mathrm{C}) \times \mathrm{F} \tag{10}$$

where GW denotes stand water regulation function (m^3/a.), S denotes stand area(ha), P denotes measured precipitation outside the forest(mm/a), E denotes measured stand evapotranspiration(mm/a), C denotes measured stand surface rapid runoff(mm/a). Forest surface runoff can be replaced by forest water yield, and its calculation formula is:

$$\mathrm{WP} = 475.181\mathrm{S}\mathrm{e}^{-0.0232BA}$$
$$\mathrm{WP} = 282.770\mathrm{S}\mathrm{e}^{-0.0077BA} \tag{11}$$

where WP denotes forest water yield (m^3/a), S denotes stand area (ha), BA denotes stand sectional area(m^2/hm^2), e=2.71828.

The value of annual soil fixation of forest can be expressed as:

$$\mathrm{GS} = \mathrm{S} \times (X_2 - X_1) \times \mathrm{F} \tag{12}$$

where GS denotes annual soil fixation of stand(t/a), S denotes stand area(ha), X_2 denote soil erosion modulus of non forest land($t.hm^{-2}.a^{-1}$), X_1 denotes measured soil erosion modulus of forest land($t.hm^{-2}.a^{-1}$), F denotes forest ecosystem service correction coefficient. The amount of soil erosion can be calculated as:

$$\mathrm{SL} = 30.437 \times \mathrm{S} \times e^{-0.0488BA} \tag{13}$$

To maximize the comprehensive benefits of forests, we need to develop a decision model to inform forest managers of the best use of a forest, including forest economic sustainable value, ecological sustainable value, and social sustainable value. We build a 0-1 integer programming model with multiple business objectives [4], which the min-max standardized formula as:

$$f_k'(X) = \frac{f_k(X) - f_{kmin}(X)}{f_{kmax}(X) - f_{kmin}(X)} \tag{14}$$

Due to the strong subjectivity of weight calculation by the analytic hierarchy process, we use the comprehensive weighting method of EWM and CVM to determine the weight of each index. The hierarchy model is shown in Fig.2.

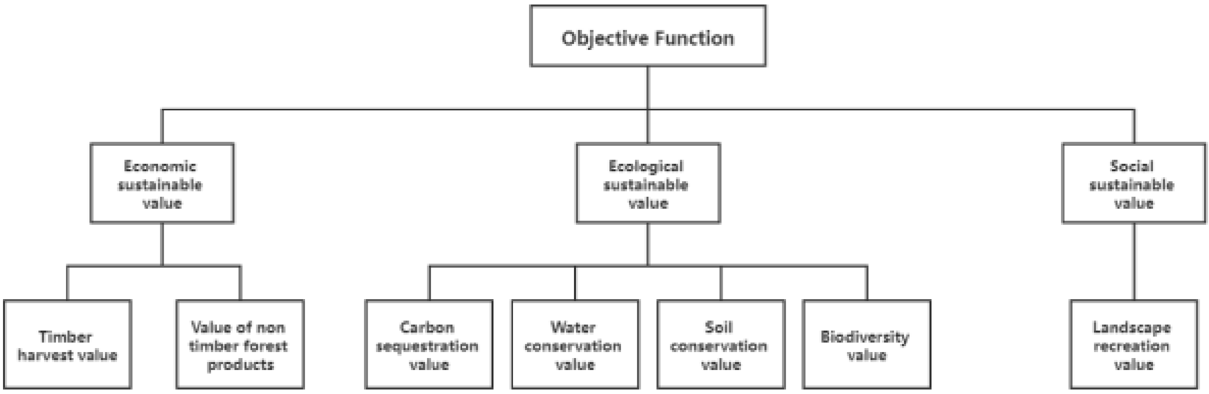

Figure 2. Hierarchy model

According to the value indicators defined above, we further determine the weight of these seven indicators to the primary indicators. First of all, since all indicators are benefit indicators, there is no need for positive words, and just normalize the index data respectively.

$$q_j = \frac{y_{ij}}{\sum_{j=1}^{n} y_{ij}} \tag{15}$$

According to the concept of information entropy in information theory, we can calculate the information entropy of each forest value index e_i and weight w_i.

$$e_i = -\ln(n)^{-1} \sum_{j=1}^{n} q_{ij} \ln(q_{ij} \tag{16}$$

$$w_i = \frac{1-e_i}{k-\sum_i e_i} \quad i = 1,2,\dots,k \tag{17}$$

where

$$\begin{cases} PSI_j = w_1 y_{1j} + w_2 y_{2j} \\ SI_j = w_3 y_{3j} + w_4 y_{4j} + w_5 y_{5j} \\ BSI_j = w_7 y_{7j} \end{cases} \tag{18}$$

On this basis, the coefficient of variation method (CVM) is used to weight the three indicators, which is an objective weighting method. The weight values of the indicators are shown in Fig.3. Considering the difference between the unit and mean value of the three comprehensive indicators, we choose to compare them with the ratio of standard deviation to mean value. The equation of each index can be expressed as:

$$\mathrm{C} \cdot V_i = \frac{\sigma_i}{\bar{x}_i} \quad i = 1,2,3,4 \tag{19}$$

where V_i denotes the coefficient of variation of PSI, RSI and BSI, σ_i denotes standard deviation. We can calculate the weight of three comprehensive indicators:

$$W_i = \frac{\mathrm{C} \cdot V_i}{\sum_{i=1}^{n} \mathrm{C} \cdot V_i} \quad i = 1,2,3,4 \tag{20}$$

Indictoes(Ⅰ)	Indictoes(Ⅱ)	Weights	Indictoes(Ⅲ)	Weights
Intensity	**Econimic** sustainable value	0.46	Timber harvest value	0.14
			Value of non-timber forest products	0.15
	Ecological sustainable value	0.52	Water conservation value	0.14
			Soil conservation value	0.16
			Carbon sequestration value	0.16
			Biodiversity value	0.14
	Social sustainable value	0.02	Landscape recreation value	0.11

Figure 3. Weight values of the indicators

We use the hierarchical clustering method to divide the comprehensive forest value into three levels. By calculating the values of PSI, RSI, BSI, CSI and ESI, the comprehensive value of specific forests can be evaluated. As shown in Fig.4, we divide different forest comprehensive values into three levels and express them in different colors. Taking the comprehensive index of forest value as an example, different stages correspond to differentiated management planning. The scores of 21.72 and 92.92 can be regarded as the transition point between forest management plans.

When the score is less than 21.72, it is a fragile forest. At this time, the comprehensive value of the forest is low. We need to pay attention to the maintenance of ecological value and gradually develop economic benefits. We will rationally allocate investment funds and labor for biodiversity protection forests, water conservation forests, windbreak and sand fixation forests, water conservation forests, carbon fixation and oxygen release forests, and set up defenses according to local conditions and disasters. In forest management planning, we should focus on the artificial promotion of natural regeneration, appropriately ban and protect ground cover plants, and manage forest resources according to the near-natural forest model.

With a score of 21.72 ~ 92.92, it is a medium value forest, which can choose reasonable and sustainable management and harvest strategy on the premise of ensuring that the ecological benefits are not reduced. It is engaged in timber forest, economic forest, greening seedlings, flower gardening, timber forest for Chinese medicine, understory planting, and understory breeding. Select selective or intermediate cutting methods to ensure the sustainable utilization of forest resources, and improve the production efficiency of forest resources with the help of supporting measures and technologies such as forest replanting, fertilization, forest fruit harvesting and primary processing.

When the score is greater than 92.92, it is considered that the forest value is strong, and all aspects of value have been fully utilized. We can selectively focus on developing forest value according to the demand.

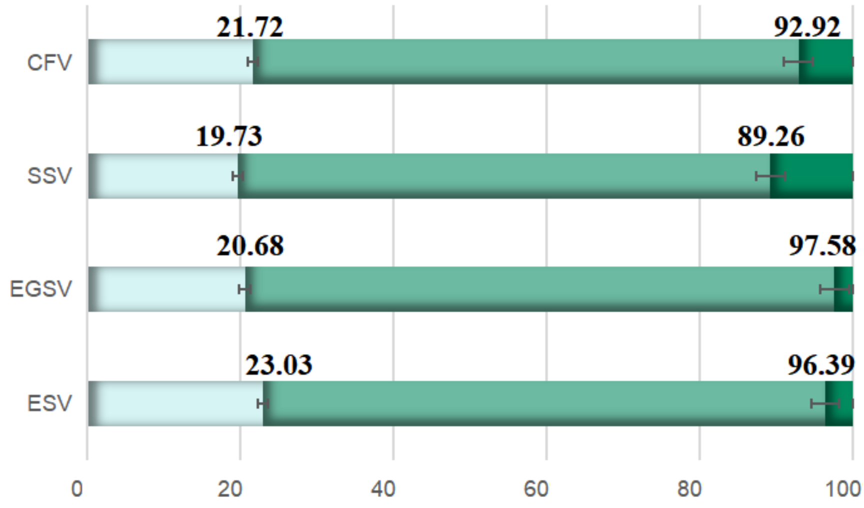

Figure 4. Forest value evaluation

For specific forests, we discuss the impact of climate factors, terrain and geographical location, socio-economic and human activities on the mature age of carbon storage, that is, the optimal cutting period, which is shown in Fig.5.

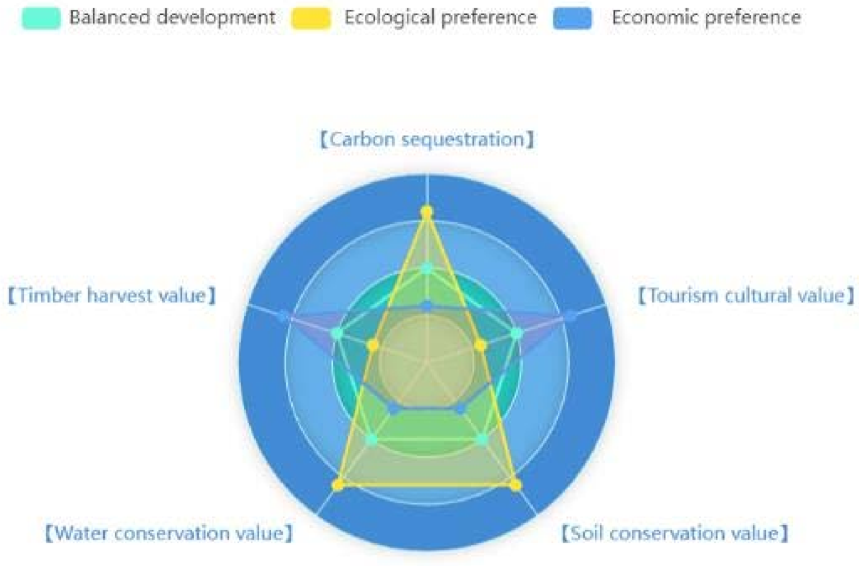

Figure 5. Effects of different factors on Forest Management

4. Model Improvements

According to the analysis of the actual situation, we have planned the cutting area and harvest and obtained the cutting schedule of each small class, so as to improve the economic, ecological and social value of Mengjiagang forest farm, which is shown in Fig.6.

Figure 6. The comparison between each index and the current plan

Taking Korean pine in Mengjiagang forest farm as the research object, this model sets the carbon storage of forest products unchanged and the life cycle of 50 years, that is, every 50 years is a rotation cutting and afforestation cycle. The result obtained is shown in Fig.7. According to the carbon sequestration model, the best cutting age of Korean pine is 52 years old. In order to achieve multi-objective management, felling is carried out in small shifts. Only one small shift is the best Felling Age. Another small shift is felled every ten years. According to the carbon storage per hectare of trees before cutting and the annual average tons of forest products after cutting, it is possible to predict the carbon storage of this tree species in 100 years [5].

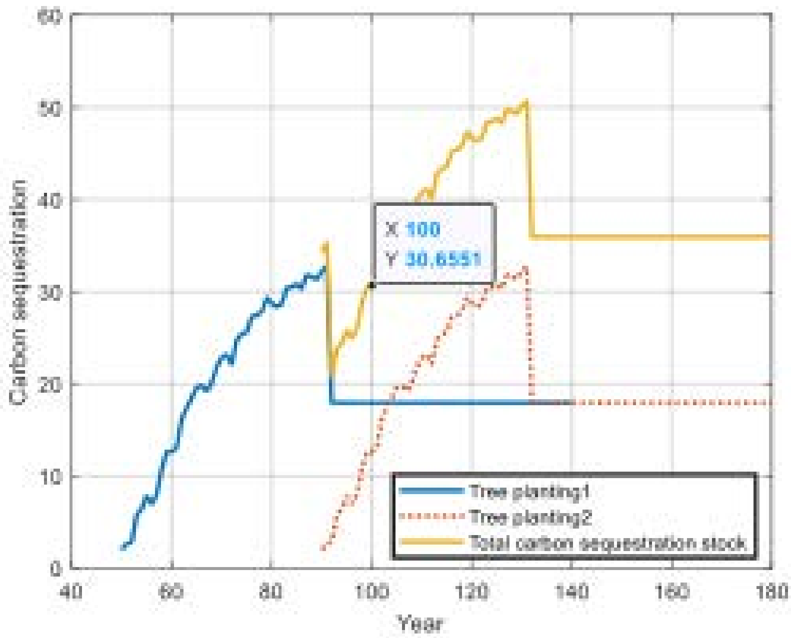

Figure 7. Forest carbon sequestration in the fifth stage

While considering the needs of forest operators and forest users, we put forward reliable and targeted decisions.

We will use DEMATEL model to identify the fundamental influencing factors from many factors affecting the transition of forest management mode from the existing time axis to the new time axis to provide a decision-making basis for the solution of management problems [6]. For the management measures in the forest transition period, we put forward ten specific indicators, including forest operators, natural environment and social environment, as follows in Fig.8.

Operator factor	Rationality of forest operator's identity and effectiveness of organizational structure F1
	Basic quality and multi-objective management consciousness of forest managers F2
	Integrity and effectiveness of forest management transition planning and design F3
Natural factors	Status of existing forest resources F4
	Forest fire and pests F5
social factors	Local economic development level F6
	Forest management investment F7
	Forestry industrial structure F8
	Population pressure in forest areas F9
	Education and technology level F10

Figure 8. Ten specific indicators

Score the correlation degree among the influencing factors, calculate the comprehensive influence matrix among the factors, calculate the influence degree R, affected degree D, center degree R + D and cause degree R-D of the influencing factors, as shown in the table, and draw the causality diagram, as shown in Fig.9.

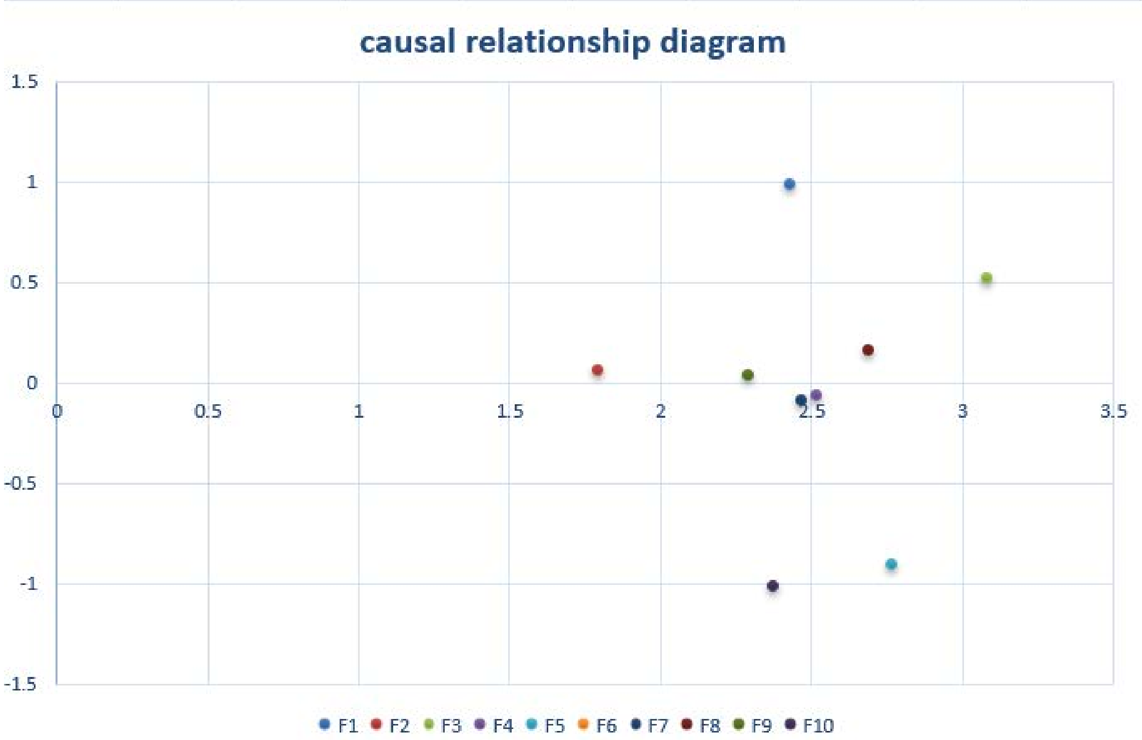

Figure 9. Ten specific indicators

The cause factors and result factors are divided according to the cause degree of each factor. The cause factors are those whose cause degree is greater than zero, which significantly impact the system and other factors. If the cause degree is less than zero, it is the resulting factor. They are more easily disturbed by other factors, resulting from the influence of causal factors.

5. Conclusion

In this paper, we propose an innovative carbon sink measurement method. Firstly, the concept of TY is proposed, which can more scientifically evaluate the carbon sequestration efficiency and carbon sequestration capacity of forests. In addition, this article adopts the combined weighting method of entropy weighting method and coefficient of variation method to determine the weights of seven forest functional value indicators. Finally, we use the DEMATEL method to identify the fundamental influencing factors from a large number of influencing factors and provide relative solutions.

References

[1] AR6 Climate Change 2021: The Physical Science Basis Sixth Assessment Report

[2] C. P. Qin, Earth system carbon cycle, Beijing: Science Press, 2004.

[3] D. Lei, S. Z. Ping, Measurement method of forest carbon storage based on forest resources inventory data, Bulletin of Soil and Water Conservation, 2011, 31(06): 143-147.

[4] Z. Yun, Research on multi-objective management planning of jindong forest farm national reserve forest, Beijing Forestry University, 2020.

[5] W. Z. Hui, Analysis of the relationship between wood life cycle and carbon sink, Furniture, 2015, 36(02): 1-6+43.

[6] Z. L, Juan, W. Z. Fang, Research on the influencing factors of sustainable management of state-owned forests based on DEMATEL, Forestry Economy, 2014, 36(05): 32-36.