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Research Article

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Forest Ecosystem Management Decision Model Based on ISM

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Abstract Forest management plans can be designed to maintain existing carbon stocks or increase carbon sequestration capacity while providing co-benefits for other sustainable resource management goals, such as timber supply, wildlife habitat or water quality. Primarily, classify forest ecosystem management types by nature factors, society factors, and operating factors. According to the sustainable development theory, the spectrum of the forest ecosystem management are constructed. Secondly, the relationship between various factors in forest ecosystem management decision-making was analyzed through the ISM, and conditions for deforestation rate are obtained. Thirdly, obtain a general forest ecosystem management decision model based on the near-natural forest theory and the uniform distribution model. Finally, in view of factors such as carbon sequestration, conservation and biodiversity aspects, recreational use and culture, through Monte Carlo simulation, the management decision transition point (Health index, Diversity and Angle ruler) of a specific forest is obtained.

Keywords Forest, Carbon Sequestration; ISM; Monte Carlo

1. Introduction

With the development of agriculture and industry, the situation of global warming is becoming more and more serious. At present, carbon neutrality has become the consensus of mankind, and countries are gradually making carbon emission reduction a priority. The carbon cycle of the earth's ecology is a dynamic balance between terrestrial and aquatic plants that alternate between life and death to form emission and absorption.

At present, it has become the consensus of mankind to achieve "carbon neutrality" to deal with climate change. Governments around the world are prioritizing the drive to reduce emissions from industry. After studying the carbon cycle model of the earth's "original ecology", we found that the forest carbon sink has a more prominent contribution to reducing the global greenhouse effect than the intentional reduction of carbon emissions by humans.

Here we need to introduce a concept: carbon sequestration, which is to store excess carbon dioxide and not emit it into the atmosphere. The carbon sequestration capacity of the earth's surface depends on the ecological volume.

Abundant vegetation, soil and water systems make forests the main force for surface carbon sequestration. In 2015, the world's forests were about 4 billion hectares (data source: FAO). If the goal is to maximize the ecological function of forests, the carbon accumulation of the world's forests can reach 73 billion tons of carbon dioxide equivalent, which is more than double the carbon dioxide emitted by the world's industry in 2018.

2. Forest Ecosystem Management Decision Model

Forest ecosystem (Figure 1) management is the ingenious and integrated application of ecological knowledge at different ecological levels to generate desired resource values, products, services and conditions, and to maintain ecosystem diversity and productivity. It regards forests as a hierarchical organization and a complex system composed of biological organisms and abiotic environments.

It is an open and complex management of large systems. In the management, the production function and ecological service function of the forest are combined, and the pursuit is the full benefit and value provided by the system.

In the management practice, it is emphasized that various management measures must be established on the basis of ecologically reasonable, economically feasible and socially acceptable. At the horizontal level, the rationality of spatial allocation of different ecosystem types and the biological effectiveness of management measures are evaluated. (Forest Ecosystem Management Assessment Team (US), The Service, 1993.)

Figure 1: Boundary of Forest Ecological System

3. Spectrum of Management Plan

3.1. Classification of Forest Ecosystem Management Types

Because the forest ecosystem management boundary includes three parts: human society, abiotic environment and forest plants. As shown in Figure 6, the factor attributes of these three parts are the main factors for the division of forest ecosystem management types.

- Natural Factors

1) Forest ecosystem function factors: Forest ecosystem management zoning is to ensure that they are connected geographically, that the system functions are consistent, and that the management methods are similar. These factors include: forest species, tree species, forest types, forest species ratio, etc.

2) Landscape factors of forest ecosystem: The landscape factor of forest ecosystem is an important factor for the differentiation of landscape structure, process and function of ecosystem, and is an important factor for the division of different landscapes. These landscape factors include: the composition of forest vegetation, topography, altitude and so on.

3) Other site factors: The site factor is an important factor that determines the level of forest productivity, and suitable trees are the basic principles of forestry production. Forest ecosystem management is to emphasize the unity of "environment, purpose and function". These factors include: climate factors, soil factors, etc.

- Society Factors: Social demand influences the direction of forest system management, and the level of social and economic development determines the level of intensive management of forest ecosystems. These factors include: population density, road density, industrial and agricultural output value ratio, etc.
- Operating Factors: The strength of the management factor determines the degree of management intensification, which is one of the indicators of the level of production management. The degree of management intensification determines the management measures. The higher the degree of intensification, the more detailed the management measures, the higher the level of management. These factors include: unit input, unit labor, unit number of technical personnel, etc.

These factors were classified according to "function + landscape" and "forest species + forest type", and were subjected to principal component analysis and systematic clustering, which are divided into 2 major categories and 5 sub-categories, as shown in Figure 2.(Buongiorno, Joseph, and J. Keith Gilless, 2003.)

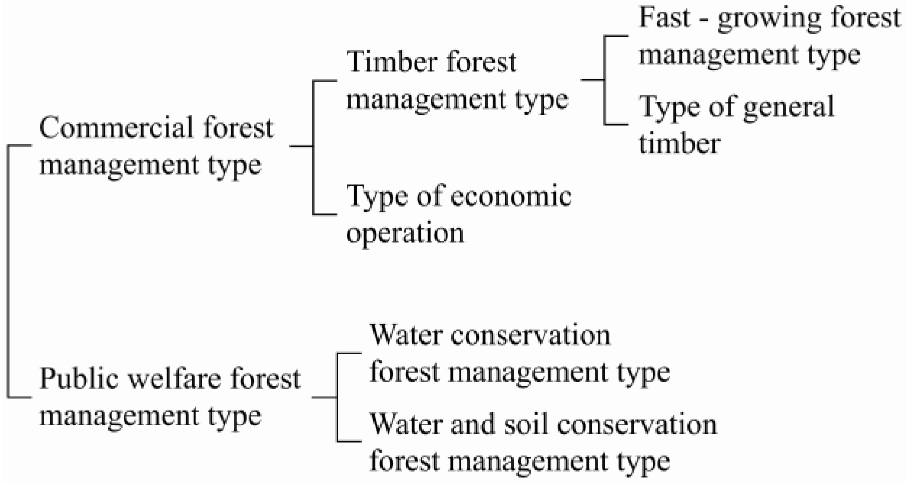

Figure 2: Types of Forest Ecosystem Management

3.2. Impact Factors of Forest Ecosystems

The forest ecosystem is an open system that exchanges material, energy and information with the environment. Environmental factors include humanities, society, economy and many other aspects; system factors include system components and system structure and function. All these factors must be considered when making decisions on ecosystem management.

There are many influencing factors of ecosystem management, including both the constituent factors within the system and the environmental factors outside the system. How to determine the main factors among the complicated factors needs to be guided by sustainability theory, hierarchy energy theory and control and feedback theory. The factors are selected as in Figure 3.

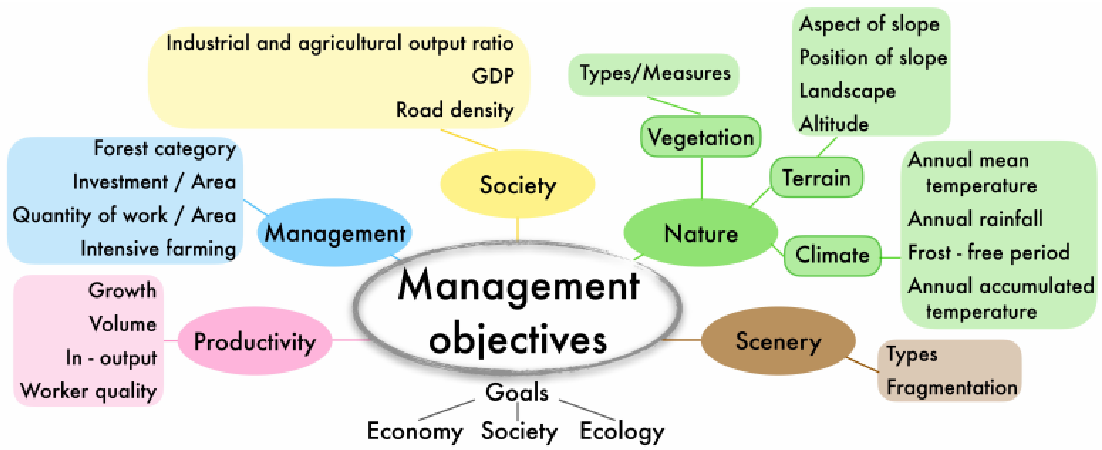

Figure 3: Impact Factors of Forests Ecology Management

4. Establishment of Interpretative Structural Model for Logging Condition Factors

ISM (Interpretative Structural Modeling) focuses on social, economic, environmental, engineering and other complex systems, focusing on the combination of elements, quickly constructing the accessibility matrix, and then trying to find the adjacency matrix (Boolean logic operation) to form a structural model of the system. (Attri, Rajesh, Nikhil Dev, and Vivek Sharma, 2013)

4.1. Classification of Forest Ecosystem Management Types

The system is composed of elements, and there are a large number of interactions between the elements. For a directed graph, it can be represented by a square matrix of $m \times m$. m is the number of system elements. When a certain element i has an influence on another element j, the matrix element a_{ij} takes the value of ***1***, otherwise it is ***0***. It can be represented as a response matrix as follows:

$$X = \begin{bmatrix} 0 & 1 & 0 \\ 0 & 0 & 1 \\ 0 & 1 & 0 \end{bmatrix}$$

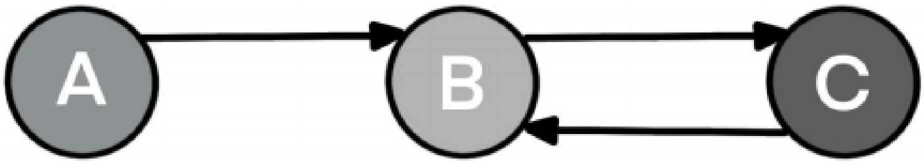

Figure 4: The directed graph between factors A, B and C

4.2. Accessibility Matrix and Its Hierarchical Decomposition

If the system satisfies the conditions of equation, then M is the accessibility matrix of system X. The accessibility matrix indicates whether there is a connected path from one element to another element.

$$M = (X + I)^{k-1} \neq (X + I)^{k} = (X + I)^{k+1}$$

There are 3 concepts in the hierarchical decomposition of the accessibility matrix as follows: 1) Accessibility Set $R(s_i)$: In the row corresponding to the element s in the accessibility matrix, the set of column elements corresponding to more than one matrix element containing ***1***; 2) Antecedent set $Q(s_i)$: the set of row elements corresponding to the matrix element containing ***1*** in the column corresponding to the element s in the reachable matrix; 3) Intersection $X = Q(s_i) \cap R(s_i)$.

The purpose of the intersection level decomposition is to have a clearer understanding of the hierarchical relationship between the elements in the system. The top layer represents the final goal of the system, and the lower layers represent the reasons for the upper layer. Using this method, analogy models for other problems can be established scientifically.

4.3. Development of an Interpretative Structural Model of the Impact Factors of Forest Ecosystems

According to the influencing factors of forest ecosystem management in 4 .2, the response matrix of each factor relationship can be established and the interpretative structure diagram can be drawn (Figure 5). Forest ecosystem is a multi-objective management system, including economic objectives, social objectives and ecological objectives. Through ISM analysis, we can understand the relationship between various factors in forest ecosystem management, and provide a theoretical basis for forest management decision-making.

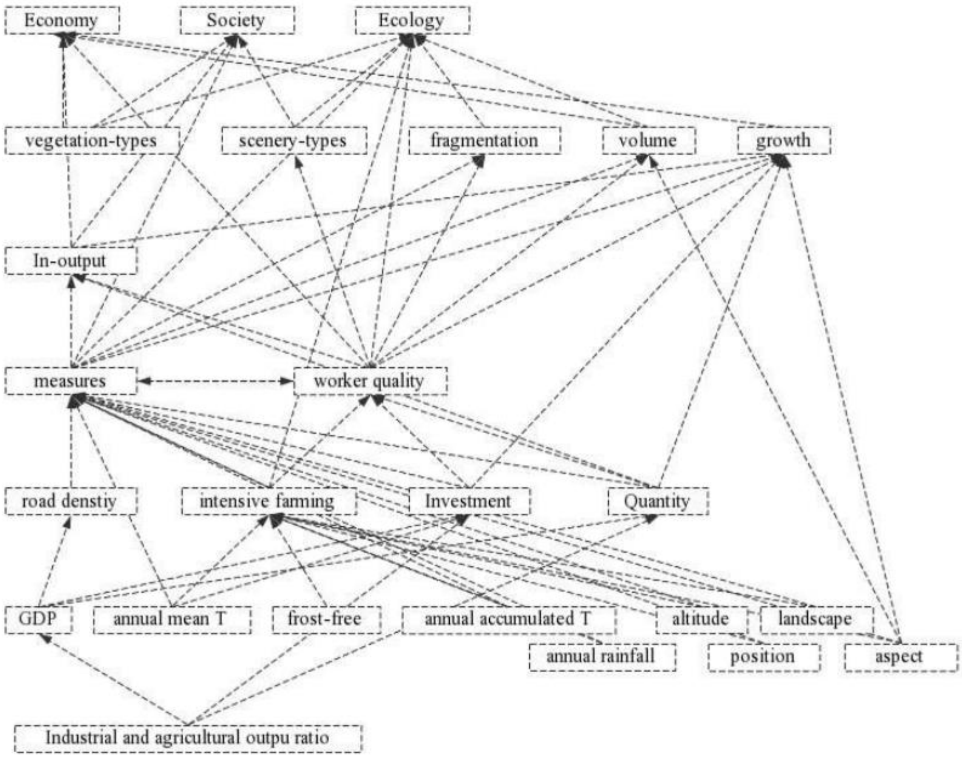

Figure 5: Interpretative Structure of Forest Ecosystem Management Impact Factors

4.4. Analysis of Logging Conditions

The ISM shows that the management practices of forest ecosystems are largely determined by climatic, topographic and vegetation factors, which in turn directly determine the forest ecological landscape, stocking and growth. Therefore, there exists a certain possibility of no deforestation for a certain type of forest ecosystem. The prerequisite constraints for no deforestation are as follows: 1) Forest ecosystems are of extreme landscape value; 2) The ecological benefits of forest ecosystems with good climatic conditions continue to rise and the direct economic benefits are not high.

5. Analysis of Transition Points for General Forest Ecosystem Management Plans

Current research shows that thinning or selective cutting of forest ecosystems and supplementary planting can better improve the ecological, economic and social benefits of forest ecosystems. Forest ecosystem management is to optimize and adjust the distribution of forest trees in the system in space after certain management measures. Establishing the decision-making system of spatial factors of forest trees is the basis of the decision-making model of forest ecosystem management. These operating decision factors include diversity index, size ratio and angle ruler. (Emborg, Jens, Morten Christensen, and Jacob Heilmann-Clausen, 2000).

- Diversity Index

The species composition and their mixture stand, the mixing ratio of planting trees is an important indicator. Gadow proposed the concept of mingling indices as an index of diversity in the near-natural management decision factor. The principle of constant tree species diversity was used for felling.

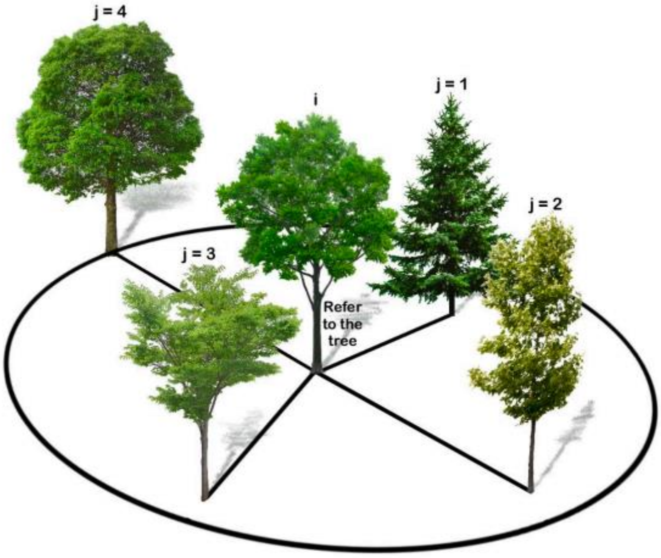

Figure 6: Interpretative Structure of Forest Ecosystem Management Impact Factors

- Size Ratio

The size ratio is defined as the proportion of adjacent trees that are larger than the reference tree to all the nearest trees under consideration. Cutting down large trees can effectively adjust the spatial structure.

- Angle Ruler

The angle ruler is a spatial index reflecting the distribution of trees around the forest. Cut down the distribution center forest to increase the public growth space and restore the natural distribution of the trees as the criterion.

- Health index

The health index reflects the difference between the health status of the forest and the surrounding trees. Cutting down unhealthy trees and supplementing with healthy trees can effectively improve forest carbon sequestration, as shown in Figure 7.

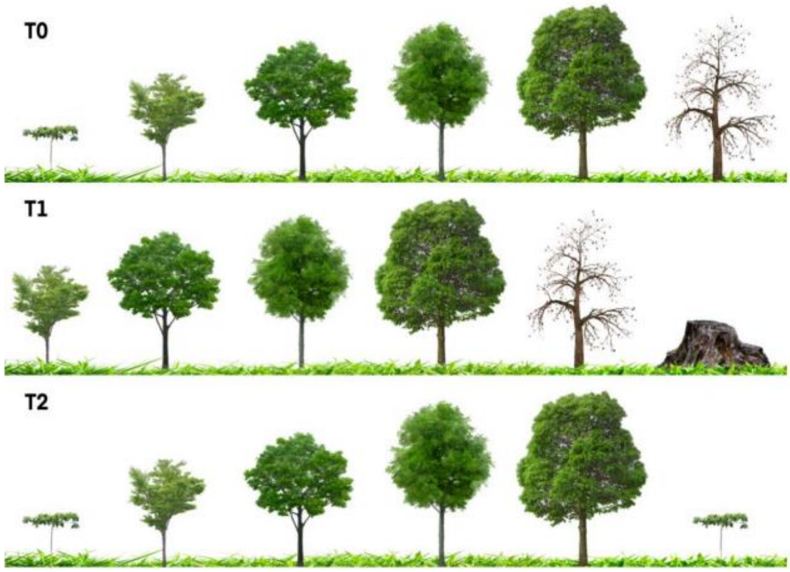

Figure 7: Logging and planting according to health index

- Spatial density index

Spatial density index is a spatial index that reflects the distribution density of trees around the forest, and trees with high density should be harvested.

- Target tree species characteristic index

Harvest non-target tree species, protect and cultivate top community tree species, and maintain the landscape of the forest ecosystem.

In summary, an ecosystem management plan for a general forest should follow the flow chart 8 below.

For the management of general forest ecosystems, the uniform distribution model can ensure the balance of ecological, economic and social goals. The model targets top-level communities and aims to maintain ecosystem health and functional continuity, forming a forest ecosystem structure characterized by a uniform spatial distribution of forest trees.

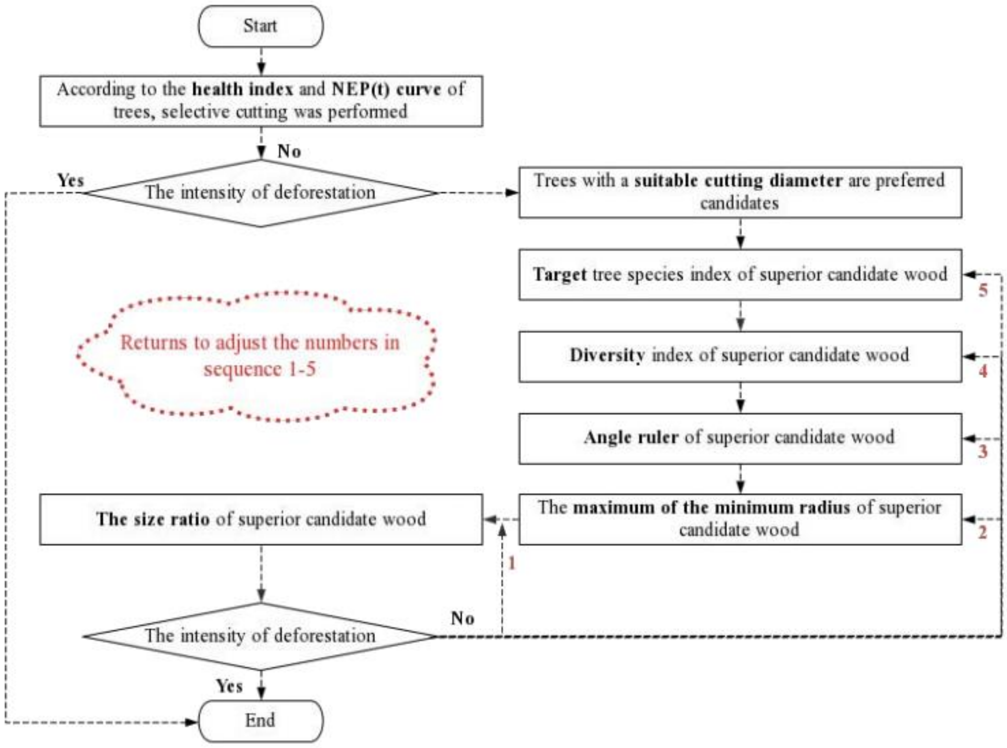

Figure 8: Ecosystem Management Plans for General Forests

6. Analysis of Transition Points for Specific Forest Ecosystem Management Plans

For a specific forest ecosystem, the standard area of the forest ecosystem, crown density, average diameter, average height, slope, aspect, landform, and thickness of humus layer of the forest ecosystem, soil thickness, etc., through a standard survey of the forest.

First, look for trees with low health index, and calculate the corresponding diversity index, size ratio, angle ruler, spatial density index, etc. in the case of the tree as a reference according to the ecosystem management decision factor.

Then judge according to the process of 4.3, and get the transition point of the management plan. According to the Weibull distribution, simulating a forest ecosystem with a standard plot area of $650m^2$. It contains only one type of tree and the tree health is consistent. The system contains 42 trees on the standard plot, and the diameter of the harvested wood should be greater than 30cm, and the required harvesting intensity is 15%, i.e., the deforestation rate is 15%.

The ecosystem management decision factor calculation shows that the minimum diameter of the forest trees is 5.3cm, the maximum diameter is 60.3cm, there are 7 trees with a diameter greater than 30cm, the maximum value of the minimum radius is 4.8cm, the minimum value is 2.1cm, and the average angle scale is 0.47.

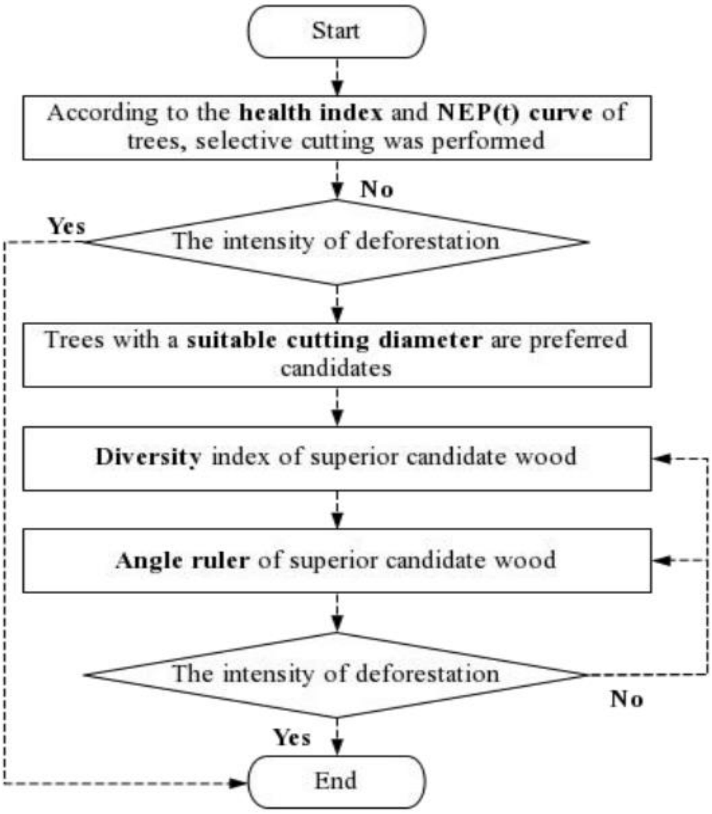

Figure 9: Specific Forest Ecosystem Management Plan

The final management flow chart is determined by Monte Carlo simulation as shown in Figure 9. The final result was that 4 trees were felled, and the forest structure was improved: the average angle scale was increased to 0.51, and the frequency of the angle scale of 0.5 increased by 21.368%; the spatial distribution density of large-diameter trees was optimized, providing better nutritional space. The comparison chart before and after cutting is shown in Figure 10.

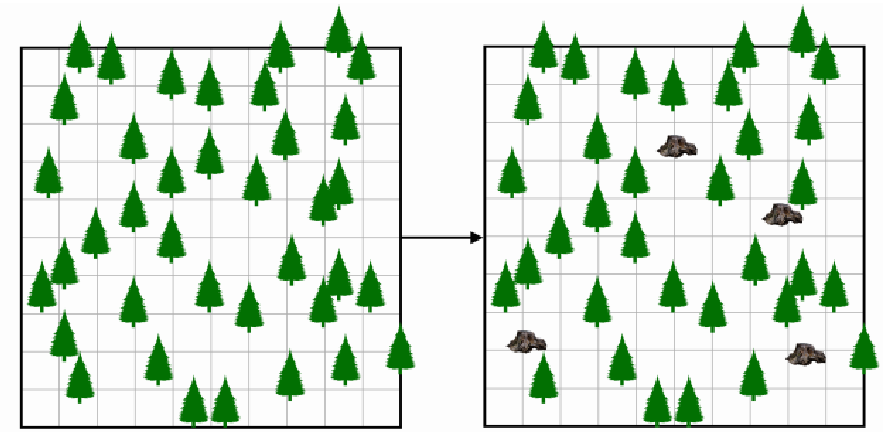

Figure 10: Comparison of forest ecosystem before and after deforestation

7. Empirical Analysis on Huang Fengqiao Forest Ecosystem

The Huang Fengqiao forest ecosystem (Figure 11) is located in the mid-subtropical monsoon humid climate zone, with an average annual temperature of 17.8 Celsius; an extreme minimum temperature of -11.9 Celsius and an extreme maximum temperature of 40 Celsius; the average frost-free period is 292 days; the average annual sunshine time is 1612 hours; The annual average amount of solar radiation is 107.254 kcal per square meter; the average annual precipitation is 1410.8 mm. The topography of the ecosystem is dominated by middle and low mountains. The east is composed of mountains above 800 meters above sea level. The mountains are undulating and the terrain is complex. The terrain runs from east to west. The highest altitude in the territory is 1270 meters, and the lowest altitude is 115 meters.

The existing forest products of the forest are mainly fir strips, fir logs and related wood products processed. Annual sales of timber 24,000 cubic meters, 140,000 bamboo. The existing area of the whole forest land is 10,122.6 hectares, and the volume of living standing trees is 879,705 cubic meters. The shelterbelt covers an area of 4764.3 hectares, including water conservation forests, soil and water conservation forests, road protection forests and other protective fences. The standard area of the empirical forest is 600 square meters, the stand canopy density is 0.8, the average stand diameter is 17.1 cm, the cut-off area is 5.5449 square meters, the average height is 11 m, there are 42 trees, the slope is 26 degrees, and the slope is half shaded. The landform is low mountain, the thickness of humus layer is 8cm, the thickness of soil is 80cm, and the altitude is 530m.

By collecting relevant data from 2007 to 2020, we estimate that the forest's accumulated carbon sequestration in 100 years is 870,454.691t by logistic regression. In the follow-up management plan, bayberry trees and Chinese varnish trees will be preferentially selected for felling. After the implementation of ecosystem management, the overall structure will be improved, maintaining the original healthy state and closer to the top community in the composition of major tree species. Considering the actual time limit of 10 years, forest managers need to pay attention to the health index of the forest ecosystem at all times to ensure the transition under the premise of prioritizing ecological value.

In the application of the model, although the forest ecosystem changes in the direction of decision-making, due to the limitation of logging intensity, only one adjustment to the system is limited, and multiple adjustments are required to achieve the management goal. If the cutting intensity is increased, the choice of tree species will be increased by two choices of Hazel and Wen Zhu.

8. Conclusions

Based on the theory of sustainable development, near-natural forest theory, etc., the forest ecosystem management decision model is constructed. By portraying the factors, the proposed spectrum of management is meteorology, economy, soil conditions, landscape, etc. According to ISM, the forest will not be harvested when the landscape value of the forest ecosystem is too high or the ecological benefits of the forest ecosystem under good climatic conditions are rising and the direct economic benefits are not high.

In the modeling of forest management transition points, process judgments need to be made by considering indicators such as health index and diversity, and process adjustments can be made for specific woods based on Monte Carlo simulations of actual parameters.

When applying the model to the Huang Fengqiao forest ecosystem, it was calculated that the forest would cumulatively sequester 870,454.691 t of CO_2 over 100 years, and that the best management plan would be: bayberry trees and Chinese varnish trees will be preferentially selected for felling, because after the implementation of ecosystem management, the overall structure will be improved, maintaining the original healthy state and closer to the top community in the composition of major tree species.

During the planned waiting period of 10 years, forest managers need to pay more attention to the health index of the forest ecosystem at all times to ensure the transition under the premise of prioritizing ecological value.

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References

[1]. Ritchie, Martin W., and Jeff D. Hamann. "Modeling dynamics of competing vegetation in young conifer plantations of northern California and southern Oregon, USA." Canadian journal of forest research 36.10 (2006): 2523-2532.

[2]. Jia-Hua, Zhang, and Y. Feng-Mei. "Simulating leaf net CO_2 assimilation rate of C3 & C4 plants and its response to environmental factors." Journal of Forestry Research 12.1(2001):9-12.

[3]. Forest Ecosystem Management Assessment Team (US). Forest ecosystem management: an ecological, economic, and social assessment. The Service, 1993.

[4]. Buongiorno, Joseph, and J. Keith Gilless. Decision methods for forest resource management. Academic Press, 2003.

[5]. Attri, Rajesh, Nikhil Dev, and Vivek Sharma. "Interpretive structural modelling (ISM) approach: an overview." Research Journal of Management Sciences 2319.2(2013): 1171.

[6]. Emborg, Jens, Morten Christensen, and Jacob Heilmann-Clausen. "The structural dynamics of Suserup Skov, a near-natural temperate deciduous forest in Denmark." Forest Ecology and Management 126.2 (2000): 173-189.

[7]. Carbon Sequestration https://www.fs.fed.us/ecosystemservices/carbon.shtml