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A Decision Model of Forest Management Plan based on PSR Model and Entropy Weight Method

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Abstract

In order to select the most suitable forest management plan which fully utilizes all aspects of the forest's value, we establish a decision model and other models.We fully measure the value of forests in all aspects, introduce multiple indicators, classify the indicators through the framework of the PSR model, and use the entropy weight method to calculate the weight of each indicator by taking the forest in Ningxia, China as an example. According to the calculation results, we give suggestions on the management scope of the local forest management plan. Based on the characteristics of the established decision-making model, the transition points at which management plans apply to all forests are discussed. In the meanwhile, we can use the characteristics of specific forests and their locations to identify specific transition points between management plans.

Keywords

Entropy Weight Method; PSR Model; Forest Management Plan; Carbon Sequestration.

1. Introduction

The 2019 Greenhouse Gas Bulletin shows that the average global CO_2 concentration level in 2018 was equivalent to 147% of pre-industrial levels,a further increase compared to 2017 levels. This long-term growth trend means that humanity willface increasingly severe climate change impacts in the future, including rising temperatures, extreme weather, water stress, sea-level rise, and destruction of terrestrial ecosystems. There are currently two main ways to mitigate the environmental impacts of greenhouse gases: reducing carbon emissions and increasing carbon sequestration. In nature, carbon is "collected" from the atmosphere through carbon pools formed in terrestrial and marine ecosystems. Forests are the major part of terrestrial ecosystems, and about 80% of the global terrestrial above-ground carbon stock and 40% of the below-ground carbon stock occur in forest ecosystems. So it is significant to study the relationship between forest management and forest carbon sequestration.

However, many people currently advocate reducing or even banning deforestation to safeguard the carbon sequestration and other values of forests. But doing so does not fully utilize the value and carbon sequestration capacity of forest ecosystems. Since forest products sequester carbon dioxide over their life cycle, appropriate deforestation strategies also have the potential to increase the carbon sequestration value of forests. Forests not only provide material goods such as forest products and forest by-products but also have environmental and ecological benefits and social functions such as recreation and culture. All these factors need to be considered when determining the deforestation plan of a forest. We should develop a more reasonable forest harvesting plan to fully utilize many potential values of forests including carbon sequestration value and better protect our earth.

2. Finding the Forest Management Plan with the Most Carbon Sequestration

This study evaluate certain existing forest management plans with the goal of maximizing carbon sequestration.

We selected two common time-dependent forest management plans that affect carbon sequestration, selected three representative countries at different latitudes and applied the formula to calculate their carbon sequestration under the corresponding forest management plans as a way to determine which forest management plan is most effective in sequestering CO_2.

The selected forest management plans are optimal harvesting decision management plan under the dynamic efficiency principle, optimal harvesting decision management plan under the intergenerational equity principle, and government acquisition of ecological forests system.

2.1. Optimal Harvesting Decision Management Plan under Dynamic Efficiency Principle

Unlike most crops, which mature in less than a year, trees mature over a very long period, making forest management unique: decisions are made not only about how many trees to plant on the land but also about when to harvest and replant; and because harvesting reduces the ecological and landscape value of the forest, a proper balance needs to be established to maximize the sum.

The management plan starts from the principle of dynamic efficiency and derives the optimal time to harvest the forest trees to ensure the maximum net benefit from the trees.

The harvesting period t satisfies:

$$\frac{dV(t')/dt}{V(t')} = \left[1 - \frac{C_0}{(p-c)V(t')}\right] \cdot \frac{r}{1-e^{-rt}} \tag{1}$$

Where, t represents the age of the tree in years; V represents the single wood product as a function of the age of the tree t; c represents the cost of tree planting, r is the radius of the tree, p is the price of wood per unit volume, and C_0 is the cost of tree planting.

2.2. Management Plan for Optimal Harvesting Decisions under the Principle of Intergenerational Equity

The principle of intergenerational equity (also known as the principle of sustainability) is the second most important principle in resource economics, and in the specific case of forest resources, it is to ensure that each generation is able to obtain no less than the benefits from the forest.

If we assume here that the ecological and social efficiency of the forest is positively related to the volume of wood stored, then the above principle can be simplified to ensure that the amount of wood that can be harvested each year does not decrease and that the volume of wood stored in the forest does not decrease, in order that the various efficiency of the forest does not decrease and that future generations have no less wealth than previous generations.

If this dynamic efficiency principle requires foresters to arrange production according to the optimal harvesting cycle, the aim is to maximize the return per unit area of forest land. However, if the number of trees of different ages on a stand varies widely, it will affect the satisfaction of the intergenerational equity principle because it will cause fluctuations in timber supply and standing timber stock. Therefore, to meet the requirements of the intergenerational equity principle, it is best for foresters to grasp the degree of afforestation and make a steady expansion of their area.

Its objective payoff function is:

$$MaxS=\left[(p-c)V(t)e^{-rt}-C_0\right]\cdot\frac{1}{1-e^{-rt}}+W(t)\lim_{x\to\infty}\frac{X}{t} \tag{2}$$

Where, *W(t)* is the cumulative ecological benefit generated by one tree in f years, and X denotes the planting density.

Unlike other forest management plans, an optimal harvesting decision management plan under the principle of intergenerational equity needs to ensure that each generation can enjoy the same amount of economic, ecological and social benefits. Of course, such planning is only a critical case for simple reproduction of the forest, i.e., to ensure that future generations do not receive less benefit than the current generation, and to meet the minimum criteria for sustainable forest production. In other words, if only the trees that are t years old are cut each year, the amount of wood harvested each year will remain the same, and the amount of wood stored on the land will remain the same. That is, it satisfies:

$$H(t+1)=H(t)-n\cdot X\cdot V(t)+n\cdot X\cdot V(t)=H(t) \tag{3}$$

where *H(t)* is the total uncut stand volume and *n* is the density variable.

2.3. Calculation and Analysis

Combining the equation with our carbon sequestration model, we calculate the amount of carbon sequestered in the forests of the three countries under three different management plans.

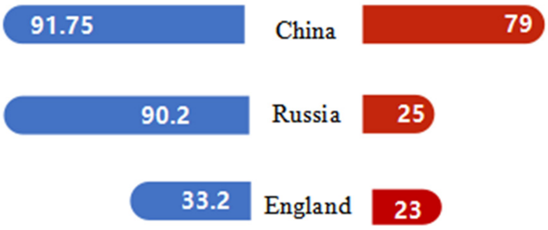


Figure 1. Carbon Sequestration in Different Countries under Different Calculation Methods

In the figure, blue is the optimal harvesting decision management plan under the principle of dynamic efficiency, and the optimal harvesting decision management plan under the principle of intergenerational fairness, and the unit of the figure is 100 million tons.

From the comparison we can easily conclude that the optimal harvesting decision management plan under the dynamic efficiency principle is the most effective forest management plan for sequestering CO_2. Under this management plan, a country's forests can sequester more CO_2 under the same conditions.

3. Build a Decision Model

In fact, when evaluating a forest management plan, we need to consider not only the total carbon sequestered by the forest but also the various ways in which the forest is valued. Multiple indicators are used to measure forest management plans.

Thus, equation (1) can again be rewritten in this case as:

$$Total(t)=f(D_1,D_2,D_3...D_n)+k \tag{4}$$

Which $D_1,D_2,D_3...D_n$ refers to the various aspects of forest values.

3.1. Selection of Indicators

We combined the characteristics of forest ecosystems, considered various factors, and also referred to some studies by other scholars, and selected the following indicators to help us construct our decision model.

1）D_1-- per unit area GDP

GDP per unit area reflects the economic output per unit area and is an important indicator to measure the impact of economic development on forest ecosystems, the calculation formula is:

$$D_1 = \frac{the\ region's\ GDP}{total\ area\ of\ the\ region} \tag{5}$$

2）D_2-- Population density

Population density refers to the number of people living on a unit area of land and is used to indicate the density of population. Forest resources are limited in a certain space, and the higher the population density, the higher the demand for forest resources and the resulting pressure. The calculation formula is:

$$D_2 = \frac{the\ total\ population\ of\ the\ region}{total\ area\ of\ the\ region} \tag{6}$$

3）D_3-- Forest coverage

Forest coverage is an important indicator reflecting the occupation of forest area or the richness of forest resources, calculated by the formula:

$$D_3 = \frac{forest\ area\ in\ the\ region}{total\ area\ of\ the\ region} \tag{7}$$

4）D_4-- Renewable land water reserves

Forests can support water, so renewable terrestrial water reserves are also a good indicator of the value of forests.

5）D_5-- Annual forest area change

In the previous analysis, we know that changes in forest area cause changes in total carbon sequestration, so it is necessary to include the indicator of annual forest area change to measure forest value.

6）D_6-- Annual carbon sequestration from forest products

Forest products can store carbon dioxide, which is also an important indicator to be considered when evaluating forest management plans.

Then, we construct a decision model with the help of the PSR model, and then evaluate the forest management plan using the entropy weight method with Wuzhong City, Ningxia Hui Autonomous Region, China as the research object.

3.2. Build the PSR Model

The PSR model reflects the interaction between humans and the environment through the "press-status - response" process. Humans obtain resources from the natural environment that are necessary for survival and development, while discharging waste into the natural world. This results in changes in the reserves of natural resources and the quality of the environment. Correspondingly, changes in the state of nature and the environment affect socio-economic activities and human welfare. In addition, society responds to these changes through environmental, economic and sectoral policies as well as changes in consciousness and behavior. This reciprocal cycle constitutes a press-state-response relationship between humans and the environment.

The PSR model answers the three fundamental questions of sustainability, namely, "what happens, why it happens, and how we do it. To represent and address these questions more specifically, the PSR model defines three types of indicators, namely exposure, sensitivity, and adaptive capacity. More specifically, these exposures are characterized by how various socioeconomic activities affect the environment, such as environmental damage and disturbance due to resource acquisition, material consumption, and emissions caused by various industries. At the same time, sensitivity reflects changes in the state of the environment and the environment itself over a given period of time, including the current state of ecosystems and the natural environment, the quality of human life and health. Finally, adaptive capacity refers to how societies and individuals act to mitigate, halt, restore, and prevent the negative impacts of climate and economic factors, as well as to remedy existing ecological changes that are detrimental to human survival.

The PSR model is based on causality and is divided into a pressure layer, a state layer and a response layer.

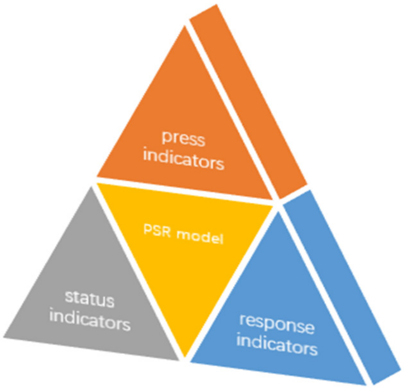


Figure 2. PSR Model

We define the indicators in the pressure layer as GDP per unit area and population density, the indicators in the state layer as forest cover and renewable terrestrial water reserves, and the indicators in the response layer as annual forest area change and annual forest product carbon sequestration, which reflect the human response to forest state change. In this way, we have completed the first step of building the decision model.

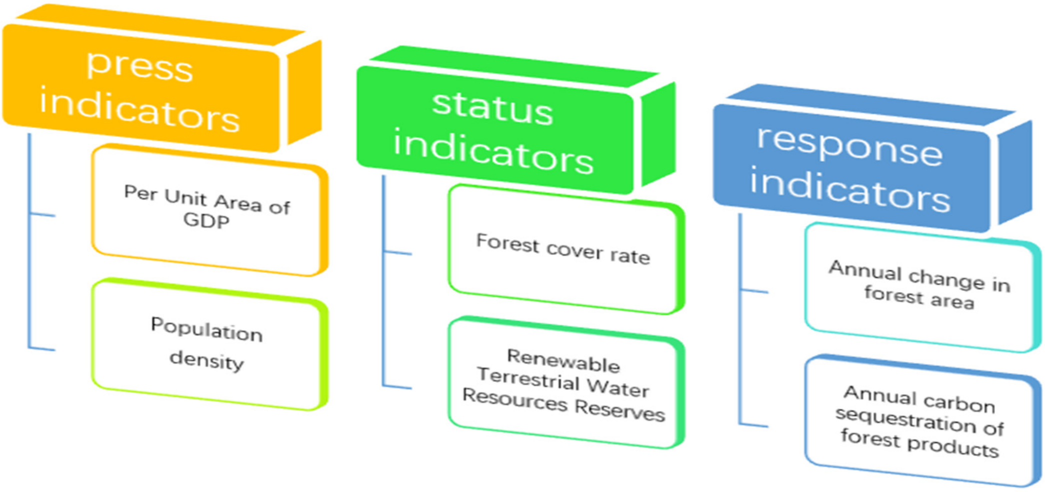


Figure 3. Indicators for Each Layer

3.3. Entropy Weight Method to Determine Index Weights

The second step of our decision model is to determine the weights of these indicators.

In terms of determining the weights of indicators, various studies have been conducted using hierarchical analysis (AHP), entropy weighting, principal component analysis (PCA), and subjective evaluation methods. In this paper, we construct a decision model for forest management plan based on PSR model and evaluate the forest management plan using entropy weight method as the research object.

In this section, we use the entropy weighting method as the method to convey the weight of each factor. In information theory, entropy is a measure of information disorder, the greater the entropy, the higher the disorder of information, the smaller the utility value of its information, and the smaller the weight of this index. Conversely, the smaller the entropy, the lower the disorder of information, the larger the utility value of its information, and the larger the weight.

The entropy method can avoid excessive subjectivity in calculating the weights; therefore, this study uses the entropy method to determine the weights of each index. It consists of several steps.

1) Build the raw data matrix

Assume that the evaluated object $M=(M_1,M_2,..,M_m)$, the evaluation index $D=(D_1,D_2,..,D_n)$, the value of the D_j index of the Mi evaluation object is X_{ij} $(i=1,2,..,m; j=1,2,..,n)$,and the original data matrix is obtained as:

$$X=\begin{pmatrix} X_{11}\cdots X_{1n} \\ \vdots\ \ddots\ \vdots \\ X_{m1}\cdots X_{mn} \end{pmatrix} \tag{8}$$

2) Standardization of data

For the original matrix, the following method is chosen for data normalization, and the characteristic weight of the *ith* evaluation object under the *jth* indicator is noted as V_{ij} , then:

positive indicators:

$$V_{ij}=\frac{X_{ij}-X_{\min}}{X_{\max}-X_{\min}} \tag{9}$$

inverse indicators:

$$V_{ij}=\frac{X_{\max}-X_{ij}}{X_{\max}-X_{\min}} \tag{10}$$

3) Calculate the weight of the characteristics of the evaluation object

Let the characteristic weight of the *ith* evaluation object under the *jth* indicator be p_{ij}， then：

$$p_{ij}=\frac{V_i}{\sum_{i=1}^{m}V_{ij}} \tag{11}$$

4) Calculate the index entropy value

The entropy value e_j of the *jth* indicator is:

$$e_j=-\frac{1}{\ln(m)}\sum_{i=1}^{m}p_{ij}\ln(p_{ij}) \tag{12}$$

5) Determine the entropy weight of the index

The weight W_i of each indicator is calculated by information entropy as:

$$W_i=\frac{1-e_j}{n-\sum_{j=1}^{n}e_j} \tag{13}$$

For each indicator, the same method is used to standardize as when calculating entropy weights.

3.4. Entropy Weight of Each Indicator

According to the standardization method of indicators above, the entropy values and entropy weights of each forest in Wuzhong City were obtained as shown in the table.

Table 1. The Entropy Values and Entropy Weights of Each Forest in Wuzhong City

indicators	entropy value	entropy weight
Per Unit Area of GDP	0.83	0.07
Population density	0.85	0.06
Forest cover rate	0.34	0.25
Renewable Terrestrial Water Resources Reserves	0.72	0.12
Annual change in forest area	0.45	0.20
Annual carbon sequestration of forest products	0.59	0.16

We visualized the weights of each indicator through radar charts as follows.

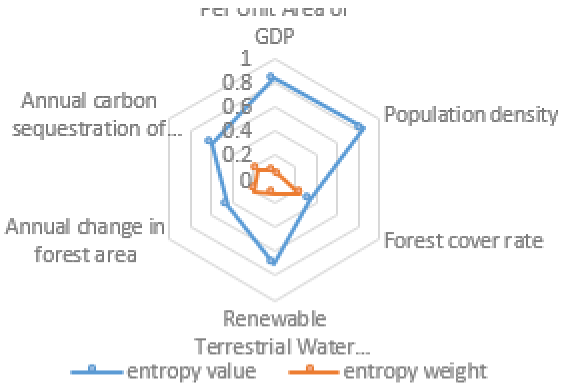


Figure 4. Radar Charts

We summed the entropy values of the indicators corresponding to the three states of the PSR model, and the results were 1.68, 1.06, and 1.04, respectively, as shown in the following figure.

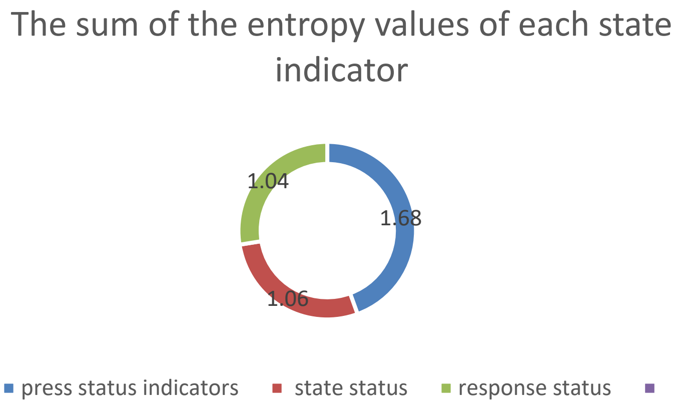


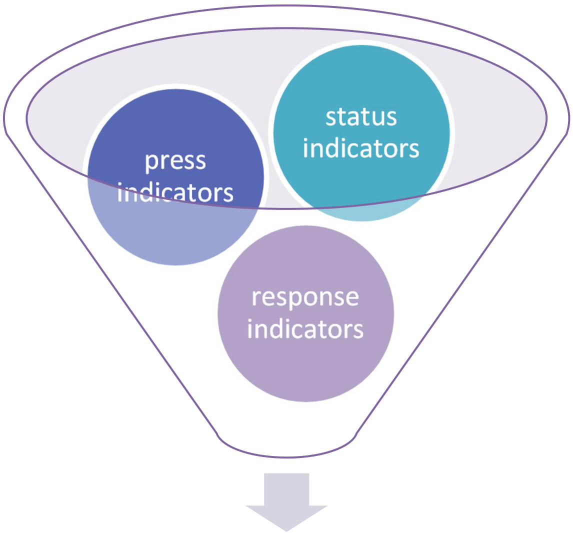
Figure 5. The Sum of The Entropy Values of Each State Indicator

4. Forest Management Plan and its Management Scope

4.1. Proposed Scope of Management of Forest Management Plans

Based on our analysis above, we can obtain the smallest entropy sum of response state indicators, so the largest weight should be assigned in the evaluation of the decision model. After checking the local information, the local situation confirms our reasoning.

From the several previously identified indicators, we give the main management scope of the forest management plan for Ningxia Wuzhong: "Annual change in forest area", "Annual carbon sequestration of forest products". Also, considering the poor local ecology, similar indicators can be added to the decision model to assist in forest management.



Tend to ‘ ‘Annual change in forest area’ ’ 、
‘ ‘Annual carbon sequestration of forest products’ ’

Figure 6. Recommended management scope

4.2. Recommendations for Determining Deforestation-free Forests

First, we suggest that the current forest management policy should be further improved, and the government or relevant functional departments should introduce corresponding laws and regulations. At present, because the relevant policies and regulations are not perfect, it leads to the situation that some operators change a large number of general timber forests into industrial raw material forests or economic forests with short rotation periods without scientific long-term planning and control and management by relevant regulations, resulting in the overall decline or slow improvement of regional forest quality.

Second, we must adhere to the forest management program to arrange the task of nurturing, determine the nurturing harvesting limit and carry out forest nurturing, restoration of degraded forests and other management activities; in the absence of a scientific forest management program, the task of nurturing should be based on the status of forest resources and the existing harvesting limit, etc., to ensure that the task of nurturing and nurturing harvesting limit is reasonable, nurturing measures to ensure scientific.

Thirdly, we should do a good job in educating and popularizing knowledge in this area, so that the public can realize the benefits of scientific deforestation to the environment as well as to human society.

5. Discussion and Determination of Transition Points

Our decision model is not fully applicable to all forests, so when applied specifically to a specific class of forests, we need to add or subtract some evaluation metrics depending on the forest's specific conditions.

Therefore, for different forests, the transition can be accomplished by examining the actual situation and modifying the model indicators when applying the model to decide the corresponding management plan. We can examine the use classification of the forest, combine it with its specific geographical location, and also take into account other characteristics to modify the indicators and find the transition point of the model between different specific forests.

We looked up the relevant information and found that the current forest is mainly divided into: protection forest, special purpose forest, timber forest, economic forest, and charcoal forest according to the use.

Taking economic forest and fuel carbon forest as an example, when deciding the management plan of these two types of forests, our indicators should be tilted toward the use of forests for human beings, adding some indicators to the model that quantify the practical application value of forests to human life, while weakening some ecological indicators, thus completing the transition of the decision model between different forest species.

When considering the geographical location characteristics of the forest, we can add some climate-related indicators to the indicators of the decision model, such as average annual temperature, average annual precipitation, etc., so that the entropy value can be calculated by the entropy weighting method for the final decision.

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