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Application of Carbon Sequestration Model in Forestry Research

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Abstract

Greenhouse gases play important roles in climate change and present a massive threat to people's life. Except for reducing the emission of greenhouse gases, forestry for carbon sequestration is also an important measure to reduce the impact of climate change. In this paper, we establish two models to make some guidelines for global forest management. Firstly, we develop a carbon sequestration model to solve how much carbon dioxide can be stored by the forest plants and products over time. Note that the utilization rate of harvested wood (URH) and the Net Ecosystem Productivity (NEP) are related to carbon dioxide storage. Therefore, we can get the amount of carbon dioxide storage by calculating the NEP and the URH, and hence we establish the model of carbon sequestration. Results indicate that if the felling rate is controlled properly over time, appropriate harvesting is economically superior to no felling, and the amount of carbon dioxide storage will exceed. Then, we develop the Measurement of Environmental and Resource Values (TEV) model, in which we calculate the direct use value of forests (DUV, e.g., the woods), the indirect use value of forests (IUV, e.g., the landscape), and the existence value of forests (EV, e.g., the carbon sequestration capacity of trees). By employing the entropy weight method and the improved TOPSIS decision algorithm, we calculate the information entropy and the attribute importance, and hence the objective weight of each relevant condition to the value of the forest ecosystem is determined. The simulation results of Tongass National Forest (TNF) Park show that, if the deforestation rate is controlled at 0.2%, the percentages of the land in the forest representing the DUV, IUV, and EV are 44.4%, 0.2%, and 55.4%, respectively. This distribution is the most consistent with the embodiment of the value of the optimal ecosystem of TNF Park. Thus, no reason can prevent forests from being cut down. Ideally, if the forest grows steadily and the value of the forest ecosystem exceeds that with appropriate harvesting, trees never be cut down. Actually, there is no such ideal situation, so we believe that the economic and environmental benefits of moderate harvesting will be better than that of no harvesting at all. Finally, we replace the TNF Park with the Yellowstone National (YSN) Park, and the main tree species in the YSN Park are also replaced with black pine. According to Model I, we can calculate that YSN Park and its products will store 153.22 million tons of carbon in 100 years. According to Model II, we conclude that if the deforestation rate is controlled at 0.2%, the percentages of the land in the forest representing the DUV, IUV, and EV are 44.4%, 0.1%, and 55.5%, respectively. This conclusion is almost consistent with that of YSN Park, which confirms the feasibility of our models. Therefore, to make the forest better transition to the best situation we have set within ten years, we can take some measures such as controlling the rate of felling, adjusting the scope of tourist areas, and so on.

Keywords

Greenhouse Gas; Forest Management; Carbon Sequestration; Harvesting Plan; Total Value of Forest Ecosystem Evaluation Model; Entropy Weight Method; Improved TOPSIS Decision Method.

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1. Introduction

1.1. Problem Background

As known to all, climate change poses a great threat to people's life. Extreme weather has a great impact on people's production and life. The impact of climate change is one of science's most notable subjects. Scientific research has shown that greenhouse gases (e.g., carbon dioxide, methane, and so on) have an important impact on climate change. In order to mitigate the impacts of climate change, we need to take some practical actions to reduce the content of greenhouse gases in the atmosphere. However, it's not enough to reduce the emissions of greenhouse gas. Some more efforts are put forth on carbon sequestration, i.e., enhancing the stocks of carbon dioxide sequestered out of the atmosphere by the biosphere or by mechanical means. Forests play important roles in mitigating climate change because the biosphere can sequester carbon dioxide in all kinds of plants, soil, and water.

There are many ways for forests to sequester carbon dioxide. Besides the living plants, forest products created from trees (e.g., furniture, lumber, plywood, paper, and other wood products) can also sequester carbon dioxide in their lifespan. The lifespan of some forest products is short, while the others may live longer than the trees that produce them. Compared with the benefits of carbon sequestration without deforestation at all, the combination of carbon sequestration in forest products and carbon sequestration due to young forest regeneration may allow more carbon sequestration over time. As early as 2000, Thornley and Cannell established an Edinburgh Forest Model to sustain timber volume yield and carbon storage in forests subjected to different harvesting regimes[1]. Kaipainen et al. pointed out that elongation of rotation length is a forest management activity to reduce the emissions of greenhouse gas, and they established a model to analyze the carbon stocks of trees, soil, and wood products depending on rotation length in different European forests[2].

1.2. Restatement of the Problem

To figure out how to use and manage their forests, an international organization, namely, International Carbon Management Collaboration was established to develop guidance for forest managers around the world. Making guidance is a complex and systematic project. Since the make-up of forests, climates, populations, interests, and values vary widely around the world, it is simply not possible to adopt the one-size-fits-all guidance. We should treat them differently. To establish the model and solve the problem effectively, we summarize the problems as follows.

Question I: Establish a model for forest carbon sequestration to determine the amount of carbon dioxide that is expected to sequester over time. The proposed model should determine the most effective forest management plan to sequester carbon.

Question II: Since there exist other ways of forest value, the forest management plan most suitable for carbon sequestration is not necessarily the most suitable plan for society. Therefore, establish a decision-making model to let forest managers understand the best use of forests. The model should identify a forest management plan to balance the various ways of assessing forests, including carbon sequestration.

Question III: Apply the established model to various forests, it can make a harvesting plan according to the forest management.

1.3. Our Approach

For Question I, we chose the famous TNF Park in the United States as an example to find out the main tree species and wood data of TNF, as well as the carbon sequestration per unit area of the forest, calculate the carbon sequestration of the whole forest, and then use function fitting to draw the comparison diagram of annual carbon sequestration and total carbon sequestration of harvested and non-harvested trees, to establish the carbon sequestration model, Answer questions.

For Question II, we plan the best management model for forest according to the total value of the forest ecosystem and divide the forest into three attributes: land for cutting trees, land for tourism, and land for carbon sequestration. The entropy weight method is used to objectively weigh the three attributes to obtain the best TEV. According to this method, various forest management modes can be evaluated, that is, the management of a single forest can be transferred to the management of all forests.

For Question III, according to the models established in the previous two questions, select a forest that will incorporate logging into its forest management plan, substitute various data of this forest into the model for evaluation and calculation, and get the total carbon sequestration of this forest and the best management plan of this forest in 100 years. According to the difference between the original management plan and the best management plan of the forest, and considering the interests of forest managers and timber loggers, write the transition plan within 10 years.

2. Model Preparation

2.1. Analysis of the Problem

Analysis of Question I: Select a forest and establish a carbon sequestration model. Calculate the carbon sequestration stock per unit area of the forest and the utilization rate of its wood products, and then calculate how much carbon dioxide the forest and its products can store over time according to the cutting rate and floor area of the forest. When establishing the model, it is necessary to consult the main tree species of the forest family, their density and average length, the annual cutting rate of the forest, and other data for calculation. Finally, it is determined according to the results whether appropriate logging will make the forest store more carbon, to formulate better forest management plans.

Analysis of Question II: In order to make a plan suitable for forest management and society, a decision-making model is established. Total ecosystem value (TEV) of the introduced forest. It is divided into three attributes: direct use value (land occupied by cutting and planting), indirect use value (land occupied by tourism), and non-use value (land occupied by carbon sequestration). Analyze the stability of these three attributes on environmental and social benefits, and carry out forest area distribution and management. The higher the stability of attributes, the greater the proportion of forest area should be given. To get a management plan suitable for forest management and society. And can thus transition to all forests.

Analysis of Question III: According to the decision-making model of Question II, we first select a forest that recommends logging into its management plan. Then, by substituting the forest data information into our carbon storage model and decision-making model, we can calculate the amount of carbon dioxide stored in the forest in 100 years. To facilitate forest managers to formulate management plans. Finally, considering the interests of forest managers and loggers, it will take 10 years to transition from the original plan of the forest to the new plan.

2.2. Assumptions

To establish the model conveniently, we make the following assumptions.

(1) Assume that the trees with the largest proportion of the forest are used to represent the trees of the whole forest.

(2) Assume that the trees in the forest die unnaturally and grow unnaturally when they are not cut down.

(3) Assume that the choice value and the legacy value of the forest ecosystem are not considered.

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(4) Assume that the forest management plan only considers tourism land, non-timber forest, timber forest, and new afforestation.

3. Model I: Carbon Sequestration Model

3.1. Establishment of Carbon Sequestration Model

We note in [3] that carbon sequestration refers to the technology that replaces the direct emission of carbon dioxide into the atmosphere by capturing carbon and storing it safely. Therefore, we in this paper refer to carbon sequestration as the ability of plants to absorb carbon and select TNF in the United States as an example. The value of net ecosystem productivity (denoted by *NEP*) is obtained by calculating net primary productivity (denoted by *NPP*) and the carbon consumption of soil respiration (denoted by *RS*), and then the carbon sequestration stock is calculated by

$$NEP = NPP - RS \tag{1}$$

As stated in [3], the value of RS is a fixed value, we only need to calculate the value of *NPP* to obtain the relevant value of carbon sequestration.

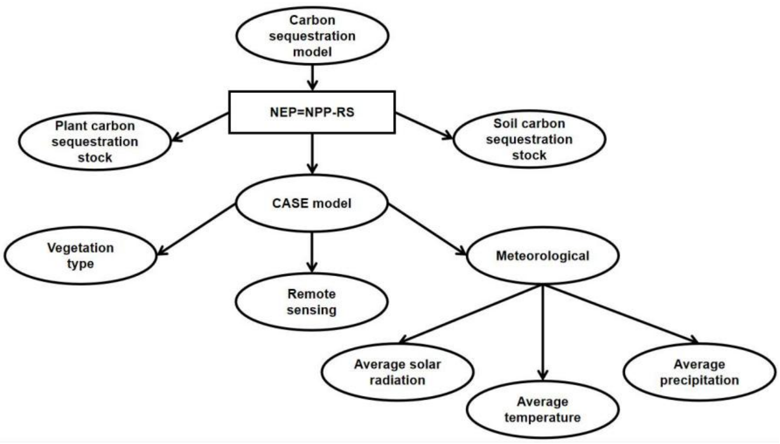

Figure 1. Flow chart of carbon sequestration

3.2. Calculating and Simplifying the Model

3.2.1. Data Preparation

We use TNF Park in the United States as an example to calculate carbon sequestration. The data used in this paper can be found in [5,6]. Since the main product of TNF is spruce, we assume all forest products in the forest are spruce. The wood density of spruce is $0.342MgDMm^{-3}$ and the average length is 7m, the time for spruce to grow into usable wood is about 20 years[7]. Based on these data, we can calculate the utilization rate of spruce is 34.2%.

3.2.2. Situation Analysis

Assuming that the total area of TNF remains unchanged, there are two situations:

(1) If the original forest vegetation is retained without felling and other operations, the *NEP* is basically unchanged.

(2) Conduct appropriate felling operations and supplement saplings every year to keep the total area of TNF Park unchanged, and calculate the number of *NEP*.

Through the comparison of time, substitute the data into the following formula to obtain the carbon sequestration stock, and then compare the two situations. In the first case, the *NEP* remains unchanged and the average value is taken. In the second case, calculate the *NEP* value after appropriate felling to obtain the *NEP* value after appropriate felling, then the annual carbon sequestration of the selected forest can be calculated by

$$R=\begin{cases} kh[p^m+b(1-p^m)], 0\le m\le x, \\ kh[b(1-p^m)+(1-20)], m>x, \end{cases} \tag{2}$$

where *m* is the selected lapse year, *h* is the selected forest area, *p* is the proportion of forest area after deforestation, and *k* is the *NEP* of the selected forest.

3.3. Results of Model I

Through the case model and its data calculation, the *NPP* of TNF Park can be obtained, and the average is 775 gC·m^{-2}·a^{-1}. The *RS* of TNF Park is 608.44 gC·m^{-2}·a^{-1}. According to (1), we can obtain *NEP*=166.56 gC·m^{-2}·a^{-1}.

By substituting the number of years *m* in (2), we can obtain the cumulative carbon content of the final forest and its products between *m* years. We set the cutting rate to 0.1% and 0.2%, respectively. The situation with no cutting is also used for comparison. We compare in Figure 2 the total carbon sequestration stock with different cutting rates.

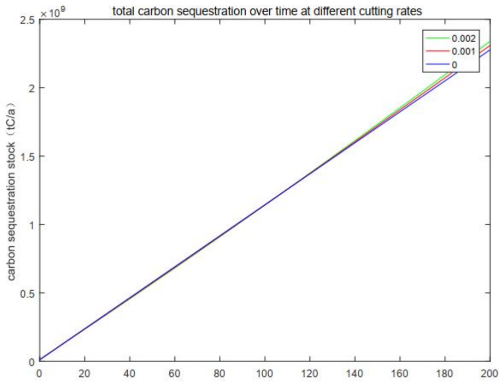

Figure 2. Comparison of total carbon sequestration

As we can see from Figure 2, when the felling rate is 0.2%, the annual carbon sequestration capacity will be more than that without felling after 60 years.

As shown in Figure 3, under the condition of appropriate felling, i.e., when the felling rate is 0.2%, the annual carbon sequestration capacity will be more than that without felling after 60 years.

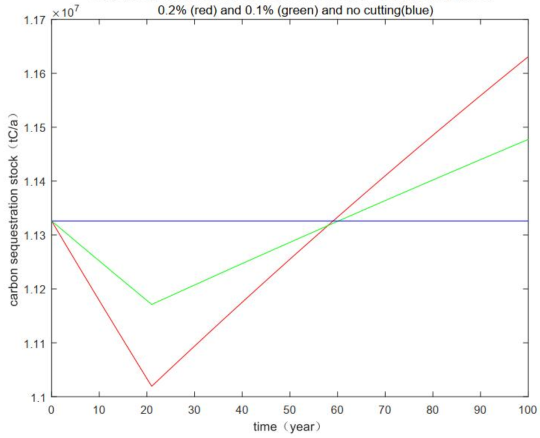

Figure 3. Annual carbon sequestration over time

From Figure 3, we can obtain the total amount of carbon sequestration and yield the following conclusions: When the deforestation rate is 0.2%, it needs to exceed the carbon sequestration of non-deforested forests in 108 years; When the deforestation rate is 0.1%, it needs to exceed the carbon sequestration of non-deforested forests in 110 years.

4. Model II: The Measurement of Environmental and Resource Values Model

4.1. Calculating and Simplifying the Model

Through consulting the data, we know that the current mainstream evaluation method for forest value is the TEV model proposed by American economist a.m. Freeman in 2023. The model divides the total value of the forest ecosystem into two parts: use value (UV) and non-use value (NUV). The use-value includes direct use value (DUV), indirect use value (IUV), choice value (CV), existence value (EV), and legacy value (LV). The flow chart is shown in Figure 4.

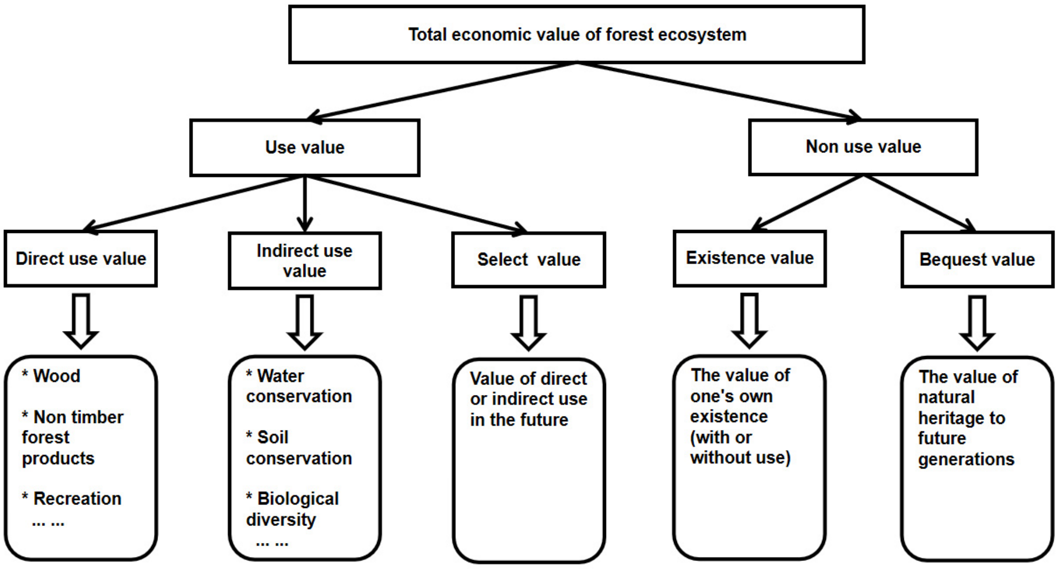

Figure 4. TEV Model Flow Chart

We in this model only consider the influence of DUV, IUV, and EV, and do not consider the influence of CV and LV. We note in [4] that the DUV is 2.034 billion USD, the IUV is 2281196.122 billion USD, and the EV is 5.8207 million USD.

Next, the improved TOPSIS decision-making algorithm based on the entropy weight method is adopted to calculate the solutions[8]. Because they can make the calculation results not focus on the subjective consciousness of decision-makers and reduce the dependence of evaluation objectives on human subjective judgment, and calculate the weight more scientifically through the analysis of the data itself. In the procedure of the improved TOPSIS decision-making algorithm, we need to calculate the information entropies, the attribute importance, and objective weights of DUV, IUV, and EV. We refer the readers to read [8] for more details about the TOPSIS decision-making algorithm.

4.2. Results of Model II

The TNF Park is replaced with YNF Park and the main forest product is also replaced with the black pine. The data required in this paper are shown in Figure 5.

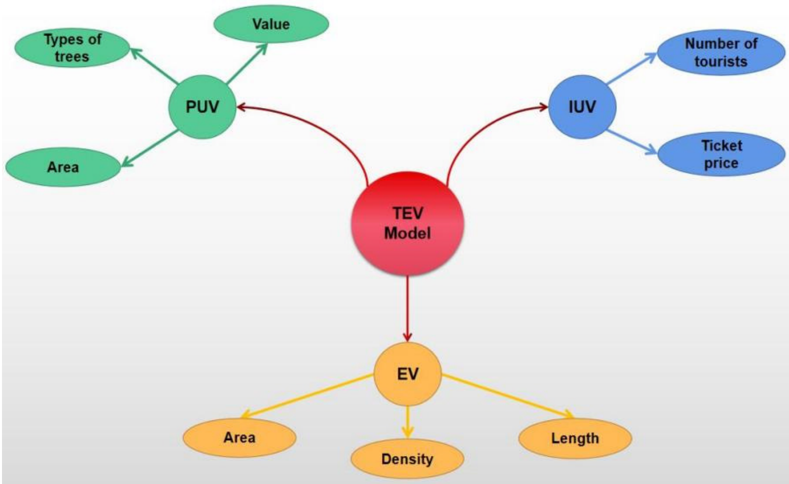

Figure 5. Data collection of TEV model

Results show that after 100 years, the carbon storage capacity of YNF Park in the United States is 153.22 million tons of carbon.

Table 1. Results of Model II for TNF Park and YNF Park

Park	E_1	E_2	E_3	A_1	A_2	A_3	ω_1	ω_2	ω_3
TNF	0.1974	0.9964	0	0.8026	0.0036	1	44.4%	0.2%	55.4%
YNF	0.1999	0.9991	0	0.9001	0.0008	1	44.4%	0.1%	55.5%

By employing the TOPSIS decision-making algorithm to solve Model II, we can obtain the results listed in Table 1. In Table 1, the information entropies of DUV, IUV, and EV are denoted by E_1, E_2, and E_3, respectively; the attribute importance of DUV, IUV, and EV is denoted by A_1, A_2, and A_3, respectively; the objective weights of DUV, IUV, and EV are denoted by ω_1, ω_2, and ω_3, respectively.

From Table 1, we can conclude that, when the felling rate is 0.2%, 44.4% of the land area of the TNF Park is used for felling and planting, 0.2% of the floor area is used for indirect use and tourism, 55.4% of the land area cannot be occupied. In other words, 55.4% of the land area is only used for carbon sequestration and forest environment protection. Similar conclusions of YNF Park also can be found in Table 1. We can understand your concern that forests are renewable resources, however, we should make better use of forest resources only by adhering to the strategy of sustainable development. We will control the amount of deforestation through the constitution and taxes to maintain the deforestation rate in an appropriate and reasonable range.

5. Verification of the Model

From Figures 2 and 3, the comparisons of the forest cutting rate of 0.1% and 0.2% with no cutting at all, it is found that the carbon sequestration stock of completely no cutting at the beginning will be greater than that of appropriate cutting, but the annual carbon sequestration of forests cut after 68 years will exceed that of forests not cut at all, and the total carbon sequestration of forests cut after 108 years will also exceed that of forests not cut at all. Therefore, it can be concluded that the carbon sequestration benefits brought by appropriate deforestation will exceed the carbon sequestration benefits brought by no deforestation over time. The model and its results meet the requirements of the title, indicating that the model can be applied to real life.

6. A Summary and Conclusion

Forests are indispensable for absorbing carbon dioxide, mitigating climate change, and preventing the greenhouse effect. Therefore, how to increase the amount of carbon dioxide absorbed by forests is a top priority. The carbon sequestration model established in this paper uses the amount of carbon dioxide absorbed by the forest per unit area and the amount of carbon dioxide sequestration of wood products made by the main tree species of the forest. It is obtained that when the deforestation rate is controlled at 0.2%, the total amount of carbon sequestration of the forest will exceed the total amount of carbon sequestration without deforestation after 108 years. The analysis concluded that: in the long run, compared with the forest intact, the appropriate cutting of trees over time can make the forest store more carbon dioxide.

We are not only concerned about the carbon sequestration of forests, but also the development of forests, the protection of biological diversity, recreational uses, cultural considerations, and economic benefits. By employing the decision-making method, we establish a model for the forest management plan, in which the direct use value, indirect use-value, and existence value of the forest are reasonably considered.

7. Evaluation of the Model

The carbon sequestration model can easily and quickly calculate the amount of carbon sequestration sequestered by forests and their products over time by only using the data corresponding to forests.

The deviation between the parameters used and the actual parameters will reduce the final accuracy of the model. When we establish the model, we ignore some factors, which may eventually lead to the deviation between the results and the actual results.

The carbon sequestration model can be applied to most forests only by changing the main wood species and floor area corresponding to the forest and calculating the annual carbon sequestration amount and the total carbon sequestration amount over time. Besides, the decision model only needs to replace its corresponding attributes to calculate various management plans in daily life, such as mall management plan, enterprise management plan, logistics management plan, etc., which is convenient for decision-makers to manage.

Acknowledgments

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