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# Research on Forest Carbon Sink Potential in China

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**Abstract:** The original variables were 14 statistics in 31 provinces and cities in mainland China (excluding Hong Kong, Macao and Taiwan) in 2019, including forest area, forest tending area, afforestation area and timber production. Factor analysis was used to study the factors affecting development potential of forest carbon sinks in mainland China. The results show that the total forest resources factor extracted from the variables related to forest stock and forest land use area was the most important affecting this potential, followed by the forest climate and output value factor extracted from variables related to climate and output. Third was the forest ecological construction factor, which was extracted from forestry afforestation area related variables and fire-damaged areas. In last place was the forest disaster prevention factor extracted from forest nurturing and pest and rodent control area variables. According to systematic clustering of the comprehensive score, development potential of forest carbon sinks in 31 provinces and municipalities across the country was divided into five categories and, based on this, targeted suggestions were put forward for improvement of the above potential in various regions.

**Keywords:** forest carbon storage; forest carbon sink; potential; factor analysis; cluster analysis

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## 1. Introduction

On 20 September 2020, Chinese President Xi Jinping proposed realization of the "Double Carbon Target", aiming to reach a "carbon peak" in 2030 and "carbon neutrality" in 2060. Mainland China takes the initiative to take responsibility and actively promote construction of a community with a shared future for mankind; this behavior fully demonstrates the demeanor of a great country. As the main body of terrestrial ecosystems, forest ecosystems play an important role in regulating global carbon balance, slowing the increase in greenhouse gas concentrations, such as $CO_2$ and ozone, in the atmosphere and maintaining the global climate. The scientific explanation of forest carbon sinks refers to use of forest plants to absorb and sink carbon dioxide in vegetation or soil. In implementation of "Double Carbon Target" action, the practical significance of forest carbon sinks is becoming more and more important. The research on forest carbon sinks is not only related to climate change but also has a certain impact on ecology, economy and society. From 1976 to 2018, the total carbon stock of forest resources (including forest trees, forest land and understory vegetation) in mainland China increased from $125.06 \times 10^8$ t to $214.39 \times 10^8$ t, and the value of forest carbon stock in mainland China increased from CNY $1482.09 \times 10^8$ to CNY $8823.85 \times 10^8$, with an average annual increase of CNY $174.80 \times 10^8$ [1]. Based on changes in forest biomass and accumulation, both forest carbon stock and value in mainland China are increasing, and, according to this development trend, the expected development goals of forestry in mainland China can be achieved when carbon reaches peak carbon neutrality in 2030 and 2060. Therefore, improving its development potential has a hugely positive effect on Chinese sustainable development.

As early as the 1960s, foreign scholars researched forest carbon sinks [2–6], while domestic scholars started their research relatively late. In the early years, relevant scholars in mainland China focused on evaluating carbon sink functions and cost–benefit analyses, exploring economic value, estimating forest carbon storage and looking forward to the forest carbon sink trading market. In recent years, there have been increasing studies on forest carbon sink potential. Chen Zhouguang [7] used the gray prediction model GM (1, 1) to estimate the forest carbon sink potential of Zhejiang Province. Wang Shuya [8] clarified the development status of forest carbon sink potential in Heilongjiang Province through the comprehensive ensemble forecasting method. Xia Ben'an et al. [9] used the analytic hierarchy process to construct a calculation model for the development potential index of forest carbon sinks in order to quantitatively evaluate the development potential of forest carbon sinks in various counties of Hunan Province. Zhou Wei et al. [10] calculated the forest carbon sink potential of Guangdong Province by using data from the seventh continuous inventory of forest resources and $CO_2$ FIX V3.2 software. Li Shuaishuai et al. [11] constructed a potential evaluation model through the objective weighting method of entropy weight and calculated the evaluation index of forest carbon sink development potential in 12 western provinces. Wang Pingda et al. [12] used the SWOT analysis method to comprehensively analyze the potential of developing a forest carbon sequestration economy in the Daxing'anling forest area from four aspects: the advantages and disadvantages of developing a forest carbon sequestration economy in the forest area and the opportunities and threats brought by the external environment. Yin Zhonghua et al. [13] used the forest stock expansion method to carry out systematic calculation of the forest carbon sink potential in the northeast Inner Mongolia forest area from 2003 to 2011. Huang Min et al. [14] used the forest stock expansion method to calculate the forest carbon sink potential in the Poyang Lake Ecological Economic Zone.

To sum up, the existing domestic research results are mostly based on idealized assumptions to estimate forest carbon sink potential, and only a few papers have analyzed factors affecting forest carbon sink potential fundamentally. Most scholars only focus on specific provinces, and few scholars analyze forest carbon sink potential nationwide. Thus, this paper will select forest land area, forest area, forest tending area, afforestation area, timber production and other data of 31 provinces and cities in mainland China in 2019 as the original variables and then use the factor analysis method to extract four common factors from the many variables. These four common factors are the total forest resources, forest climate and output value, forest ecological construction and forest disaster prevention. In the end, development potential of forest carbon sinks in 31 provinces and municipalities across the nation was clustered and analyzed according to a comprehensive score, and provided with targeted recommendations depending on the actual circumstances in each region.

## 2. Variable Selection and Data Description

Fourteen original variables were selected to evaluate forest carbon sink development potential. The explanations for each variable are as follows (data come from "China Statistical Yearbook 2019" [15], "China Statistical Yearbook 2020" [16] and "China Forestry and Grassland Statistical Yearbook 2019" [17]):

$X_1$: Forestry land area can be interpreted as the area of land growing various types of trees, including forest land (arbor forest with canopy density above 0.20, economic forest, bamboo forest), sparse forest land, shrub land, unforested forest land, immature forest closed land, nursery land, logging remnants, burning remnants, people above the county level land suitable for forestry and forestry auxiliary production land planned by the government. Land use change is the main factor causing the dynamic change in capacity of forests to absorb and sink carbon dioxide. Therefore, the variable of forest land area can be used to evaluate forest carbon sink potential. The data of each province (autonomous region) were taken from entry "Forest Resources by Region" in "China Statistical Yearbook 2019".

$X_2$: Forest area, including arbor forest area with canopy density above 0.20, bamboo forest area, shrub forest area specially stipulated by the state, farmland forest network and surrounding tree area. As mentioned above, forest carbon sink is manifested as the ability of forest vegetation to absorb and sink carbon dioxide, so the size of forest area can be used as one of the characterizations of the connotation of forest carbon sink. The data of each province (autonomous region) were taken from the entry of "National Forest Resources" in "China Forestry and Grassland Statistical Yearbook 2019".

$X_3$: Afforestation area can be interpreted as the total area of forests, trees and shrubs that meet the afforestation survival rate standards in the "Afforestation Technical Regulations" (GB/T 15776-2016) on land suitable for afforestation through sowing, seedling raising and split planting in land suitable for afforestation. Human-made afforestation activities have promoted restoration and improvement of forest vegetation, and are conducive to development and utilization of the carbon sink ability of forest vegetation to a greater extent. Therefore, the amount of afforestation area can be used as a characterization of the extension of forest carbon sink. The data of each province (autonomous region) were taken from the entry of "Afforestation and Nurture by Region" in "China Forestry and Grassland Statistical Yearbook 2019".

$X_4$: Afforestation area of key forestry projects refers to the afforestation area completed through implementation of natural forest resource protection projects, conversion of farmland to forest projects, Beijing–Tianjin sandstorm source control projects and Three-North and Yangtze River Basin and other shelterbelt system projects. Similar to variable $X_3$, steady increase in afforestation area of key forestry projects has laid the foundation for improvement of forest ecological environment, which is a sign of extension of forest carbon sinks. The data of each province (autonomous region) were taken from the entry of "forestry key ecological project afforestation area by region" in "China Forestry and Grassland Statistical Yearbook 2019".

$X_5$: Area of pest and rodent control refers to the actual area of forest pest and rodent control through chemical control, biological control, artificial control and bionic agents. If forest vegetation is subjected to severe biological disasters during the growth process, its growth will weaken or even die and the forest vegetation will turn into a carbon source. It can be seen that pests and rodents are also one of the main factors affecting forest carbon sinks. For this reason, the author selects the area of pest and rodent control as an aspect to evaluate forest carbon sink potential. The data of each province (autonomous region) were taken from the entry of "Forestry Pest Control by Region" in "China Forestry and Grassland Statistical Yearbook 2019".

$X_6$: The total stock of standing trees can be interpreted as the total stock of all trees on land within a certain range, including forest stock, sparse forest stock, scattered wood stock and surrounding tree stock. The data of each province (autonomous region) were taken from the entry of "Forest Resources by Region" in "China Statistical Yearbook 2019".

$X_7$: Forest stock can be interpreted as the total volume of tree trunks existing in a certain forest area. The data of each province (autonomous region) were taken from the entry of "National Forest Resources" in "China Forestry and Grassland Statistical Yearbook 2019". The two variables $X_6$ and $X_7$ can reflect the total scale and level of forest resources and are the basic indicators for measuring forest ecological status and calculating forest carbon storage.

$X_8$: Forest tending refers to various forest management activities adopted in the process of forest resource cultivation to ensure survival rate of young forests, promote healthy growth of trees and improve quality of forest stands. By strengthening forest tending management, the quality of forests can be effectively improved and the function of forest carbon sinks can be promoted. Therefore, the variable of forest tending area is selected as characterization of forest carbon sink extension. The data of each province (autonomous region) were taken from the entry of "Afforestation and Nurture by Region" in "China Forestry and Grassland Statistical Yearbook 2019".

$X_9$, $X_{10}$: The process of forest vegetation absorbing and depositing carbon dioxide is essentially photosynthesis of green plants, which will inevitably be affected by various natural conditions, such as temperature and precipitation. Therefore, the annual average temperature and precipitation are selected to investigate the influence of climate factors on forest carbon sequestration. The data of each province (autonomous region) take the corresponding value of the provincial capital city. The data for each province (autonomous region) were taken from the entries of "Average temperature of major cities (2019)" and "Precipitation of major cities (2019)" in "China Statistical Yearbook for the provincial capital cities 2020".

$X_{11}$: In addition to causing devastating damage to forest resources, forest fires will also release large amounts of carbon that forests have fixed over many years of growth. Therefore, forest-fire-damaged area is also one of the main factors affecting forest carbon sinks. The data for each province (autonomous region) were taken from the entry "Forest Fires (2019)" in "China Statistical Yearbook 2020".

$X_{12}$: Prolonging the service life of wood products, improving wood utilization efficiency, reducing wood demand and moderately limiting wood production can also increase forest carbon storage and improve forest carbon sink potential. Therefore, total production of coniferous wood, logs and fuelwood in the yearbook is selected as the variable of wood production to investigate its impact on forest carbon sink potential. The data of each province (autonomous region) were taken from the entry "Production of major wood products by region" in "China Forestry and Grassland Statistical Yearbook 2019".

$X_{13}$: Gross output value of the forestry industry can be interpreted as the total production value of forestry material production departments and non-material production departments within a certain period (usually 1 year) by using forest resources to provide economic, ecological and social benefits to society. A series of policies and measures introduced to achieve the goal of vigorously promoting construction of ecological civilization will inevitably provide a broad space for development of forest carbon sinks. Therefore, the forestry production value of the primary industry, secondary industry and tertiary industry in the yearbook is selected as one of the influencing factors. The data of each province (autonomous region) were taken from the entry of "total output value of forestry industry by region" in "China Forestry and Grassland Statistical Yearbook 2019".

$X_{14}$: Forestry investment involves the construction and protection of ecosystems and forestry support and guarantees, including afforestation, regeneration, ecological benefit compensation, tree seedlings and pest control. These will greatly affect the potential of forest carbon sinks in mainland China, so the total investment in ecological restoration and management, forest product processing and manufacturing, forestry services, security and public management since the beginning of the year is selected as the variable of forestry investment completed in the yearbook to examine its impact on development potential of forest carbon sinks. The data of each province (autonomous region) were taken from the entry of "Forestry Investment Completion (2019)" in "China Statistical Yearbook 2020".

## 3. Model Building and Solving

### *3.1. Model Construction*

The concept of factor analysis originated from statistical analysis of intelligence tests by Karl Pearson and Charles Spearman in the early 20th century [18]. This method uses the idea of dimensionality reduction and, under the principle of ensuring the least loss of data information, starts from the correlation matrix of the original variables to determine truly related variables, classifies the variables with strong correlation into one category and finally forms several variables. The hypothetical variable is used as a common factor to reflect most of the information of the original data to achieve the purpose of data simplification. Combined with the 14 original variables selected above, the mathematical model is constructed as follows:

$$\left\{\begin{array}{l} x_1 = a_{11}f_1 + a_{12}f_2 + a_{13}f_3 + \cdots + a_{1k}f_k + \varepsilon_1 \\ x_2 = a_{21}f_1 + a_{22}f_2 + a_{23}f_3 + \cdots + a_{2k}f_k + \varepsilon_2 \\ x_3 = a_{31}f_1 + a_{32}f_2 + a_{33}f_3 + \cdots + a_{3k}f_k + \varepsilon_3 \\ \quad\vdots \qquad \vdots \qquad\qquad\qquad\qquad \vdots \\ x_{14} = a_{141}f_1 + a_{142}f_2 + a_{143}f_3 + \cdots + a_{14k}f_k + \varepsilon_{14} \end{array}\right. , \tag{1}$$

There are 31 samples in the original data, and each sample is described by 14 factors. In the model, $x_1$, $x_2$,..., $x_{14}$ are the original variables, $f_j$ (j = 1, 2,..., k) are independent common factors decomposed by the index, with a mean of 0 and a variance of 1, and they are unobservable; their meanings should be interpreted according to specific situations. $\varepsilon_i$ is a special factor, indicating the part of $x_i$ that cannot be explained by the common factor, and $a_{ij}$ is the factor loading, indicating the load of the i-th original variable on the j-th common factor. In this paper, the factor analysis method is used to classify the selected variables, such as forestry land area, forest area, forest tending area, afforestation area and timber production, and explain the original data with common factors to achieve the purpose of reducing the dimension of variables.

### *3.2. Model Solution*

As mentioned above, factor analysis requires a relatively strong correlation between the original variables, so correlation analysis is carried out first. Among them, the correlation coefficient between the forestry investment completion variable and other variables is mostly less than 0.3, and the Kaiser–Meyer–Olkin (KMO) test value is also less than 0.5, so this variable was excluded.

It can be seen from Table 1 that the KMO value is 0.662, which is suitable for factor analysis. In addition, the association probability given by Bartlett's sphericity test is 0.000, which is less than the significance level, so the null hypothesis of Bartlett's sphericity test is rejected; that is, there is a correlation between the original variables, which is suitable for factor analysis.

**Table 1.** KMO and Bartlett's test.

| | | |
|---|---|---|
| KMO Sampling Suitability Quantity | | 0.662 |
| Bartlett's test for sphericity | Approximate chi-square | 515.514 |
| | Degrees of freedom | 78 |
| | Significance | 0.000 |

Table 2 shows the total variance explained by extraction of common factors. According to the cumulative variance percentage in the initial eigenvalues, when four common factors are extracted, the explanation for the original variable has reached 85.017%. These four common factors can well explain the raw data.

**Table 2.** Total explained variance percent and cumulative percent for each factor.

| Element | Initial Eigenvalue | | | Extract Loading Sum of Squares | | | Rotational Load Sum of Squares | | |
|---|---|---|---|---|---|---|---|---|---|
| | Total | Percent Variance | Accumulation % | Total | Percent Variance | Accumulation % | Total | Percent Variance | Accumulation % |
| 1 | 5.312 | 40.858 | 40.858 | 5.312 | 40.858 | 40.858 | 3.494 | 26.880 | 26.880 |
| 2 | 3.005 | 23.117 | 63.975 | 3.005 | 23.117 | 63.975 | 2.917 | 22.441 | 49.321 |
| 3 | 1.663 | 12.792 | 76.767 | 1.663 | 12.792 | 76.767 | 2.763 | 21.255 | 70.576 |
| 4 | 1.073 | 8.251 | 85.017 | 1.073 | 8.251 | 85.017 | 1.877 | 14.441 | 85.017 |
| 5 | 0.631 | 4.855 | 89.873 | | | | | | |
| 6 | 0.402 | 3.096 | 92.968 | | | | | | |
| 7 | 0.324 | 2.490 | 95.458 | | | | | | |
| 8 | 0.276 | 2.121 | 97.579 | | | | | | |
| 9 | 0.137 | 1.057 | 98.635 | | | | | | |
| 10 | 0.125 | 0.959 | 99.595 | | | | | | |
| 11 | 0.046 | 0.350 | 99.945 | | | | | | |
| 12 | 0.007 | 0.053 | 99.998 | | | | | | |
| 13 | 0.000 | 0.002 | 100.000 | | | | | | |

Note: the extraction method in Table 2 is principal component analysis.

The factor loading matrix [19] was rotated according to the maximum variance method, and the results are shown in Table 3. After rotation, the meaning of each factor is clearer. The first factor has a higher load on the $X_1$, $X_2$, $X_6$ and $X_7$ variables; these four variables include forest stock and forest land use area and can indicate forest resources. Therefore, F1 can be named as the total forest resources factor. The second factor is on $X_9$, $X_{10}$, $X_{12}$ and $X_{13}$ variables have relatively high loads. Among them, the two variables of annual average temperature and precipitation are related to climate, while total output value of forestry industry and timber production are both outputs, so F2 can be named forest climate and output value factor. The third factor has relatively high loads on $X_3$, $X_4$ and $X_{11}$ variables. These three variables emphasize forestry ecological afforestation, so F3 can be named forest ecological construction factor. The fourth factor has higher loads on $X_5$ and $X_8$ variables. These two variables focus on improving forest quality and reducing severe biological disasters, so F4 can be named forest disaster prevention factor. From the explained total variance (Table 2), among the extracted four common factors, the first factor is the most important affecting forest carbon sink potential, which explains 40.858% of the original variables, and the remaining three factors are 23.117%, 12.792% and 8.251%.

**Table 3.** Loadings of 13 variables on 4 factors are shown in the rotated component matrix.

| | Element | | | |
|---|---|---|---|---|
| | **1** | **2** | **3** | **4** |
| Forest stock ($X_7$) | 0.986 | −0.059 | 0.093 | 0.029 |
| The total stock of standing trees ($X_6$) | 0.985 | −0.054 | 0.109 | 0.050 |
| Forest area ($X_2$) | 0.859 | 0.053 | 0.417 | 0.269 |
| Forestry land area ($X_1$) | 0.762 | −0.098 | 0.556 | 0.269 |
| Annual average temperature ($X_9$) | −0.203 | 0.887 | −0.069 | −0.089 |
| Precipitation ($X_{10}$) | 0.020 | 0.878 | −0.014 | −0.129 |
| Gross output value of forestry industry ($X_{13}$) | 0.007 | 0.810 | −0.037 | 0.379 |
| Timber production ($X_{12}$) | 0.147 | 0.588 | −0.083 | 0.548 |
| Afforestation area ($X_3$) | 0.132 | 0.011 | 0.854 | 0.210 |
| Forest fire damaged area ($X_{11}$) | −0.227 | −0.072 | −0.837 | −0.065 |
| Afforestation area of key forestry projects ($X_4$) | 0.242 | −0.416 | 0.786 | 0.100 |
| Forest tending area ($X_8$) | 0.196 | 0.175 | 0.218 | 0.872 |
| Area of pest and rodent control ($X_5$) | −0.075 | 0.360 | −0.388 | −0.665 |

Note: The extraction method in Table 3 is the principal component analysis method; the rotation method is the Kaiser normalization maximum variance method.

## 4. Results and Analysis

### *4.1. Factor Score*

By constructing the factor score function from the factor score coefficient matrix, the factor scores of each province and city can be calculated, as shown in Table 4 below. To improve the reader's readability of the following factor score analysis, the 2019 LULC map of China with 30 m accuracy can be used to show the forest profile of the study area, as shown in Figure 1.

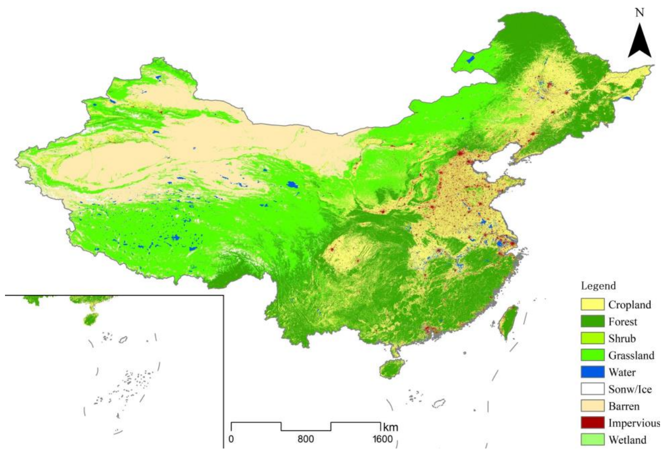


**Figure 1.** LULC map of China in 2019 (30 m accuracy).

**Table 4.** Ranking of 31 provinces and municipalities on the 4 factor scores and the ranking of the comprehensive score.

| Area | F1 | Sequence | F2 | Sequence | F3 | Sequence | F4 | Sequence | F | Sequence |
|---|---|---|---|---|---|---|---|---|---|---|
| Beijing | −0.661 | 25 | −0.637 | 22 | −0.916 | 28 | −0.570 | 25 | −0.598 | 29 |
| Tianjin | −0.700 | 27 | −0.593 | 21 | −0.917 | 29 | −0.710 | 26 | −0.619 | 30 |
| Hebei | −0.894 | 30 | −0.492 | 19 | 0.792 | 6 | 0.142 | 11 | −0.162 | 17 |
| Shanxi | −0.943 | 31 | −0.647 | 23 | 1.823 | 2 | −1.093 | 28 | −0.169 | 19 |
| Inner Mongolia | 1.295 | 5 | −0.935 | 26 | 3.557 | 1 | 0.738 | 6 | 1.001 | 1 |
| Liaoning | −0.426 | 15 | −0.523 | 20 | 0.378 | 9 | −0.425 | 20 | −0.213 | 23 |
| Jilin | 0.674 | 6 | −0.882 | 25 | −0.883 | 27 | 0.021 | 14 | −0.201 | 21 |
| Heilongjiang | 2.262 | 2 | −1.027 | 27 | −1.159 | 30 | 0.830 | 4 | 0.251 | 9 |
| Shanghai | −0.649 | 24 | 0.244 | 13 | −0.665 | 24 | −1.250 | 30 | −0.442 | 27 |
| Jiangsu | −0.621 | 23 | 0.269 | 12 | −0.803 | 26 | −0.318 | 17 | −0.323 | 25 |
| Zhejiang | −0.183 | 11 | 0.902 | 7 | −0.454 | 20 | −0.558 | 24 | −0.024 | 13 |
| Anhui | −0.544 | 19 | 0.023 | 16 | −0.798 | 25 | 1.120 | 3 | −0.149 | 16 |
| Fujian | 0.295 | 8 | 1.273 | 3 | −0.443 | 19 | 0.157 | 10 | 0.294 | 8 |
| Jiangxi | 0.043 | 9 | 1.098 | 5 | 0.195 | 11 | −0.005 | 15 | 0.299 | 7 |
| Shandong | −0.763 | 29 | 0.225 | 15 | −0.618 | 22 | 0.787 | 5 | −0.172 | 20 |
| Henan | −0.600 | 21 | −0.275 | 17 | −0.421 | 18 | 0.517 | 7 | −0.238 | 24 |
| Hubei | −0.481 | 18 | 0.459 | 9 | 0.656 | 7 | 0.161 | 9 | 0.136 | 10 |
| Hunan | −0.289 | 14 | 0.955 | 6 | 1.083 | 3 | 0.119 | 12 | 0.384 | 6 |
| Guangdong | −0.042 | 10 | 2.499 | 1 | 0.446 | 8 | 0.278 | 8 | 0.685 | 4 |
| Guangxi | 0.468 | 7 | 2.027 | 2 | −0.581 | 21 | 2.797 | 2 | 0.861 | 2 |
| Hainan | −0.436 | 16 | 1.163 | 4 | −0.416 | 17 | −1.509 | 31 | −0.163 | 18 |
| Chongqing | −0.674 | 26 | 0.301 | 11 | 0.343 | 10 | −0.545 | 23 | −0.119 | 15 |
| Sichuan | 1.924 | 4 | 0.481 | 8 | 0.194 | 12 | −0.380 | 18 | 0.612 | 5 |
| Guizhou | −0.204 | 13 | 0.365 | 10 | 0.184 | 13 | 0.075 | 13 | 0.077 | 11 |
| Yunnan | 2.112 | 3 | 0.228 | 14 | 0.912 | 4 | −0.827 | 27 | 0.693 | 3 |
| Tibet | 2.623 | 1 | −0.807 | 24 | −1.475 | 31 | −1.151 | 29 | 0.044 | 12 |
| Shaanxi | −0.190 | 12 | −0.400 | 18 | 0.835 | 5 | −0.432 | 21 | −0.026 | 14 |
| Gansu | −0.463 | 17 | −1.156 | 30 | 0.164 | 14 | −0.060 | 16 | −0.358 | 26 |
| Qinghai | −0.559 | 20 | −1.116 | 29 | −0.173 | 15 | −0.419 | 19 | −0.498 | 28 |
| Ningxia | −0.756 | 28 | −1.063 | 28 | −0.663 | 23 | −0.507 | 22 | −0.656 | 31 |
| Xinjiang | −0.620 | 22 | −1.960 | 31 | −0.180 | 16 | 3.018 | 1 | −0.209 | 22 |

Combining the names of the factors mentioned above and the factor scores of the provinces and municipalities calculated in Table 4, Tibet, Heilongjiang, Yunnan, Sichuan and Inner Mongolia all scored more than 1.25 on the factor of total forest resources, ranking in the order of top five scores for that factor. They are all located in famous Chinese forest areas, among which the Tibet forest area has complex terrain, high mountains and deep valleys, rich resources and high stock volume per unit area. Northeast and Inner Mongolia forest areas are located in high-latitude mountainous areas, with source and upstream water source areas of the Nen River, Songhua River, Tumen River and Yalu River. Yunnan and Sichuan Provinces are located in the alpine forest area of southwest China. Due to the influence of the Indian Ocean monsoon, the climate is warm and humid, and the environment is especially conducive to growth of trees. These areas are rich in total forest resources and their development potential of forest carbon sinks is remarkable. On the other hand, Tianjin, Ningxia, Shandong, Hebei, Shanxi and other regions have low scores on factor F1 and development potential of forest carbon sinks will be limited by total amount of forest resources to a large extent.

Guangdong, Guangxi, Fujian, Hainan, Jiangxi and other regions are mostly located in the subtropics and the tropics. The climate is mainly hot and humid, with high temperatures throughout the year, with an average temperature above 15 °C. Precipitation is abundant and rainfall is sufficient. These areas have higher scores on forest climate and output value factor F2, indicating that annual temperature and precipitation in these regions are conducive to photosynthesis of forest green plants and development of forestry industry and moderate restrictions in terms of timber production, it is at the forefront, and development potential of forest carbon sinks is huge. However, Heilongjiang, Ningxia, Qinghai, Gansu, Xinjiang and other places mostly have temperate climates and alpine plateau climates, characterized by cold winters and hot summers, large annual temperature differences, four distinct seasons, less annual rainfall and average annual precipitation is generally less than 600 mm, characteristic of semi-arid or arid regions. These areas have lower scores on the F2 factor, indicating that development potential in these areas is greatly affected by climate. Compared with other provinces and municipalities, there is still a large gap in total output value of forestry production departments in these areas.

Forest ecological construction factor scores vary greatly among different regions. The top five are Inner Mongolia, Shanxi, Hunan, Xinjiang, Yunnan and Shaanxi; the highest score can reach 3.557, showing that these areas have been effective regarding afforestation and forestry construction and construction of key forestry ecological projects. Development of forest carbon sinks has great potential. However, Jilin, Beijing, Tianjin, Heilongjiang, Tibet and other places have low scores on the F3 factor, which shows that forest ecological construction in these provinces and municipalities is relatively backward, and there are still gaps in forest fires protection compared with other provinces and municipalities. This large gap limits development of forest carbon sinks to a large extent.

Xinjiang, Guangxi, Anhui, Heilongjiang, Shandong and other provinces have higher scores on forest disaster prevention factor F4, indicating that these provinces have relatively complete forest disaster prevention and tending measures that are conducive to healthy growth of trees, improve quality of forest stands and promote function of resources of forest carbon sinks. However, Yunnan, Shanxi, Tibet, Shanghai, Hainan and other provinces and regions have lower scores on the F4 factor, indicating that their development potential is greatly affected by the factors of disease, pest and rodent control.

### *4.2. Comprehensive Score*

In order to obtain unified ranking of development potential of forest carbon sinks, four factors must be considered comprehensively. For this reason, variance contribution rate after rotation of each factor is used as the weight to carry out weighted summation, and the comprehensive score F of each province and city can be calculated, which is:

$$F = 0.26880 \times F1 + 0.22441 \times F2 + 0.21255 \times F3 + 0.14441 \times F4 \tag{2}$$

Among them, F1, F2, F3 and F4 are the scores of factor 1, factor 2, factor 3 and factor 4, respectively, and the previous coefficients are the variance contribution rate of each factor. Table 4 includes the comprehensive score values and corresponding rankings.

From the comprehensive score results, there are large differences in development potential of forest carbon sinks in the 31 provinces and municipalities. Among the comprehensive scores, 12 provinces and municipalities are above the average level, and the other 19 provinces and municipalities are lower than the average level. The top five regions with comprehensive scores are Inner Mongolia, Guangxi, Yunnan, Guangdong and Sichuan, and the bottom five are Shanghai, Qinghai, Beijing, Tianjin and Ningxia. Development potential of forest carbon sinks in the bottom five regions is far below the average level. To further analyze the relationship between development potential of forest carbon sinks in 31 provinces and municipalities across the country, the average Euclidean distance method of systematic clustering can be used to measure the interval, and the 31 provinces and municipalities can be divided into five categories. The results are shown in Figures 2 and 3.

The first category includes two regions, Inner Mongolia and Guangxi, whose comprehensive scores rank in the top two and have a significant advantage over other regions. These two autonomous regions are rich in forest resources and attach great importance to protection and cultivation of forest resources and prevention and control of pests and rodents. Therefore, they have high scores in the total forest resources factor and forest disaster prevention factor. Inner Mongolia's forest ecological construction factor score is higher than that of Guangxi, and Guangxi's forest climate and output value factor is higher than that of Inner Mongolia, indicating that Inner Mongolia pays more attention to forest ecological construction, such as afforestation and regeneration, while Guangxi tends to make full use of its climate advantages, resource advantages and location advantages to develop the forestry industry. They can set an example for other regions and jointly improve development potential of forest carbon sinks in mainland China.

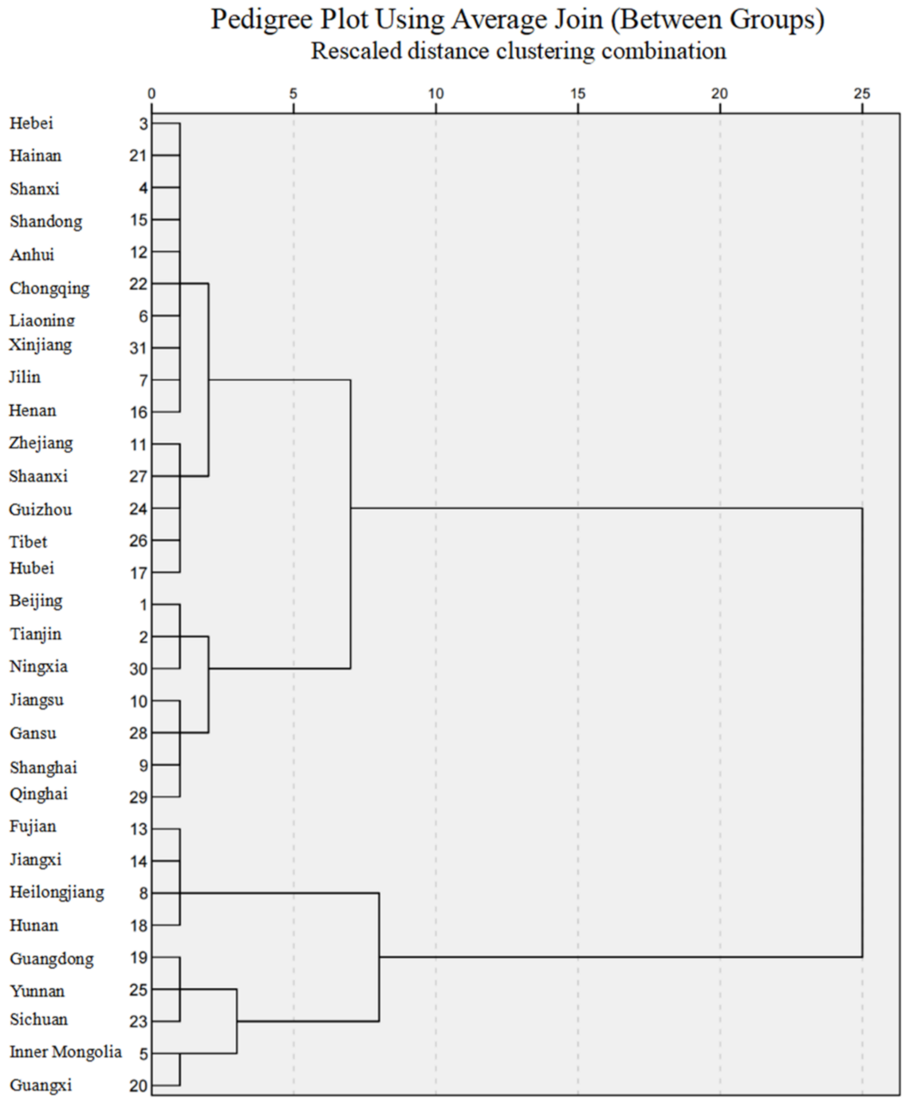


**Figure 2.** The 31 provinces in mainland China were classified into five categories according to their comprehensive scores using the clustering method of between-group linkage.

The second category includes Yunnan, Guangdong and Sichuan, and their comprehensive scores are all greater than 0.60, which is at the upper level of forest carbon sink development potential. The comprehensive scores of Yunnan Province and Guangdong Province are similar, and the two places rank high in the factor of total forest resources, especially Yunnan Province, which ranks first in the score of this factor and is known as the "Kingdom of Plants". However, Guangdong Province is significantly higher than Yunnan Province in terms of forest climate and output value factor and forest disaster prevention and control factor; that is, Guangdong pays more attention to forest tending and prevention of pests and rodents, and the forestry industry develops rapidly, but the comprehensive score of Yunnan Province ranks ahead of Guangdong Province, showing that total forest resources have a more important role in promoting development of forest carbon sinks. The comprehensive score of Sichuan Province is slightly lower, and its total forest resource factor score is relatively high. The relatively rich forest resources have laid a solid foundation for development of forest carbon sinks, but the forest disaster prevention factor score is not high. In the future development process, prevention and control of forest diseases, pests and rodents should be strengthened to prevent them from becoming a "bottleneck" for further improvement in this development potential.

The third category includes Hunan, Jiangxi, Fujian and Heilongjiang, whose comprehensive scores are all greater than 0.25, which is at the upper-middle level. Although Hunan Province is deficient in total amount of forest resources, the region pays attention to construction of forest ecological infrastructure. Rapid advancement in key forestry projects has effectively protected forest resources and achieved continuous "double growth" in forest area and stock accumulation. The advantage of the forest climate is more conducive to development of the forestry industry; it is recommended to continue to innovate and upgrade based on maintaining the current level. Jiangxi Province and Fujian Province not only have similar comprehensive scores but also have similar scores on the four common factors. They both have relatively rich forest resources and relatively mature forestry industry development levels, which have created favorable conditions for forest carbon sinks. However, the scores of these provinces are not high in forest ecological construction and forest disaster prevention. In the future development process, afforestation, forest tending and pest and rodent control should be strengthened to avoid restricting development of forest carbon sinks. Heilongjiang Province scores are very high in the factors of total forest resources and forest disaster prevention and control. Abundant forest resources and scientific and effective prevention and control of pests and rodents provide a broad space for development of the above potential. However, the cold climate conditions in this region are not conducive to development of the forestry industry and forest ecological construction and restrict development of forest carbon sinks to a certain extent.

The fourth category contains fifteen regions, such as Hubei, Guizhou, Tibet, Zhejiang, Shaanxi and Chongqing, whose comprehensive scores fluctuate around 0.00 at a medium level. Although the comprehensive scores of Hubei, Guizhou and Tibet are greater than zero, the scores are relatively small. Among them, development of forest carbon sinks in Hubei Province is more restricted by the factor of total forest resources, while the Tibet Autonomous Region is just the opposite: forest climate and output value, forest ecological construction and forest disaster prevention and control are the main factors that limit its development. Guizhou Province does not do well in terms of the four common factors and should improve relevant forestry policies, strengthen forest ecological construction and disaster prevention and comprehensively improve the level of the above-mentioned development. Although the comprehensive scores of the 12 provinces and cities headed by Zhejiang are less than zero, they are not far behind Hubei, Guizhou and Tibet. Among them, this potential development of Chongqing, Hebei, Shanxi and Shandong is affected by the limitation of total forest resources. The forest carbon sinks in Jilin, Xinjiang, Liaoning and Henan are greatly affected by lagging forestry industry development. The forest carbon sinks in Zhejiang, Shaanxi, Anhui and Hainan are greatly affected by serious pests and rodents.

The fifth category includes seven regions, including Jiangsu, Gansu, Shanghai, Qinghai, Beijing, Tianjin and Ningxia. Their comprehensive scores are all less than −0.32, and they are at a lower level of development potential. Among them, although the economies of Jiangsu, Shanghai, Beijing and Tianjin develop rapidly, due to insufficient total forest resources, forestry development lags behind other industries. Therefore, rational development of forestry industry resources and strengthening forest ecological construction are effective ways to expand forestry development space and increase development potential of forest carbon sinks. The comprehensive scores of Gansu, Qinghai and Ningxia have a certain gap compared with the provinces in the fourth category and a larger gap with the provinces in the first category. They have the lowest scores in forest climate and output value, and drought climate conditions seriously affect healthy growth of forest vegetation: dry climate has become the main factor restricting development of forest carbon sinks.

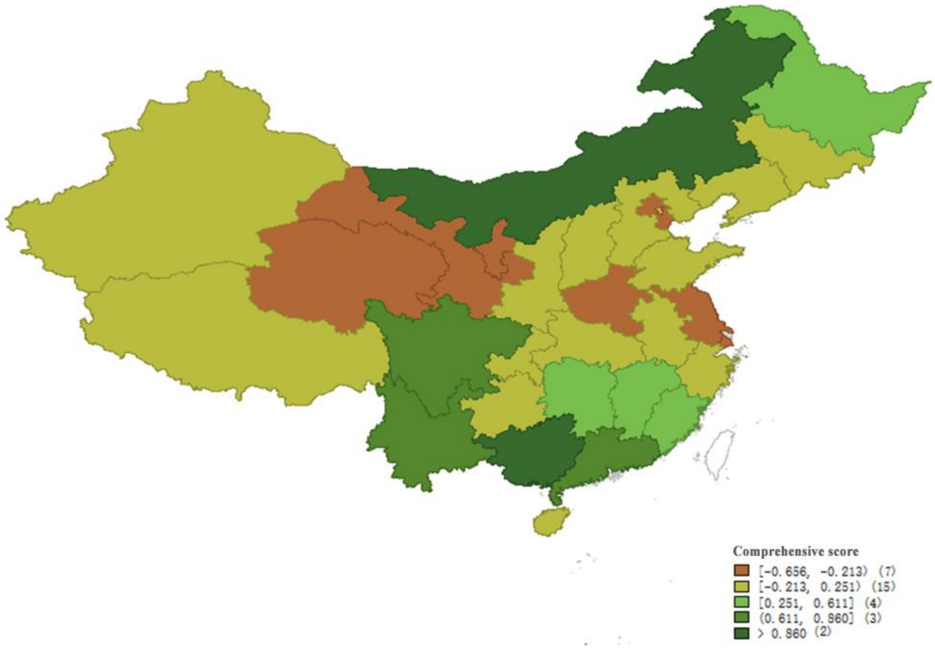


**Figure 3.** The results of the cluster analysis according to the comprehensive scores are shown in the map of mainland China.

## 5. Conclusions

Using the GM(1, 1) gray model, Zhang Ying et al. predicted that forest carbon stock will reach $100.13 \times 10^8$ t in 2030 and $180.32 \times 10^8$ t in 2060 and the forestry development target in Chinese independent emission reduction commitments can be accomplished [20]. If enough attention is paid to factors affecting forest carbon sink potential and the current forest management level is improved, the rate of change in forest carbon stock will gradually increase and the potential will be huge. This paper relatively comprehensively analyzes the influencing factors of forest carbon sink potential and concludes that total amount of forest resources is the most important factor affecting this potential, followed by forest climate and output value, forest ecological construction and forest disaster prevention and control. From the above analysis, ranking of factor scores and comprehensive score ranking of the 31 provinces and municipalities are quite different, indicating that development potential depends on the comprehensive influence of the four factors. At the same time, this ranking difference also shows that development of these four influencing factors in various provinces and municipalities is generally uneven. All regions should take appropriate measures according to their restrictive factors and local conditions and fully utilize carbon sink potential of forest resources. When a province has a low score on a common factor, this factor can be identified as a limiting factor of the province. The following are suggestions from the perspective of four common factors, namely four limiting factors, and improvement suggestions of each province are put forward.

(1) The potential development of Tianjin, Ningxia, Shandong, Hebei, Shanxi and other provinces is limited in terms of total forest resources. These areas should vigorously promote reform of the collective forest ownership system, fully mobilize enthusiasm of the masses through development of non-public forestry, realize afforestation of the whole people and promote steady increase in total amount of forest resources. In afforestation activities, all provinces and autonomous regions should not only consider the local climate and terrain conditions and pay attention to rational distribution of forest species but also ensure survival rate of trees, prevent afforestation from becoming a mere formality and expand the total amount of forest resources through multiple measures, improving development potential of forest carbon sinks.

(2) The potential development of Heilongjiang, Ningxia, Qinghai, Gansu, Xinjiang and other provinces and regions is limited in terms of forest climate and output value.

These areas can optimize the structure of the forestry industry and tap the development potential of the forestry industry through two aspects. The first aspect is to reduce impacts on forest resources and improve the economic and social benefits of forestry by developing non-wood products as the leading industry. The other aspect is to establish a unified forestry resource database and a good network platform to provide effective support for forestry e-government, forestry information disclosure and decision-making, and improve efficiency and level of forestry management [21]. In addition to optimizing the forestry industry structure, in the whole process of forest cultivation in these areas, the timber rotation period can be appropriately extended according to different forest species and tree species and harvesting can be completed in a controlled manner so that forest resources can be effectively managed and protected, which is conducive to forest carbon sinks development.

(3) The potential development of Jilin, Beijing, Tianjin, Heilongjiang, Tibet and other provinces and municipalities is limited in terms of forest ecological construction. These areas should strengthen forest ecological construction and reduce forest fires by strengthening scientific forest management. In afforestation projects, appropriate tree species should be selected in light of local actual conditions so that biological characteristics of afforestation tree species can adapt to site conditions of afforestation and give full play to production potential of forest land; in forest fire prevention work, all localities should strengthen forest fire prevention for awareness and legal concepts and an administrative accountability mechanism for forest fire prevention should be established. For situations such as ineffective supervision, it is necessary to determine the reasons and strictly hold them accountable to minimize area of forest fires and provide favorable conditions for development of forest carbon sinks.

(4) The potential development of Yunnan, Shanxi, Tibet, Shanghai, Hainan and other provinces and municipalities is limited in forest disaster prevention and control. These areas should first increase complexity of tree species structure, improve the overall stability of the forest ecosystem and the ability to resist natural disasters and, second, do a good job in forecasting of forest diseases, insect pests and rodents. In the work of rodent disaster prediction, implement a working policy of "prevention first, comprehensive management". When forest diseases, pests and rodents occur, measures such as chemical control, biological control, artificial control and bionic preparations should be taken in time to suppress or eliminate harmful organisms, minimizing damage from diseases, pests and rodents and protecting forest resources to the greatest extent, improving development potential of forest carbon sinks.

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