Sensors and Materials, Vol. 37, No. 1 (2025) 309–321
MYU Tokyo

S & M 3909

Construction and Application of a Model for Accounting the Forest Ecosystem Service Value in China Based on Forest Ecosystem Emergy Theory

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(Received August 19, 2024; accepted January 24, 2025)

Keywords: Chinese forest ecosystems, emergy, forest ecosystem service value

In this study, the multisource-obtained meteorological and vegetation data were used as basic data, and the distribution of forest biomass in China was dynamically simulated and calculated on the basis of emergy theory. At the same time, the forest ecosystem service value in China was estimated. According to the estimation results of China's forest ecosystem emergy and the ecosystem service value, the relationship between emergy and the service value of China's forest ecosystem was established, and the accounting model of China's forest ecosystem service value was constructed. Finally, the model was used to estimate and analyze the value of forest ecosystem services in China in 1990 and 2009. The results showed that the value density of national forest ecosystem services net increased by 54.46 USD/hm^2 from 1990 to 2009. In addition, forest ecosystem destruction was most severe in areas with high urbanization levels, such as Shanghai, Beijing, Jiangsu, Tianjin, and Hebei, followed by the middle and lower reaches of the Yangtze River, the lower reaches of the Yellow River, and the northern and central parts of northeast China. Forest destruction was also evident in Guangxi, Tibet, Gansu, Inner Mongolia, Sichuan, Yunnan, and Ningxia. In other areas, the density of forest ecosystem service values increased to different degrees. The results showed that the density of forest ecosystem service values in many provinces was still decreasing, which indicates that the forest ecosystem was still not fully restored, and human activities had a huge negative impact on the ecosystem.

1. Introduction

Forest ecosystems provide a wide range of services to humans, including soil conservation, climate regulation, and biodiversity, as well as economic, social, and cultural values.(1,2) With the rapid development of China's society and economy, in order to meet the needs of agricultural

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https://doi.org/10.18494/SAM5315

development and infrastructure construction, people have cut down forests in large quantities, which has led to serious damage to forest ecosystems and produced a series of ecological and environmental problems, such as air pollution, soil erosion, high-temperature climate, and species reduction. The global temperature rise caused by environmental pollution has changed precipitation patterns and distribution patterns, leading to the frequent occurrence of extreme weather events, which have a significant impact on forest ecosystems. At the same time, the rapid development of the economy and society has further intensified its impact on the structure and function of natural ecosystems.(3) According to the Ecosystem Assessment report, about 60% of global ecosystem services are facing degradation and this trend is expected to continue.(4) In this context, it is of great significance to clarify the ecosystem service value and development trends.

As early as the 1990s, people began to pay attention to ecology and environment and launched research on ecological and environmental issues. Researchers and scholars have extended the overall research direction to three research directions, namely, the species diversity of ecosystems, global change, and the sustainable development of ecosystems, and the value assessment of ecosystems has gradually become one of the research focuses. Currently, there are two main methods for valuing forest ecosystems, namely, the value of ecosystem services and emergy theory. In 1997, Costanza *et al.* pioneered a method for assessing the value of global ecosystem services and arrived at the average value of the services of various ecosystems worldwide.(5) Since then, scholars from various countries have conducted ecosystem service value assessment and theoretical research on several ecosystems in different regions of the globe on the basis of this methodology and have achieved meaningful research results.(6–14) However, owing to the need for a large amount of data on climate, natural resources, and economics in the process of calculating the ecosystem services value, data acquisition is difficult, calculations are complex, and long-term accounting is challenging. The emergy theory and analysis method proposed by Odum and Jiang(15) to quantitatively analyze the value of resources, commodities or services in ecosystems and economic systems solve the problem that substances of different grades and types cannot be analyzed and compared simultaneously. In this regard, scholars in China have carried out research on the emergy of many ecosystems in China, such as forests, grasslands, cities, and farmlands.(16–20)

The forest ecosystem is an important terrestrial ecosystem in China. Compared with other terrestrial ecosystems, the forest ecosystem has a more complete composition and structure, a more vigorous material cycle and energy flow, and a richer variety of living organisms; thus, they have the strongest ecological effect. Information from the Ninth National Forest Resources Inventory(21) shows that from 2014 to 2018, China's forest cover was 2.205 billion hm^2, the forest cover rate was 22.96%, and the forest stock was 17.56 billion. Changes in the forest ecosystem play an important role in the environment and ecology of China. The method of applying emergy theory to evaluate forest ecosystems is relatively simple, the information is easy to obtain, and it can be extrapolated over long time scales. If we can determine the relationship between the forest ecosystem service value and forest ecosystem emergy, we can calculate the ecosystem service value using the forest ecosystem emergy to solve the problems of the cumbersome calculation of the ecosystem service value and the difficulty in obtaining information. Therefore, the research objectives of this paper are as follows: (1) to construct an ecosystem service function value accounting model based on the emergy theory, and to study the functional relationship between the value of forest ecosystem services and the emergy of the forest ecosystems in China, and (2) to estimate the density of the forest ecosystem service value in 1990 and 2009 on the basis of the ecosystem service value accounting model in China. In the construction of the ecosystem service value accounting model, since Costanza *et al.*(5) estimated the global terrestrial ecosystem service value on the basis of the monetary standard of 1994, to maintain the consistency of the research data and reduce the error in the estimation process, in this study, we used 1994 as the benchmark for the construction of the ecosystem service value accounting model.

2. Materials and Methods

2.1 Data sources

The meteorological data selected for this study were obtained from the yearly annual precipitation and annual mean temperature data at a 0.5° × 0.5° grid resolution released by the Climatic Research Unit from 1901 to 2009. The vegetation data were derived from the main forest type data of 1266 forest sample plots in China, the 1995 national 1-km-grid land-use-type data from the Institute of Geographic Sciences and Resources of the Chinese Academy of Sciences, as well as from the 1994 global forest cover data and the 2009 global land-use-type data released by the European Space Agency.

2.2 Research methodology

2.2.1 Calculation of vegetation biomass data

On the basis of the research by Song *et al.*(22) and She *et al.*(23) on the growing season of forests, China was divided into three regions to calculate the actual evapotranspiration (ET), apoptosis, and net primary productivity (NPP). The northern region includes Heilongjiang, Jilin, Liaoning, Inner Mongolia Autonomous Region (IMAR), northern Gansu, and Xinjiang Uygur Autonomous Region (XUAR); the central region includes Shandong, Hebei, Beijing, Tianjin, Shaanxi, northern Jiangsu, northern Anhui, northern and northeastern Henan, northern and central Shaanxi, Ningxia Hui Autonomous Region (NHAR), most of the southern part of Gansu, Qinghai Province, most of Tibet, and the western part of Sichuan Province. The rest are southern regions.

Actual ET: Using the annual precipitation and annual mean temperature data with a grid resolution of 0.5° × 0.5° for each year from 1901 to 2009, data for the Chinese regions were extracted and linearly interpolated to obtain the annual precipitation and annual mean temperature data with a grid resolution of 0.1° × 0.1° for the years from 1901 to 2009 in China. The actual ET data with a grid resolution of 0.1° × 0.1° for China for 109 years were calculated by combination with the model proposed by Turc.(24) The calculation formulas used are

$$AET = P/[0.9 + (P^2/L^2)^{1/2}], \tag{1}$$

$$L = 300 + 25T + 0.05T^3. \tag{2}$$

In these formulas, P is the annual precipitation (mm/a) and T is the annual average temperature (℃).

The NPP data were calculated using the Miami model.(25) The formula used is

$$NPP = 3000\{1 - \exp([-0.0009695 \times (AET - 20)])\}. \tag{3}$$

In this formula, NPP is in g/m^3.

Biological withering is derived from the functional relationship between the biomass and annual withering of the major forest types in China established by Wang.(26)

Biomass data: Vegetation biomass (BIO) consists of the previous year's biomass (BIO_0) and the current year's community growth (ΔBIO). According to Wang *et al.*,(26) NPP can be approximated as equal to the community growth (ΔBIO) and annual withering (L). From this, it can be deduced that biomass (BIO) can be calculated as the sum of the previous year's biomass (BIO_0) and the current year's NPP minus the previous year's withering amount (L).

2.2.2 Calculation of emergy of forest ecosystems

Emergy theory is a new scientific theory system proposed by the famous ecologist H. T. Odum.(15) Odum defines emergy as the amount of another category of energy contained in one type of flowing or stored energy, and further explained it as the total amount of effective energy that is directly or indirectly put into application in the process of forming a product or a labor service. Since the energy of all types of natural resources, products, and services is directly or indirectly derived from solar energy, the solar emergy is mostly used to measure the emergy of a certain energy in units of solar energy joules (sej).(27) The forest biomass was simulated dynamically on the basis of emergy theory.(15,27–30) In this method, the data of major forest types in 1266 forest sample plots across the country, annual precipitation, and annual precipitation at a grid resolution of 0.1° × 0.1° year by year from 1901 to 2009 in China, which was derived by linear interpolation in calculating actual ET, were applied to simulate the forest biomass distribution of China in 1994 and calculate its emergy. Then, the nonforested grid points were assigned as 0 on the basis of the 1-km-grid land use data of China in 1995, and the following were obtained:

$$EN_{(BIO)} = BIOMASS \times 3.6\ (\text{kcal/g}) \times 4186\ (\text{J/kcal}), \tag{4}$$

$$EM_{(BIO)} = EN_{(BIO)} \times Tr_{(BIO)} \times S_{(BIO)}. \tag{5}$$

Here, $EN_{(BIO)}$ is the energy from the forest biomass in J/(hm^2.a), $EM_{(BIO)}$ is forest emergy in sej, $Tr_{(BIO)}$ is the solar emergy conversion rate in sej/J, and $S_{(BIO)}$ is the area of the forested land in the grid in hm^2.

2.2.3 Calculation of forest ecosystem service value

The value of forest ecosystem services in China in 1994 was estimated referring to Costanza *et al.*'s study(5) of global ecosystem services and natural capital values in 1994 and combined with the corresponding 0.25° × 0.25°-grid-resolution land-use-type coverage data (ISLSCPII) published by NASA. The service value data is based on the classification method of land-use-type coverage data in the IGBP plan, which divides the global land into 17 land use types. Each grid corresponds to a land use type with an average service value. Therefore, in this study, we first interpolate the land-use-type coverage data to a grid resolution of 0.1° × 0.1°, then determine the land use type of the grid and extract the total value of service for all land use types under each grid, without considering nonforest grids (Fig. 1). Finally, the relationship between the forest ecosystem service value, forest ecosystem energy value, and geographic coordinates on a provincial basis is established. Since the number of forested land grids in Shanghai and Tianjin was very small, they were combined with Jiangsu and Hebei, respectively, to jointly establish the relationship.

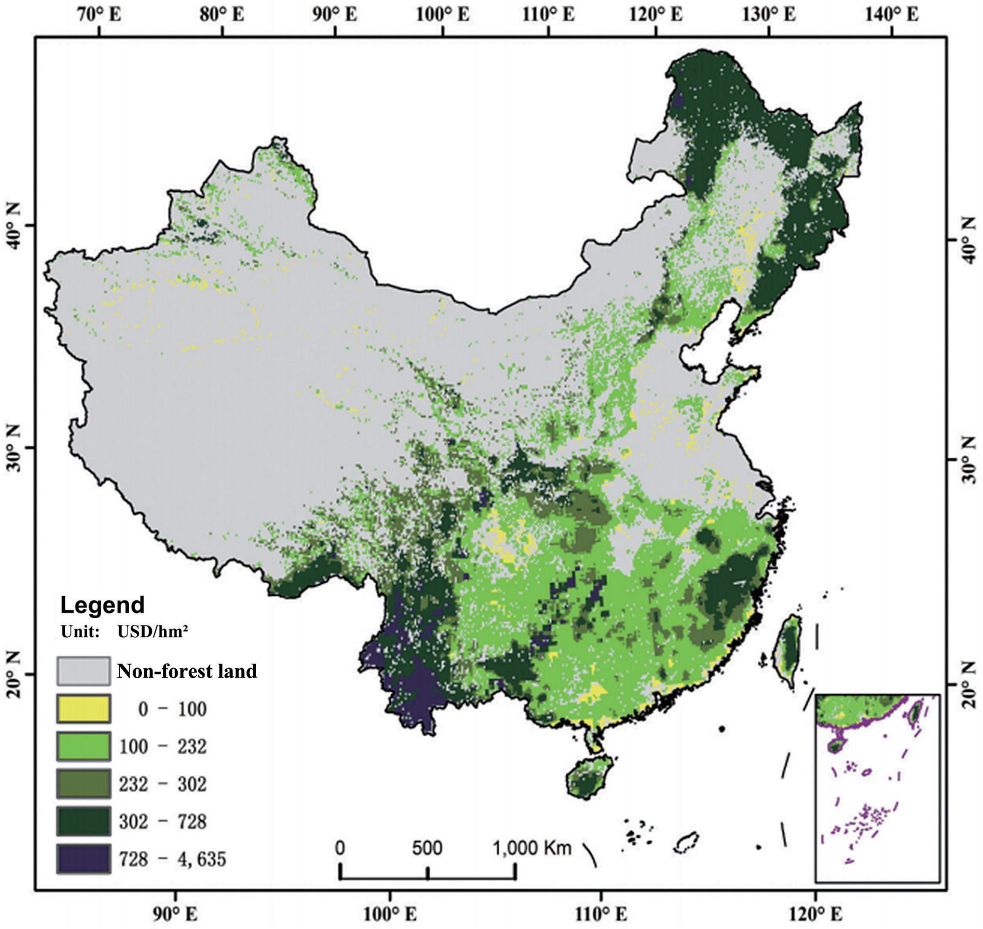

Fig. 1. (Color online) Value of forest ecosystem services in China in 1994.

3. Results and Analysis

3.1 Distribution of emergy in forest ecosystems

According to the simulation results of the emergy dynamic model (Fig. 2), in 1994, China's forest emergy reserve was better in the south than in the north. From the spatial distribution of emergy in forest ecosystems in each province, the distribution of the forest emergy basically coincided with the distribution of the forest area. The average forest energy density of the forest ecosystems in each province was the highest in the Tibet Autonomous Region (TAR) with 2.87×10^{17} sej/hm^2, followed by Qinghai, Fujian, and Jiangxi Provinces with 2.28×10^{17}, 2.21×10^{17}, and 1.86×10^{17} sej/hm^2, respectively. The average forest energy densities of the forest ecosystems in Shanghai, Jiangsu, and Shandong Provinces were the lowest at 8.31×10^{16}, 7.80×10^{16}, and 6.84×10^{16} sej/hm^2, respectively. However, in terms of the total forest emergy of the forest ecosystems in the provinces, there was a slight difference in the distribution of the forest emergy and forest emergy density. The province with the highest total forest emergy is Yunnan with 3.61×10^{24} sej, followed by TAR, Heilongjiang, and Sichuan with 3.59×10^{24}, 3.16×10^{24}, and 2.92×10^{24} sej, respectively. The regions with the lowest forest emergy are Jiangsu Province, Tianjin Municipality, and Shanghai Municipality with 2.07×10^{22}, 2.60×10^{21}, and 2.99×10^{19} sej, respectively. It can be seen that the emergy of the forest ecosystem is affected not only by the density of the forest emergy, but also by the forest area. The spatial distributions of the total forest ecosystem emergy and the forest ecosystem service value had high consistency (Figs. 1 and 2).

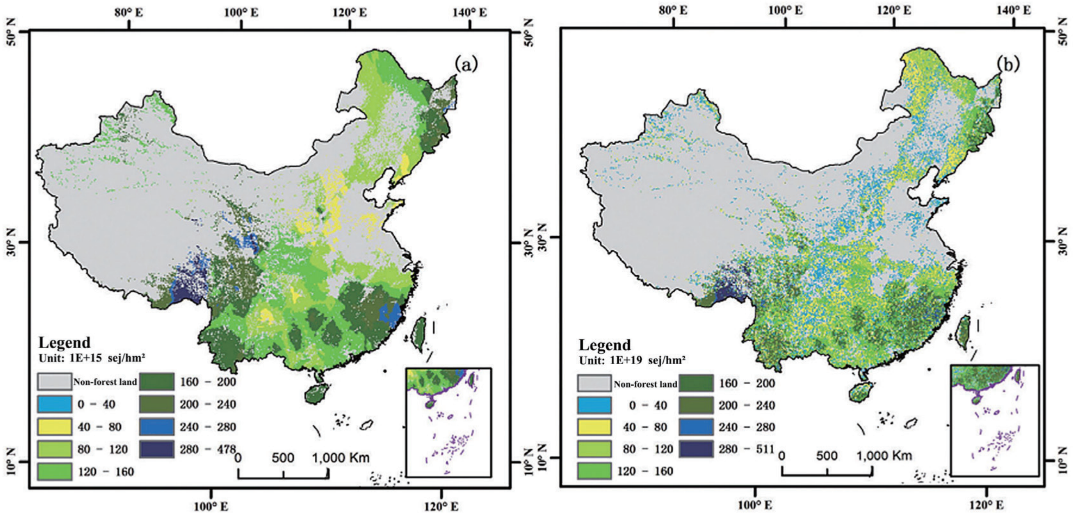

Fig. 2. (Color online) (a) Density of forest emergy in China 1994 and (b) total forest emergy on every 0.1° × 0.1° grid of China in 1994.

3.2 Model construction for accounting the value of forest ecosystem services

On the basis of the average forest ecosystem energy density data and the raster data of the forest service value in 1994, combined with latitude and longitude coordinates, the relationship between forest energy density and service value was established (Table 1). FSV is the forest ecosystem service value (unit: USD/hm^2), X is longitude, Y is latitude, and DEN is the forest emergy density, i.e., $EN_{(BIO)} \times Tr_{(BIO)}$ (unit: 1×10^{15} sej/hm^2). The significance test indicated a significant correlation at the 0.01 level ($p < 0.01$). The relationship between forest ecosystem emergy and service value was used to simulate the average FSV density in China in 1994. The simulation results showed that China's FSV was 0.3–1011.19 USD/(hm^2.yr) in 1994, and its change pattern was consistent with the results estimated by Costanza *et al.*(5) and Chen and Zhang(9) (Fig. 3). However, the mean value of the ecosystem services of the forest per unit area was lower than that estimated by Costanza *et al.*(5) and Chen and Zhang.(9) The roughness of the

Table 1
Relationship between forest ecosystem emergy and service value.

Province	Service Value − Emergy Equation	*n*	*R*
Anhui	$FSV = 14.403 \times X - 32.850 \times Y + 2.625 \times DEN - 763.028$	486	0.55^{**}
Beijing	$FSV = - 61.249 \times X + 202.436 \times Y - 5.424 \times DEN - 281.426$	119	0.85^{**}
Fujian	$FSV = 37.284 \times X + 80.941 \times Y - 0.153 \times DEN + 2590.789$	1009	0.77^{**}
Gansu	$FSV = - 4.855 \times X - 23.368 \times Y - 0.230 \times DEN + 1620.022$	928	0.33^{**}
Guangdong	$FSV = - 4.760 \times X + 34.919 \times Y + 0.255 \times DEN - 160.495$	1331	0.59^{**}
Guangxi	$FSV = 57.016 \times X + 38.484 \times Y - 0.286 \times DEN + 5541.518$	1865	0.70^{**}
Guizhou	$FSV = 52.239 \times X - 53.432 \times Y + 0.928 \times DEN - 4023.813$	1462	0.45^{**}
Hainan	$FSV = 0.091 \times X - 62.952 \times Y + 10.826 \times DEN - 400.617$	216	0.44^{**}
Hebei[a]	$FSV = - 9.994 \times X + 27.163 \times Y - 0.406 \times DEN + 230.978$	862	0.53^{**}
Henan	$FSV = - 30.274 \times X - 36.724 \times Y - 1.536 \times DEN + 4963.812$	457	0.60^{**}
Heilongjiang	$FSV = 24.491 \times X + 33.580 \times Y - 1.569 \times DEN - 3983.125$	3337	0.48^{**}
Hubei	$FSV = 5.437 \times X + 11.126 \times Y + 0.792 \times DEN + 1497.928$	1293	0.61^{**}
Hunan	$FSV = - 49.713 \times X - 24.774 \times Y - 1.605 \times DEN + 6729.276$	1763	0.25^{**}
Jilin	$FSV = 34.312 \times X - 43.649 \times Y - 0.972 \times DEN - 2218.864$	1279	0.64^{**}
Jiangsu[b]	$FSV = - 12.536 \times X - 13.358 \times Y - 1.134 \times DEN + 2112.845$	84	0.42^{**}
Jiangxi	$FSV = 12.287 \times X - 11.455 \times Y - 0.631 \times DEN - 785.422$	1346	0.28^{**}
Liaoning	$FSV = 86.061 \times X - 40.867 \times Y + 3.122 \times DEN - 8907.368$	984	0.74^{**}
Inner Mongolia	$FSV = - 8.023 \times X + 49.801 \times Y + 0.153 \times DEN - 1002.052$	3366	0.69^{**}
Ningxia	$FSV = 4.796 \times X - 12.272 \times Y - 0.083 \times DEN + 173.886$	86	0.49^{**}
Qinghai	$FSV = 15.046 \times X - 11.582 \times Y - 0.073 \times DEN - 876.818$	781	0.53^{**}
Shandong	$FSV = - 7.055 \times X + 18.402 \times Y + 0.789 \times DEN + 226.407$	300	0.38^{**}
Shanxi	$FSV = - 1.292 \times X - 2.775 \times Y + 0.204 \times DEN + 407.927$	823	0.25^{**}
Shaanxi	$FSV = - 17.629 \times X - 5.959 \times Y + 0.671 \times DEN + 2312.608$	1052	0.60^{**}
Sichuan	$FSV= - 21.732 \times X - 4.793 \times Y - 0.152 \times DEN + 2704.639$	3690	0.19^{**}
Taiwan	$FSV = 06.024 \times X + 122.685 \times Y + 8.597 \times DEN - 17051.409$	227	0.35^{**}
*X*izang	$FSV =3.108 \times X - 39.398 \times Y + 0.205 \times DEN + 1089.818$	1560	0.44^{**}
*X*injiang	$FSV = - 6.979 \times X + 21.440 \times Y + 0.193 \times DEN - 194.805$	1169	0.52^{**}
*Y*unnan	$FSV= - 101.968 \times X - 96.942 \times Y + 0.011 \times DEN + 13321.155$	2971	0.72^{**}
Zhejiang	$FSV = 41.664 \times X - 107.529 \times Y - 0.729 \times DEN + 8435.438$	762	0.63^{**}
Chongqing	$FSV =42.034 \times X - 15.042 \times Y + 0.653 \times DEN - 3995.561$	556	0.49^{**}

(1) a: including Tianjin; b: including Shanghai: (2) ** indicates significance at the 0.01 level; (3) *n*: number of forest grids; *R*: correlation coefficient.

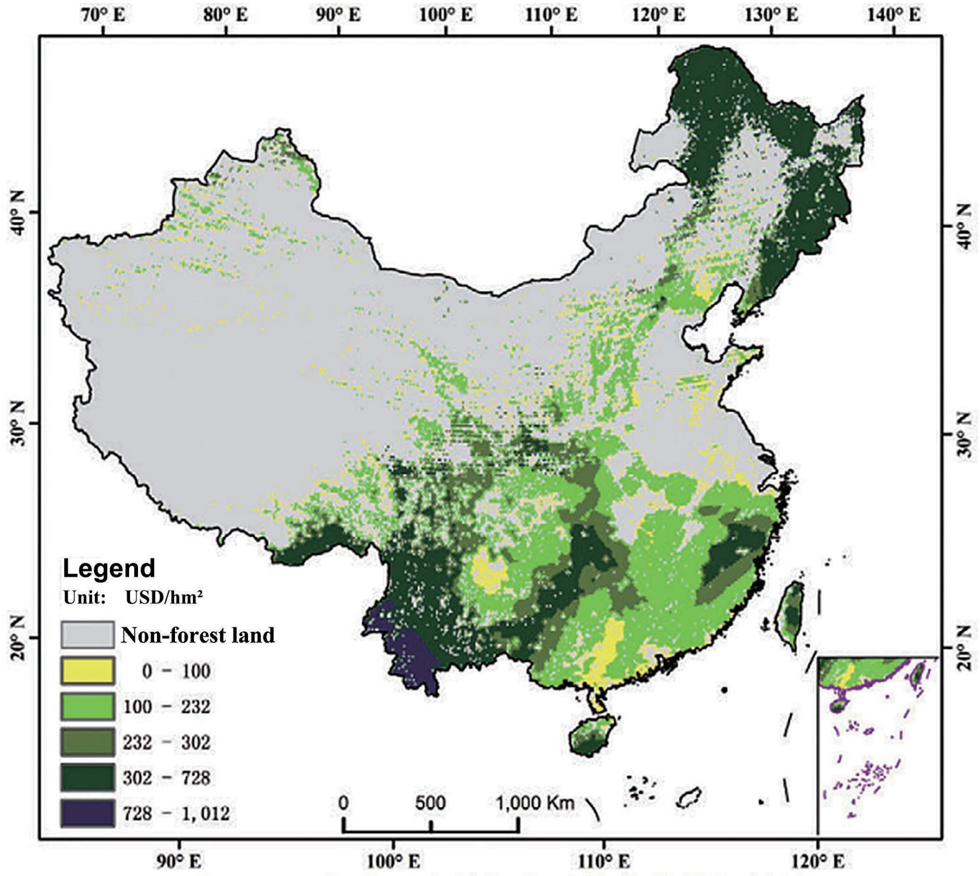

Fig. 3. (Color online) Model result of Chinese FSV in 1994.

forest cover data and the small amount of biomass data are the main reasons for the deviation of the calculation results.

3.3 Dynamic changes in Chinese FSV

On the basis of the relationship established between emergy and FSV in China in 1994, the densities of FSV in China in 1990 and 2009 were estimated. The total FSV was not estimated because China has not yet published data on the area occupied by each land use type in the raster for China's land cover data after 2000.

Raster-by-raster calculation revealed that the number of rasters of the forested land nationwide increased by 14.02% in 2009 compared with that in 1990. Thirteen provinces and municipalities directly under the central government showed an increasing trend in the average FSV density, and 19 provinces and municipalities directly under the central government showed a decreasing trend in the average FSV density (Figs. 4 and 5). The national average density of FSV increased from 229.50 USD/hm^2 in 1990 to 282.96 USD/hm^2 in 2009. Among them, except for the three provinces of Heilongjiang, Inner Mongolia, and Liaoning, the forest services

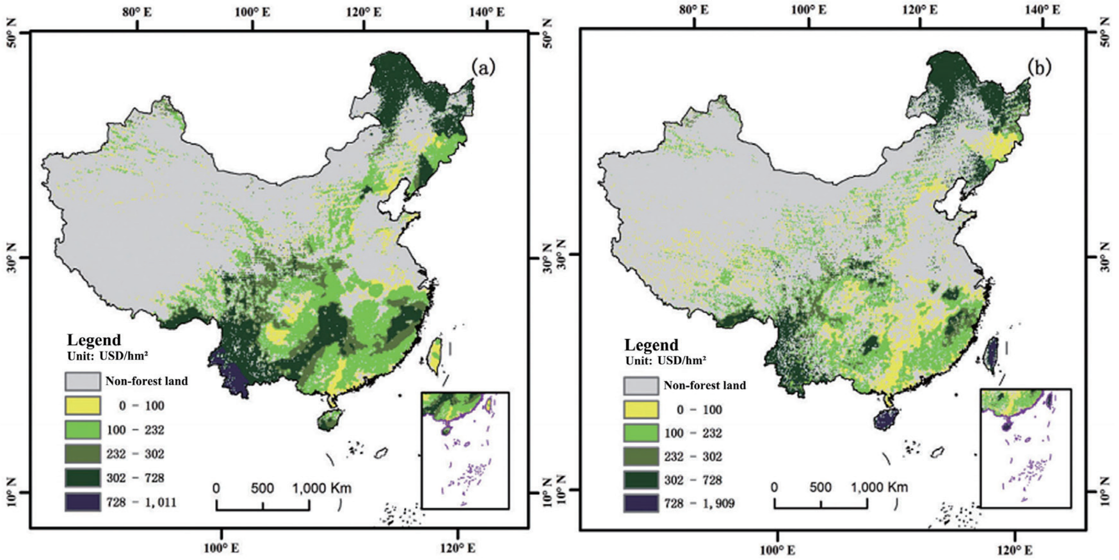

Fig. 4. (Color online) FSV of China in (a) 1990 and (b) 2009.

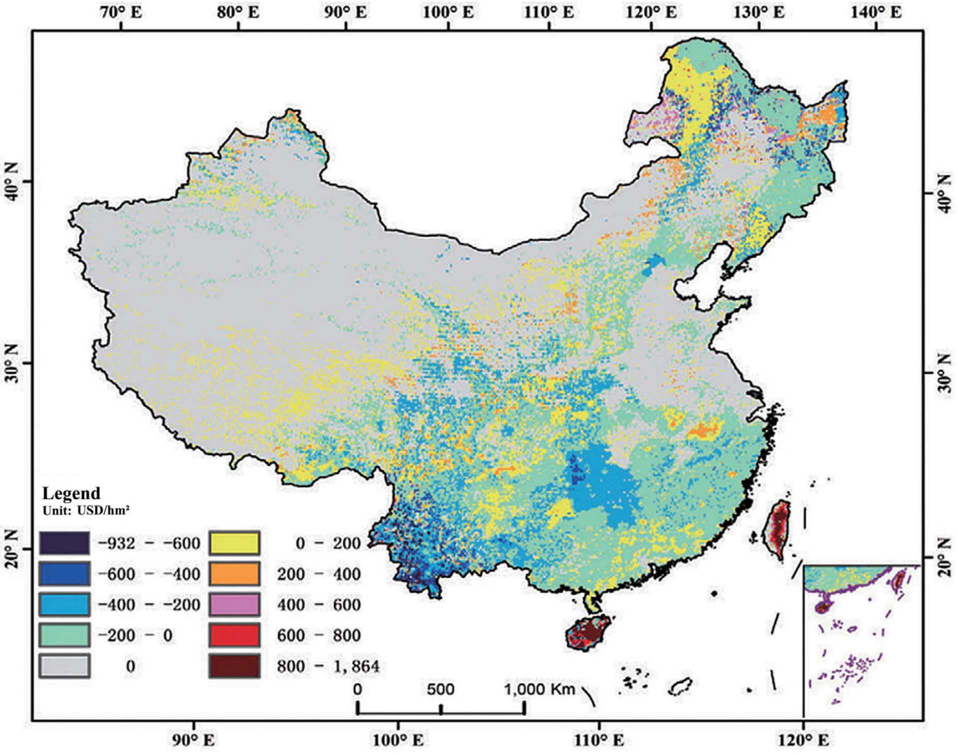

Fig. 5. (Color online) Change in FSV in China between 1990 and 2009.

provided by the southern region are greater than those provided by the northern region, which is consistent with the spatial distribution pattern of China's forests and biodiversity.

Until 2009, the highest average densities of FSV of each province and city were in Hainan, Taiwan, and Yunnan with 1689.19, 900.66, and 540.58 USD/hm^2, followed by Liaoning, Heilongjiang, and Inner Mongolia with 433.88, 424.83, and 401.53 USD/hm^2, and the lowest average FSV densities were in Tianjin, Beijing, Jiangsu, and Shanghai with 59.83, 50.42, 21.80, and 14.11 USD/hm^2, respectively. In terms of the amount of change in the density of FSV, four areas, namely, Beijing, Hunan, Henan, and Heilongjiang, showed the least change in FSV density, whereas those in Hainan, Taiwan, Anhui, and Liaoning increased the most.

In terms of spatial distribution, forest ecosystems are most severely damaged in areas with high levels of urbanization. For example, in Shanghai, Beijing, Jiangsu, Tianjin, and Hebei, the average FSV density decreased by 86.87, 85.45, 81.99, 46.48, and 23.07%, respectively, followed by the middle and lower reaches of the Yangtze River and the lower reaches of the Yellow River, as well as the northern and central regions of Northeast China. The average FSV density in Henan, Hunan, Jilin, Jiangxi, Heilongjiang, and Zhejiang decreased by 71.35, 58.65, 52.70, 34.56, 23.36, and 23.36%, respectively. In Henan, Hunan, Jilin, Jiangxi, Heilongjiang, and Zhejiang, the average FSV density decreased by 71.35, 58.65, 52.70, 34.56, 23.36, and 22.03%, respectively. In Guangxi, Tibet, Gansu, Inner Mongolia, Sichuan, Yunnan, and Ningxia, forest destruction is also relatively obvious; the average FSV density decreased by 22.36 to 2.89%. The FSV density in other regions increased to different degrees. The above results show that the main reasons for the decrease in FSV density are frequent human activities, continuous urban expansion, and the long-term development of agriculture in these areas. According to the 4th and 7th National Forest Inventory Reports, China's forest area has continued to increase in recent years, but the FSV density is still in a declining trend, which indicates that forest ecosystems are recovering more slowly and also that the rate of destruction of the forest ecosystems in China is much higher than the rate of recovery, so that forest protection and sustainable development need to be carried out over a long period of time.

4. Discussion

The FSV has been emphasized, and there are more and more methods of assessment. However, the research on the service functions and value assessment of forest ecosystems in China still faces many challenges, such as insufficient theoretical research, an incomplete value assessment system, inconsistent assessment methods, and single data acquisition methods, which considerably affect the development of forest ecosystem services in China.(31,32) In this study, we only initially established the relationship between forest emergy and service function value referring to forest ecosystem emergy and service function value at the provincial level. We provided a new idea for future ecosystem service function value assessment: to determine the relationship between ecosystem emergy and service value, and then established the ecosystem service function value model for simplifying the cumbersome estimation method. In the course of this study, we found that although China's forest area is large, its ecological environment is not ideal, and the impact of human activities on forest ecosystems is huge. The service value of

China's forest ecosystems is slightly lower than the world average level. Although the economy is developing at a high rate, deforestation should be reduced, afforestation should be promoted, and the protection of forest ecosystems should be strengthened. There are still many shortcomings in the research process because the forest service function information is based on Costanza *et al.*'s(5) research results, which show the average global forest service value, and a functional relationship based on the forest type cannot be established. Secondly, there is a lack of data on forest roots and biomass, and there are also some errors in estimating forest emergy. In future research work, we will strive to obtain more diverse and accurate data for in-depth and detailed analysis, providing scientific methods and approaches to support the accounting and evaluation of the value of ecosystem services in China.

5. Conclusions

On the basis of emergy theory and ecosystem service function theory, we established a functional relationship between emergy and FSV density in China. Thus, a model for accounting forest ecosystem services in China was constructed and used to study the service value density of Chinese forest ecosystems and their changes in 1990 and 2009. The results of this study show the following:

(1) On the basis of forest emergy, service function value density, and coordinate data, the relationship between emergy and FSV in China was established, and significance tests showed a significant correlation at the 0.01 level. The average FSV density in China in 1994 was simulated to be 0.3–1011.19 USD/(hm^2.yr), and the pattern of change was consistent with the results estimated by Costanza *et al.*(5) and Chen and Zhang.(9) However, the average value of ecological services per unit area was lower than those estimated by Costanza *et al.*(5) and Chen and Zhang.(9)

(2) The analysis of the change in FSV per unit area in 1990 and 2009 showed that the national average FSV density in 2009 increased by 54.46 USD/hm^2 compared with that in 1990. However, the results of the analysis of each province showed that, compared with that in 1990, the average FSV density in 13 provinces (municipalities directly under the central government) in China in 2009 showed an upward trend and 19 provinces (municipalities directly under the central government) showed a downward trend. Among them, Beijing, Hunan, Henan, and Heilongjiang had the largest decreases in average FSV density, while Hainan, Taiwan, Anhui, and Liaoning had the largest increases.

(3) In terms of spatial distribution, forest ecosystems in areas with high levels of urbanization have been most severely damaged, with the average FSV density in Shanghai and Beijing declining by 86.87 and 85.45%, respectively, followed by the middle and lower reaches of the Yangtze River and the lower reaches of the Yellow River, as well as the northern and central parts of Northeast China. The average FSV densities in Henan, Hunan, Jilin, Jiangxi, Heilongjiang, and Zhejiang declined by 71.35–22.03%. Forest ecosystems in remote areas in the west and south were also damaged to varying degrees. The average FSV densities in Guangxi, Tibet, Gansu, Inner Mongolia, Sichuan, Yunnan, and Ningxia decreased by 22.36–2.89%, and all other areas had increases of varying degrees.

References

1 T. Q. Zhao, Z. Y. Ouyang, H. Zheng, X. K. Wang, and M. Hong: J. Nat. Resour. **19** (2004) 480. https://kns.cnki.net/kcms2/article/abstract?v=l4Uq_U3qQ8M-Z2XkYAsWoc4w-RguHmp04Lr-DMDbzrC7kqeBZy5IdToPyKzdJrIsfyB9MP095N-MRJM7uAXLYalTHolw0SomjQ2Wb-Kf764xIEcyUQapQeT8_7RsVzpwneEupp_Wc66bPaMwirh1Rvf8kdeL2xJAwSlTK87fSWcfOHwHGc60GAnad6sqroP9&uniplatform=NZKPT&language=CHS

2 Q. Sun and H. Zhou: Arid Land Geogr. **43** (2020) 1327. https://kns.cnki.net/kcms2/article/abstract?v=l4Uq_U3qQ8OoDPyLDhyP-_dNb-ujnxIdoODmNP0p8miSEyTC1if9UttKLPFZseMna0WtL7CdxHBmcv7p_vulQOOhBbrLXFVbS5yMbIVyOZryLrS0b5GzE8OL18e-z6IOj89Gdti-W-NS0C1Zobv_iuQePP6pn9jUJsLOCayhD1L2jIghGzeyywZ5NTQDHUCg&uniplatform=NZKPT&language=CHS

3 J Pandit and A. K. Sharma: J. Water Clim. Change **14** (2023) 4273. https://iwaponline.com/jwcc/article/14/11/4273/98526/A-comprehensive-review-of-climate-change-s-imprint

4 J. A. Foley, R. Defries, G. P. Asner, C. Barford, G. Bonan, C. R. Stephen, C. F. Stuart, C. T. Coe, D. C. Gretchen, G. K. Holly, H. H. Joseph, H. Tracey, H. A. Erica, K. J. Christopher, M. Chad, P. A. Jonathan, P. I. Colin, R. Navin, and S. K. Peter: Science **309** (2005) 570. https://www.science.org/doi/10.1126/science.1111772

5 R. Costanza, d'R. Arge, R. Groot, S. Farber, M. Grasso, B. Hannon, K. Limburg, S. Naeem, R. V. O'Neill, J. Paruelo, R. G. Raskin, P. Sutton, and M. Belt: Nature **387** (1997) 253. https://doi.org/10.1016/S0921-8009(98)00020-2

6 T. Tscharntke, A. M. Klein, A. Kruess, I. S. Dewenter, and C. Thies: Ecol. Lett. **8** (2005) 857. https://onlinelibrary.wiley.com/doi/epdf/10.1111/j.1461-0248.2005.00782.x

7 I. J. Bateman, G. M. Mace, C. Fezzi, G. Atkinson, and K. Turner: Environ. Resour. Econ. **48** (2011) 177. https://link.springer.com/content/pdf/10.1007/s10640-010-9418-x.pdf

8 Y. L. Jiang and G. S. Zhou: Chin. J. Plant Ecol. **25** (1999) 426. https://www.plant-ecology.com/CN/Y1999/V23/I5/426

9 Z. X. Chen and X. S. Zhang: Chin. Sci. Bull. **45** (2000) 17. https://kns.cnki.net/kcms2/article/abstract?v=l4Uq_U3qQ8OXBX5cBKT4baTaAYPYrTBlOJWU7ZufJopA-yzeNG5mzIUpQSnG0VfAzB7lnNdks4mSZdUKi7GovEQ9j3DV5alYzl48tfpMiDQEVP1SziMUhN1k02CoFT2hvBFwdU2OTzxrYkFN4DUYTsIpSJ_06mm4rBhDNsbRLuCwsm6vOaSjsXhDnudWOj9W&uniplatform=NZKPT&language=CHS

10 G. D. Xie, Y. L. Zhang, C. X. Lu, D. Zheng, and S. K. Cheng: J. Nat. Resour. **16** (2001) 47. https://kns.cnki.net/kcms2/article/abstract?v=l4Uq_U3qQ8PeIs3_r85C4bDr4CNRdJJal8z-tL-s6doTbAFrd8DPXpWyBZ8U8woEAKNPZEBsDbGscqZERCXvtFH0J9cAF5wxFlYN-w8y2qVg708d_orhNrTlIWIN9oMW5QOM3AxLe9nD4kDPzqzUeIIx4NPR30KCaR6HVTuGnUxmC4XluLaFKaaD9Ou8KCT5&uniplatform=NZKPT&language=CHS

11 T. Q. Zhao, Z. Y. Ouyang, H. Zheng, X. K. Wang, and M. Hong: J. Nat. Resour. **19** (2004) 480. https://kns.cnki.net/kcms2/article/abstract?v=l4Uq_U3qQ8M-Z2XkYAsWoc4w-RguHmp04Lr-DMDbzrC7kqeBZy5IdToPyKzdJrIsfyB9MP095N-MRJM7uAXLYalTHolw0SomjQ2Wb-Kf764xIEcyUQapQeT8_7RsVzpwneEupp_Wc66bPaMwirh1Rvf8kdeL2xJAwSlTK87fSWcfOHwHGc60GAnad6sqroP9&uniplatform=NZKPT&language=CHS

12 H. P. Huang, P. Z. Li, Y. P. Han, S. H. He, X. D. Huang, W. B. Mu, and C. Y. Wang: Yellow River **46** (2024) 90. https://kns.cnki.net/kcms2/article/abstract?v=l4Uq_U3qQ8N87XV6vRuet2kWVdUNuzNzKLJalPZWkaxzrIgPDVq1ezntagHuN2QK62xp6MCo1sxg34L3lbqE--rAnbq5Q0rE0_eilP8a9lgRF3q0bZ8s_IzzmzbFUHnTUmaryvyZyvZzTFMc2Qf8Wb1-8oUo7qEQ_Tsfi9D31UjwPOScr9x-Z55mECT-YTqh&uniplatform=NZKPT&language=CHS

13 X. M. Tang, M. Liu, Y. Wu, H. J. Wei, and X. W. Liu: Acta Ecol. Sin. **44** (2024) 5974. https://kns.cnki.net/kcms2/article/abstract?v=l4Uq_U3qQ8MgnsBj_voBZIsq3YFJj6B6QPdTBpCoVAqNA2HO2vODYGKf4ZBVw5BZLfqTLoV_fMXU8tilfOlSarjeyhdUjMPBBeNBQmkVthcW0nEIpe2oB22Uky3lsQebaOYlqZ6ckk1n9FaeiV8hhJEojzQuXHg0-hrIKmDupXgM0Te5p9LGNRiuwKA0deGC&uniplatform=NZKPT&language=CHS

14 H. Jiang and Q. Wu: Resour. Environ. Yangtze Basin **30** (2021) 2712. https://kns.cnki.net/kcms2/article/abstract?v=l4Uq_U3qQ8NbR6ZlBwHd-LSrNA919MAfDpaavGCBKaBZvVV21-PCNvfbAOAWpFCLf0oNlNZrDmFl1VZEgTH0AfRDX_vqHA5H6EAK4pmNZjhLKNarCaZZClZylrCAdlLomI8eRLSTjJAWzMSyBU-wiskyxmoFkeFNtzECTcs4Fl18ZGUFIL8Pn0AQoJsofv6m&uniplatform=NZKPT&language=CHS

15 H. T. Odum and Y. X. Jiang: The Ecological System. Science Press (Beijing, China, 1993).

16 L. P. Zhu, H. T. Li, J. Q. Chen, J Ranjeet, T Liang, and M. C. Liang: J. Geogr. Sci. **22** (2012). https://kns.cnki.

net/nzkhtml/xmlRead/trialRead.html?dbCode=CJFD&tableName=CJFDTOTAL&fileName=ZGDE201205008&fileSourceType=1&invoice=i3KqtHWIYGK00xc6Z7kdSjXZ3F2xqB8ketD2m0El1q3OdQJDrAuLO543%2bh2RhhkOvqaCCy7K6MjMmeeksYm7cVJwU1Gd8I0D6TP4AFaGUy8Los0f6NTDO6szUB5tAIYKqaH4uRtA8gKXCRdnh%2byLeOVTsR4b4MKD0Rr%2bXbDvy0%3d&appId=KNS_BASIC_PSMC

17 Q. C. Guan, H. Li, Y. G. Fan, D, L, Zhu, and J. M. He: Chin. Land Sci. **38** (2024) 137. https://kns.cnki.net/kcms2/article/abstract?v=l4Uq_U3qQ8O_A7B18wgprYt4Q6lwdC9qJT3LJJce0eDUw1T6osOz5BHPDkYv-YNBBRcH6MSR6W9MsvYYuoaAVFHyJTPApIU-KUWxjQoeJqAADGGfauCnsBAbfe-nqStS2VipG9yTDf4ZykfF7-20zDxg-5hbcEkjKewqE1yj-jaP8NxzRy6dy-PCnhJ3Pmhv&uniplatform=NZKPT&language=CHS

18 J. Li, L. Q. Guo, Z. P. Wang, Z. P. Wang, Z Hong, and H. X. Li: Ecol. Econ. **38** (2012) 131. https://kns.cnki.net/kcms2/article/abstract?v=l4Uq_U3qQ8Nnx3o3jVcXX6Z4UOp1rTM9nUmd7-DXULm8BoJqVq2QcTzR-xfsdEgak6G2UB2ysT_0jTSagZrw3bwXJkQN1bMBeJkZ5Xqg6-pxKM7WWr7jAlVympuGcFY854l5MG41eATbPQsKgaYEVxU8Q7BkmiepnkdRl3nxUi9eis9C-xrn8wLJuKSSD611&uniplatform=NZKPT&language=CHS

19 J. Su and S. F. Lan: World For. Res. **13** (2000) 32. https://kns.cnki.net/nzkhtml/xmlRead/trialRead.html?dbCode=CJFD&tableName=CJFDTOTAL&fileName=SJLY200001007&fileSourceType=1&invoice=XQUcTNzJ%2bm0rc5H04FMkLf5QPwQd2fkudaQeoXiZLzXH3jVAX2GCjFGX0XRzhts5e0S983l1%2fciw6Entyrb%2b4sgGJJjsL2FWVIPu3HM4gUWp0YslE256Z6ipbCwdxy%2bB9YQwxn4s70ovROHYhYv2Vn%2bvCIcZJDROmFOj1Xacf2k%3d&appId=KNS_BASIC_PSMC

20 S. R. Shen, H. F. Lu, X. F. Zhao, and S. F. Lan: J. Trop. Subtrop. Bot. **12** (2004) 268. https://kns.cnki.net/reader/flowpdf?invoice=XLePoW7NaJrWPNtEgLhgHm8vtCGfztz%2FxE1G4OnvUinlokQKXtgsnL8IYIfhoY56VuZZX1cKO%2FHc9mwQil5fwuuUELmJKW31GkvPvEhbI9PyQVCtss9grAXHYtHAjvXGrtcp0vG4%2B%2FT%2FABxk6csV%2Bordp2KBNVFfIp%2B0Fm0H7kE%3D&platform=NZKPT&product=CJFQ&filename=RYZB200403014&tablename=cjfd2004&type=JOURNAL&scope=trial&dflag=pdf&pages=&language=CHS&trial=&nonce=1D6F97CA41BE43B89072A8D6950619C2&cflag=pdf

21 The National Forestry and Grassland Administration: https://www.forestry.gov.cn/c/www/lcdt/149914.jhtml

22 Y. L. Song, H. W. Linderholm, D. Chen, and A. Walther: Int. J. Climatol. **30** (2010) 33. https://www.semanticscholar.org/paper/Trends-of-the-thermal-growing-season-in-China%2C-Song-Linderholm/cde3542a2327a312dbe4e37486da2a6bb1295f5a.

23 M. G. She, Y. H. Tang, J. Chen, and W. Yang: Clim. Change **114** (2012) 783. https://link.springer.com/article/10.1007/s10584-012-0434-4

24 L. Turc: Ann. Agron. **12** (1961) 13. https://www.scirp.org/reference/ReferencesPapers?ReferenceID=926529

25 R. Siche and E. Ortega: Ecol. Questions **10** (2008) 99. https://doi.org/10.2478/v10090-009-0011-2

26 B. Wang, M. Liu, and B. Zhang: (2009) 35. https://kns.cnki.net/kcms2/article/abstract?v=l4Uq_U3qQ8PP7po8SHZO_0glvTYcZI495TJmxDEGrNkzfxrZEhrTIoMxmPOL6Torh0mecGd4TbnHPyHr4mblpf9gC8w-JOX3R8dPAFMQOaFWliOJtxz5gHNHRrUoOGs9p43jKKd6syeGhKDtT4iolfKzs6ZBw-q3kYuzEW7bmAz2h0zCo6qn8M3RPLYBKdOy&uniplatform=NZKPT&language=CHS

27 D. R. Tilley: Emergy Basis of Forest Systems (University of Florida, USA, 1999). http://hdl.handle.net/1903/2812

28 H. T. Odum: The Emergy of Natural Capital.Investing in Natural Capital: The Ecological Economics Approach to Sustainability. Island Press. (Washington (DC), USA ,1994).

29 M. Brown and S. Ulgiati: R. Swed. Acad. Sci. **28** (1999) 486. https://www.jstor.org/stable/4314939

30 M. T. Brown and E. Bardi: Handbook of Emergy Evaluation Folio 3: Emergy of Ecosystems. Center for Environmental Policy, (University of Florida, Gainesville, USA, 2001). https://archive.epa.gov/emap/aed/html/collaboration/web/pdf/folio3.pdf

31 Z. Wu and H. Zeng: Acta Ecol. Sin. **41** (2021) 5533. https://kns.cnki.net/kcms2/article/abstract?v=l4Uq_U3qQ8Oj31caNSWrUZjpSMhQRGfst8j2KOjhmMqCrExe3fMJ0o8AK_IPTrNOCgxQHcW0wkJh1MZhHZb8QQE7bSnx9mIBimyUP_Tt4VZ7M53tG5U14eN-J5GTQZ1LAjuqaYwDU6c3iC4A-Z0HJrQwEKccX0P6IFojYVLhoZ7z_iP0oiwD6ru6Ux_nM4LG&uniplatform=NZKPT&language=CHS

32 Y. Yu, M. Xu, and Y. Ye: Ecol. and Environ. Sci. **29** (2020) 421. https://kns.cnki.net/kcms2/article/abstract?v=l4Uq_U3qQ8MTFVLPNUOzmU4yno8NMrG8DtAeX-hxVAuFHdWfTG32O1ytwylo2ycOKSR-j1j6ifWzXJJ5Vsj2U5gMDhwZpD4LTFePHMkHZF7JxNXejkNoPA1y5gu4LHFufgg2fDzVfUqaB7Fo8zV60ku3JNOvpcSWtObERZEwS-yUmg8uuLbPzgEGcisGx2t5&uniplatform=NZKPT&language=CHS