Article
Assessing Changes in the Value of Forest Ecosystem Services in Response to Climate Change in China
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Abstract: Ecosystem services are the basis of human survival and development and play an irreplaceable role in maintaining the dynamic balance of the earth’s life support system and environment. This study evaluated the annual forest ecosystem service values (ESVs) and their spatial evolution characteristics from 2001 to 2020 in China and revealed the impact of climatic factors as well. The equivalent factor method was applied to calculate ESVs in combination with net primary productivity (NPP) calculated by the CASA model. The water conservation results based on the InVEST model and equivalent factor method were compared to test the reliability of the method. From 2001 to 2020, the annual forest ESVs ranged from RMB 9.17 trillion to 10.81 trillion, with an average of RMB 9.99 trillion in China. The forest ESVs increased from the northwest to the southeast regions of China with the lowest values of less than RMB 3 million per square kilometer and relatively high values of more than RMB 9 million per square kilometer. In the past 20 years, the forest ESVs have shown a significant increasing trend, especially in the Northeast Forest Region and Southeast Forest Region. The ESVs have decreased only in very few forest areas such as Cuona and Motuo counties on the southern edge of Tibet Province in Southwest China and Pingtung and Kaohsiung counties in southern Taiwan. The mean annual forest ESV was necessarily higher in the recent 10 years (2011–2020, RMB 10.43 trillion) than in the previous 10 years (2001–2010, RMB 9.55 trillion), while the spatial growth rate was usually less than 20%. The annual forest ESVs were significantly correlated with temperature, precipitation and evapotranspiration but not with sunshine hours and relative humidity across the 20 years. In most areas (>60%), the positive impact of various climatic factors was dominant, and the area positively affected by precipitation was the largest (76%). The mean annual forest water conservation from 2001 to 2020 was RMB 1.46 trillion based on the InVEST model and was RMB 1.77 trillion based on the equivalent factor method. Overall, the results obtained by the two methods are roughly equal and mostly spatially matched. This study has some guiding significance for utilizing resources rationally, strengthening ecological environment protection and improving adaptability to climate change.

Keywords: ecosystem service values; CASA model; InVEST model; forest; climate change; China

1. Introduction
Ecosystem services are all the benefits provided by an ecosystem to human society and are divided into four general categories: provision, regulation, support and cultural services [1–3]. They are the basis of human survival and development and therefore play an irreplaceable role in maintaining the dynamic balance of the earth’s life support system and environment. However, under the increasing pressure of climate and socio-economic drivers, more than 60% of the world’s ecosystem services have degraded to varying degrees [2,4–7]. This seriously threatens human safety and health and is becoming one of the main problems affecting human sustainable development.

Over the past century, the earth’s climate has undergone significant changes characterized by global warming, which may have a profound impact on the global ecosystem and its important services [8]. The effects, both positive and negative, are expected to increase
rapidly all over the world [9–12]. The progressing climate change has a negative impact on 59% of ecosystem services [13]. It may profoundly affect the behavior patterns and sensitivities of biotic/abiotic organisms, thereby promoting the regulation, support and cultural services [10] or modifying the relationships and benefits related to the ecosystem services [14]. The provision and regulatory services might be negatively affected through altering ecosystem functions [9,15–18]. This may further aggravate the imbalance of regional development and pose a threat to ecological security and sustainable development. Although it is well known that climate change, as well as anthropic activities, may be an important cause of ecosystem service change, the exact influencing factors and driving effects remain largely unclear [19,20], which is a gap in ESV research. One of our objectives of this study was to investigate this relationship pattern and reveal their causal effects. This will help to further understand the driving mechanism of ecosystem services change and lay a scientific foundation for mitigation and adaptation to climate change.

Some studies have analyzed or quantified the effects of climatic factors on ecosystem services. For instance, radiation, precipitation and wind speed influenced sand fixation, water yield and soil conservation, while temperature and precipitation affected carbon sequestration in a forest–steppe ecotone [21]. In terms of temperature effect, both photosynthesis and respiration are controlled by temperature, which determines the increase or decrease in ecosystem NPP [22]. Meanwhile, there is a warming threshold for promoting NPP growth. Simulation results show that, with a temperature increase of 1.5 °C and 2 °C, the NPP of most vegetation types in Northeast China increased by 0.58–10.34%. However, with a temperature rise above 3 °C, the NPP of all vegetation types decreased, with a maximum decrease of 10.48% [23]. Furthermore, temperature and precipitation usually act synergistically on forest NPP, and thus the impact results may be interactive or fluctuating [22]. According to IPCC AR6 [24], the current global average surface temperature is about 1 °C higher than pre-industrial levels. Therefore, we hypothesize that there may be a pattern of positive correlation between forest ecosystem services and climate warming in China over the last 20 years.

The forest ecosystem provides various ecological services, such as net primary material production, climate regulation, soil and water conservation and biodiversity maintenance, and in beneficial ways regulates the atmosphere [25]. However, due to the long-term influence of natural factors including climate change and human activity, primary products may be overconsumed, and even forest ecosystems may be seriously damaged. As a result, ecological and economic problems are becoming increasingly prominent, which directly affects the sustainable development of regional ecology, economy and society. To some extent, this situation reflects the lack of human understanding of the function of service, status and potential economic value of the forest ecosystem. In this situation, evaluating the economic value of forest ecosystem service has important practical significance for protecting and restoring the utilization of forest material and non-material resources and making reasonable decisions regarding regional ecological protection and economic development in China.

With the increase in the world population, the demand for the provision service and other services is also increasing [8]. In the same instance, governments and managers always expect the maximization of ecosystem service value [26], and therefore it is particularly important to promote the evaluation and application of ecosystem service. Since the launch of the Millennium Ecosystem Assessment Project in 2001, many countries have carried out ecosystem service assessments at different scales. At the end of the 20th century, some Chinese scholars of ecology and eco-economics made a preliminary exploration of the theory, method and practical application of ecosystem service evaluation. In recent years, especially since entering the 21st century, a large number of ESV studies have emerged [27], which has accumulated rich data and achieved some valuable research results. This has greatly promoted the correct understanding of ecological assets and the active implementation of ecological protection measures. However, there are still many deficiencies in the current research, especially in the estimation and verification of ecosystem service
value and its response to climate change. For example, although numerous studies have appeared in recent years, from assessing ESVs of different types of ecosystems to analyzing the influencing factors, they are mainly based on a certain year rather than a long time series and rarely analyze the impact of individual climate factors. With regard to forest ecosystem service value, the evaluation scope is mainly concentrated in some provinces and cities of China (e.g., Shaanxi Province [28], Shanxi Province [29], Jianyang City [30], etc.) and specific areas (e.g., Qinling Mountains [31], forest-steppe ecotone [21]). What is more, there are few studies on the comparative analysis and mutual verification of the ESV results obtained by different methods. This study fills these gaps in the literature by quantifying the value of forest ecosystem services and their relationship with climate factors over a continuous 20-year time series nationwide.

In view of this, this study constructed an evaluation index system, comprehensively assessed the forest ecosystem service value in the time series of 20 consecutive years and its response to climate change and compared and verified some evaluation results. Our objectives were: (1) to find out how the value of forest ecosystem services has evolved over time and space; (2) to test whether the afore-mentioned pattern of the relationship of ecosystem service values with climate warming exists and which variable is the dominant factor involved; and (3) to determine the long-term economic benefits and ecological conditions of forest in China. This study can enrich the current cognition of ecosystem services and ecological assets. In addition, it provides a scientific basis for ecosystem decision-making management and ecological security maintenance.

2. Data and Methods

2.1. Study Area

China lies in the east of Eurasia and on the west coast of the Pacific Ocean. The latitude is 3°51′–53°33′ N, longitude is 73°33′–135°05′ E, and the elevation is −100–8000 m. It spans tropical, subtropical, warm temperate, middle temperate and cold temperate zones. The annual precipitation is between 50 and 2000 m.

According to the Ninth China Forest Resources Inventory, the national forest area is 2.2 × 108 hm², and the forest coverage rate is 22.96% [32]. China’s forests are mainly distributed in East China, South China, the south of Central South China, the east of Southwest China and the northern mountainous areas of Northeast China and North China. The forest is divided into evergreen coniferous forest, evergreen broad-leaved forest, deciduous coniferous forest, deciduous broad-leaved forest and coniferous broad-leaved mixed forest (Figure 1; [33]).

2.2. ESV Evaluation Method

Theory, index and model are the core and focus of ecosystem service evaluation. Multiple approaches have been used to quantify the value of ecosystem services in recent years. Nevertheless, a universally accepted theory and method system of ecosystem service value evaluation are still rare.

Costanza et al. [34] first proposed the equivalent factor method to quantify the value of global ecosystem services. Xie et al. [35,36] showed that, since ecosystem services give different subjective satisfaction to people in different social geographical environments, it will lead to different marginal utility unit values. Therefore, Xie et al. [35,36] revised the ecosystem service classification and ESV equivalent value per unit area according to a survey of 700 ecological experts to estimate ESVs of China. Based on the equivalent factor method proposed by Costanza et al. [34] and “the unit price of ecosystem service value per unit area under the average state in China” put forward by Xie et al. [36] (Table 1), the value of forest ecosystem services from 2001 to 2020 in China was calculated.
Figure 1. Distribution of the study area (NW, Northwest China; SW, Southwest China; N, North China; C, Central China; S, South China; NE, Northeast China; E, East China; same as below).

Table 1. Ecosystem service value per unit area of forest ecosystem type in China (RMB/hm$^2$).

<table>
<thead>
<tr>
<th>Service Item</th>
<th>Definition</th>
<th>Unit Price ($p_i$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gas regulation</td>
<td>Ecosystems maintain the chemical balance of atmosphere, absorbing SO$_2$, fluoride and nitrogen oxides</td>
<td>3097.0</td>
</tr>
<tr>
<td>Climate regulation</td>
<td>Regulation of regional climate, such as increasing precipitation and reducing temperature</td>
<td>2389.1</td>
</tr>
<tr>
<td>Water conservation</td>
<td>Freshwater filtration, retention and storage functions of ecosystems and freshwater supply</td>
<td>2831.5</td>
</tr>
<tr>
<td>Soil formation and protection</td>
<td>Accumulation of organic matter and the role of root matter and organisms in soil conservation, nutrient cycling and accumulation</td>
<td>3450.9</td>
</tr>
<tr>
<td>Waste treatment</td>
<td>The role of vegetation and organisms in the removal and decomposition of excess nutrients and compounds, and the retention of dust</td>
<td>1159.2</td>
</tr>
<tr>
<td>Biodiversity protection</td>
<td>Genetic origin and evolution of wild animals and plants, and habitat of wild plants and animals</td>
<td>2884.6</td>
</tr>
<tr>
<td>Food production</td>
<td>To convert solar energy into edible plant and animal products</td>
<td>88.5</td>
</tr>
<tr>
<td>Raw material production</td>
<td>To convert solar energy into bioenergy for use in buildings or other purposes</td>
<td>2300.6</td>
</tr>
<tr>
<td>Recreation and culture</td>
<td>Landscape with potential artistic and recreational value</td>
<td>1132.6</td>
</tr>
</tbody>
</table>

2.2.1. Model and Index System

The ESV evaluation equation \cite{35,36}, relevant indicators and parameters were set as follows:

$$ESV = \Sigma P_i \times A$$  \hspace{1cm} (1)

ESV is the total value of forest ecosystem services in China, RMB. $P_i$ is the revised unit price of ecosystem services $i$ of the forest ecosystem, RMB/hm$^2$. $i = 1, 2, \ldots, 9$, respectively, represent nine ecosystem services: gas regulation, climate regulation, water conservation, soil formation and protection, waste treatment, biodiversity protection, food production,
raw material production, recreation and culture (Table 1; [36]). \( A \) is the area of forest ecosystem in China, \( \text{km}^2 \).

The biomass (aboveground + underground) factor is used to further modify the unit prices of ecosystem service according to the following formula:

\[
P_i = (b/B)p_i
\]

where \( P_i \) is the same as above. \( B \) is the average biomass per unit area of “primary forest ecosystem type” in China, which is 77.4 Mg/hm² [37]; \( p_i \) is the national average price of the ecosystem service type \( i \) (in Table 1); \( b \) is the biomass of forest ecosystem (gC/m²), and the calculation formula is: \( b = 17 \text{NPP}/0.5 \).

The parameter setting and calculation process are as follows:

At present, the correlation between biomass and net primary productivity of different species or forest types in specific areas of China has been simulated, but there is no report on simulating the relationship between them on the national scale of long-time series. Therefore, \( b \) here is the biomass transformed by NPP through the comprehensive analysis of relevant domestic literature. References here mainly include [38–42]. In these five studies, the ratios of biomass to productivity were 6.04, 24.59, 27.52, 14.74 and 11.93, respectively, with an average of 17. The conversion coefficient between biomass and carbon varies with tree species, and 0.5 is usually used as the conversion coefficient in the world [43]. In this study, the unit of NPP is gC/m². When converting carbon weight to dry matter weight, we take 0.5 as the conversion coefficient (divided by 0.5).

2.2.2. Assumptions

(1) ESV is linearly related to biomass. Costanza et al. [34] showed that biomass not only reflects the raw material production capacity of an ecosystem but also has an important impact on other services of the ecosystem during the formation and accumulation of biomass. Xie et al. [35,36,44] assumed that biomass can largely reflect the differences in service capacity of different types of ecosystems. Based on this assumption, the ecosystem service intensity is linearly related to biomass.

(2) Forest area remained unchanged. In order to reveal the possible impact of climate change on ESVs and verify the hypothesis of their relationships put forward in the Introduction section, the impact of land-use type change induced by human activities should be eliminated as much as possible. Therefore, this study assumed that forest area did not change over the past 20 years, and thus only 1-year land-use type data (2015) were used.

2.3. Net Primary Productivity (NPP) Based on CASA Model

The process-based Carnegie Ames Stanford Approach (CASA) model, jointly developed by Stanford University, the Nature Conservation Society (TNC) and the World Wide Fund for nature (WWF), is used to estimate forest NPP. The performance of the CASA model was evaluated by comparing it with in situ NPP and MODIS-NPP. The CASA model is a satellite-based light-use efficiency model. The model expression and parameter setting were detailed in the literature [45–47]. In brief, absorbed photosynthetically active radiation (APAR) and actual light-use efficiency (\( \varepsilon \)) are used to estimate NPP. The formulas are listed in the literature [48] as follows:

\[
\text{NPP} (x, t) = \text{APAR} (x, t) \times \varepsilon (x, t)
\]

where NPP is the net primary productivity (gC/m²); \( \text{APAR} (x, t) \) represents the absorbed photosynthetically effective radiation (MJ/m) absorbed by pixel \( x \) in the month \( t \), which is calculated from the normalized difference vegetation index (NDVI); \( \varepsilon (x, t) \) represents the actual light-use efficiency of pixel \( x \) in the month \( t \) (gC/MJ).
Estimation of APAR

The effective solar radiation absorbed by vegetation and the absorption ratio of the vegetation layer to the incident photosynthetically active radiation are used to estimate APAR, using the following relation.

\[
\text{APAR}(x, t) = \text{SOL}(x, t) \times \text{FPAR}(x, t) \times 0.5
\]

where \(\text{SOL}(x, t)\) represents the total solar radiation (gC/m\(^2\)·month) at pixel \(x\) in month \(t\), and \(\text{FPAR}(x, t)\) represents the absorption ratio of vegetation layer to the incident photosynthetic effective radiation. The constant 0.5 represents the effective solar radiation that the vegetation can use as a proportion (wavelength is 0.4–0.7 \(\mu\)m) of total solar radiation. \(\text{FPAR}\) is derived based on NDVI, and the calculations for \(\text{FPAR}\) were detailed in the literature [45–47].

Estimation of light-use efficiency

Light-use efficiency refers to the ratio of the chemical potential of dry matter formed per unit area in a given time to the photosynthetic effective radiant energy projected onto the same area during the same period. Environmental factors affecting the photosynthetic capacity of plants, viz., air temperature, soil moisture status and the difference in atmospheric water and vapor pressures, etc., can regulate the NPP of vegetation.

\[
\varepsilon(x, t) = T_{\varepsilon1}(x, t) \times T_{\varepsilon2}(x, t) \times W_{\varepsilon}(x, t) \times \varepsilon_{\text{max}}
\]

where \(T_{\varepsilon1}(x, t)\) and \(T_{\varepsilon2}(x, t)\) indicate the stress effect of low temperatures and high temperatures on light-use efficiency; \(W_{\varepsilon}(x, t)\) is the influence coefficient of water stress, reflecting the influence of water conditions; \(\varepsilon_{\text{max}}\) is the maximum light-use efficiency under ideal conditions.

\[
T_{\varepsilon1}(x, t) = 0.8 + 0.02 \times T_{\text{opt}}(x) - 0.0005 \times [T_{\text{opt}}(x)]^2
\]

where \(T_{\text{opt}}(x)\) is the optimum temperature for plant growth, representing the average monthly temperature of a region measured in degree Celsius when the NDVI values reach the maximum in a given year.

\[
T_{\varepsilon2}(x, t) = 1.184/[1 + \exp(0.2 \times (T_{\text{opt}}(x) - 10 - T(x))) \times 1/[1 + \exp(0.3 \times (-T_{\text{opt}}(x) - 10 + T(x)))]
\]

When the average monthly temperature \(T(x, t)\) is 10 °C higher or 13 °C lower than the optimum temperature \(T_{\text{opt}}(x)\), then the monthly average temperature \(T(x, t)\) is equal to \(2(x, t)\), and the optimum temperature \(T_{\text{opt}}(x)\) is equal to the half of \(2(x, t)\).

\[
W(x, t) = 0.5 + 0.5 \times \frac{EET(x, t)}{EPT(x, t)}
\]

where \(EET\) is the actual regional evapotranspiration (mm), and \(EPT\) is the potential regional evapotranspiration (mm).

2.4. Water Conservation Evaluation Method

Water conservation is one of the nine important functions of ecosystem services (in Table 1), which belongs to regulation services. It is mainly reflected in the retention of water through vegetation interception of precipitation, enhancement of soil infiltration and inhibition of evapotranspiration. Here, it refers to the remaining part of precipitation after subtracting evaporation and runoff.

2.4.1. The InVEST Model

The water yield module of InVEST3.9.0 (Integrated Valuation of Ecosystem Services and Tradeoffs) model was employed to calculate the water yield of each grid unit. The formula and detailed process were described in detail in the literature [21,46,49]. The steps
for estimating forest water conservation through InVEST model combined with water balance principle are as follows:

\[
WY = P - ET = \Sigma (P_j - ET_j) \times A_j \times 10^{-3}
\]

\[
Q = WY - R = WY - \Sigma R_j \times A_j \times 10^{-3}
\]

\[
R_j = P_j \times \alpha
\]

\[
V_Q = Q \times C
\]

where \( WY \) refers to the amount of water yield, calculated by InVEST model, m\(^3\). \( Q \) refers to the amount of water conservation, m\(^3\). \( P \) is the annual rainfall, mm. \( ET \) is the annual actual evapotranspiration, mm. \( R \) is the surface runoff, mm. All these data are grid data with a resolution of 1 km × 1 km. \( j \) is the grid point. \( A_j \) is the grid area. \( C \) refers to the reservoir construction cost. \( V_Q \) is the economic value of water conservation, RMB. \( \alpha \) is the surface runoff coefficient.

Relative parameters are set as follows:

The research object is forest ecosystem, and thus only forest water conservation is analyzed here. Forest ecosystem types are divided into five categories, namely, evergreen coniferous forest, evergreen broad-leaved forest, deciduous coniferous forest, deciduous broad-leaved forest and coniferous broad-leaved mixed forest (Figure 1). The surface runoff coefficients (\( \alpha \)) are 3.02%, 2.67%, 0.88%, 1.33% and 2.29%, respectively, according to the literature [50]. The reservoir construction cost (\( C \)) is set at the common value of 2,789 RMB/m\(^3\) [51].

For running the InVEST model, the root depth was set as 6300 mm, referring to the maximum root depth of forest; the PAWC was set as 0.4, illustrating the Plant Available Water Contents’ fraction; \( Z \) was set as 15, related to the frequency of the precipitation each year [21, 49].

2.4.2. Results Comparison and Method Validation

The forest water conservation in the same period and region was evaluated by using the equivalent factor method and InVEST model method combined with the principle of water balance. The evaluation results of forest water conservation obtained by the two methods were compared to verify the reliability of the evaluation methods and ensure the accuracy of the evaluation results as much as possible so as to provide further support for decision-making management.

2.5. Data Sources and Processing

2.5.1. Data Used

The input and output data of the models and data sources can be visible in Table 2. In all the models, the land-use type in 2015 was used. The classification of forest land-use cover was adjusted by combing the data (~100 m × 100 m) generated from Copernicus Global Land Service website (https://land.copernicus.eu/global/products/1c (accessed on 1 July 2021)) with the data (30 m × 30 m) provided by the Data Center for Resources and Environmental Sciences of the Chinese Academy of Sciences (RESDC) (http://www.resdc.cn (accessed on 1 July 2021)). All the climate data (2400 sites) were from the meteorological dataset downloaded from the Chinese Meteorological Information Center (http://cdc.cma.gov.cn (accessed on 1 July 2021)).
Table 2. Input and output data of the model and data source.

<table>
<thead>
<tr>
<th>Model/Output</th>
<th>Input Data</th>
<th>Data Source</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Area/land-use data</td>
<td>Five sources mentioned above (As in Section 2.2.1)</td>
</tr>
<tr>
<td></td>
<td>b</td>
<td>Liu et al. [37] (As in Section 2.2.1)</td>
</tr>
<tr>
<td></td>
<td>B</td>
<td>CASA (as follows)</td>
</tr>
<tr>
<td></td>
<td>NPP</td>
<td>CASA/NPP</td>
</tr>
<tr>
<td></td>
<td>NDVI</td>
<td>The EOS/MODIS portal of NASA (<a href="https://ladsweb.modaps.eosdis.nasa.gov">https://ladsweb.modaps.eosdis.nasa.gov</a> (accessed on 1 May 2021))</td>
</tr>
<tr>
<td></td>
<td>Climate data</td>
<td>Chinese Meteorological Information Center (<a href="http://cdc.cma.gov.cn">http://cdc.cma.gov.cn</a> (accessed on 1 July 2021))</td>
</tr>
<tr>
<td>Invest/Water Yield</td>
<td>Climate data</td>
<td>Chinese Meteorological Information Center (<a href="http://cdc.cma.gov.cn">http://cdc.cma.gov.cn</a> (accessed on 1 July 2021))</td>
</tr>
<tr>
<td></td>
<td>Parameters</td>
<td>Empirical constant from studies (e.g., [21,46])</td>
</tr>
</tbody>
</table>

(1) CASA model. The data used for the NPP estimation by the CASA model included vegetation index, land use/land cover and climate. The remote sensing data (1 km × 1 km) of MOD17A3 annual NPP and monthly MOD13A2 normalized vegetation index (NDVI) of global land vegetation were accessed for 20 years from 2001 to 2020 via the EOS/MODIS portal of NASA (https://ladsweb.modaps.eosdis.nasa.gov (accessed on 1 May 2021)).

(2) InVEST model. Input data of the InVEST model included climate data, land-use data and other parameter sources. The input climate data for running InVEST model were annual grid data of precipitation and actual evapotranspiration.

2.5.2. Data Analysis

All these spatial data were interpolated or resampled to a 1 km × 1 km resolution on an annual scale before being input into the models. All of these climate data were interpolated with the algorithm of thin-disk spline using ANUSPLIN software [52]. The spatial resolution of ESV, NPP and water conservation values output by the model was 1 km × 1 km.

According to the test, the annual ESV and climate factor data conform to the normal distribution. Therefore, Pearson’s rank correlation analysis was conducted to explore the relationship of forest ESVs with climate factors. In order to examine whether ecosystem service values were related to climatic factors over the 20 years, we plotted variations in forest ESVs and temperature, precipitation, evapotranspiration, sunshine hours and relative humidity across an annual range at the national scale. The change trend and significance of climate factors in time series were judged by linear regression analysis. $p < 0.05$ (i.e., 95% confidence level) was defined as statistical significance level. All statistical analyses were performed using SPSS version 13.0 software package. All grid data analysis and processing were carried out using ArcGIS 10.0 (Esri, Redlands, CA, USA).

3. Results

3.1. The Temporal Distribution of Forest ESVs

The annual forest ecosystem service values (ESVs) ranged from RMB 9.17 trillion to 10.81 trillion, with the maximum of RMB 10.81 trillion, the minimum of 9.17 trillion and
an average of 9.99 trillion from 2001 to 2020 in China (Figure 2). In the recent 20 years, the annual forest ESVs have shown a significant increasing trend \((p < 0.05)\), with a peak in 2016. Since 2016, the ESVs have declined, similar to the changes in precipitation. The mean annual forest ESV was necessarily higher in the recent 10 years (2011–2020, RMB 10.43 trillion) than in the previous 10 years (2001–2010, RMB 9.55 trillion). Similar results were observed in the last five years compared with the previous five years. It indicates that the forest ecological environment and ecosystem service have been generally enhanced in recent years in China.

Spatially, the values of forest ecosystem service increased from the northwestern to the southeastern regions in China. The lowest values were less than RMB 3 million per square kilometer, mainly distributed in the forests of western and northern China. The relatively high values of more than RMB 9 million per square kilometer were mostly observed in the forests of southern China, mainly distributed in Taiwan and Hailan islands, the south of Guangdong and Guangxi provinces, the southwest edge of Sichuan Province and the southern edge of Tibet Province (Figure 3).

In the recent 20 years, the service values of most forest ecosystems in China have shown an increasing trend \((p < 0.05, \text{ or } R > 0.445)\), especially in the Northeast Forest Region and Southeast Forest Region. The values have decreased only in very few forest areas, mainly in Cuona and Motuo counties on the southern edge of Tibet Province in Southwest China and Pingtung and Kaohsiung counties in southern Taiwan (Figure 4).

The mean annual forest ESV was markedly higher in the recent 10 years than in the previous 10 years of the 21st century in most areas, and the growth rate was usually less than 20%. Meanwhile, compared with the previous 10 years, the mean annual forest ESVs in some areas in the recent 10 years tended to decline. These areas were distributed in patches, mainly in Mohe, Jiamusi and Mudanjiang cities from north to south in the Northeast Forest Region, Cuona and Motuo counties on the southern edge of Tibet Province in Southwest China and Pingtung and Kaohsiung counties in Taiwan (Figure 5).
Figure 3. Spatial distribution of mean annual service values per square kilometer of forest ecosystem from 2001 to 2020 in China.

In the recent 20 years, the service values of most forest ecosystems in China have shown an increasing trend ($p < 0.05$, or $R > 0.445$), especially in the Northeast Forest Region and Southeast Forest Region. The values have decreased only in very few forest areas, mainly in Cuona and Motuo counties on the southern edge of Tibet Province in Southwest China and Pingtung and Kaohsiung counties in southern Taiwan (Figure 4).

Figure 4. Spatial significance test of regression coefficient of annual forest ecosystem service values from 2001 to 2020 in China ($R = 0.445$ represents the significance level $p = 0.05$).
The mean annual forest ESV was markedly higher in the recent 10 years than in the previous 10 years of the 21st century in most areas, and the growth rate was usually less than 20%. Meanwhile, compared with the previous 10 years, the mean annual forest ESVs in some areas in the recent 10 years tended to decline. These areas were distributed in patches, mainly in Mohe, Jiamusi and Mudanjiang cities from north to south in the Northeast Forest Region, Cuona and Motuo counties on the southern edge of Tibet Province in Southwest China and Pingtung and Kaohsiung counties in Taiwan (Figure 5).

Figure 5. Change percentage of mean annual forest ecosystem service value (ESV) from 2011 to 2020 relative to 2001–2011 in China.

3.2. Comparison of Water Conservation from Two Different Models

A high forest water conservation of more than 800 mm per kilometer was detected mostly in the southeastern forest regions, concentrated in several provinces such as Zhejiang, Jiangsu, Jiangxi, Hunan, Guangdong and Guangxi, as well as the outer edge of Sichuan Province. By contrast, some low and negative water conservation values were observed in the western forest regions, mainly near the southern edge of Tibet and around the deserts in Xinjiang Province. The amount of water conservation mostly ranged from 0 to 400 mm per kilometer in other forest areas (Figure 6).

Two methods were employed to calculate forest water conservation from 2001 to 2020 in China. One was based on the water yield mode in the InVEST model combined with the water balance principle; the other was based on the equivalent factor combined with the CASA-NPP. The mean annual forest water conservation of the two methods was RMB 1.46 and 1.77 trillion, respectively. A marginal positive correlation ($p = 0.066$) was examined in the annual forest water conservation between the two methods. The comparative analysis indicates that the forest water conservation values according to the two models were roughly equal.

Spatially, a positive correlation between the annual forest conservation values obtained by the two methods was detected in most forest areas, and the correlation was generally significant ($p < 0.05$) in such areas as the Northeast Forest Region and the middle and lower reaches of the Yangtze River. Nevertheless, a negative but statistically insignificant correlation was observed in a small part of forest areas ($p > 0.05$), mainly distributed in the Northeast Forest Region, the Southeast Forest Region and the Southwest Forest Region. The comparative analysis further shows that the forest water conservation obtained by the two methods has spatial matching (Figure 7).
Figure 6. Spatial distribution of mean annual forest water conservation from 2001 to 2020 in China based on InVEST model combined with water balance principle.

Figure 7. Correlations between the forest water conservation values obtained by two methods from 2001 to 2020 in China ($R = 0.445$ represents the significance level $p = 0.05$).

3.3. The Main Climatic Regulators of Ecosystem Service Values

As shown in Figure 8, in the recent 20 years, the temperature and evapotranspiration of the forest ecosystem in China have shown a significant increase trend ($p < 0.05$), the precipitation has shown a marginal increase ($p = 0.072$), but the sunshine hours and relative
humidity have not shown a significant change trend ($p > 0.05$). This result confirms the fact that China’s climate has been warming in recent decades.

In order to examine whether forest ecosystem service values are related to climatic factors across the 20 years, we plotted variations in forest ESVs and temperature, precipitation, evapotranspiration, sunshine hours and relative humidity. The results show that climate factors had a significant impact on the change in the value of ecosystem services ($p < 0.05$). There was a significant positive correlation between forest ESVs and temperature, precipitation and evapotranspiration during 2001–2020 ($p < 0.05$). In contrast, no such significant relationship was observed for the relative humidity and sunshine hours ($p > 0.05$). Nevertheless, the area with a significant correlation between forest ESVs and sunshine hours ($p < 0.05$) was the largest (20%, 17% positive and 3% negative), followed by precipitation (17%, 16% positive), temperature (11%, 9% positive), relative humidity (10%, 8% positive) and evapotranspiration (9%, 3% positive). Sunshine hours exhibited a positive impact on forest ESVs in the Northeast Forest Region, especially in Changbai Mountain and the great and small Xing’an Mountains. Sunshine hours exhibited a negative influence on forest ESVs in the forest areas of southern and eastern China, especially in the middle and lower reaches of the Yangtze River, while temperature, precipitation and relative humidity had a positive impact. Overall, in most areas (>60%), the positive impact of various climatic factors was dominant, and the area positively affected by precipitation was the largest (76%) (Figure 9).

![Figure 8](image-url)
Figure 8. The change trend of temperature (a), sunshine hour (b), relative humidity (c), precipitation (d) and evapotranspiration (e) in forest ecosystem of China from 2001 to 2020.
Figure 9. Correlations between forest ecosystem service values and temperature ($R_{tem}$; (a)), precipitation ($R_{pre}$; (b)), relative humidity ($R_{rh}$; (c)), sunshine hour ($R_{ssh}$; (d)) and evapotranspiration ($R_{et}$; (e)) from 2001 to 2020 in China ($R = 0.445$ represents the significance level $p = 0.05$).

4. Discussion

4.1. Quantity and Distribution Characteristics of ESVs

The forest ecosystem provides abundant material and non-material benefits for human beings [34,53], and thus it is an important ecological foundation for social and economic sustainable development. In our study, the mean annual forest ESV was RMB 9.99 (9.17–10.81) trillion from 2001 to 2020 in China (Figure 2), which is huge spiritual and material wealth. The forest ESVs should be slightly larger if considering the positive effects of the Grain for Green Program (GTGP) in the past 20 years in China. This result is in agreement with some previous findings in the literature [44,54,55]. However, it is substantially higher than the values described by other predecessors using different methods, e.g., [56–59]. The diversity of results may be attributed to the inconsistency of methods, evaluation index system and the research period [60]. Therefore, it is essential to develop objective, scientific and widely accepted methods and indicators so as to enhance comparability between results. Different evaluation objects may also be another reason for inconsistent results (see Table 3).
Table 3. Comparison of forest ecosystem service value in different studies ($i = 1, 2, \ldots, n$, respectively, representing $n$ ecosystem services).

<table>
<thead>
<tr>
<th>Studies</th>
<th>Currency Used for ESV</th>
<th>Evaluation Object</th>
<th>Calculation Method/Cited</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>RMB/10$^12$</td>
<td>US $/10^12$</td>
<td></td>
</tr>
<tr>
<td>Our study</td>
<td>9.99 i.e., 1.31</td>
<td>Total</td>
<td>$\Sigma(ESV_i \text{ per area} \times \text{area})/Xie et al. [36]$</td>
</tr>
<tr>
<td>Hou et al. [54]</td>
<td>13.7/11.1</td>
<td>Part</td>
<td>$\Sigma(ES_i \times \text{price}_i)/\text{a method cited for Each ES}$</td>
</tr>
<tr>
<td>Xie et al. [44]</td>
<td>17.5</td>
<td>Total</td>
<td>$\Sigma(ESV_i \text{ per area} \times \text{area})/Xie et al. [61]$</td>
</tr>
<tr>
<td>Wang et al. [55]</td>
<td>10.01</td>
<td>Total</td>
<td>$\Sigma(ES_i \times \text{price}_i)/\text{a method cited for Each ES}$</td>
</tr>
<tr>
<td>Zhao et al. [56]</td>
<td>0.0117401</td>
<td>Part</td>
<td>$\Sigma(ESV_i \text{ per area} \times \text{area})/Costanza et al. [34]$</td>
</tr>
<tr>
<td>Chen et al. [57]</td>
<td>1.406</td>
<td>Total</td>
<td>$\Sigma(ES_i \times \text{price}_i)/\text{a method cited for Each ES}$</td>
</tr>
<tr>
<td>Jin et al. [58]</td>
<td>3.06</td>
<td>Total</td>
<td>$\Sigma(ESV_i \text{ per area} \times \text{area})/\text{ Costanza et al. [34]}$</td>
</tr>
<tr>
<td>Lu [59]</td>
<td>2.141/3.643/4.120</td>
<td>Total</td>
<td>$\Sigma(ESV_i \text{ per area} \times \text{price}_i)/\text{a method cited for Each ES}$</td>
</tr>
</tbody>
</table>

Understanding the spatial distribution characteristics of ESVs is conducive to providing comprehensive reference for regional forest management and development decision making. In our study, the forest ESVs were notably characterized by increasing from the northwest to the southeast regions (Figure 3). In most forest areas, the ESVs have shown an increasing trend in the past 20 years. By contrast, they decreased in very few forest areas such as the southern edge of Tibet Province and Taiwan Island (Figure 4). At the same time, the mean annual forest ESV was apparently higher in the recent 10 years than in the previous 10 years in most areas, but it was lower in the minority of areas, mainly distributed in patches in Mohe, Jiamusi and Mudanjiang cities from north to south in the Northeast Forest Region, Cuona and Motuo counties on the southern edge of Tibet Province in Southwest China and Pingtung and Kaohsiung counties in Taiwan (Figure 5). All these results indicate that China’s forest ecosystem has been improved on the whole and is in a stable state, whereas the regional development is not balanced. Therefore, more attention needs to be paid to these areas where the value of ecosystem services is getting lower and lower. Meanwhile, the protection and construction of these areas should be strengthened, since governments and managers always hope to maximize ESVs through effective management measures [26]. The decline of forest ecosystem service value may be due to the regional impact of climate change and the marginalization effect of forest segments, coupled with human disturbances.

4.2. Key Climatic Controlling Factors of ESVs

4.2.1. Effect of Climate Variations

In our study, temperature, precipitation and evapotranspiration have significantly increased over the past 20 years (Figure 8). They had a significant positive impact on forest ESV (Figure 9) and were therefore the main regulators of the increase in ESVs as land-use and unit price equivalent factors were assumed to be constant. This validated our hypothesis about the pattern of the relationship between ESVs and climate warming. It is speculated that global warming may create a more suitable plant growth environment by accelerating the photosynthesis rate of vegetation and prolonging the growing season, which is conducive to improving the quality of forests and thus enhancing the ecosystem service value. This result is consistent with some regional studies in China (in [22]), but it is contrary to some conclusions of IPCC AR5 [8] and some countries (e.g., Finland [62]). IPCC AR5 [8] speculated that the provision and regulation of ecosystem services might be negatively affected by progressing climate change with the increasing demand in provision services due to world population growth. The inconsistency of these results could potentially be explained by the differences or the interaction between regional natural conditions and human activities.

The area with significant correlation between forest ESVs and sunshine hours was the largest, whether positive or negative. Sunshine hours showed a deep positive impact in the Northeast Forest Region with relatively low temperature, while it mainly displayed an
inhibitory influence in the eastern and southern forest areas with sufficient water and heat (Figure 9). Therefore, it is speculated that the effect of sunshine may vary with temperature. When the temperature is relatively low, the sunshine exerts a strong complementary effect on plant growth, while when the temperature is sufficient, the sunshine in turn exhibits an inhibitory effect, thus limiting the growth of vegetation. This conclusion is consistent with some previous studies [21,63] and also confirms that the impact of climate factors on ESVs is very complex and may be fluctuant, interactive and synergistic at the same time.

4.2.2. Policy Implications Related to ESVs and Climate Change

Since the launch of the Millennium Ecosystem Assessment, the need to integrate ecosystem services into decision making has become increasingly prominent [64]. Ecosystem services are closely related to human well-being and sustainable development [65]. In view of the huge ecological and economic benefits of ecosystem service brought to human beings, it is necessary to integrate the research or assessment of ecosystem service value into the socio-economic and environmental protection decision-making system. If only economic indicators are used as the basis for decision making, it is easy to reduce ecological benefits, damage the ecological environment and even make mistakes in some important decisions [66].

According to the current pattern of the positive relationship between ESVs and climate warming and the continuation of this positive effect under RCP4.5 and RCP8.5 by 2050 [66], decision makers can determine the protection and management measures of forest ecosystems and ecological environments in the short- to medium-term. In this period, a wise choice is to make good use of this positive effect of climate warming and the powerful opportunity of national policy, give full play to the ecosystem functions and maximize their ecological and economic effects. However, it is necessary to actively monitor forest resources and the environment and pay attention to the unbalanced regional development of the ecological environment and the marginalization effect of forest segments, especially in areas with reduced ecosystem services.

Due to the threshold existing of forest growth in a positive response to warming [22], forest ecosystem functions may be weakened after 2050, and the negative impact of climate warming may be prominent. Therefore, in the long term, we should strengthen climate monitoring and early warning, enhance forest carrying capacity assessment, focus more on the ecological rather than economic effects of forest ecosystems and ensure forest quality so as to guarantee the ability to cope with climate change and human disturbance.

4.3. Methods to Calculate ESVs

Many approaches, including market, non-market, biomass, productivity and benefit transfer methods, have been widely applied to evaluate ecosystem services [7,34,67,68]. In general, these methods have great diversity and their own defects, and almost none of them have been unanimously recognized, resulting in the use of mixed methods in some cases. Although all existing methods provide a useful tool to measure the capacity of ecosystem services, considerable efforts are still required to continuously improve the methodology and validation, since the estimated results are sensitive to valuation methods [27].

The methods of quantifying ecosystem service value can be roughly divided into two categories [69], as shown in Table 3. One is based on the equivalent factor per unit area, which mainly depends on the constructed value equivalent of various services, combined with the distribution area of the ecosystem. This method has strong operability and simple calculation and can quickly provide ecosystem services to larger-scale areas with high reliability. The other is based on the transformation of market value. In this method, the production equation is established to simulate a single ecosystem function of small areas, and then value transformation is conducted using the direct market price method, alternative market price method or simulated market method. This method needs more data, and the calculation process is complicated, but the calculation result is relatively accurate.
The actual measure of ecosystem service value is not easy. Therefore, the evaluation results of different methods can be compared to verify the reliability of methods and ensure the accuracy of results as much as possible. In our study, Xie et al.’s equivalent factor method was used to evaluate the value of ecosystem services. Xie et al. [36] confirmed that the unit prices of ecosystem services determined by them were close to those estimated based on material quality, and the two were well comparable after comparing a large number of results. At the same time, the comparison analysis shows that forest water conservation values derived from the two methods were roughly equal and spatially matched (Figure 7). This suggests that our results are credible to some extent.

4.4. Limitations

Our study has some limitations in the quantification of ESVs due to limited data availability. In this study, the equivalent factors were mainly based on biomass [70–74], but the biomass was not always positively correlated with ecosystem services [75]. In addition, the determination of equivalent factors mainly depended on the cognitive level of ecological experts without considering the spatial heterogeneity of ecosystem services and the inflation; therefore this method has high subjective limitations. In reality, ecosystem services/functions such as diversity of forests, especially urban forests [76], are seriously influenced by regional geographic and human environments. In addition, some ecosystem services are intangible, e.g., cultural ecosystem [77], but the equation used in this study may be limited in reflecting these services. All these limitations or weaknesses brought more or less uncertainty to the research results.

It is very important to take into account the influence of anthropogenic and natural factors in social development decisions. Given data availability, some anthropogenic activity factors affecting ESVs, other than climate factors, were not considered, such as land-use change [21], population and economy [78] and even some green infrastructures [79]. Furthermore, the impact of extreme weather events has not yet been reflected separately. Therefore, it is necessary to conduct more in-depth research and further analysis to provide more valuable information. Nevertheless, this study has some advantages in quantifying the impact of climate change and demonstrating the long-term evolutionary trends and regional differences in forest ESVs. These findings are expected to play a role in decision making on the sustainable utilization of forest resources and adaptation to climate change.

5. Conclusions

This study assessed forest ESVs from 2001 to 2020 in China and quantitatively disclosed its characteristic of spatial evolution, uncovered the key climate driving factors behind ESV changes and preliminarily identified the eco-environmental status and vulnerable areas. The main conclusions are as follows:

(1) From 2001 to 2020, the average annual forest ESV in China was RMB 9.99 (9.17–10.81) trillion. The regional distribution of forest ESVs was notably characterized by increasing from the northwest to the southeast regions. In most forest areas, the ESVs have shown an increasing trend in the past 20 years. By contrast, they have decreased in very few forest areas such as Cuona and Motuo counties on the southern edge of Tibet Province in Southwest China and Pingtung and Kaohsiung counties in southern Taiwan. At the same time, the mean annual forest ESV was higher (usually less than 20%) in the recent 10 years than in the previous 10 years in most areas.

(2) Temperature, precipitation and evapotranspiration significantly and positively affected forest ESVs and were therefore the major regulatory factors across the 20 years. Nevertheless, the forest area with a significant influence of sunshine hours on ESVs was the largest, whether positive or negative. Sunshine hours showed a deep positive impact in the Northeast Forest Region with relatively low temperature, while it mainly displayed an inhibitory influence in the eastern and southern forest areas with sufficient water and heat. In most areas (>60%), the positive impact of various
c climatic factors was dominant, and the area positively affected by precipitation was the largest (76%).

(3) The forest water conservation was RMB 1.46 trillion based on the InVEST model in combination with the water balance principle and was RMB 1.77 trillion based on the modified equivalent factor method in combination with the CASA-NPP during 2001–2020. Overall, the results from the two methods are roughly equal and mostly spatially matched.

All these results indicate that China’s forest ecosystem provided huge spiritual and material wealth for human beings. In general, the forest ecosystem has been improved on the whole and is in a stable state, while the regional development is not balanced. Particular attention should be given to areas where the value of ecosystem services is declining. Climatic factors have profoundly affected the forest ecosystem service values, which should be considered in adaptation plan decision making. These results can provide an important reference for eco-environment protection and sustainable development policies, as well as an inclusive and in-depth view of the complex socio-ecological nexus between ecosystem management decisions and human development.

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