MULTI-SCALE VALUATION OF FOREST ECOSYSTEM SERVICES IN CHANGDE CITY, CHINA

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Abstract. Forest ecosystem services value (FESV) at multiple scales is crucial for the implementation of asset management and ecological compensation policies. This study focuses on Changde City in the Dongting Lake area, China, evaluating FESV across stand scale (scale I), regional scale (scale II), and grid scale (scale III), and examining their relationships with population and GDP metrics. Results indicate consistent spatial distribution patterns across scales, characterized by higher values in the northwest and southwest, and lower values in the southeast and east. Broad-leaved forests contribute most significantly to FESV at all scales. The study reveals that FESV is inversely related to urban development level and the proportion of plain areas, yet positively correlated with forest coverage. Nonlinear characteristics in FESV distribution are observed at the stand and grid scales, while regional scale evaluations show uniform value proportions across districts, suggesting spatial equivalency. The coefficient of variation of FESV across scales surpasses that of GDP, highlighting the substantial potential value of forest ecosystems relative to economic metrics. The research addresses the gap in multi-scale FESV valuation within the same region, aiming to establish management and enhancement strategies for forest ecosystem services. This study addresses the lack of research as well on forest ecosystem service value evaluation at different scales within the same region, providing reference and decision-making basis for regional forest ecosystem service management and improving the realization mechanism of forest ecological product value.
Keywords: *multi-scale, forest ecosystem, service value, evaluation, China*

Introduction

Forest ecosystems are the largest terrestrial ecosystems and play an essential role in providing ecosystem functions and service values. They are irreplaceable natural resources and assets fundamental to human survival and development. Forest ecosystem services have extremely high and often immeasurable value, closely related to human well-being (Brockerhoff et al., 2017; Acharya et al., 2019; Sanesi et al., 2019; Chen et al., 2022; Forbes et al., 2022). Historically, forest ecosystem services have been regarded as inexhaustible free public goods (Daily et al., 2000; Egoh et al., 2007; Lautenbach et al., 2011). However, how important are forest ecosystem services? How can this importance be quantified across time and spatial scales? How should items difficult-to-quantify be addressed? Given these questions, we urgently need to make choices and trade-offs regarding forest ecosystem services, which means rational quantification and valuation are necessary to provide references and decision-making bases for forest ecosystem service management and to improve the realization mechanism of forest ecological product value (Acharya et al., 2019).

Since Costanza (Costanza et al., 1997) defined ecosystem services as the benefits humans obtain from ecosystems, extensive research has been conducted. Currently,

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the main methods for accounting forest ecosystem service values include economic methods and ecological methods (Daily et al., 2000; Lautenbach et al., 2011). Chinese scholars, in addition to drawing on international methods, have also proposed evaluation methods suitable for China's forest ecosystem characteristics, such as those by Zhiyun Ouyang (Ouyang et al., 2016), Gaodi Xie (Xie et al., 2003, 2015), and the assessment specifications formulated by the State Forestry Administration. Scholars have evaluated forest ecosystem service values from the perspective of natural ecological functions (Iocoli et al., 2019), exploring influencing factors and mechanisms (Fisher et al., 2009; Carriger et al., 2019), including climate change (Jonsson et al., 2020), economic demands (Tang et al., 2020), forest management practices (Joos-Vandewalle et al., 2018), and technological aspects (Ling et al., 2020), as well as the trade-offs among different forest ecosystem services (Jiang et al., 2022; Morán-Ordóñez et al., 2022).

The research on forest ecosystem service value evaluation (Wu and Zeng, 2021) and trade-offs (Qi et al., 2021) has primarily focused on administrative regions (Huang et al., 2019), nature reserves (Yin et al., 2016), mountainous areas (Zhang et al., 2020), forest regions (Qiu et al., 2018), and natural geographic areas (Sun and Zhou, 2020; Ou et al., 2021). Studies have been conducted from national (Wang et al., 2011; Xu et al., 2018), provincial (Xiao et al., 2014), and regional perspectives (Li et al., 2020; Yang et al., 2021) on forest ecosystem service value evaluation at different scales. Existing literature provides references for accounting forest ecosystem service values, but variations in methodologies, data, and parameters used lead to significant differences in conclusions. Accurately assessing forest ecosystem service values in a specific region still faces several challenges. Therefore, further research is needed to accurately assess the value within the framework of forest ecosystem service value accounting, conduct scale-specific accounting and comparisons for the same regional service values, and develop models for reversing ecological parameters.

The Dongting Lake Eco-economic Zone is a significant Chinese regional development strategy, with the Dongting Lake area characterized by homogeneity in natural resources and integrity in environmental functions. This study takes Changde City, a typical region around Dongting Lake, as an example. It calculates the value of forest ecosystem services in Changde, evaluates and compares the multi-scale value of forest ecosystem services from stand scale, county scale, and grid scale, and analyzes the scientific and accurate accounting of forest ecosystem service values at different scales. This aims to provide references for evaluating forest ecosystem service values in the Dongting Lake area and other regions, contributing to the realization of forest ecosystem service pricing, protection of forest ecosystems, maintaining ecological security in the Dongting Lake area.

Material and methods

Study area

Situated in the northwest of Hunan Province, China, Changde City spans the coordinates 111°39′00″E to 112°17′52″E and 28°24′31″N to 30°07′53″N. It lies within the middle Yangtze River basin, at the downstream section of the Yuan River and the middle-to-lower reaches of the Li River. The city oversees nine districts and counties as well as five administrative regions, encompassing a total area of 18,200 km^2. Changde is located in a mid-northern subtropical humid climate zone, with an

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elevation range from -10 m to 2077 m, and features a terrain that gently declines from northwest to southeast. The northwestern portion belongs to the Wuling Mountain Range, dominated by low- and medium-altitude mountains. The central region is marked by red sandstone hills, while the southeastern area is primarily flat. The geographical distribution comprises 24.8% mountainous regions, 35.9% plains, 31.2% hills, and 8.1% water bodies (*Fig. 1*). The city enjoys an average annual temperature of 17.3°C, with yearly precipitation reaching 1386.9 mm and approximately 1589.5 h of sunshine. Boasting a forest coverage rate of 48%, Changde is rich in vegetation and ecological resources.

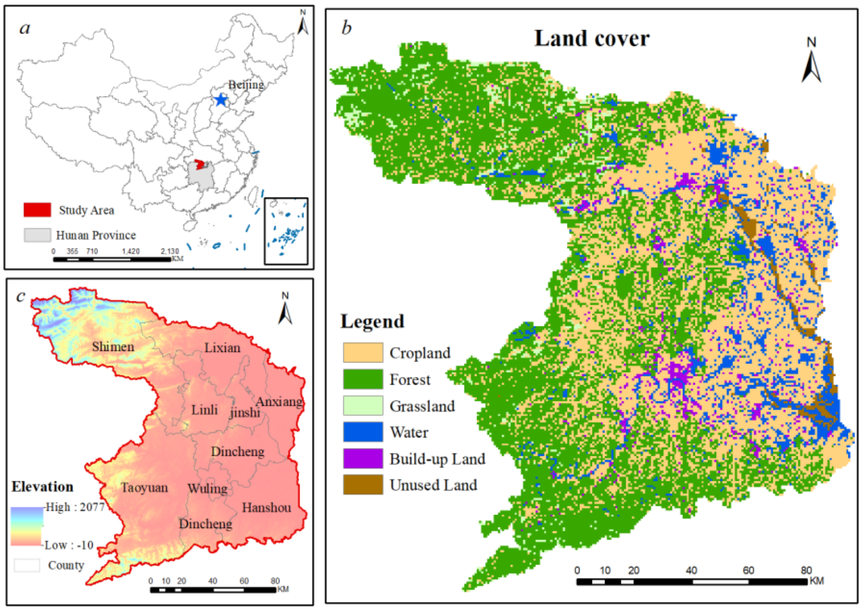

Figure 1. *Study regional spatial resource distribution map*

Data sources

The data used in this study include Landsat 8 OLI_TIRS satellite data products (acquired in 2019), featuring seven bands, primarily for calculating remote sensing-related data parameters, sourced from the Computer Network Information Center, Chinese Academy of Sciences (https://www.gscloud.cn/). We selected remote sensing data from the vegetation growth season in the study area and, through resampling, produced a 1 km × 1 km normalized difference vegetation index (NDVI) distribution dataset for the region; Digital elevation model (DEM) sourced from the Computer Network Information Center, Chinese Academy of Sciences, mainly for calculating elevation and slope factors (https://www.gscloud.cn/). Forest resource data from the 2019 forest resource survey of Changde City, mainly for extracting forest area and tree species information; Soil data sourced from the Soil Science Data Center, Nanjing Institute of Soil Science, Chinese Academy of Sciences, selecting basic soil information data of Changde City, primarily for calculating organic matter content, nitrogen, phosphorus, and potassium content in the soil (http://data.issas.ac.cn/); Meteorological data sourced from the China Meteorological Data network, obtaining annual precipitation and evaporation data for 2019 for the districts and counties of Changde City (http://data.cma.gov.cn/site/index.html); Social public data required for value

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evaluation from the National Food and Strategic Reserves Administration, Changde Municipal People's Government, Changde Statistics Bureau, and the Hunan Statistical Yearbook; and calculation parameters refer to relevant materials and literature (Xie et al., 2015; Xu et al., 2022; Zuo et al., 2022).

Methods

(1) Research framework

This study evaluates the forest ecosystem services value (FESV) from the stand perspective, regional perspective, and grid perspective, as shown in *Figure 2*.

At the stand scale (scale I), combined with the forest resource data of Changde City, commonly used international accounting indicators are selected for value evaluation, including three primary indicators (regulating services, supporting services, and cultural services), six secondary indicators (water conservation, carbon sequestration and oxygen release, air purification, soil conservation, nutrient accumulation, and forest recreation), ten physical quantity indicators, and twelve value quantity indicators.

At the regional scale (scale II), combined with data on major grain crops in the counties, the value equivalent factor method is used to estimate the value of forest ecosystem services within the county. According to the value equivalent types, forest ecosystem services are divided into four indicators (supply services, regulating services, supporting services, and cultural services) for value evaluation.

At the grid scale (scale III), systematic sampling points are arranged within the study area, and the corresponding NDVI and calculated FESV grid data are superimposed. The grid data corresponding to the sample points are extracted for FESV estimation modeling, exploring the quantitative relationship between NDVI and FESV grid data.

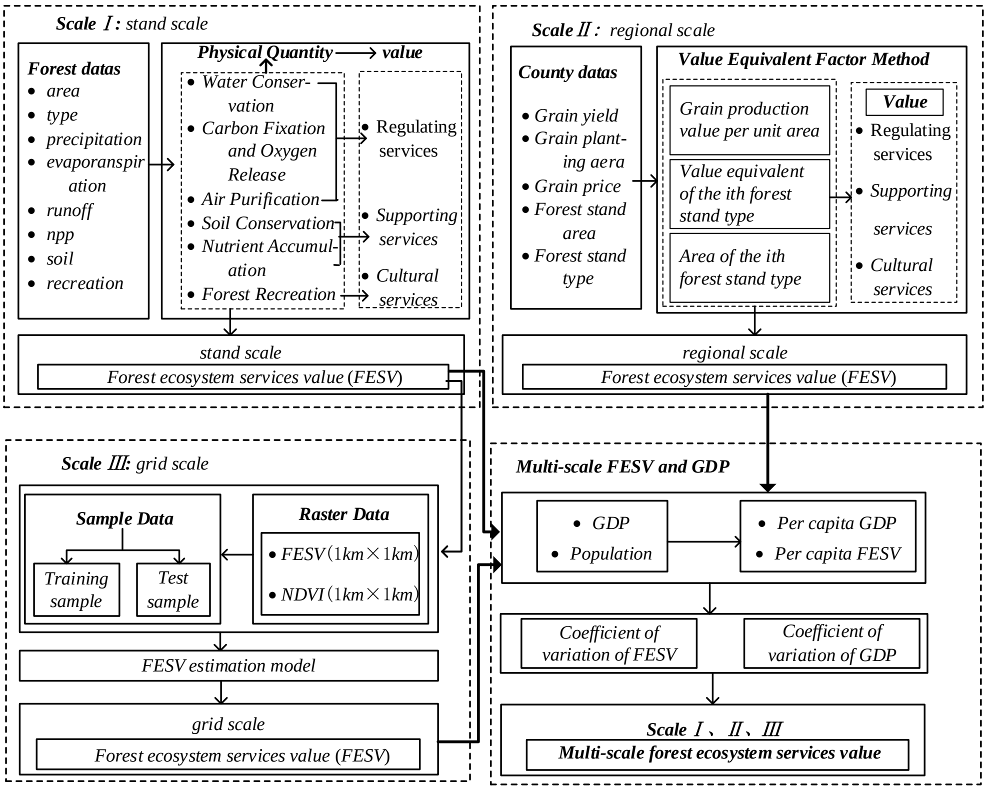

Figure 2. *Research framework of multi-scale forest ecosystem service value evaluation*

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(2) Calculation methods of forest ecosystem service value at the stand scale

According to the "Specifications for the Assessment of Forest Ecosystem Service Functions" (GB/T 38582-2020), ArcGIS is used to process and calculate relevant raster data of remote sensing images. Combined with forest stand data and existing forest ecosystem service value evaluation indicator parameters and data, the main indicator parameters for the physical quantity of forest ecosystem services are calculated. Common value assessment methods such as the replacement market method, simulated market method, and replacement engineering method are used to calculate the value of forest ecosystem services (*Table 1*).

Table 1. *Calculation formula and index of forest ecosystem service value under scale I*

Service value	Calculation formula	Variables and parameters
Water conservation	$E=\sum a_i \times 10(Q_{pr}-Q_{tr}-Q_{ro})$ $U_{aw}=P_{sc}\cdot E$ $U_{pw}=P_{pc}\cdot E$	E is the physical quantity of water conservation; U_{aw} is the value of water regulation; U_{pw} is the value of water purification; a_i is the area of the *i*th forest type; Q_{pr} is the precipitation; Q_{tr} is the evapotranspiration; Q_{ro} is the surface runoff; P_{sc} is the cost per unit capacity of reservoirs; P_{pc} is the water purification cost
Carbon fixation and oxygen release	$U_{cf}=1.63a\cdot R_c\cdot B_{npp}\cdot P_{cf}$ $U_{or}=1.19a\cdot B_{npp}\cdot P_{or}$	U_{cf} is the value of carbon fixation; U_{or} he value of oxygen release; R_c the carbon content in CO_2; B_{npp} is the net primary productivity
Air purification	$U_{ap}=\sum K_i\cdot Q_i\cdot a_i$ $U_{rd}=a\cdot Q_{rd}\cdot P_{rd}$	U_{ap} is the annual value of harmful gas absorption; U_{rd} is the annual value of dust retention; Q_i is the absorption quantity of harmful gases; K_i is the treatment cost of harmful gases; Q_{rd} is the annual physical quantity of dust retention; P_{rd} is the dust treatment cost
Soil conservation	$A=R\cdot K\cdot L\cdot S\cdot C\cdot P$ $U_{sf}=A\cdot M_0\cdot a$ $U_{sk}=\sum A\cdot FC_i\cdot FP_i$	A is the physical quantity of soil conservation; U_{sf} is the value of soil consolidation; U_{sk} is the value of fertility preservation; FC_i is the pure content of nitrogen, phosphorus, and potassium in the soil; FP_i is the price of fertilizers
Nutrient accumulation	$Q_N=a\cdot B_{npp}\cdot N_{tree}$ $Q_P=a\cdot B_{npp}\cdot P_{tree}$ $Q_K=a\cdot B_{npp}\cdot K_{tree}$ $U_{an}=Q_N/18\%\cdot M_1+Q_P/46\%\cdot M_1$ $+Q_K/60\%\cdot M_2$	U_{an} is the value of nutrient accumulation; Q_N is the nitrogen fixation quantity by trees; Q_p is the phosphorus fixation quantity by trees; Q_K is the potassium fixation quantity by trees; M_1 and M_2 is the price of diammonium phosphate and potassium chloride
Forest recreation	$U_r=\sum(Y_i+Y_i')$	U_r is the value of forest recreation; Y_i is the direct income from forest parks; Y_i` is the indirect income from forest parks

(3) Calculation methods of forest ecosystem service value at the regional scale

How should the economic value of a baseline ecosystem service value equivalent factor be defined? According to Gaodi Xie (Xie et al., 2003), the annual financial benefit derived from the naturally produced grain yield per hectare of farmland can serve as the benchmark for a single equivalent factor. This method is intended to highlight the ecosystem's inherent capacity to provide ecological services. Nonetheless, eliminating human-induced disturbances at a regional scale and precisely quantifying

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farmland's grain yield based solely on natural processes remains challenging. Therefore, in this study, we interpret the net profit generated by an ecosystem as its overall production value, and we designate the unit-area net profit from farmland grain production as the ecosystem service value of one standard equivalent factor. Using the modified unit area ecological service value equivalent proposed by Gaodi Xie (Xie et al., 2015), the value equivalent factor method is used to calculate the value of forest ecosystem services. Based on the total area and yield of major grain crops in the counties, the economic value of food production services in the farmland ecosystem per unit area is calculated, as shown in *Equation 1*. Based on the modified forest ecosystem service value equivalents and equivalent factor values, the forest ecosystem service value in the regional scope is calculated using *Equation 2*.

$$E_a = \frac{1}{7} \times \frac{\sum_{i=1}^{n} N_i}{\sum_{i=1}^{n} M_i} \quad \text{(Eq.1)}$$

$$FESV = \sum_{k=1}^{n} \sum_{i=1}^{m} \sum_{j=1}^{l} (E_a \times E_{jk} \times A_{ij}) \qquad (k = 1,2,3,4; i = 1,2,\cdots,9; j = 1,2,3) \quad \text{(Eq.2)}$$

In *Equations 1* and *2*, the constant 1/7 signifies that the economic value contributed by a purely natural ecosystem, free from human intervention, amounts to one-seventh of the existing per-unit-area farmland's economic value of food production services. E_a is the economic value of food production services provided by the farmland ecosystem per unit area, N_i is the total price of major grain crops in the ith county, M_i is the planting area of major grain crops in the ith county, *FESV* is the total value of forest ecosystem services in the study area, E_{jk} is the value equivalent of the kth forest ecosystem service function of the jth forest type, A_{ij} is the area of the jth forest type in the ith region.

(4) Calculation methods of forest ecosystem service value at the grid scale

Combining the NDVI grid data (1 km × 1 km) of the growing season in the study area, the spatial distribution data of FESV calculated at the stand scale is converted into grid data and resampled at 1 km × 1 km. Sample points are arranged at 5 km × 5 km and superimposed with the NDVI and FESV grid data. The grid data values corresponding to the sample points are extracted, excluding water bodies, farmland, grassland, built-up land, and unused land. The sample data are randomly divided into training samples and test samples at a 7:3 ratio. The least-squares regression fitting is performed on the NDVI and FESV grid data training samples, as shown in *Equation 3*. The mean absolute error (MAE) and root mean square error (RMSE) between the test samples and corresponding simulated values are analyzed, as shown in *Equations 4* and *5*, and an FESV grid data estimation model is established.

$$\begin{aligned} y_i &= \beta_1 + \beta_2 x_i \\ x_i &= \{x_1, x_2, x_3, \cdots\} \\ y_i &= \{y_1, y_2, y_3, \cdots\} \end{aligned} \quad \text{(Eq.3)}$$

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$$MAE = \frac{1}{n}\sum_{i=1}^{n}\left|y_i' - y_i\right| \qquad \text{(Eq.4)}$$

$$RMSE = \sqrt{\frac{\sum_{i=1}^{n}(y_i' - y_i)^2}{n}} \qquad \text{(Eq.5)}$$

In *Equations 3‒5*, x_i is the NDVI grid dataset, y_i is the FESV grid dataset, n is the number of test samples, MAE is the mean absolute error, RMSE is the root mean square error, y_i` is the simulated value of the test sample.

(5) Coefficient of variation of forest ecosystem services and economic development

By calculating the coefficient of variation (CV) of FESV and gross domestic product (GDP), the deviation and aggregation degree of FESV and GDP are analyzed. A smaller CV value indicates less difference in FESV or GDP among the research units, and vice versa, to explore the coordination between forest ecosystem services and economic development. The calculation equation is as follows:

$$CV = \frac{1}{\overline{Y}}\sqrt{\frac{\sum_{i=1}^{n}(Y_i - \overline{Y})^2}{n}} \qquad \text{(Eq.6)}$$

In *Equation 6*, $\overline{Y}$ is the mean value of FESV or GDP in different regions or types, n is the number of research units, Y_i is the standard deviation of FESV or GDP in the *i*th research unit.

Results and analysis

Evaluation of forest ecosystem service value at the stand scale

The results show that the total value of forest ecosystem services at the stand scale (scale I) in Changde City is 22447.98 billion CNY (*Table 2*). In terms of ecological service function categories, supporting services, regulating services, and cultural services account for 69.52%, 29.92%, and 0.56% of the total service value, respectively. The spatial distribution of the total value of forest ecosystem services in Changde City is shown in *Figure 3a*. The areas with the highest unit area value are mainly distributed in the northwest and southwest of the study area, which are densely vegetated mountain and hilly regions. *Figure 3b-f* show the spatial distribution of different service function values. Overall, the trend decreases from the northwest and southwest to the southeast and east, consistent with the spatial distribution of major forests in the study area. This reflects that vegetation growth is better in mountain and hilly areas with less human disturbance and higher forest coverage, resulting in higher unit area values of various forest ecosystem services.

The ecological service values of different forest types are shown in *Figure 4*. The results show that the total ecological service value of broadleaf forests is the highest, followed by coniferous forests, mixed coniferous and broadleaf forests, and bamboo forests. The ecological service value of different forest types varies significantly, which

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corresponds to the area differences of different forest types in the study area. For the same forest type, the proportion of ecological service value composition follows the same trend, with soil conservation accounting for the largest proportion of ecological service value, exceeding 50% of the total ecological service value. Overall, broadleaf forests contribute the most to ecological services, likely due to their richer and more comprehensive vertical space, which is more conducive to exerting their ecological service functions and higher ecological carrying capacity. This is followed by Masson pine forests, mixed coniferous and broadleaf forests, Chinese fir forests, bamboo forests, and cypress forests.

Table 2. *Ecological service values of different types of forest ecosystem services in Changde City*

Primary type	Secondary type	Tertiary type	Physical quantity of forest ecological services (10,000 tons)	Value of forest ecological services (100 million CNY)	Value composition (%)
Regulating services	Water conservation	Water regulation quantity	436413.23	264.99	1.17
	Carbon sequestration and oxygen release	Carbon sequestration quantity	20933.99	77.39	0.34
		Oxygen release quantity	55965.88	5932.38	26.08
	Air purification	Pollutants absorption quantity	9.88	266.90	1.17
		Dust retention quantity	1809.99	262.45	1.15
Supporting services	Soil conservation	Soil consolidation quantity	15315.10	32.7	0.14
		Fertility preservation quantity	33787.29	14522.89	63.86
		Nitrogen fixation quantity	701.44	857.31	3.77
	Nutrient accumulation	Phosphorus fixation quantity	169.33	80.98	0.36
		Potassium fixation quantity	793.61	317.44	1.40
Cultural services	Forest recreation	Value of forest recreation	—	127.63	0.56

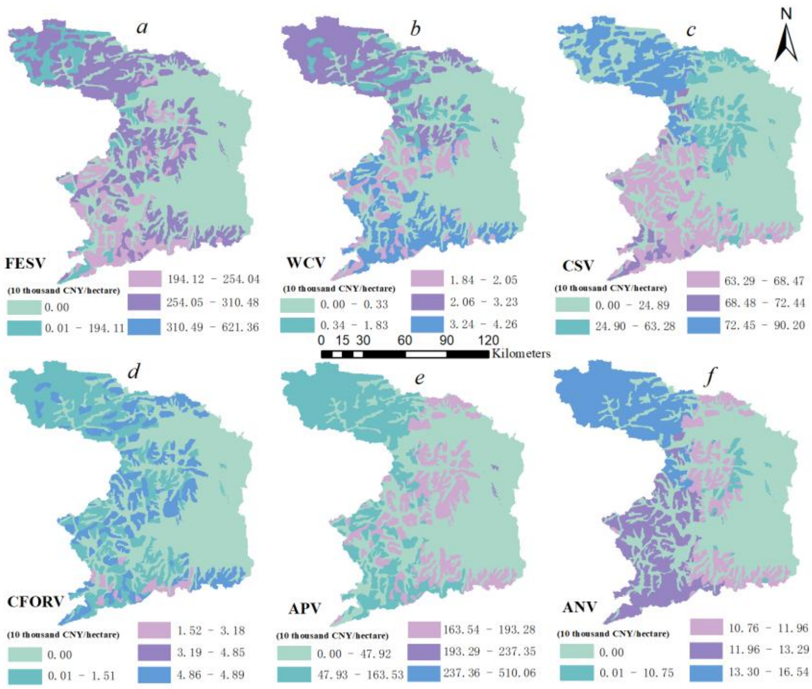

Figure 3. *Study regional spatial resource distribution. FESV: forest ecosystem service value, WCV: water conservation value, CSV: conservation soil value, CFORV: carbon sequestration and oxygen release value, APV: air purification, ANV: accumulated nutrient value*

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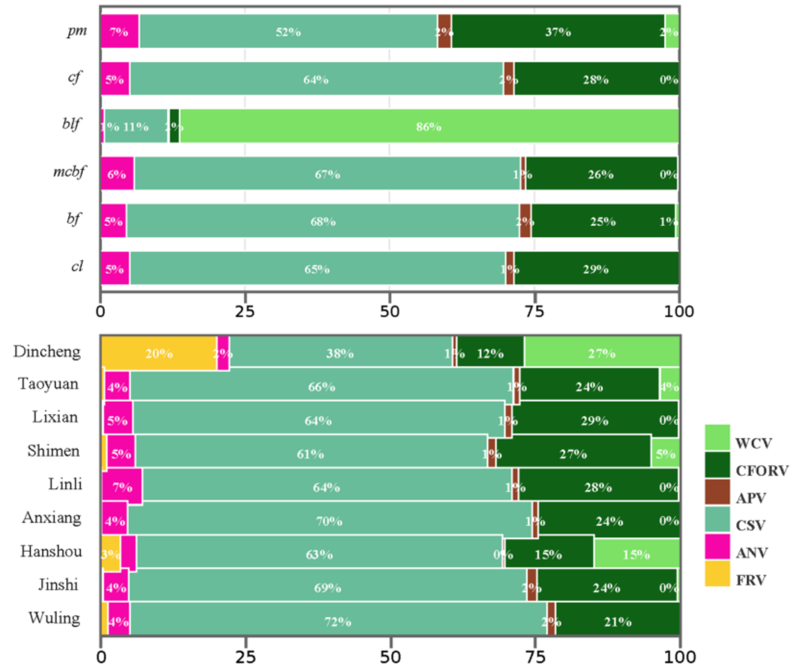

Figure 4. *The Value and value composition ratio of forest ecological services in different stands, districts, and counties under Scale I in Changde city. cl: Chinese Fir Forests, pm: Masson Pine Forests, cf: Cypress Forests, blf: Broadleaf Forests, mcbf: Coniferous and Broadleaf Mixed Forests, bf: Bamboo Forests. WCV: water conservation value, CSV: conservation soil value, CFORV: carbon sequestration and oxygen release value, APV: air purification value, ANV: accumulated nutrient value, FRV: forest recreation value*

The composition of forest ecosystem service values in different districts and counties is shown in *Figure 4*. It can be seen that, similar to the composition of forest ecosystem service values for different forest types, soil conservation and carbon sequestration and oxygen release are the main contributors to forest ecosystem services in each district and county, accounting for 68.67% to 91.2% of the total forest ecosystem service value. There are significant regional differences in the forest ecosystem service value among different districts and counties, with Shimen County, Taoyuan County, Dingcheng District, Lixian County, Linli County, Hanshou County, Jinshi County, Anxiang County, and Wuling District showing varying values. These regional differences are related to the area, topography, forest coverage rate, and urban development level of the regions, reflecting that areas with high urban development levels, large plain areas, and low forest coverage have lower forest ecosystem service values, and vice versa.

Evaluation of forest ecosystem service value at the regional scale

The results show that the total value of forest ecosystem services at the regional scale (scale II) in Changde City is 33.74 billion CNY (*Table 3*), with regulating services having the highest value, accounting for 74.5% of the total ecological service value, followed by supporting services (13.88%), supply services (6.39%), and cultural services (5.24%). The spatial distribution of forest ecosystem service values at the regional scale is shown in *Figure 5*. The results show that the spatial distribution of

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different service function values has a generally consistent trend, gradually decreasing from the northwest and southwest to the southeast and east, consistent with the spatial distribution of major forests in the study area. Overall, the spatial distribution characteristics are similar to scale I, but the spatial distribution differences in service function values are not obvious, with significant spatial consistency in the distribution of different forest ecosystem service values, related to the calculation method of ecological service values at scale II, which uses the value equivalent factor method, resulting in spatial equivalence of each ecological service value.

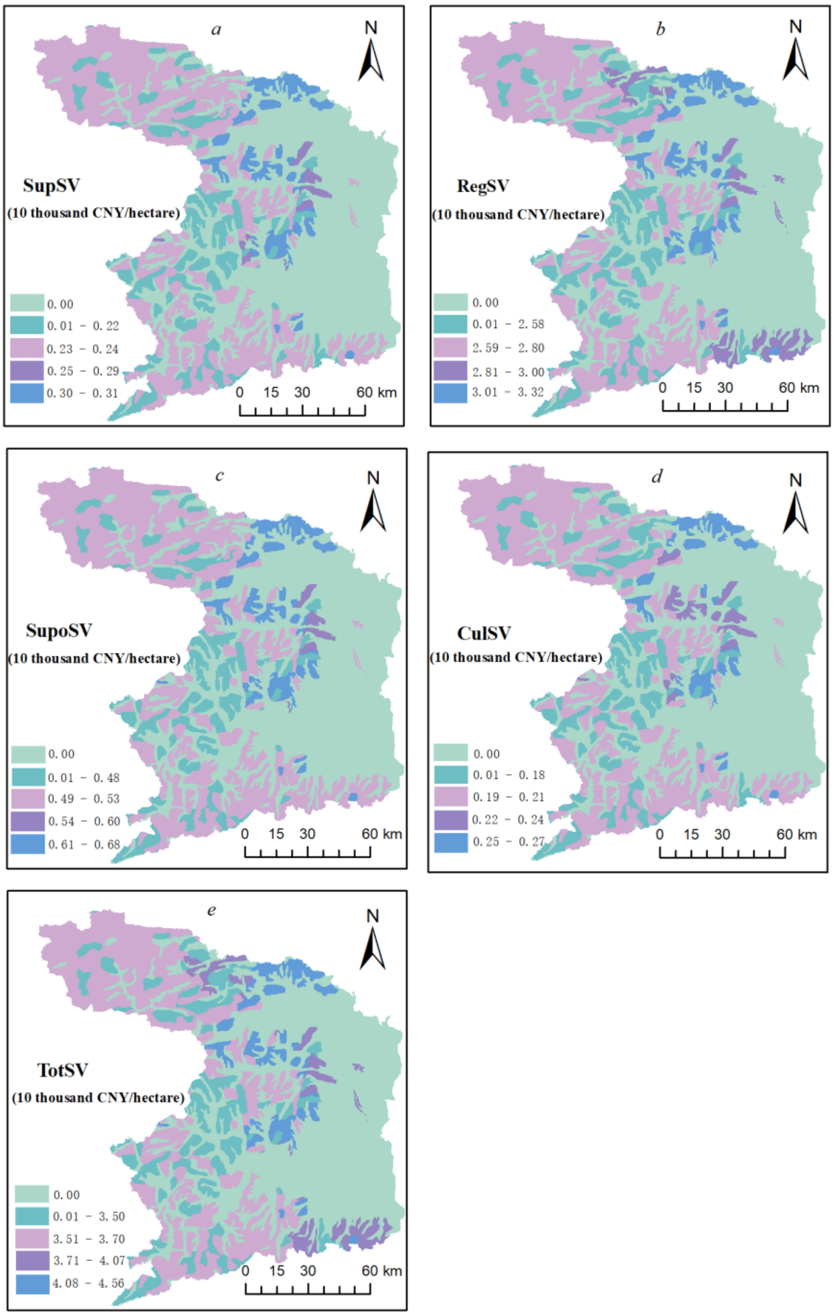

Figure 5. *Spatial distribution map of forest ecosystem service value under scale ii in Changde City. SupSV: supply service value, RegSV: regulatory service value, SupoSV: support service value, CulSV: cultural service value, TotSV: the total of service value*

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Table 3. *Ecological service value of different forest ecosystem service types under scale II (100 million CNY)*

District	Supply service value	Regulatory service value	Support service value	Cultural service value	FESV	Value proportion (%)
Wuling	0.05	0.53	0.10	0.04	0.72	0.21
Dincheng	2.30	26.49	5.00	1.89	35.68	10.57
Taoyuan	6.33	74.32	13.75	5.18	99.57	29.51
Lixian	1.89	21.06	4.12	1.55	28.61	8.48
Shimen	7.68	90.94	16.68	6.30	121.61	36.04
Linli	1.62	18.57	3.53	1.33	25.06	7.43
Anxiang	0.07	0.79	0.14	0.05	1.05	0.31
Hanshou	1.06	12.58	2.31	0.87	16.82	4.98
Jinshi	0.55	6.07	1.21	0.45	8.28	2.46
Total	21.55	251.36	46.83	17.66	337.4	100.00

The ecological service values of different forest types and service functions in the county range are shown in *Figure 6*. The results show that the total ecological service value is highest for broadleaf forests, followed by coniferous forests and mixed coniferous and broadleaf forests, with broadleaf forests accounting for 63.37% of the total regional forest ecosystem service value, contributing the most to regional forest ecosystem services, followed by coniferous forests (21.85%) and mixed coniferous and broadleaf forests (14.78%). In the forest ecosystem service value composition of Shimen County, Taoyuan County, Dingcheng District, and Linli County in the northwest, southwest, and central parts of the study area, broadleaf forest ecological services account for the largest proportion, consistent with the rich vegetation resources in these mountainous and hilly regions. The total ecological service value of different districts and counties shows significant regional differences, with Shimen County, Taoyuan County, Dincheng District, Lixian County, Linli County, Hanshou County, Jinshi County, Anxiang County, and Wuling District showing varying values. These differences correspond to the topographical variations, with more mountainous and hilly areas in the northwest, southwest, and central parts and more plains in the eastern part of the study area. For different service functions, the proportion of regulating services, supporting services, supply services, and cultural services is generally consistent across different districts and counties, matching the spatial equivalence characteristic of ecological service values shown in *Figure 5*.

Evaluation of forest ecosystem service value at the grid scale

The estimated and spatial distribution simulation of forest ecosystem service values at the grid scale (scale III) in Changde City are shown in *Figure 7*. *Figure 7a-d* display the quantitative relationship between stand scale FESV sample points and NDVI and establish an FESV estimation model to test the simulated values against the observed values of the test samples. The results show that the mean absolute error (MAE) is 93,600 CNY/hm², and the root mean square error (RMSE) is 108,600 CNY/hm², with a paired simulation fit coefficient of 0.89. The test results indicate that the fit error of the test samples is relatively large, which may be related to the diversity and complexity of influencing factors associated with stand scale FESV, leading to significant differences in estimated simulated values for the same or similar NDVI values. The grid scale simulation results are shown in *Figure 7e*. Overall, the spatial distribution trend is consistent with *Figure 7a*, and combined with the MAE and RMSE of the test samples, the grid estimation and simulation of FESV meet the accuracy requirements for local analysis of the spatial distribution of forest ecosystem service values.

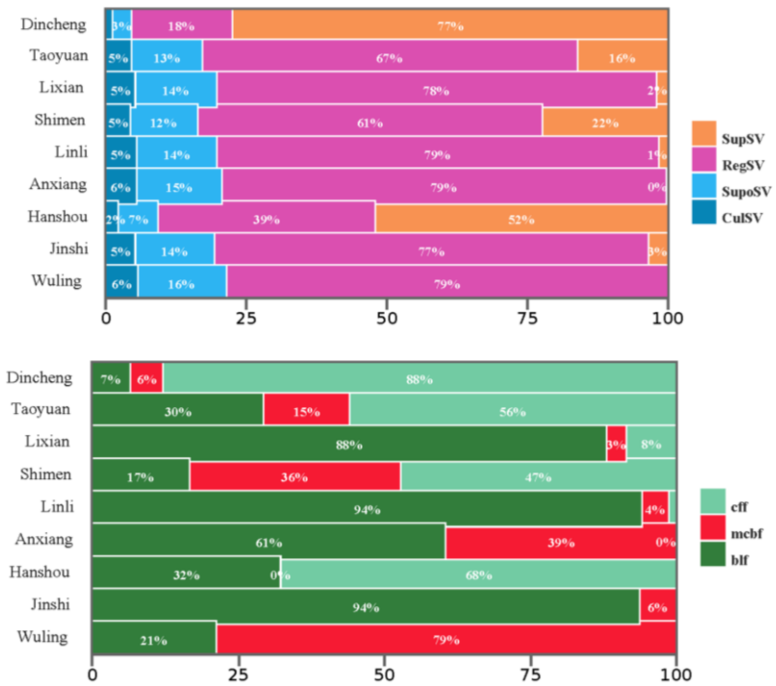

Figure 6. *The value and value composition ratio of forest ecological services in different stands, districts, and counties under scale II in Changde City. SupSV: supply service value, RegSV: regulatory service value, SupoSV: support service value, CulSV: cultural service value. cff: coniferous forest, mcbf: Coniferous and Broadleaf Mixed Forests, blf: Broadleaf Forests*

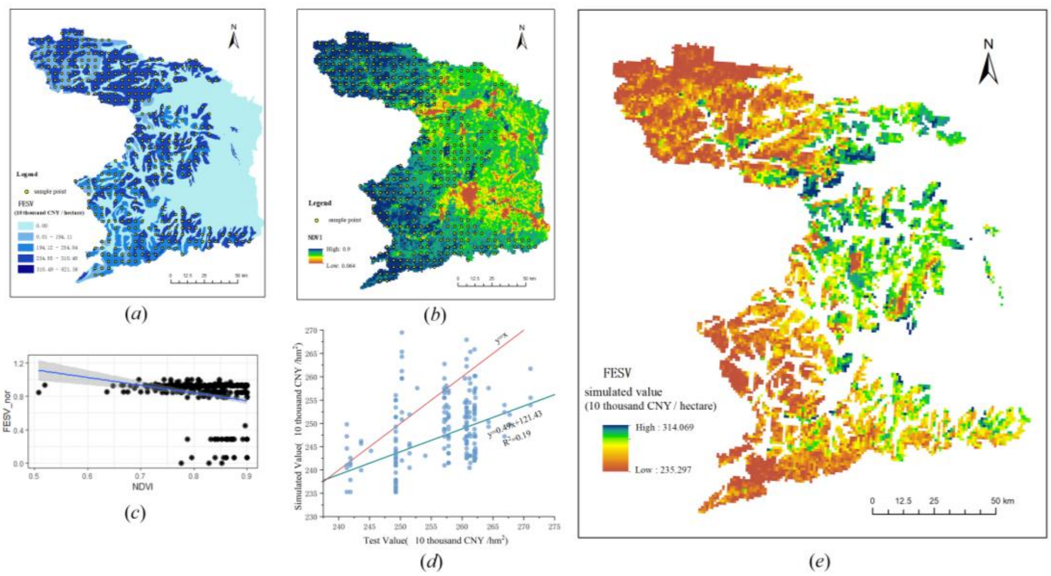

Figure 7. *Spatial estimation and simulation of forest ecosystem service value under scale iii in Changde City*

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The relevant statistical results of the estimated and simulated FESV for different districts and counties at the grid scale (scale III) are shown in *Table 4*. The average unit area FESV values for different districts and counties range from 2.4177 to 2.6457 million CNY/hm². The highest FESV estimation standard deviation is in Wuling District (213,600 CNY/hm²), and the lowest is in Hanshou County (21,360 CNY/hm²). The total estimated FESV values for different districts and counties show significant differences, with the highest in Shimen County (8063.08 billion CNY), accounting for 35.24% of the city's total FESV, and the lowest in Wuling District (55.56 billion CNY). This regional difference in spatial distribution is consistent with the FESV estimation results at scales I and II.

Table 4. *Statistics of FESV in different districts and counties under scale III in Changde City*

District	Average unit area FESV (10,000 CNY/hm²)	Standard deviation (10,000 CNY/hm²)	Maximum value (10,000 CNY/hm²)	Minimum value (10,000 CNY/hm²)	FESV (100 million CNY)	Value proportion (%)
Wuling	264.57	21.36	314.07	238.41	55.56	0.24
Dincheng	247.8	6.82	297.49	235.3	2339.21	10.22
Taoyuan	241.77	6.31	291.27	235.3	6905.1	30.18
Lixian	250.62	7.34	275.72	235.3	1774.41	7.75
Shimen	241.99	8.04	305.26	235.3	8063.08	35.24
Linli	253.31	8.3	293.86	235.3	1671.87	7.31
Anxiang	253.78	6.33	277.79	242.03	98.97	0.43
Hanshou	247.06	6.11	295.41	235.3	1138.95	4.98
Jinshi	253.14	6.89	292.82	236.33	835.35	3.65
Total	250.45	8.61	314.07	235.3	22882.5	100

Comparison of forest ecosystem service value and GDP at different scales

In 2019, the estimated total value of forest ecosystem services in Changde City was 22447.98 billion CNY, 33.74 billion CNY, and 22882.50 billion CNY at scales I, II, and III, respectively. The GDP was 3624.21 billion CNY, and the total population was 5.8228 million. Therefore, the per capita forest ecosystem service values at scales I, II, and III were 385,500 CNY, 8,500 CNY, and 393,000 CNY, respectively, and the per capita GDP was 62,200 CNY. Overall, the ratios of per capita GDP to per capita forest ecosystem service values were approximately 1:6, 1:0.1, and 1:6, respectively. This indicates that the forest ecosystem service value relative to the socio-economic value varies significantly at different scales. At scales I and III, the forest ecosystem services have a greater potential value relative to GDP, whereas at scale II, the forest ecosystem service value is relatively scarce compared to socio-economic value.

The per capita forest ecosystem service value and GDP of different districts and counties at different scales are shown in *Table 5*. It can be seen that the forest ecosystem service value provided by different regions at each scale shows significant differences. In economically developed, densely populated areas with large plains and water bodies, the per capita forest ecosystem service value is extremely low. For example, the annual per capita forest ecosystem service values in Wuling District at scales I, II, and III are 17,700 CNY, 200 CNY, and 12,800 CNY, respectively, and in Anxiang County, the values are 16,400 CNY, 200 CNY, and 18,500 CNY, respectively. In Hanshou County, the values are 136,800 CNY, 1,900 CNY, and 130,600 CNY, respectively. Notably, the low forest ecosystem service value in economically developed areas like Wuling is expected. However, the low per capita forest ecosystem service value in Anxiang

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County, Hanshou County, and Li County, less than half of the city's average, suggests that the scarcity of forest ecosystem services in these areas is becoming more prominent with economic and social development, warranting attention.

Table 5. *Comparison of FESV and GDP at different scales in various counties in 2019*

District	FESV (100 million CNY)			Population (10,000 people)	GDP (100 million CNY)	Per capita FESV (10,000 CNY)			Per capita GDP (10,000 CNY)
	Scale I	Scale II	Scale III			Scale I	Scale II	Scale III	
Wuling	76.58	0.72	55.56	43.37	1258.6	1.77	0.02	1.28	29.02
Dincheng	2378.27	35.68	2339.21	75.60	364.60	31.46	0.47	30.94	4.82
Taoyuan	6883.44	99.57	6905.1	96.65	407.52	71.22	1.03	71.44	4.22
Lixian	1845.7	28.61	1774.41	91.42	373.6	20.19	0.31	19.41	4.09
Shimen	7774.79	121.61	8063.08	66.69	295.67	116.58	1.82	120.9	4.43
Linli	1652.79	25.06	1671.87	44.6	193.04	37.06	0.56	37.49	4.33
Anxiang	87.49	1.05	98.97	53.51	210.9	1.64	0.02	1.85	3.94
Hanshou	1193.34	16.82	1138.95	87.24	303.08	13.68	0.19	13.06	3.47
Jinshi	555.58	8.28	835.35	23.20	171.5	23.95	0.36	36.01	7.39
Total	22447.98	337.4	22882.5	582.28	3578.51	38.55	0.58	39.30	6.15

From the perspective of counties, forest types, and service function types, the coefficients of variation for forest ecosystem service values at scales I, II, and III are higher than those for GDP (*Table 6*), indicating that the differences in forest ecosystem service values in the study area are greater than those for GDP. At the county level, the coefficients of variation for forest ecosystem service values at different scales are consistent, indicating that the differences in FESV at scales I, II, and III within the county range are not significant. For forest types, the coefficients of variation for FESV at scales I and III are significantly higher than those at scale II. For service functions, the coefficient of variation for FESV at scale I is higher than that at scale II. This suggests that the differences in FESV for forest types and service functions at scale II are smaller, consistent with the spatial equivalence characteristic of FESV estimation at scale II. Compared with the coefficients of variation for FESV at scale II, the results show that the differences in FESV at scales I and III are greater, corresponding to the diversity and complexity of influencing factors in FESV estimation at scales I and III.

Table 6. *The coefficient of variation between forest ecosystem service value and GDP in different types of Changde City*

Type	Coefficient of Variation of FESV			Coefficient of variation of GDP
	Scale I	Scale II	Scale III	
County	1.08	1.09	1.08	0.79
Forest type	1.18	0.64	1.16	−
Service function	1.4	1.15	−	−

Discussion and conclusions

Discussion

This study takes Changde City around Dongting Lake as an example and evaluates forest ecosystem service values from the perspectives of forest types, geographic

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regions, and grid images. The multi-scale forest ecosystem service values (FESV) and their relationships with population and GDP are discussed, addressing the lack of research on forest ecosystem service value evaluation at different scales within the same region. The conclusions are briefly discussed as follows:

(1) Selection Strategy of FESV Evaluation Methods at Multiple Scales. Ecosystem services are crucial for sustaining human society. However, how can we quantify their importance? At what time and spatial scales should it be reflected? To what extent will pressure cause a shift to less desirable states? These questions require understanding and simulating the interactions between humans and nature. Apart from academically addressing these issues, humans must make choices and trade-offs regarding ecosystem services, necessitating valuation to select higher-value options from competing alternatives. The unit ecosystem service product price method (scale I) better reflects the heterogeneity of service value spatial distribution and quantitatively reflects forest ecosystem service value but involves many accounting methods and parameters, making it less practical for real-world applications. The unit area value equivalent factor method (scale II) is more practical and easy to compare, making it a quick evaluation tool for FESV but presents spatial equivalence characteristics in forest types and service functions with less spatial distribution difference. The grid scale method (scale III) produces similar spatial distribution characteristics to scale I, accurately reflecting forest ecosystem service values, and combines long-term remote sensing data for FESV estimation with strong operability and accuracy.

(2) Differences in the Relationship between FESV and GDP at Multiple Scales. Under the influence of human activities and nature, the sustainable development of a region inevitably aims to maximize GDP and ecosystem service values. The ratios of per capita FESV to per capita GDP at scales I and III are close to 6:1, while at scale II, it is less than 0.1. This difference is mainly due to the unit area value equivalent factor method (scale II) producing significantly lower FESV estimates than scales I and III, consistent with the findings of Zhiyun Ouyang (Ouyang et al., 2016) and Gaodi Xie (Xie et al., 2015) that the unit area value equivalent factor method’s results may be lower than other methods. The method’s practicality and ease of comparison make it widely used in ecosystem service trade-off and coordination studies, but it underestimates value and lacks spatial heterogeneity. Conversely, the unit ecosystem service product price and remote sensing image methods (scales I and III) may overestimate FESV, with soil conservation value accounting for over 50% of the total, directly related to soil fertility preservation and basic data on organic matter, nitrogen, phosphorus, and potassium.

(3) Improving FESV Estimation Accuracy. Ecosystem service value represents trade-offs in promoting sustainable well-being, expressed in competitive market units, time, labor, energy, life satisfaction, or various composite indices. Most ecosystem services are non-competitive, non-market public goods. Current capabilities in understanding, quantifying, and valuing ecosystem services remain limited, with a range from relatively easy to impossible to quantify. Addressing uncertainty in decision-making rather than ignoring difficult-to-quantify items is crucial. Costanza (Costanza et al., 1997) proposed maintaining accuracy without ignoring imprecise estimates and stressed the urgent need for integrated system approaches to efficiency, fairness, and sustainability in ecosystem service valuation. This study evaluates non-competitive public goods of forest ecosystem services at three scales as accurately as possible but lacks in integrating efficiency, fairness, and sustainability values. Differences in evaluation methods lead to significant valuation differences, with scales I and III

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potentially overestimating FESV, reflecting high potential value relative to GDP. At scale II, FESV may be underestimated, indicating a relative scarcity of forest ecosystem services compared to socio-economic value. This highlights the uncertainty of multi-scale FESV estimation, necessitating comprehensive consideration of potential overestimation and underestimation to improve accuracy. Future research should focus on balancing overestimation and underestimation across scales and establishing links between scales I, III, and II to develop multi-scale FESV valuation models incorporating efficiency, fairness, and sustainability.

Conclusions

Using the unit ecosystem service product price method (scale I), unit area value equivalent factor method (scale II), and remote sensing image method (scale III), this study evaluates the forest ecosystem service value (FESV) in Changde City around Dongting Lake. The analysis of multi-scale FESV and its relationship with population and GDP yields the following conclusions:

(1) Spatial Consistency of Multi-scale FESV. The estimated FESV for the study area at scales I, II, and III is 22447.98 billion CNY, 33.74 billion CNY, and 22882.50 billion CNY, respectively. The areas with the highest unit area value are mainly distributed in the northwest and southwest, showing a spatial distribution of “high in the northwest and southwest, low in the southeast and east.”

(2) Trend Consistency of FESV with Forest Types at Multiple Scales. The total ecological service value is highest for broadleaf forests, followed by coniferous forests and mixed coniferous and broadleaf forests, indicating that broadleaf forests contribute the most to regional forest ecosystem services. FESV at multiple scales also shows the same trend with county-level changes, reflecting that forest ecosystem service value is inversely related to urban development level and the proportion of plain areas but positively related to forest cover rate.

(3) Nonlinear Spatial Characteristics of FESV at Scales I and III. There are significant differences in the ecological service value of different stands, with supporting services having the highest value at scale I, accounting for 69.52%, and soil conservation value accounting for 64% of the total supporting services value. At scale II, FESV has linear characteristics, with consistent value proportions across different districts and counties, showing spatial equivalence.

(4) Variation Coefficients of FESV and GDP at Multiple Scales. The coefficients of variation for forest types are scale I, III > scale II, and for service functions are scale I > scale II. The differences in FESV for forest types and service functions at scale II are smaller, consistent with the spatial equivalence characteristic of FESV estimation at scale II. The coefficients of variation for FESV at multiple scales are higher than those for GDP.

(5) Comparison of Per Capita FESV and GDP at Multiple Scales. The ratios of per capita FESV to per capita GDP at scales I and III are close to 6:1, indicating a higher potential value of forest ecosystem services relative to GDP. At scale II, the ratio is less than 0.1, indicating a relative scarcity of forest ecosystem services compared to socio-economic value.

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