ASSESSMENT OF FOREST ECOSYSTEM SERVICES VALUE IN THE DONGTING LAKE AREA: A CASE STUDY OF CHANGDE CITY, CHINA

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Abstract. Forest ecosystem services are of immense value and crucial for human well-being. Assessing the value of these services is essential for forest ecosystem asset management, ecological compensation, and policy implementation regarding the compensated use of ecological services. This study develops a value assessment index system specific to the forest resources of China's Changde City and quantitatively evaluates their ecosystem service value. Key findings include: (1) The total value of Changde City's forest ecosystem services is estimated at 227.43 billion CNY, with the highest per-unit area values found in the northwest and southwest regions. (2) Supporting services hold the highest value at 69.52%, followed by regulating services at 29.92%, and cultural services at 0.56%. Broadleaf forests are the largest contributors, making up 58.9% of the total ecological service value, followed by coniferous forests (24.12%), mixed coniferous and broadleaf forests (12.56%), and bamboo forests (4.43%). (3) Shimen County contributes the most to the forest ecosystem service value of the city at 34.63%, followed by Taoyuan County (30.66%), Dingcheng District (10.59%), Lixian County (8.22%), Linli County (7.36%), Hanshou County (5.32%), Jinshi County (2.47%), Anxiang County (0.39%), and Wuling District (0.34%). (4) The per capita value of forest ecosystem services in Changde City is 390,600 CNY, with a per capita GDP of 62,200 CNY. The ratio of per capita GDP to per capita forest ecosystem service value is nearly 1:6, highlighting the relative scarcity of forest ecosystem services in densely populated and economically active areas.
Keywords: *forest ecosystem, service value, assessment, spatial quantification, Dongting Lake area*

Introduction

Ecosystems are the foundations of human survival and development, representing irreplaceable natural resources and assets. Ecosystems and their ecological processes continuously provide goods and services that form and sustain the environmental conditions and material bases upon which human life depends. The value of ecosystem services is immensely high, often immeasurable, and intricately linked to human well-being. Historically, due to the socio-economic systems' failure to fully appreciate the assets and values of ecosystem services, these services have been treated as abundant, inexhaustible, and free public goods, leading to the scarcity of ecological service supply and the overconsumption of these services (Costanza et al., 1997; Mamat et al., 2018; Sannigrahi et al., 2019; Ahammad et al., 2018; Chen et al., 2022). To alleviate the scarcity of ecological services, a full assessment of the value of ecosystem services has become a pressing need in the asset management of ecosystems, ecological compensation, and the compensated use of ecological services (Acharya et al., 2019; Yang et al., 2023). Forest ecosystems, being the largest terrestrial ecosystems, play a

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crucial role in providing significant ecosystem functions and service values. Accounting for the value of forest ecosystem services quantifies the impact of forests on the environment and socio-economic sectors, facilitating the inclusion of these contributions in the national economic accounting systems, which is essential for evaluating the effectiveness of ecological civilization construction and promoting the development of a green national economic accounting system (Sanesi et al., 2019; Li et al., 2019; Nitoslawski et al., 2021).

Scholars have assessed the value of forest ecosystem services from the perspective of natural ecological functions, examining the influencing factors and mechanisms of these services, including climate change, forest ecological factors, economic demands, forest management practices, and technological aspects (Naudiyal et al., 2017; Jonsson et al., 2020; Iqbal et al., 2020; Pui et al., 2020; Abad-Segura et al., 2020). This research spans various scales from national to provincial and regional levels, providing a diverse view on the assessment of forest ecosystem service values. Previous literature offers a reference for the accounting of forest ecosystem service values, but variations in methodologies, data, and parameters used in studies lead to significant differences in conclusions. Accurate assessment of the value of forest ecosystem services in a specific region still faces several challenges: (1) existing theoretical research frameworks show a degree of convergence, yet there are considerable differences in the specific accounting content and indicators; (2) the commonly used remote sensing (RS) and Geographic Information Systems (GIS) technologies for quantitatively reversing ecological parameters are still under exploration and lack standardized technical methods applicable to all scales and regions, leading to discrepancies in accounting results (Dai et al., 2021; Tang et al., 2022).

Therefore, further research is needed to accurately assess the value of forest ecosystem services within the accounting framework, to perform scale-specific accounting and comparisons for the same regional service values, and to develop models for reversing ecological parameters. Changde City, a key node city along the Yangtze River Economic Belt and an important part of the rise of central China and the Dongting Lake ecological economic zone, relies on its forest resource advantages. Accurately assessing the value of forest ecosystem services in Changde is crucial for the scientific protection and rational utilization of the forests in the Dongting Lake area. This study relies extensively on existing frameworks and outcomes of forest ecosystem service value assessments, systematically organizing and analyzing the theoretical foundations and methods of forest ecosystem value assessment. By focusing on forest types and geographic regions, it selects an assessment framework system, model methods, and technical parameters suitable for Changde City, utilizing RS and GIS technologies to achieve a spatially quantified evaluation of the forest ecosystem service values in Changde.

Material and methods

Study area overview

Changde City, located in the northwest of Hunan Province, China (between longitude 111°39′00″E and 112°17′52″E, and latitude 28°24′31″N and 30°07′53″N), lies within the middle reaches of the Yangtze River, downstream of the Yuan River, and the middle and lower reaches of the Li River. The city governs nine districts and counties, and five administrative areas, covering a total area of 18,200 km². It is situated in the mid-northern subtropical humid climate zone. The terrain of Changde

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slopes from northwest to southeast, with the northwestern part belonging to the Wuling Mountain Range, characterized mostly by low to middle elevation mountains. The central area is known for its red rock hills, while the southeastern part features flat terrain. The geographical features include mountains covering 24.8% of the total area, plains 35.9%, water bodies 8.1%, and hilly regions 31.2% (*Fig. 1*). The annual average temperature is 17.3°C, with an average annual precipitation of 1386.9 mm, and an average annual sunshine duration of 1589.5 h. The city boasts a forest coverage rate of 48%, with rich vegetation resources. The predominant plant species include Chinese cork oak (*Quercus fabri Hance*), ring-cupped oak (*Quercus variabilis Bl.*), glaucous-leaf oak (*Cyclobalanopsis glauca (Thunb.) Oerst.*), Chinese chestnut (*Castanea seguinii Dode*), Masson’s pine (*Pinus massoniana Lamb.*), Chinese fir (*Cunninghamia lanceolata (Lamb.) Hook.*), and moso bamboo (*Phyllostachys heterocycla (Carr.) Mitford cv. Pubescens*).

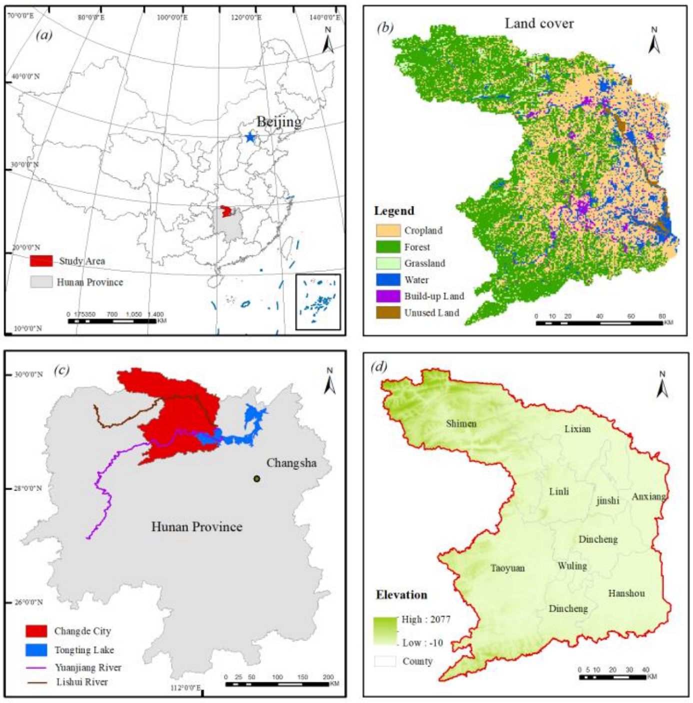

Figure 1. *Study regional spatial resource distribution map*

Assessment framework and indicator system

According to the Millennium Assessment (MA) by the United Nations, ecosystem services refer to the benefits that humans derive from ecosystems. These “services” primarily include “provisioning services,” “regulating services,” and “cultural services,” usually measured annually, specifically referring to the indirect use value provided by forest ecosystems. Based on existing theories and considering the forest resource data of Changde City, this paper selects well-established assessment methods and widely adopted international accounting indicators (including water conservation, carbon sequestration and oxygen release, air purification, soil conservation, nutrient accumulation, and forest recreation) for evaluation. The framework and content indicators for assessing the value of forest ecosystem services include three primary

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indicators, six assessment directions (secondary indicators), ten physical quantity indicators, and twelve value quantity indicators (*Table 1*).

Table 1. *Forest ecosystem services assessment indicator system*

Primary indicator	Secondary indicator	Tertiary indicator
Regulating services	Water conservation	Quantity of water regulation
		Value of water regulation, value of water purification
	Carbon sequestration and oxygen release	Quantity of carbon sequestration, quantity of oxygen release
		Value of carbon sequestration, value of oxygen release
	Air purification	Quantity of pollutants absorbed, quantity of dust absorbed
		Value of pollutants absorbed, value of dust absorbed
Supporting services	Soil conservation	Quantity of soil consolidation, quantity of fertility preservation
		Value of soil consolidation, value of fertility preservation
	Nutrient accumulation	Quantity of nitrogen fixed by trees, quantity of phosphorus fixed by trees, quantity of potassium fixed by trees
		Value of nitrogen fixed, value of phosphorus fixed, value of potassium fixed
Cultural services	Forest recreation	Value of forest recreation

Main data sources

(1) Imagery data: Utilizes Landsat 8 OLI_TIRS satellite data products, 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/).

(2) 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/).

(3) Forest resource data: Selects the 2019 forest resource survey data of Changde City, mainly for extracting information on forest area and tree species types.

(4) 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/).

(5) 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).

Models and related parameters

Based on existing research results on different ecosystem service values, with the help of ArcGIS for remote sensing image processing and raster data calculation, the main indicator parameters for the physical quantity assessment of forest ecosystem

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services are obtained. Common value quantity assessment methods like the replacement market method, simulated market method, and replacement engineering method are used for value accounting. Technical indicator parameters such as average runoff coefficients for forest stands, transpiration rates, pollutant absorption and dust retention capabilities, soil erosion factors, and nutrient contents of trees are mainly obtained by reviewing related assessment cases and authoritative journal articles. The parameters related to the forest ecosystem service value assessment are shown in *Table 2*.

Table 2. *Parameters related to the valuation of forest ecosystem services*

Parameter description	Value	Parameter description	Value
Average runoff coefficient for evergreen broadleaf forest	2.67 (Gong, 2016)	Investment per unit capacity of reservoirs	3.17 (CNY/m³)
Average runoff coefficient for evergreen coniferous forest	3.02 (Gong, 2016)	Excavation cost per unit area	21.35 (CNY/m³)
Average runoff coefficient for mixed broadleaf and coniferous forest	2.29 (Gong, 2016)	Average water price	2.902 (CNY/t)
Average runoff coefficient for deciduous broadleaf forest	1.33 (Gong, 2016)	Carbon sequestration price	36.97 (CNY/t)
Average runoff coefficient for deciduous coniferous forest	0.88 (Gong, 2016)	Oxygen release value	1060 (CNY/t)
Transpiration rate for pine species	71.70% (Yang, 2007)	SO_2 treatment cost	2.15 (CNY/kg)
Transpiration rate for fir species	71.51% (Yang, 2007)	HF treatment cost	1.23 (CNY/kg)
Transpiration rate for broadleaf species	51.46% (Liu, 2011)	NO_x treatment cost	1.13 (CNY/kg)
Transpiration rate for bamboo species	44.48% (Niu, 2016)	Dust management cost	1.45 (CNY/kg)
SO_2 absorption by pine and fir species	0.1176 (t/ha)	Nitrogen content in diammonium phosphate fertilizer	18.00%
SO_2 absorption by broadleaf species	0.0887 (t/ha)	Phosphorus content in diammonium phosphate fertilizer	46.00%
SO_2 absorption by bamboo species	0.0761 (t/ha)	Potassium content in potassium chloride fertilizer	60.00%
HF absorption by pine and fir species	0.00465 (t/ha)	Price of diammonium phosphate fertilizer	2200 (CNY/t)
HF absorption by broadleaf species	0.0005 (t/ha)	Price of potassium chloride fertilizer	2400 (CNY/t)
HF absorption by bamboo species	0.00258 (t/ha)	Organic matter price	800 (CNY/t)
NO_x absorption by pine, fir, broadleaf, and bamboo species	0.006 (t/ha)	Nitrogen content in trees	13.09 (g/kg)
Dust retention by pine and fir species	33.2 (t/ha)	Phosphorus content in trees	3.16 (g/kg)
Dust retention by broadleaf species	10.1 (t/ha)	Potassium content in trees	14.81 (g/kg)
Dust retention by bamboo species	21.655 (t/ha)	Carbon content in CO_2	27.28%

(1) Assessment of water resource conservation value

Based on the precipitation in forested areas, forest transpiration, and surface runoff, the physical amount of forest water conservation is calculated using *Equation 1*; employing the alternative engineering approach, the value of water conservation is computed using the unit values of water quantity regulation and purification (*Eqs. 2* and *3*).

$$E = \sum a_i \times 10(P - D - C) \quad \text{(Eq.1)}$$

$$U_{Wqr} = P_{Sc} E \quad \text{(Eq.2)}$$

$$U_{Wqp} = P_{Wpc}E \quad \text{(Eq.3)}$$

In *Equations 1–3, E* represents the physical amount of water yield (ton); *P* represents precipitation (mm/yr); a_i represents the area of forest type i (hm^2); D represents forest evapotranspiration (mm/yr); *C* represents surface runoff (mm/yr). U_{Wqr} is the value of regulated water quantity (CNY); P_{Sc} is the unit storage cost (CNY/ton); P_{Wpc} is the cost of tap water purification (CNY).

(2) Assessment of carbon sequestration and oxygen release Value

Vegetation carbon sequestration, and oxygen release are respectively represented by *Equations 4* and *5*. The fixed value of carbon dioxide is evaluated using the China Carbon Sink Trading Price, while the value of oxygen release is assessed using industrial oxygen production methods. The formulas for carbon sequestration value and oxygen release value are respectively represented by *Equations 6* and *7*.

$$G_{Cse} = 1.63 R_{Ccc} aB \quad \text{(Eq.4)}$$

$$G_{Ore} = 1.19 aB \quad \text{(Eq.5)}$$

$$U_{Csv} = P_{Cv} G_{Cse} \quad \text{(Eq.6)}$$

$$U_{Orv} = P_{Ov} G_{Ore} \quad \text{(Eq.7)}$$

In *Equations 4–7*, G_{Cse} represents the annual amount of carbon fixation (ton/yr); G_{Ore} denotes the annual release of oxygen (ton/yr); R_{Ccc} stands for the carbon content in CO_2; *a* represents the area of forest stands (hm^2); *B* represents the net primary productivity ($ton \cdot hm^{-2} \cdot yr^{-1}$); U_{Csv} represents the economic value of carbon fixation ($ton \cdot hm^{-2} \cdot yr^{-1}$); U_{Orv} represents the economic value of oxygen release (CNY); P_{Cv} denotes the price of carbon fixation (CNY/ton); P_{Ov} represents the price of oxygen release (CNY/ton).

(3) Assessment of air purification value

The area-absorption capacity method is used to evaluate the physical quantities of pollutants such as sulfur dioxide (SO_2), fluorides (HF), nitrogen oxides (NO_x), and dust retained by forests. The calculation formulas are provided in *Equations 8–11*. The value of pollutant absorption and the value of dust retention are calculated using *Equations 12* and *13*, respectively.

$$G_{SO_2} = aQ_{SO_2} \quad \text{(Eq.8)}$$

$$G_{HF} = aQ_{HF} \quad \text{(Eq.9)}$$

$$G_{NO_x} = aQ_{NO_x} \quad \text{(Eq.10)}$$

$$G_{Da} = aQ_{Da} \quad \text{(Eq.11)}$$

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$$U_{Pa} = \sum_{i=1}^{3} K_i Q_i A \quad \text{(Eq.12)}$$

$$U_{Da} = P_{Da} G_{Da} \quad \text{(Eq.13)}$$

In *Equations 8–13*, Q_{SO2}, Q_{HF}, Q_{NOx} and Q_{Da} represent the quantities of SO_2, HF, NO_x, and dust absorbed per unit area of forest stand respectively ($ton·hm^{-2}·yr^{-1}$), U_{Pa} is the annual value of pollutants absorbed by the ecosystem (CNY/yr), K_i is the treatment cost of pollutants (CNY/kg), Q_i is the pollutants absorbed per unit area of the ecosystem ($ton·hm^{-2}·yr^{-1}$), U_{Da} is the annual value of dust retention (CNY), P_{Da} is the treatment cost of dust (CNY/ton), G_{Da} is the annual physical quantity of dust retained (ton/yr).

(4) Assessment of soil conservation value

The Universal Soil Loss Equation (RUSLE) is used to predict and estimate the annual soil erosion volume, utilizing ArcGIS processing methods. The physical quantity of soil conservation is calculated using *Equations 14* and *15*. The physical quantity of soil conservation is converted into equivalent fertilizer quantities to estimate the value of soil fertility conservation, including the physical quantities of organic matter, nitrogen, phosphorus, and potassium in the soil. The calculation equations are *Equations 16–19*. Based on the soil content of nitrogen, phosphorus, and potassium, soil conservation volume, and the average price of fertilizers, the value of these nutrients is estimated using the shadow pricing method. The calculation formula for the average content of nitrogen, phosphorus, and potassium in the soil is *Equation 20*.

$$A = RKLSCP \quad \text{(Eq.14)}$$

$$F = AM_0 a \quad \text{(Eq.15)}$$

$$F_Y = AY\% \quad \text{(Eq.16)}$$

$$F_N = AN\% \quad \text{(Eq.17)}$$

$$F_P = AP\% \quad \text{(Eq.18)}$$

$$F_K = AK\% \quad \text{(Eq.19)}$$

$$E_f = \sum AP_i C_i \quad \text{(Eq.20)}$$

In *Equations 14–20*, *A* is the soil conservation volume per unit area ($ton·hm^{-2}· yr^{-1}$), *R* is the rainfall erosivity factor, *L* and *S* are the slope length and steepness factors, *C* is the cover management factor, *P* is the support practice factor, $\sum Aa_i$ is the physical quantity of soil conservation ($ton·hm^{-2}·yr^{-1}$), a_i is the area of different forest types (hm^2), P_i are the pure contents of nitrogen, phosphorus, and potassium in the soil, C_i is the price of fertilizer (CNY).

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(5) Assessment of nutrient accumulation value

The nutrient accumulation value of the forest ecosystem is assessed by calculating the annual absorption of nutrients (nitrogen, phosphorus, potassium) by trees. The equations for calculating the annual increases of nitrogen, phosphorus, and potassium in forests are *Equations 21–23*. The physical quantities of these nutrients are then converted into equivalent fertilizer quantities. Using the corresponding market prices of fertilizers, the value of accumulated nutrients is calculated. The evaluation in this study converts the nutrient accumulation into diammonium phosphate and potassium chloride equivalents. The calculation equation for the value of accumulated nutrients is *Equation 24*.

$$G_N = aN_{Nc}B \quad \text{(Eq.21)}$$

$$G_P = aP_{Nc}B \quad \text{(Eq.22)}$$

$$G_K = aK_{Nc}B \quad \text{(Eq.23)}$$

$$F = G_N / 18\% \cdot M_1 + G_P / 46\% \cdot M_1 + G_K / 60\% \cdot M_2 \quad \text{(Eq.24)}$$

In *Equations 21–24*, G_N, G_P and G_K represent the amounts of nitrogen, phosphorus, and potassium fixed by trees (ton). N_{Nc}, P_{Nc} and K_{Nc} represent the nitrogen, phosphorus, and potassium contents in trees. a is the forest area (hm^2). B is the net primary productivity of the forest stand ($ton \cdot hm^{-2} \cdot yr^{-1}$). F is the total value of accumulated nutrients (CNY). M_1 and M_2 are the prices of diammonium phosphate and potassium chloride (CNY).

(6) Assessment of forest recreation value

The value of forest recreation is calculated using the following equation:

$$U_r = \sum (Y_i + Y'_i) \quad \text{(Eq.25)}$$

where U_r represents the annual value of forest recreation, Y_i is the direct income from forest parks, and Y'_i is the indirect income from forest parks.

Results and analysis

Total value of forest ecosystem services

The total value of forest ecosystem services in Changde City is calculated to be 22,743.06 billion CNY (*Table 3*). In terms of service categories, the value of supporting functions is the highest at 15,811.32 billion CNY, followed by regulating services at 6804.11 billion CNY, representing 69.52% and 29.92% of the total value, respectively. Recreation values from forests account for 0.56% of the total service value. Among supporting services, the value for soil conservation reaches 14,555.59 billion CNY, significantly higher than other service types, making up 64% of the total service value, with fertility preservation valued at 14,522.89 billion CNY (63.86% of the total) and soil consolidation at 32.7 billion CNY (0.34% of the total). In regulating services, carbon sequestration and oxygen release are valued the most at 6009.77 billion CNY,

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which is 26.42% of the total service value, with the carbon sequestered amounting to 20,933.99 million tons (0.34% of total value) and oxygen released valued at 55,965.88 million tons (26.08% of total value). Other forest ecosystem service values are relatively lower, collectively constituting 9.58% of the total service value (*Table 3*).

Table 3. *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	436,413.23	264.99	1.17
	Carbon sequestration and oxygen release	Carbon sequestration quantity	20,933.99	77.39	0.34
		Oxygen release quantity	55,965.88	5932.38	26.08
	Air purification	Pollutants absorption quantity	9.88	266.9	1.17
		Dust retention quantity	1809.99	262.45	1.15
Supporting services	Soil conservation	Soil consolidation quantity	15,315.1	32.7	0.14
		Fertility preservation quantity	33,787.29	14,522.89	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	1.4
Cultural services	Forest recreation	Value of forest recreation	—	127.63	0.56

The spatial distribution of ecosystem services value in Changde City is illustrated in *Figure 2*. *Figure 2a* shows the spatial distribution of the total value of forest ecosystem services. The maximum spatial density of service value is 621.36 thousand CNY per hectare. It can be observed that the areas with the highest unit area value of forest ecosystem services are mainly distributed in the northwest and southwest regions of the study area, which are mountainous and hilly areas with dense vegetation. *Figure 2b-f* respectively represent the spatial distribution of water conservation, soil conservation, carbon sequestration and oxygen release, air environment purification, and nutrient accumulation value. Overall, there is a gradual decrease in value from northwest to southeast, consistent with the spatial distribution of the main forests in the study area. This reflects better vegetation growth in mountainous and hilly areas, less disturbance and destruction by human activities, higher forest coverage, and higher unit area values of various forest ecosystem services, whereas the opposite is true in areas with lower values.

Variations in forest ecosystem service values among different forest types

The physical quantities of ecosystem services by different forest types are shown in *Table 4*. Broadleaf forests exhibit the highest total ecological service value at 370,618 million tons/year. Water conservation, carbon sequestration and oxygen release, soil conservation, and nutrient accumulation quantities are highest in broadleaf forests, exceeding those in coniferous forests by 326.41%, 109.74%, 162.07%, and 160.26%, respectively. The quantity for water conservation in broadleaf forests reaches 295,631.2 million tons/year, followed by coniferous forests at 69,330.5 million tons/year. Carbon sequestration and oxygen release quantities in broadleaf forests are 43,438.12 million tons/year, and for coniferous forests, it is 20,758.62 million tons/year. The purification of air is highest in coniferous forests at 732.71 million tons/year.

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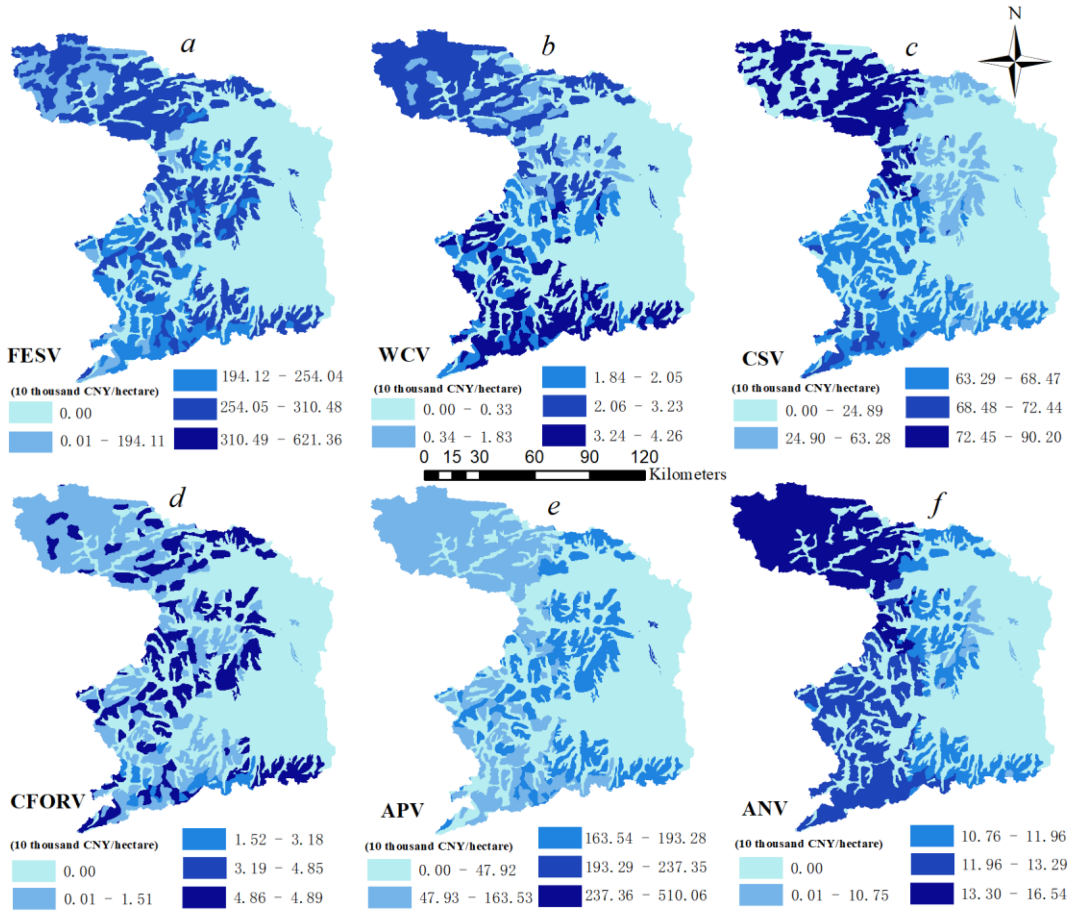

Figure 2. *Study regional spatial resource distribution. FESV: forest ecosystem service value, WCV: water conservation value, CSV: conservation soil value, CFORV: carbon sequestration and oxygen release value, APV: air purification, ANV: accumulated nutrient value*

Table 4. *Physical quantities of forest ecosystem services by different forest types in Changde City*

Forest type		**Water conservation (10,000 t·yr⁻¹)**	**Carbon sequestration and oxygen release (10,000 t·yr⁻¹)**	**Air purification (10,000 t·yr⁻¹)**	**Conservation soil (10,000 t·a⁻¹)**	**Accumulated nutrient (10,000 t·yr⁻¹)**
Coniferous forests	Chinese fir forests	19,213.27	5868.96	202.89	2927.5	111.52
	Masson pine forests	49,608.44	14,821.39	524.81	8357.47	281.6
	Cypress forests	508.79	68.27	5.01	86.94	2.38
Broadleaf forests		295,631.2	43,538.12	618.3	29,801.87	1029.31
Coniferous and broadleaf mixed forests		42,032.8	8871.67	377.55	5369.92	168.57
Bamboo forests		27,980.55	3531.51	88.6	2407.88	67.1

The ecological service values of different forest types are shown in *Figure 3*. The results indicate that the total ecological service value of broadleaf forests is the highest, followed by coniferous forests, mixed coniferous-broadleaf forests, and bamboo forests. Specifically, the total ecological service value of broadleaf forests is 144.24% higher than that of coniferous forests, suggesting significant differences in the ecological

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service values among different forest types, which is consistent with the variations in the areas of these forest types in the study region. For the same forest type, the proportional composition of ecological service values exhibits a similar trend. In all forest types, the value of soil conservation accounts for the largest proportion, exceeding 50% of the total ecological service value. This is followed by the values of carbon sequestration and oxygen release, nutrient accumulation, air purification, and water conservation. Among them, the value of soil conservation is the highest in broadleaf forests, reaching 8646.68 billion yuan, which accounts for 66.02% of the total ecological service value of broadleaf forests. The proportions of soil conservation value in other forest types are 52.39% for Chinese fir forests, 64.01% for Masson pine forests, 77.4% for cypress forests, 67.72% for mixed coniferous-broadleaf forests, and 63.76% for bamboo forests. The value of carbon sequestration and oxygen release accounts for the second-largest proportion, which are 37.39% for Chinese fir forests, 28.22% for Masson pine forests, 12.84% for cypress forests, 25.99% for broadleaf forests, 24.84% for mixed coniferous-broadleaf forests, and 28.05% for bamboo forests.

Overall, the statistical analysis of ecosystem service values across different forest stands indicates that the primary contributions of forest ecosystems lie in soil conservation, carbon sequestration, and oxygen release, with these two services collectively accounting for over 85% of the total value. Broadleaf forests contribute the most to ecosystem services, possibly due to their richer and more diverse composition and vertical structure compared to other forest types, which are more conducive to realizing their functional value in forest ecosystem services and exhibit higher ecological carrying capacity. Following broadleaf forests in order of contribution are Masson pine forests, mixed conifer-broadleaf forests, Chinese fir forests, bamboo forests, and cypress forests.

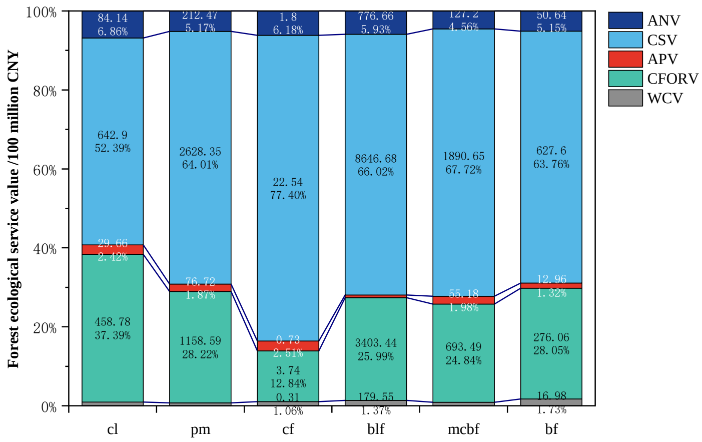

Figure 3. *Ecological service values and their composition ratios for different forest types in Changde City. cl: Chinese Fir Forests, pm: Masson Pine Forests, cf: Cypress Forests, blf: Broadleaf Forests, mcbf: Coniferous and Broadleaf Mixed Forests, bf: Bamboo Forests. WCV: water conservation value, CSV: conservation soil value, CFORV: carbon sequestration and oxygen release value, APV: air purification, ANV: accumulated nutrient value*

Variations in forest ecosystem service values among districts and counties

The physical quantities of forest ecosystem services across different districts and counties are detailed in *Table 5*. Shimen County and Taoyuan County, both located in

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mountainous and hilly areas in the northwestern and southwestern parts of Changde City respectively, show the highest quantities due to dense vegetation. These areas reflect the abundant forest resources contributing significantly to human well-being. Conversely, areas with lower forest ecosystem service quantities like Anxiang County, Dingcheng District, Jin City, and Hanshou County correlate with their greater plain and water body coverage, suggesting significant potential for enhancing forest services in these regions.

Table 5. *Physical quantities of forest ecosystem services by different districts and counties in Changde City*

District/county	Water conservation (10,000 t·yr⁻¹)	Carbon sequestration and oxygen release (10,000 t·yr⁻¹)	Air purification (10,000 t·yr⁻¹)	Soil conservation (10,000 t·yr⁻¹)	Nutrient accumulation (10,000 t·yr⁻¹)
Wuling District	69.04	158.98	4.75	108.32	3.01
Dingcheng District	45,943.81	7497.21	194.23	4561.56	142.45
Taoyuan County	141,137	24,986.83	601.28	14,658.79	475.77
Lixian County	32,132.27	6581.92	188.02	3625.46	125.08
Shimen County	154,913.7	27,211.18	504.35	19,277.67	719.16
Linli County	28,495.16	5098.55	124.56	3428.45	96.86
Anxiang County	1438.16	199.98	2.76	150.84	3.8
Hanshou County	24,686.35	3654.79	141.21	2188.82	69.45
Jinshi County	7597.79	1510.46	58.76	1102.51	28.7
Total	436,413.2	76,899.9	1819.92	49,102.42	1664.28

The composition of forest ecosystem service values in different counties is shown in *Figure 4*. It can be observed that the main contribution to the forest ecosystem services in each county is the conservation of soil and carbon sequestration, which accounts for 68.67% to 91.2% of the total forest ecosystem service value. The values of nutrient accumulation, air purification, water conservation, and forest recreation are secondary. There are significant regional differences in the forest ecosystem service values among the counties. Shimen County has the highest forest ecosystem service value of 777.479 billion yuan, followed by Taoyuan County (688.344 billion CNY), Dingcheng District (237.827 billion CNY), Lixian County (184.57 billion CNY), Linli County (165.279 billion CNY), Hanshou County (119.334 billion CNY), Jinshi County (55.558 billion CNY), Anxiang County (8.749 billion CNY), and Wuling District (7.658 billion CNY). These regional differences in forest ecosystem service values are related to the regional area, topography, forest coverage, and urban development level. The results reflect that in regions with high urban development, large plain areas, and relatively low forest coverage, the forest ecosystem service value is lower, and vice versa. Meanwhile, the proportion of forest recreation value in Wuling District is the highest, reaching 27.4%, while the proportions of forest recreation in the other counties are relatively low, indicating that the full realization of the forest recreation value is related to the urban development level of the region.

Comparison of forest ecosystem service values and GDP among districts and counties

In 2019, the total value of forest ecosystem services in Changde City was 22,743.06 billion CNY, with a GDP of 3624.21 billion CNY and a total population of 5.82 million. This results in a per capita forest ecosystem service value of

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39.06 thousand CNY and a per capita GDP of 6.22 thousand CNY, indicating a ratio of nearly 1:6. This ratio underscores the relative scarcity of forest ecosystem services compared to socio-economic values. *Table 6* shows the per capita forest ecosystem service values and GDP across different areas, highlighting substantial regional variations, especially in economically developed and densely populated areas with large plain and water body areas, where the per capita value of forest ecosystem services is notably low. Certainly, it is expected that the forest ecosystem service value obtained in the relatively economically developed Wuling area is low. However, it is worth noting that the per capita forest ecosystem service value in Anxiang County, Hanshou County, and Lixian County is also relatively low, less than half of the city’s average. This indicates that with the development of the economy and society, the scarcity of forest ecosystem services in these areas is becoming more prominent, warranting attention.

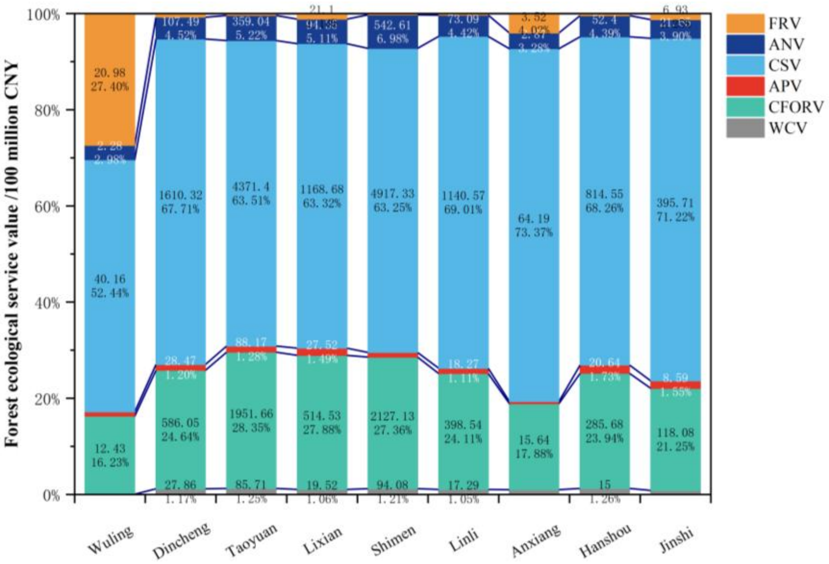

Figure 4. *Ecological service values and their composition ratios for different districts and counties in Changde City*

Table 6. *Comparison of forest ecosystem service values and GDP in different districts and counties of Changde City in 2019*

District/county	Forest ecosystem service value (FESV) (100 million CNY)	GDP (100 million CNY)	Population (10,000 people)	Per capita FESV (10,000 CNY)	Per capita GDP (10,000 CNY)
Wuling District	55.63	1258.6	43.37	1.28	17.02
Dingcheng District	2361.97	364.6	75.6	31.24	4.8
Taoyuan County	6865.54	407.52	96.65	71.04	4.22
Li County	1826.48	373.6	91.42	19.98	4.09
Shimen County	7772	295.67	66.69	116.54	4.43
Linli County	1649.43	193.04	44.6	36.98	4.33
Anxiang County	83.97	210.9	53.51	1.57	3.94
Hanshou County	1188.9	303.08	87.24	13.63	3.47
Jin City	549.02	171.5	23.2	23.66	7.39
Total	22,743.06	3624.21	582.28	39.06	6.22

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Conclusions and discussion

Forest ecosystem services are crucial for human survival and sustainable regional socio-economic and environmental development. Despite challenges in identifying, quantifying, and monetizing these services, their accurate assessment is vital for forest ecosystem asset management, ecological compensation, and compensated use of ecological services. This study develops a tailored assessment framework for Changde City, incorporating six types of forest ecosystem services across various forest types and regions, using ten physical quantity indicators and twelve value indicators. The study findings indicate:

(1) Changde City’s forest ecosystem services were valued at 227.43 billion CNY, with the highest values per unit area in the northwest and southwest, peaking at 621.36 million CNY/ha.

(2) Supporting services had the highest value at 69.52%, followed by regulating services at 29.92% and cultural services at 0.56%. Soil conservation dominated supporting services at 64% of the total value, while carbon sequestration and oxygen release were prominent in regulating services at 26.42%.

(3) Broadleaf forests contributed the most to the total ecological service value at 58.9%, followed by coniferous forests (24.12%), mixed coniferous and broadleaf forests (12.56%), and bamboo forests (4.43%). Masson’s pine forests had the highest total ecological service value among coniferous forests, followed by fir and cypress forests.

(4) Shimen County had the highest ecosystem service value at 34.63% of the city’s total, followed by Taoyuan County (30.66%), Dingcheng District (10.59%), Lixian County (8.22%), Linli County (7.36%), Hanshou County (5.32%), Jinshi County (2.47%), Anxiang County (0.39%), and Wuling District (0.34%).

(5) The per capita forest ecosystem service value in 2019 was 390,600 CNY, with a per capita GDP of 62,200 CNY, resulting in a ratio of nearly 1:6, indicating the relative scarcity of forest ecosystem services compared to socio-economic values.

Using ArcGIS for remote sensing and raster data calculations, this study applied valuation methods such as the replacement market method, simulated market method, and replacement engineering method to quantify the value of forest ecosystem services. These monetized values underscore the significance of regional forest ecosystem services and support the integration of environmental accounting into the national economic system for achieving a green GDP and sustainable development. However, due to the complexity and interdisciplinary nature of forest ecosystem service valuation, as well as ongoing exploration of technical methods and indicators, there remains some uncertainty in the assessment results, requiring further refinement in future studies.

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Conflict of interest. The authors declare no conflict of interest.

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