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Value Accounting of Climate Ecological Products: A Case Study of Wuzhishan City, Hainan Province, China

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Abstract

The valuation and sustainable utilization of climate-related ecological products in Wuzhishan, the core zone of Hainan Tropical Rainforest National Park, are essential for regional ecological security. On the basis of the "Technical Guidelines for Gross Terrestrial Ecological Product Accounting" (GB/T 46869–2025), this study developed a value accounting framework for climate-related ecological products in Wuzhishan City. By employing market value, replacement cost, and travel cost methods as well as official statistical meteorology, remote sensing, culture/tourism, and electricity data from 2019 to 2022, three product categories in Wuzhishan City were quantified: climate provisioning products, climate regulation services, and climate cultural services. Furthermore, sustainable utilization pathways were proposed. The average annual total value of climate-related ecological products over the period was 27.26 billion yuan, equivalent to 26.42% of the city's average annual GDP during the same period. Climate cultural services represented the greatest share (52.29%), followed by climate provisioning products (32.00%) and climate regulation services (15.71%). Among provisioning services, direct meteorological supply products, including freshwater and temperature, contributed most significantly (49.10%). The value of PM2.5 purification driven by precipitation accounted for the majority of regulating services (77.24%). The accounting system provides a quantifiable tool for transforming Wuzhishan city's "green mountains and clear waters" into "golden and silver mountains". This county-scale accounting model of "climate elements → service functions → economic value" offers a replicable and scalable exemplary case. The findings contribute to valuing climate-related ecological products, realizing regional ecological product value and fostering green, high-quality development.

Keywords: climate-related ecological products, value accounting, sustainable utilization, Wuzhishan City.

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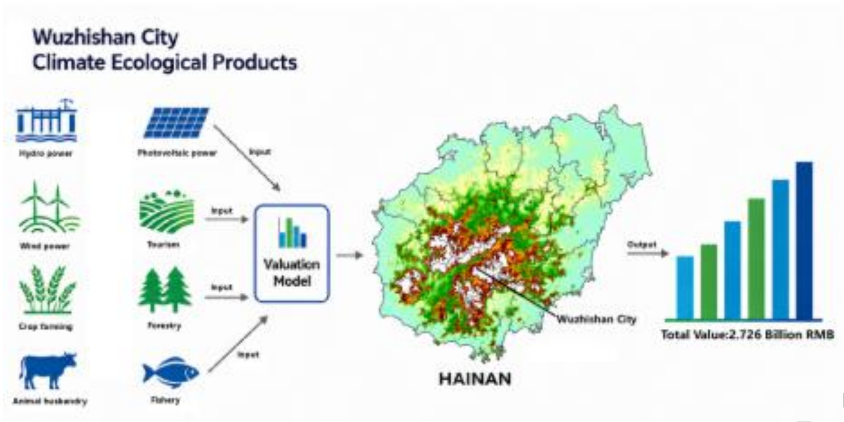
Graphical abstract



1. Introduction

The gross ecosystem product (GEP) represents the total value of final products and services provided by ecosystems for human well-being and sustainable socioeconomic development. It primarily includes three major categories: material products, regulating services, and cultural services (Ouyang *et al.*, 2013; Song *et al.*, 2020; Bai *et al.*, 2020; Zou *et al.*, 2019). As a key tool for quantifying regional ecological benefits and driving the transformation of "lucid waters and lush mountains" into "invaluable assets," GEP accounting has emerged as a major topic in the fields of ecological economics and sustainable development. Climate ecological products, as a special category of ecological resources with asset attributes, refer to material goods or services provided sustainably by ecosystems, predominantly influenced by climatic conditions, to meet human production and living needs (Chen *et al.*, 2021). This concept not only retains the service functions of ecological products but also highlights the dominant role of climatic elements (Shu *et al.*, 2023; Civeira *et al.*, 2020; Ouyang *et al.*, 2015), representing a refinement and extension of the broader ecological product framework. On the basis of the functions of climate resources, climate ecological products can be classified into two categories: first, material products formed under suitable climatic conditions, such as wind and solar energy as clean energy sources; and second, service-oriented products derived from specific climatic conditions, such as climate wellness tourism, summer and winter resort destinations, and carbon sequestration regulation services (Fan *et al.*, 1997). Scientifically accounting for their value can not only reveal the economic potential of climate resources but also provide robust support for the formulation of ecological compensation policies and the optimization of regional development models. This holds significant practical importance for practising the "two mountains" theory and promoting green, low-carbon transitions.

Recent research has explored the valuation of climate-related ecological services. For instance, studies have assessed the effects of climate change on ecosystem services (Costanza R *et al.*, 1997; MEA, 2005; Zhao *et al.*, 2024; Ouyang *et al.*, 2020; Wu *et al.*, 2022; Burdon *et al.*, 2024; Das *et al.*, 2025; Kalra *et al.*, 2025) and measured the economic value of individual functions, such as carbon sequestration (Khan *et al.*, 2025). There has also been a shift from evaluating single elements towards constructing comprehensive accounting systems (Zhao *et al.*, 2021; Yu, 2024), with pilot practices for valuing climate-related ecological products being carried out in regions such as Lishui (Zhejiang), Shenzhen, and Fujian in China (Shenzhen Municipal Ecology and Environment Bureau, 2021; Xu *et al.*, 2019; Shen, 2019). However, studies on valuing climate-related ecological products often concentrate on single service types, such as provisioning or regulating services, and lack a holistic accounting of provisioning, regulating, and cultural service values. Furthermore, there is still a gap in the development of a tailored and operable accounting indicator system and methodology specifically designed for tropical mountainous cities that possess unique climatic and ecological characteristics. Finally, effectively linking accounting results with regional economic development levels (e.g., GDP) to quantify the actual contribution of climate-related ecological capital remains a challenge in current practice.

As the core protected area of Hainan Tropical Rainforest National Park and the city at the highest altitude on Hainan Island, Wuzhishan City has abundant climate-related ecological resources. However, scientifically and effectively determining their value remains an urgent scientific issue. Therefore, drawing on the GEP accounting framework and relevant domestic and international research, this study takes Wuzhishan City as a case study to develop an indicator system and accounting methodology for climate-related ecological product valuation. This research quantifies the value of climate-related ecological products from 2019 to 2022 and proposes pathways and mechanisms for realizing their value, focusing on enhancing the value of provisioning products, realizing the value of regulating services, and tapping into the value of cultural services. This study aims to provide technical support and scientific evidence for advancing the accounting and value transformation of climate-related ecological products in Wuzhishan City.

2. Data and methods

2.1. *Data sources*

Meteorological data: Daily meteorological data from 2019 to 2022 for all townships in Wuzhishan City, including daily average temperature, average wind speed, precipitation, and daily pollutant concentrations, were sourced from the Wuzhishan City Meteorological Bureau. Actual evapotranspiration: The ET product from the MOD16A2 dataset (Mu *et al.*, 2007; Mu *et al.*, 2011) was utilized. The data cover the period from 2001 to 2019, with spatial and temporal resolutions of 250 m and 8 days, respectively. Culture and tourism data: Annual data for 2019 to 2022, including visitor numbers and tourism revenue for different attractions, were obtained from the Wuzhishan Tourism and Cultural Development Bureau. Electricity data: Annual data for 2019 to 2022, including electricity consumption, hydroelectric power generation, photovoltaic power generation, and grid-connected electricity prices, were sourced from the Wuzhishan City Power Supply Bureau of China Southern Power Grid, Hainan Power Grid Company. Statistical data: Annual data for 2019 to 2022, including water and electricity prices for production and domestic use, the urban population, and the city's GDP, were derived from the Wuzhishan Statistical Yearbook (Wuzhishan City Bureau of Statistics, 2024).

2.2. *Accounting indicators*

The climate product amount refers to the quantity (yield or usage amount) of final products or services directly or indirectly obtained by humans from the climatic elements within an ecosystem. The climate value account refers to the monetary value of these final products or services.

In the research process, domestic and international studies on the evaluation of climate-related ecological service functions and climate economic accounting were reviewed (Zhang *et al.*, 2025; Niu *et al.*, 2023; Lv *et al.*, 2023; Zhang *et al.*, 2024). By integrating pilot experiences in climate-related ecological products from other regions in China and analysing the characteristics of climate-related ecological resources in Wuzhishan City while adhering to principles of data availability and indicator practicality, a three-tier accounting indicator system (**Table 1**) was established. The first-tier indicators included climate provisioning products, climate regulation services, and climate cultural services. Climate provisioning products refer to climate products that can be directly or indirectly utilized by humans, such as fresh water, thermal energy, energy conversion products (e.g., photovoltaic power, hydroelectric power, and wind power), and products from agriculture, forestry, animal husbandry, and fisheries. Climate regulation services refer to climate products that can improve human living conditions and the environment, such as by providing lightning protection, disaster prevention and mitigation, and air purification. Climate cultural services refer to climate products that satisfy human needs in cultural leisure, entertainment, and knowledge acquisition and include meteorological tourism, including tourism leisure, sightseeing holidays, and climate wellness.

Table 1. Accounting indicator system for climate ecological products.

Tier-1 Indicator	Tier-2 Indicator	Tier-3 Indicator	Pricing Method (Research Center for Eco-Environmental Sciences, Chinese Academy of Sciences *et al.*, 2025; China Meteorological Service Association *et al.*, 2023) [31, 32]
Climate Provisioning Products	Freshwater	Assessable regional available freshwater	Market Value Method
	Temperature	Temperature-related electricity consumption	Market Value Method
	Climate Conversion and Utilization Supply Products	Products derived from the conversion of solar, hydro, and wind energy resources into utilizable forms	Market Value Method, Expert Scoring Method
	Climate-Augmented Utilization Supply Products	Agriculture, forestry, animal husbandry, and fishery products	Market Value Method, Expert Scoring Method
Climate Regulation Services	Air Purification	Purification of Atmospheric Pollutants by Precipitation and Wind	Replacement Cost Method
	Disaster Prevention and Mitigation	Protective Effect of Lightning Protection on Buildings	Input–Output Ratio
	Lightning Protection		
Climate Cultural Services	Meteorological Tourism	Climate Wellness	Travel Cost Method
		Meteorological Landscape Attractions	Travel Cost Method

2.3. *Accounting methodology*

Considering the attributes and characteristics of each climate-related ecological product within the accounting indicator system and drawing upon the functions and evaluation models of climate ecosystems, appropriate characterization parameters and variables were selected. Statistical methods, statistical monitoring approaches, and ecosystem evapotranspiration models, among others, were applied to construct physical quantity accounting models for each climate-related ecological product. The market value method, replacement cost method, cost–benefit ratio method, travel cost method, and expert scoring method were subsequently used to price these products. Building on this foundation and accounting for the meteorological contribution rate and other relevant factors, value accounting models for each climate-related ecological product were developed on the basis of the relationships among physical quantity, price, and monetary value. Finally, summing these individual values yielded the total value of the climate-related ecological products for Wuzhishan City.

2.3.1. Provisioning product value

The value of climate-related ecological provisioning products encompasses the direct supply value of meteorological elements, such as precipitation and air temperature; the value of products derived from the conversion and utilization of climate resources, such as wind power, hydroelectric power, and photovoltaic power generation; and the added value of products from agriculture (planting), forestry, animal husbandry, and fisheries that incorporate climate benefits.

2.3.1.1 Freshwater

The valuation of the total amount of effectively utilizable freshwater within the accounting region is used as the accounting indicator. The total physical quantity of freshwater resources in an area is primarily based on its annual precipitation and annual average actual evapotranspiration.

In the research process, the Thiessen polygon method was employed to calculate the average rainfall for Wuzhishan City, with the resulting value recorded as r_M. The value r_E represents the average actual evapotranspiration of the accounting region, which is obtained from the average annual evapotranspiration for the Wuzhishan area within the Hainan Island MOD16 annual evapotranspiration dataset for 2001–2019 (Li *et al.*, 2022). Both r_M and r_E are expressed in millimetres (mm).

$$E_w = \left(r_M - r_E\right) \times S \times \rho \times P_w \tag{1}$$

Where E_W represents the monetary value of the total amount of effectively utilizable freshwater. The term (r_M–r_E) indicates the difference between the average precipitation and the average actual evapotranspiration. ρ denotes the density of water under standard conditions, with units of kg/m³, taken here as 1000 kg/m³. S represents the area of the accounting region. P_W represents the price of water for production and domestic use, taken as 2.9 yuan per tonne.

2.3.1.2 Air temperature

The accounting indicator is the monetary value corresponding to the increase or decrease in energy consumption (primarily electricity) due to comfortable or uncomfortable weather conditions within the accounting region.

$$E_d = \left(-W_{dt}\right) \times N \times P_e \tag{2}$$

Where W_{dt} represents the difference in electricity consumption between the accounting region and the provincial average temperature during the accounting period, with units of kW·h. If W_{dt} is greater than 0, it indicates the daily electricity savings per household due to a comfortable climate (unit: kW·h). Conversely, if it is less than 0, it indicates the additional daily electricity consumption per household due to an uncomfortable climate. N denotes the number of households (unit: household), referenced from the townshipwise household data for 2019–2022 in the Wuzhishan Statistical Yearbook. P_{e} represents the residential electricity unit price (unit: yuan/(kW·h)), taken here as 0.7 yuan/(kW·h) on the basis of the electricity price in Wuzhishan City.

The temperature-related electricity load refers to the electricity consumption generated by cooling (at high temperatures) or heating (at low temperatures) (specifically, the difference between electricity usage in winter/summer and the average usage in spring/autumn). Given that electricity consumption is closely linked to factors such as the level of urban economic development and population size, a regression method was employed to establish a calculation model for the temperature-related electricity load in this region.

$$M = aT^2 + bT + c \tag{3}$$

Where M represents the daily temperature-related electricity load, with units of kW·h. T denotes the five-day (the current day and the preceding four days) moving average of the daily mean air temperature in °C. a, b and c are model coefficients and are dimensionless.

Statistical robustness validation of the temperature–electricity model (**Table 2**) reveals that although the model violates classical assumptions, including non-normal residuals, heteroskedasticity, and autocorrelation, the overall goodness-of-fit is high (R^2 = 0.887). Moreover, the results of fivefold cross-validation are stable, indicating that the model still possesses good generalizability and predictive ability.

2.3.1.3 Climate conversion-use provisioning products

The valuation of hydroelectric and photovoltaic power generation outputs was used as the accounting indicator.

$$E_e = \sum_{i=1}^{n_1} \left(Y_{ei} \times \left(P_{ei} - C_{ei}\right) \times \theta_{ei} \right) \tag{4}$$

Where E_e represents the monetary value of photovoltaic and hydroelectric power generation. n_1 denotes the number of climate-converted energy product types within the accounting region. Y_{ei} represents the electricity generation output from either photovoltaic or hydroelectric facilities. P_{ei} represents the grid-connected feed-in tariff price for hydroelectric and photovoltaic power, taken as 0.34 yuan/(kW·h) and 0.43 yuan/(kW·h), respectively. C_{ei} indicates the operational and maintenance costs; since Wuzhishan City has no wind power facilities, the operational costs for hydroelectric power and photovoltaic power were taken as 0.07 yuan/(kW·h) and 0.3 yuan/(kW·h), respectively. θ_{ei} is the climate resource contribution ratio, which was determined using the expert scoring method and is set at 30% (Sun *et al.*, 2025).

Table 2 Validation of Coefficients in the Temperature–Electricity Regression Model.

Variable	Coefficient	Std. Error	t-statistic	p value	95% Confidence Interval
c (Intercept)	2.548	1.211	2.104	0.036*	(0.172, 4.924)
a (T^2 coefficient)	0.0037	0.0021	1.734	0.083	(-0.0005, 0.0078)
b (T coefficient)	0.804	0.102	7.877	<0.001***	(0.604, 1.005)

*Note: *p < 0.05, *p < 0.001*

2.3.1.4 Climate value-added products

The valuations of agricultural (planting), forestry, animal husbandry, and fishery products were calculated according to the following formula:

$$E_a = \sum_{i=1}^{n_2} \left(Y_{ai} \times \left(P_{ai} - C_{ai} \right) \times \theta_{ai} \right) \quad (5)$$

Where E_a represents the monetary value of agricultural (crop planting), forestry, animal husbandry, and fishery products. n_2 denotes the number of product types from these sectors within the accounting region, totalling 4. Y_{ai} represents the yield of the product. P_{ai} represents the market price of the product. C_{ai} indicates the labour, maintenance, and input costs. θ_{ai} is the climate resource contribution ratio, which is 35%, 40%, 25%, and 15% for agriculture, forestry, animal husbandry, and fishery, respectively.

The determination of climate contribution rates is based on the following methods. According to Deng Jiliang *et al.* (Deng *et al.*, 2018), the climate contribution rate for early rice in Hainan is set as 35%. According to Ma Yiwen *et al.* (Ma *et al.*, 2025), the climate contribution rates for rubber, mango, pineapple, and banana in Hainan are 13.6%, 18.75%, 21.3%, and 21.3%, respectively. Considering the actual planting structure of Wuzhishan City, the proportions of rice, rubber, mango, pineapple, and banana are set at 0.75, 0.1, 0.015, 0.015, and 0.15, respectively. Thus, the climate contribution rate for the planting industry in Wuzhishan City is calculated as follows: 35% × 0.75 + 13.6% × 0.1 + 18.75% × 0.025 + 21.3% × 0.025 + 21.3% × 0.1 = 30.7%. After adjustment using the expert scoring method, it is taken as 35%. In reference to the studies of Lei Jizhou, Liu Yingshuai *et al.* (Lei *et al.*, 2024, Liu *et al.*, 2025) and combined with the expert scoring method, the climate contribution rate for forestry is taken as 40%. Considering the heat adaptation capacity of local livestock and poultry breeds in Hainan (Shi *et al.*, 2016; Wu *et al.*, 2024) and the regulatory role of facilities on large-scale farms (the higher the degree of facility-based production is, the smaller the climate impact), the climate contribution rate for animal husbandry is set at 25% using the expert scoring method. Wuzhishan City primarily engages in freshwater aquaculture, and climate fluctuations can be buffered through artificial feeding, water quality regulation, shading facilities, etc., which makes its climate dependence significantly lower than that of the planting industry and forestry. On the basis of relevant studies (Wang *et al.*, 2026) and the expert scoring method, the climate contribution rate for fisheries is considered 15%.

To examine the impact of the climate contribution rate setting (θ) on the valuation of climate-added utilization supply products, a one-factor sensitivity analysis was conducted for the θ parameters of agriculture, forestry, animal husbandry, and fishery. On the basis of the data characteristics of each industry, the θ values for agriculture and forestry were set to fluctuate by ±10% around the baseline value, those for animal husbandry by ±5%, and those for fishery by ±3%. The annual average value for each industry from 2019 to 2022 was then calculated, and the trend of its variation with θ was analysed. The results (**Table 3**) show that as θ increases from the lower bound to the upper bound, the total values of agriculture, forestry, animal husbandry, and fishery increase linearly. Taking 2022 as an example, the total value increases from 340.44 million yuan to 594.89 million yuan, with a variation range of approximately ±27.20% relative to the baseline value (467.67 million yuan). From 2019 to 2022, the baseline total value increased annually from 360.20 million yuan to 467.67 million yuan, while the relative variation range caused by parameter fluctuations remained stable between ±25.8% and ±27.2%. This finding indicates that the model has good robustness with respect to the θ parameter: even with some uncertainty in the parameter, the estimated total value remains stable.

2.3.2. Value of climate regulation services

The value of climate regulation services manifests primarily in two aspects: (1) the economic benefit (E_Q) derived from the improvement in air quality due to the deposition or dilution of atmospheric pollutants (such as $PM_{2.5}$) by precipitation, wind, etc., which lower pollutant concentrations; and (2) the avoided loss value (E_L) achieved by preventing or reducing damage to buildings, rail transit systems, etc., caused by lightning strikes through lightning protection operations.

Table 3. Annual average values of climate-related supplementary supply products as a function of θ.

Item	Agriculture	Forestry	Animal Husbandry	Fishery	Total
Lower bound	0.25	0.3	0.2	0.12	—
Baseline	0.35	0.4	0.25	0.15	—
Upper bound	0.45	0.5	0.3	0.18	—
Value (lower)	19.06	6.2	5.2	0.37	30.83
Value (baseline)	26.69	8.27	6.5	0.47	41.93
Value (upper)	34.31	10.34	7.8	0.56	53.01

2.3.2.1 Value of Air Pollution ($PM_{2.5}$) Purification by Precipitation

The value (E_Q) of atmospheric pollutant ($PM_{2.5}$) purification by precipitation is calculated according to the following formula:

$$Q = \sum_{j=1}^{lv} \left(\left(q_j - q_0 \right) \times S \times H_j \times d_j \right) \times 10^{-6} \quad (6)$$

$$E_Q = Q \times P_Q \quad (7)$$

where Q represents the purification amount of atmospheric pollutants ($PM_{2.5}$), with units of metric tons (t). q_j denotes the average $PM_{2.5}$ concentration on precipitation days of the *j*-th intensity category within the accounting month, while q_0 is the average $PM_{2.5}$ concentration on nonprecipitation days within the accounting month, both in units of µg/m³. S represents the area of the accounting region in units of km². H_J is the mixed layer height on precipitation days of the *j*-th intensity category for the accounting region, in units of metres (m); for simplification, a value of 1000 m is adopted. d_J indicates the number of days with precipitation in the *j*-th intensity category within the accounting month. lv represents the total number of precipitation intensity categories. P_Q represents the economic loss due to health hazards caused by $PM_{2.5}$ emissions, taken as 4897.0 yuan/kg (Zhao *et al.*, 2021).

2.3.2.3 Valuation of the protective effect of lightning protection on buildings

The valuation of the protective effect of lightning protection on buildings is calculated according to the following formula:

$$E_L = \sum_{i}^{nl} \left(\left(W_i \times P_i \right) \times \theta_L \right) \quad (8)$$

where E_L represents the value of the protective effect of lightning protection on buildings; *nl* denotes the number of building types in the assessed area, which is taken as 2 here, namely, Type II flammable and explosive sites and Type III general buildings; refers to the workload of lightning protection operations for the i-th building type; P_i represents the cost per operation for the i-th type, including manual inspection, maintenance, and investment in professional equipment; and θ_L is the input–output ratio for meteorological services in lightning protection, taken as 50 (China Meteorological News Press, 2024).

2.3.3. Climate cultural service value

Climate cultural service value refers to the economic value (E_V) generated by natural and cultural tourism activities dominated by climate resources, including benefits from tourism consumption driven by activities such as escaping summer heat or winter cold and enjoying meteorological landscapes. The calculation formula is as follows:

$$E_v = R \times P_v \quad (9)$$

where R represents the total number of tourist visits attracted directly by weather-related tourism destinations or indirectly by climate conditions in other tourism destinations within the assessed region and P_V denotes the average per capita tourism consumption level, measured in yuan per visit.

3. Results and Analysis

3.1. *Overview of the study area*

Wuzhishan City in Hainan Province is the city with the highest altitude on Hainan Island (328.5 metres) and is located in the central-southern hinterland of the island. It falls within the core protected area of Hainan Tropical Rainforest National Park, with a forest coverage rate of nearly 90%. Known as the “Emerald Mountain City,” it features a typical tropical mountainous climate characterized by warm winters, cool summers, and distinct wet and dry seasons. The annual average temperature is 23.4 °C, and the annual precipitation reaches 1,855 mm.

3.2. *Climate provisioning service value*

From 2019 to 2022, the temperature-related electricity consumption values in Wuzhishan City were 62.6295 million kWh, 44.3696 million kWh, 28.7832 million kWh, and 13.0570 million kWh (10^4 kW·h) each year, respectively, generating economic benefits of 43.8407 million yuan, 31.0587 million yuan, 20.1482 million yuan, and 9.1399 million yuan, respectively. During the research process, an analysis of temperature-related electricity consumption in the seven townships of Wuzhishan City revealed that spatial heterogeneity in regional climatic characteristics and the distribution of urban and rural populations contributes to variations. Regional differences stem primarily from microclimate variations caused by the complex topography and landforms within Wuzhishan City. Although the entire area of Wuzhishan has a tropical mountainous climate, differences among townships in elevation, slope aspect, vegetation coverage, and terrain shading directly influence the spatial redistribution of meteorological factors, such as temperature, precipitation, and sunlight, thereby forming unique local climate units. This small-scale climatic variation serves as a critical natural background for the significant spatial heterogeneity in energy consumption intensity observed across townships. Furthermore, the intensity of the response to meteorological factors varies notably across townships (**Figure 1**), with weather comfort being negatively correlated with electricity consumption. The value of temperature is reflected in energy-saving benefits.

Figure 1. Comparison of temperature values across townships in Wuzhishan city from 2019 to 2022.

From 2019 to 2022, the effective utilization of freshwater resources in Wuzhishan City was 105.6725 million yuan, 331.9377 million yuan, 562.3549 million yuan, and 713.2992 million yuan, respectively. The variation in value across different years is attributed primarily to changes in areal precipitation. The average areal precipitation increased from 1,287.98 mm in 2019 to 1,547.49 mm in 2022 (**Table 4**), leading to a widening difference between r_M and r_E, which in turn caused a sharp increase in value. For instance, in 2022, the value of freshwater resources accounted for 41.63% of the total E_w over the four-year period. This trend, observed in the time series, highlights the decisive impact of abundant precipitation in that year (average areal precipitation: 1,547.49 mm) on the value of the regional water resource supply, reflecting the significant influence of increased precipitation on the valuation of regional water resources.

From 2019 to 2022, the supply values derived from climate conversion and utilization, such as wind power, hydropower, and photovoltaic power generation, were 9.4939 million yuan, 13.3000 million yuan, 15.591 million yuan, and 16.9013 million yuan each year, respectively. The values of meteorologically augmented products, including agricultural (crop cultivation), forestry, animal husbandry, and fishery products, were 36019.8 million yuan, 41308.8 million yuan, 43596.35 million yuan, 46766.6 million yuan, and 167691.55 million yuan, respectively (**Table 5**).

In summary, from 2019 to 2022, the total values of climate provisioning services in Wuzhishan City were 488, 769, 1025, and 1207 million yuan each year, with an annual average of 896 million yuan. Among these, the total value of climate-augmented products was 1.773 billion yuan, accounting for the largest proportion at 49.45%. This was followed by the value of climate-direct provisioning products, which amounted to 1.757 billion yuan, accounting for 49.01%. The value of climate conversion and utilization products was 55 million yuan, representing 1.54%.

Table 4. Annual changes in E_W from 2019 to 2022.

Year	2019	2020	2021	2022	Total
Areal Average Precipitation (or Average Areal Rainfall)	1288.98	1384.61	1483.02	1547.49	5703.11
E_W (10,000 yuan)	10567.25	33193.77	56235.49	71329.92	171326.42
E_W Proportion	6.2%	19.4%	32.8%	41.6%	100.0%

Table 5. Annual changes in the values of meteorological value-added products from 2019 to 2022.

Year	2019	2020	2021	2022	Total
E_d(10,000 yuan)	1278.19	1091.05	1100.84	913.99	4384.07
E_e(10,000 yuan)	949.39	1330.00	1559.17	1690.13	5528.69
E_a(10,000 yuan)	36019.8	41308.8	43596.35	46766.6	167691.55

3.3. *Climate regulation service value*

From 2019 to 2022, the purification values of different precipitation levels for atmospheric pollutants ($PM_{2.5}$) significantly varied (**Table 6**). Among them, light rain and moderate rain accounted for 36.28% and 34.17% of the total purification value, respectively, with a cumulative contribution rate of 70.45%, dominating the overall effect. This is closely related to their high frequency of occurrence and stable purification processes. In contrast, heavy rains and torrential rains, despite their high single-event removal efficiency, contributed only 2.03% and 4.24%, respectively, to the cumulative value because of their low frequency of occurrence, resulting in a limited overall contribution to pollutant purification.

From 2019 to 2022, the total protective values of lightning protection for Type II flammable and explosive sites and Type III general buildings in Wuzhishan City were 338 million yuan and 52 million yuan, respectively.

In summary, the total values of climate regulation services in Wuzhishan City from 2019 to 2022 were 373 million yuan, 382 million yuan, 376 million yuan, and 374 million yuan each year. Among these, the annual average value of precipitation purification was 275 million yuan, accounting for 73.08% of the average annual climate regulation service value. The annual average protective value of lightning protection was 97 million yuan, accounting for 25.90%, while the annual average regulatory value of weather modification was 4 million yuan, accounting for 1.01%.

3.4. *Climate cultural service value*

The meteorological tourism destinations in Wuzhishan City mainly fall into two categories. The first category includes climate wellness destinations (such as natural oxygen bars and summer retreat destinations), covering all seven townships within the city. The second category consists of five meteorological landscape attractions, including rural tourism sites and rainforest rafting/hiking scenic spots: Red Canyon, Grand Canyon, Maona Village in Shuiman Township, Fangnuozhai Tropical Rainforest Scenic Area, and the Wuzhishan section of the Hainan Tropical Rainforest National Park.

Table 6. Effects of different precipitation levels on Q and E_Q from 2019 to 2022.

Precipitation Level	Light rain	Moderate rain	Heavy rain	Torrential rain	Downpour	Total
Q(t)	98.05	92.35	62.91	5.50	11.46	270.26
E_Q(10, 000 yuan)	48014.72	45221.59	30805.56	2691.27	5613.31	132346.44
E_QProportion	36.3%	34.2%	23.3%	2.0%	4.2%	100.0%

Table 7. Annual changes in different categories of E_V from 2019 to 2022.

Year	2019	2020	2021	2022	Total
Rural tourism sites E_V(10, 000 yuan)	27333.18	24367.27	31048.97	22583.76	105333.18
Rainforest rafting and hiking scenic areas E_V(10, 000 yuan)	24885.43	22666.02	30541.76	23911.73	102004.94
Climate Wellness E_V(10, 000 yuan)	65024.26	72011.40	119120.24	106638.55	362794.45
Total	117242.87	119044.69	180710.97	153134.04	570132.57

Table 8. Summary of the value of climate ecological products in Wuzhishan City from 2019 to 2022

Category	Product	Value (10, 000 yuan)	Proportion
Value of Climate Provisioning Services	Freshwater	171326.42	32.0%
	Temperature	4384.07	
	Wind power, hydropower, and photovoltaic power generation	5528.69	
	Agriculture, forestry, animal husbandry, and fishery	167691.55	
Value of Climate Regulation Services	Purification of Atmospheric Pollutants by Precipitation and Wind	132346.44	15.7%
	Protective Effect of Lightning Protection on Buildings	38991.6	
Value of Climate Cultural Services	Rural tourism sites	105333.18	52.3%
	Rainforest rafting and hiking scenic areas	102004.94	
	Climate Wellness	362794.45	
Total	–	1090401.34	100.0%

From 2019 to 2022, the numbers of tourists visiting Wuzhishan City directly and other tourism destinations because of meteorological factors were 2.3613 million, 1.6492 million, 2.5685 million, and 2.0077 million person-times each year. The per capita tourist consumption (P_v) amounted to 496.52 yuan, 721.85 yuan, 703.57 yuan, and 762.72 yuan per person-time each year, resulting in cultural service values of 1.172 billion yuan, 1.190 billion yuan, 1.807 billion yuan, and 1.531 billion yuan, respectively (**Table 7**).

The proportion of cultural service value contributed by rural tourism sites and rainforest rafting/hiking scenic areas decreased annually, from 42.04% and 38.27% to 21.18% and 22.42%, respectively. In contrast, the number of tourists for climate wellness tourism increased annually, as did the associated share of cultural service value, growing from 19.69% to 56.40% and holding a dominant position.

From 2019 to 2022, the average annual value of climate cultural services in Wuzhishan City was 1.425 billion yuan. Among these, the cultural service value of climate wellness tourism was 907 million yuan, accounting for 39.77%, which was the highest proportion. This was followed by the cultural service value of rural tourism sites, which totalled 1.053 billion yuan, accounting for 30.78%. The smallest proportion was contributed by the cultural service value of rainforest rafting and hiking scenic areas, amounting to 1.020 billion yuan and accounting for 29.45%.

In summary, from 2019 to 2022, the total value of climate ecosystem services in Wuzhishan City was approximately 10.904 billion yuan (**Table 8**), with an average annual value of approximately 2.726 billion yuan. This is equivalent to 26.42% of the average annual GDP of the city, which indicates that climate ecosystem services significantly contributed to regional economic development. Specifically, the average annual value of the climate cultural service value was 1.425 billion yuan, which accounted for 52.29% of the total value of climate ecosystem services in Wuzhishan City and represented the greatest proportion. The average annual value of climate provisioning services was 8.72 million yuan, accounting for 32.00%, and the average annual value of climate regulation services was 428 million yuan, accounting for 15.71%.

4. Discussion

In this study, Wuzhishan City was taken as an example to establish for the first time a climate ecosystem service value accounting system tailored to tropical mountainous cities, and the three categories of services—climate provisioning, regulation, and culture—were systematically evaluated from 2019 to 2022. The accounting results reveal that the average annual total value of climate ecosystem services in Wuzhishan City from 2019 to 2022 was 2.726

billion yuan, which is equivalent to 26.42% of the average annual GDP of the city during the same period. This finding indicates that climate ecological resources constitute a “hidden asset” that cannot be overlooked in the regional economic system. Therefore, the valuation results of climate ecological products should be incorporated into government performance assessments and the calculation basis for ecological compensation. Efforts should be made to explore the establishment of a horizontal compensation mechanism whereby areas with a higher proportion of climate ecological value receive greater compensation. This could transform the quantifiable advantages of “lucid waters and lush mountains” into tangible policy benefits. Realising this value, however, ultimately depends on coordinating the multiple actors that make up the ecological value chain, in line with configurational actor–network perspectives on value creation (Ma S *et al.*, 2025).

From the perspective of accounting methodology, this study draws on relevant domestic and international research findings as well as pilot experiences to establish an accounting system that demonstrates strong scientific validity and operability. This study develops a valuation framework for climate ecological products that differs in three fundamental aspects from current gross ecosystem product (GEP) accounting frameworks (e.g., cases in Fuzhou City, Lu'an City, and Jingde County) (Zhao *et al.*, 2021; Yu, 2024; Sun *et al.*, 2025). First, in terms of focus, current GEP accounting focuses on overall ecosystem services, whereas this framework focuses on climatic elements (temperature, precipitation, wind speed, etc.) as core driving factors, representing a deepening and expansion of the “climate regulation” category within the GEP. Second, with respect to attribution logic, previous accounting attributes value to ecosystems, while this framework introduces a meteorological contribution rate to isolate and characterize the independent contribution of climate resources. Third, concerning service emphasis, cultural services account for a relatively small proportion of previous accounting, whereas this framework highlights the dominant role of climate cultural services, making it more applicable to regions where ecotourism is a pillar industry. Compared with existing assessment studies, which are largely limited to individual services (e.g., cooling and energy savings (Zhang *et al.*, 2025; Niu *et al.*, 2023), climate comfort (Lv *et al.*, 2023; Zhang *et al.*, 2024), and wind and solar energy, in this study, a comprehensive system was constructed at the county scale. The system covers three major categories—climate provisioning, regulation, and cultural services—and includes seven indicators, achieving a transition from “single-service assessment” to “full-category value accounting." Furthermore, on the basis of four consecutive years of data from 2019 to 2022, this study reveals interannual value fluctuations and their sensitivity to climate change, addressing the limitations of static assessments. This framework offers differentiated innovations in terms of accounting logic, indicator systems, and service focus, providing a new accounting reference for regions rich in climate resources. Although artificial precipitation enhancement operations can improve soil moisture, alleviate drought, and generate economic benefits—reflecting the value of climate regulation services—their key benefit lies in increasing natural precipitation. To prevent double counting with the freshwater supply account, this study incorporates the volume of artificially enhanced precipitation (Huang *et al.*, 2006; Huang *et al.*, 2019) into the total precipitation for valuing freshwater supply and does not include it in the total value of climate ecological products. However, uncertainties remain during the accounting process. For instance, the determination of meteorological contribution rates relies primarily on expert scoring methods and literature references. While these approaches possess a certain degree of scientific rigor, more refined studies tailored to specific local crops and energy facilities in Wuzhishan City are still needed. Future efforts could integrate controlled experiments, long-term observations, and model simulations to further enhance the localization and precision of key parameters. Furthermore, regarding the temperature-electricity model, in this study, quadratic models of temperature versus electricity consumption were constructed for both Wuzhishan City and Hainan Province. The differences in the coefficients for T^2 and T between the two models were 7.3% and 1.9%, respectively (acceptable), the difference in R^2 was only 0.6%, and the model shapes were similar. The difference in the intercept term (-2.8%) reflects different baseline levels of electricity consumption, providing a basis for horizontal comparability between the models. This quadratic model attributes temperature-related load variations to climate. However, electricity consumption is also influenced by nonclimatic factors, such as income, household appliance penetration rates, and electricity prices. To address this, a multiple regression model incorporating per capita GDP, the number of permanent households, and a pandemic dummy variable was further established. The results indicate that nonclimatic factors contribute significantly and that climatic factors alone cannot fully explain fluctuations in electricity consumption. Although the multiple regression model implicitly assumes that differences in economic structure are negligible, nonclimatic factors, such as the pandemic, had synchronized and concurrent effects on both regions, cancelling each other out in the calculation of the difference in W_{dt}. A dual-track comparison experiment with and without the pandemic dummy variable reveals that the original W_{dt} and the revised W_{dt} after the pandemic effect are almost exactly equal (difference < 10^{-12}), which verifies the effectiveness of the differencing mechanism. In summary, the results of the model comparisons have practical reference value.

In terms of the compositional characteristics of climate ecosystem service value, Wuzhishan City is characterized by a structure dominated by cultural service value (with an average annual proportion of 52.29%). This stands in sharp contrast to the value structures of traditional agricultural regions, where provisioning services are predominant (e.g., Fuzhou City, where provisioning services account for 94.1%) (Yu, 2024), or industrial cities, where regulation services dominate (e.g., Lu'an City, with regulation services accounting for 82.77%, and Jingde County, with 77.49%)

(Zhao *et al.*, 2021; Sun *et al.*, 2025). This compositional feature aligns closely with the role of Wuzhishan City as the core area of the tropical rainforest national park and its position in terms of comprehensive tourism development, indicating that the integration of “climate and cultural tourism” serves as a critical pathway for regions with ecological advantages to realize value transformation. Therefore, relevant departments can focus on themes such as “climate wellness” and “rainforest leisure” to strengthen brand cultivation and product innovation and thereby effectively translate climate resources into tourism economic benefits.

With respect to the interannual fluctuations in value, the accounting results reveal significant year-to-year variations. For example, the value of freshwater provisioning in 2022 significantly increased because of high precipitation (accounting for 41.63% of the freshwater value from 2019 to 2022), and the benefits of temperature-related electricity savings fluctuated across different years because of variations in comfort levels. This highlights the high sensitivity of the regional climate–ecosystem–economic system to climate change. In the context of the increasing frequency of extreme events driven by global climate change, the stability of climate ecosystem service provisioning faces challenges. Such physical climate risks may, moreover, propagate beyond the local system through supply-chain linkages and generate negative spillovers (Zhong *et al.*, 2025). Therefore, incorporating climate change risks into long-term assessment and management systems is essential. Adaptive measures, such as strengthening water resource regulation, protecting rainforest ecosystems, and developing climate insurance, should be implemented to ensure the stability of climate regulation and provisioning functions.

Moreover, this study has certain limitations: (1) The scope of accounting focuses primarily on services with available data and ease of monetization, with insufficient coverage of potential services, such as biodiversity maintenance, the economic materiality of which is increasingly evidenced in cross-national analyses of biodiversity risk (Zeng *et al.*, 2025). (2) The analysis of value realization pathways emphasizes policy recommendations, while specific market mechanisms and implementation effects require empirical validation. Future research should focus on the following areas: (1) refining accounting methods and localizing parameters; (2) establishing a regularized dynamic monitoring and reporting mechanism; (3) expanding the accounting of potential service values, such as carbon sequestration and climate regulation; and (4) exploring value realization mechanisms on the basis of accounting results, such as ecological compensation and green finance, to provide more systematic scientific and technological support for the transformation of ecosystem service value in Wuzhishan City and similar regions. In pursuing these mechanisms, the present framework can draw on evidence linking ESG disclosure to green-innovation performance among new-energy firms and on capital-market channels for realising green value (Xu *et al.*, 2025; Yan *et al.*, 2025), and more broadly on configurational analyses of green and high-quality industrial transformation (Li *et al.*, 2026).

5. Conclusion

In this study, a set of indicator systems and methods for valuing climate ecosystem services tailored to tropical mountainous cities were constructed. Using Wuzhishan City in Hainan Province as a case study, the value of its climate ecosystem services from 2019 to 2022 was assessed. The results revealed that the average annual total value of climate ecosystem services in Wuzhishan City was 2.726 billion yuan, accounting for 26.42% of its average annual GDP during the same period. This fully demonstrates the significant economic contribution of the climate-related ecological capital of the region.

In terms of value structure, meteorological cultural services dominated (average annual value of 1.425 billion yuan, accounting for 52.29%), reflecting the ecological advantages of the city as the “Emerald Mountain City” and the core area of Hainan Tropical Rainforest National Park. Among these, climate wellness services significantly increased and emerged as the core component, highlighting the increasing societal demand for high-quality climatic environments and providing direction for the development of local cultural and tourism industries. The average annual value of climate provisioning services was 872 million yuan, accounting for 32.00% of the total, representing another key pillar. Within this category, the value of meteorologically augmented products, such as agriculture, forestry, animal husbandry, and fisheries, was particularly prominent, underscoring the stabilizing role of climatic conditions in supporting traditional industries. Additionally, the freshwater supply was notably influenced by interannual precipitation fluctuations, indicating that water resources are key sensitive elements in the climate ecosystem of the region.

The average annual value of climate regulation services was 428 million yuan, accounting for 15.71%, representing nonnegligible ecological benefits. Precipitation contributed 77.24% to the value of regulation services through PM2.5 purification, highlighting the significant positive environmental externalities resulting from high forest coverage and frequent rainfall. These findings also reinforce the functional role of the region as an ecological security barrier in the central part of Hainan Island.

In summary, the climate ecological product values of Wuzhishan City are substantially and structurally diverse. Its scientific accounting not only provides a quantitative basis for regional green accounting and ecological civilization performance assessment but also lays theoretical and empirical foundations for the design of ecological compensation mechanisms and the development of new climate economy sectors (such as carbon trading, climate insurance, and ecotourism). Furthermore, integrating cutting-edge research on climate governance and sustainable development, this accounting work extends theoretical and practical boundaries in the following aspects: First, drawing on the transmission mechanisms between urban climate governance and corporate environmental responsibility, Wuzhishan City can enhance the effective supply of ecological products by strengthening government regulatory incentives and promoting the participation of multiple stakeholders (such as social organizations, enterprises, and individuals), thereby constructing a differentiated evolutionary mechanism for ecological product supply and achieving a win-win outcome of carbon emission reduction and improved public welfare(Shao *et al.*, 2026; Piao *et al.*, 2025). Second, in light of the negative impacts of extreme precipitation and climate events on corporate innovation persistence and operational stability, Wuzhishan City, while developing a climate-resilient ecological economy, should focus on enhancing regional organizational resilience, alleviating financing constraints, and encouraging the participation of talents with R&D backgrounds and international experience in the construction of climate-ecological industries to ensure sustained innovation momentum(Lei *et al.*, 2025). This accords with evidence that organisational, technological and environmental conditions jointly sustain the persistence of green innovation (Yan *et al.*, 2026) and that financial- and human-capital channels mediate firm innovation under institutional reform (Zhong *et al.*, 2026) . Third, in the process of promoting climate-resilient infrastructure (such as resilient power grids and disaster prevention and mitigation systems), attention should be paid to the risks of "adaptation inequality" and "selective vulnerability," avoiding the exacerbation of energy poverty or social exclusion due to the transfer of climate protection costs, and ensuring that the value realization process of climate ecological products is both efficient and equitable(Lei, 2026). In conclusion, the accounting of climate ecological product value in Wuzhishan City not only serves local green development but also provides an important regional example and policy insights for how to realize ecological product value, prevent negative spillover effects of adaptation policies, and promote inclusive sustainable development in the context of global climate governance.

Conflict of Interest

The authors declare that they have no conflicts of interest.

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Authors contributions

M.Z. conceived the study, designed the experimental methodology, contributed to data analysis and interpretation, contributed to writing the original draft and reviewed the manuscript. M.F. conducted the literature review and synthesis; performed data collection, curation, analysis, and interpretation; wrote the original draft; and reviewed the manuscript. L.W., X.C., G.L., Y.S., and G.Q. contributed to the literature review and data collection. M.Z. and M.F. contributed equally to this work. All the authors read and approved the final manuscript.

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