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Payments for forest ecosystem services in China: a multi-function quantitative ecological compensation standard based on the Human Development Index

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Forest ecosystems provide many ecosystem services, and payment for these ecosystem services has recently become a policy-relevant issue. This paper puts forward a multi-function quantitative standard (MQECS) for forest ecosystem services based on the Human Development Index and the six distinct forest ecosystem service values. Using the MQECS method, the MQECS_i and total ecological compensation amount (TECA_i) for forest ecosystem services in Guangdong and Liaoning provinces in 2012 were calculated. The MQECS_i of Guangdong and Liaoning were 663.02 and 225.27 RMB·hm⁻², and the TECA_i of these provinces were 66.82 × 10⁸ and 13.67 × 10⁸ RMB, respectively. The MQECS_i of Guangdong is approximately three times that of Liaoning, and the government needs to increase investment per unit forest area by 176.25% and 50.20% of the current compensation amount in Guangdong and Liaoning to achieve the target quantitative compensation standards. Additionally, the MQECS method was also applied to calculate the ecological compensation for forest ecosystem services of different cities in Guangdong and Liaoning. The MQECS method not only considers the local government's ability to pay but also incorporates factors influencing human wellbeing and the valuation of distinct forest ecosystem services. It is suitable for application to current forest management in China.

KEYWORDS

forest ecosystem services, multi-function quantitative ecological compensation, human development index, sustainability, human wellbeing

1 Introduction

Forests are multi-functional, renewable resources that provide a great assortment of ecological benefits for humans (Snall et al., 2021), including soil and water conservation, carbon sequestration and oxygen release, nutrient accumulation, air quality improvement, and biodiversity conservation (Costanza et al., 1997; Niu and Wang, 2013; Boskidis et al., 2012). However, forest ecosystems are open systems that provide many of their benefits indirectly. There is often no direct link between the benefactors and the beneficiaries (Yu H. Q. et al., 2023). Ecosystem services, as the foundation

of human survival and development, directly determine the state of human wellbeing (Millennium Ecosystem Assessment, 2005). As an important component of the ecosystem, humans are in a dynamic equilibrium state of interaction and constraint with various components in the ecosystem (Zhou et al., 2024). Welfare is the ability of humans to freely and selectively engage in ecosystem services such as supply, regulation, culture, and support services. On one hand, continuously changing human conditions can directly or indirectly drive changes in ecosystems, and on the other hand, changes in ecosystems can lead to changes in human wellbeing (Fisher et al., 2014; Leviston et al., 2018). At the same time, many other factors unrelated to the environment can also change human wellbeing, and many natural driving forces are continuously affecting ecosystems (Millennium Ecosystem Assessment, 2005). From an economic perspective, the ecosystem services provided by forests constitute positive economic externality (Taye et al., 2021), and these benefits are consumed by non-forestry operations, and even by society as a whole, without any consideration of the costs incurred in the production of ecosystem services or of compensation to those who oversee or are otherwise responsible for the production of these benefits (Naime et al., 2022; Cai et al., 2005).

In recent years, there has been an increasing focus on compensation for ecosystem services in the academic and public sectors (Hou and Wang, 1995; Wu et al., 2024; Yang et al., 2018), which is called payment for ecosystem services (PES) worldwide (Wang et al., 2017). Ecological compensation is an institutional arrangement aimed at protecting and sustainably utilizing ecosystem services, primarily through economic means, and regulating the interests of stakeholders (Ju et al., 2022). The aim of ecological compensation is to optimize resource allocation and adjust the interest relationship between ecological service providers and demanders, realizing the value of ecological capital and services (Gao et al., 2020). 'Forest ecological compensation,' as it is called in China, is a form of value repayment for the ecosystem services that forests provide, objectively reflecting the forests' functional value in a commodity economy (Li et al., 2018). Moreover, forest ecological compensation also serves as a transfer mechanism that internalizes the externality of forest ecosystem services by compensating individuals or companies for the losses or costs resulting from the provision of these functions (Shi et al., 2024; Yang et al., 2024). Based on the cost of afforestation and management of different types of forest resources and the multiple functions of the forest ecosystem, factors such as quantity structure and economic location (Deng et al., 2020) are considered, which are crucial to construct a scientific ecological compensation standard system and establish a comprehensive and diversified forest compensation mechanism for accurately optimizing forest structure, improving forest quality, and enhancing forest ecosystem services (Deng et al., 2011).

However, establishing an optimal compensation mechanism for ecosystem services is a long and involved process (Guan et al., 2024), and some implementation issues await more thorough research, including compensation methods, compensation standards, the scope of forest ecosystem services for which compensation is made, and the management of compensation funds (Zhou et al., 2023; Sierra and Russman, 2006). In some countries, studies of ecological compensation have been carried out, revealing the use of compensation mechanisms and types, including

self-organized payments for environmental services, public payments for the management of areas of important ecological function, compensation for the restoration of landscapes affected by mining, and compensation for agro-ecological environmental protection (Liu et al., 2024). Direct investment and subvention from the government was adopted in developed countries, and the strategy of sustainable development of forestry in these countries is unitive between the government and the market (Deng et al., 2011). Some Western countries have also begun to collect ecological taxes and have established a suitable system for ecological taxation, which may be a very important direction for traditional tax innovation (Medynska et al., 2024). Moreover, some Asian countries (Singapore, India, and Korea) and Eastern European countries such as Poland and Hungary have also adopted ecological tax policies. In these countries, governments subsidize forestry services and collect fees from beneficiaries of forest ecosystem services, thereby solving the double relation between material compensation and value compensation of ecological resources (Delgado et al., 2022; Cornelia and Lenuța, 2012). Three countries, the United States, Brazil, and Costa Rica, have successfully implemented compensation policies for ecosystem services. Their common experience is that the government is the main purchaser of ecosystem services (Lara et al., 2009). The U.S. government chose some active measures to improve the provision of ecosystem services; for example, the government purchased ecosystem services and supplied the compensation funds (Adhikari et al., 2022). In England and France, the income from state-owned forests is not turned back to higher authorities but is used for further forest development, and shortfalls are remedied by government allocations or preferential loans (Wang et al., 2022). German state-owned forests have a budget policy, and funds are appropriated after examination and approval of the budget by the national parliament. The investment of former Soviet Union countries accounted for 10% of state-owned forest management expenditure (Fisher et al., 2008; Hashim et al., 2010).

In China, studies of compensation for ecosystem services were carried out more recently. The "Regulations on Ecological Protection Compensation" promulgated by the State Council in April 2024 marked significant progress in the legalization of ecological protection compensation in China, and China became the world's first country to comprehensively legislate on ecological protection compensation. China's policy of compensation for forest ecosystem services was formally put forward in 1989, and it includes fees imposed upon activities leading to the destruction or degradation of forest ecosystems, fees collected from the beneficiaries of ecosystem services, and compensation for individual or regional ecological conservation activities (Shang et al., 2018). The funding system for Chinese forest ecological compensation was first listed in the Forest Law of the People's Republic of China in 1998. The traditional approach to the provision of environmental services has been through ecological compensation payments made directly from the government to the supplier of forest ecosystem services (such as the very large "Grain for Green" program). In 2001, the Ministry of Finance and the National Bureau of Forestry designated 658 counties in 11 provinces and 24 state-level natural reserves as experimental units that would receive subsidies for ecosystem services, marking the first implementation of a compensation policy for ecosystem services in the country. In 2004, the Central Government Financial Compensation Fund for

forest ecological compensation was formally established in China (Niu et al., 2012). The forestry subsidy policy implemented in China promotes land greening, improves forest quality, enhances forest ecosystem services, and ensures the basic livelihood of the people (Lu et al., 2020). Han and Chen (2021) found that forestry subsidy policies can directly increase transfer payment income, effectively improve the forestry production capacity of forest workers, and increase their household income.

Selomane et al. (2015) evaluated the contribution of nature-based sectors (agriculture, forestry, and fisheries) to income and employment rates and found that from 1991 to 2010, nature-based sectors helped 18% of the world's population escape poverty and provided 37% of employment opportunities. Yang et al. (2013) constructed indicators reflecting the degree of dependence of human wellbeing on ecosystem services, including income from food, meat, and non-timber forest products that represent the contribution of provisioning services, electricity subsidies obtained due to protecting watersheds that represent the contribution of regulating services, and ecological tourism income that represents the contribution of cultural services. At present, studies on compensation for forest ecosystem services are mostly policy compensation studies, and individual reports are mainly concerned with the size of ecological compensation payments. However, the ecological compensation payment size may be too large and far beyond local governments' ability to afford, resulting in non-achievement of the desired ecological benefits (Chen et al., 2020). The regional development level and actual carrying capacity should be considered comprehensively in reasonable ecological compensation. There are many studies using the compensation coefficient method, which is based on integrating Engel's coefficient with the Peel growth curve model (Liang, 2008). The Peel growth curve model is used to express the enhancement of human ecological awareness and payment ability. Engel's coefficient is a measure of residential food expenditure as a proportion of the total consumer spending and does not take into account the relationship between forest ecosystem services and human wellbeing. So, the above ecological compensation methods are only based on the national economic level and cannot reflect the actual value of forest ecosystem services. It caused the phenomenon of coexistence of inadequate compensation and overcompensation; the benefit of the compensation funds was low, and it seriously reduced the project implementation effects. The essence of ecological compensation is that the forest ecological benefit value should be balanced between the beneficiary, who should pay for forest ecosystem services, and the supplier, who should gain from providing forest ecosystem services (Farley and Costanza, 2010). The ecological compensation standard should be the embodiment of combining information about both the beneficiary and the supplier of forest ecosystem services.

The present study integrates domestic and international theories and methods of compensation for ecosystem services and puts forward the multi-functional quantitative ecological compensation standard (MQECS) for forest ecosystem services based on the Human Development Index (HDI) and the values of six distinct forest ecosystem services (11 quantitative indicators). It takes into account the contribution of the supplier of forest ecosystem services and the contribution of the beneficiary (the national and local governments' ability to afford). Moreover, by the MQECS method,

the ecological compensation standards for forest ecosystem services in Guangdong and Liaoning provinces and in different city levels within the single provinces in 2012 were calculated. It showed that the MQECS method and analysis was reasonable and feasible and supported the quantitative operationalization of the administration of forest ecosystem services compensation policy in China.

2 Methodology and data

2.1 Study area

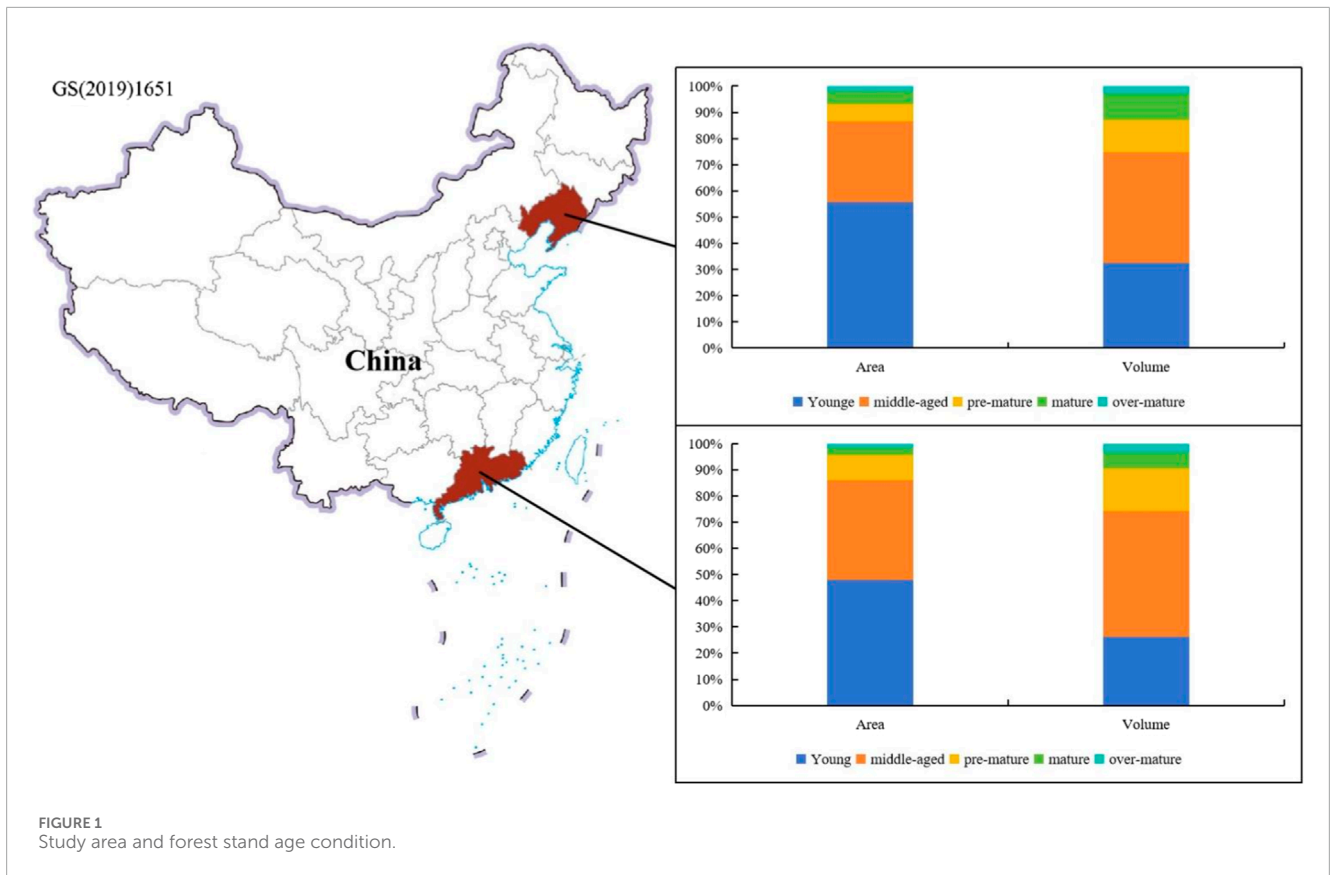
Guangdong province is located in southern China (Figure 1), with 21 provincial-level cities. Guangdong belongs to the East Asian monsoon region, with central subtropical, southern subtropical, and tropical climates from north to south. Precipitation is abundant, with an average annual precipitation of 1,777 mm, showing a trend of high in the south and low in the north, and is mainly concentrated from April to September, accounting for more than 80% of the annual precipitation. The average annual temperature is 22.3°C. The forest resource area in Guangdong province was 892.71×10^4 hm², and the volume was 3.98×10^8 m³.

Liaoning province is located in the northeast part of China (Figure 1), belonging to the warm temperate continental monsoon climate zone. It has the same period of rain and heat, sufficient sunlight, and an average annual temperature of 5°C–11°C. The annual precipitation is between 400 and 1,150 mm, decreasing from east to west. The rainy season lasts from July to August, accounting for approximately 70% of the annual precipitation. The forest resource area in Liaoning province was 449.51×10^4 hm², and the volume was 2.62×10^8 m³.

2.2 Data acquisition

We set 2012 as the evaluation base year. The data from the statistical yearbook of Guangdong and Liaoning provinces were collected in the calculation of ecological compensation, including the total residential consumer food expenditure, healthcare expenditure, cultural and educational entertainment products expenditure, and gross domestic product (GDP).

When calculating ecosystem services, three data sources including the forest resource data, eco-station and experiment data, and public data were coupled and integrated (Figure 2). The forest resource inventory data contain the forest areas and volume from the second category survey of forest resources in Guangdong and Liaoning provinces. The data collected by the eco-stations and experiments in the study area and adjacent areas, all based on the national standards "Methodology for field long-term observation of forest ecosystem" (SFA, 2016), and the data on different dominant trees, species origins, stand ages, and site conditions were collected. Meanwhile, the public data released via government statistics and prices include social expenses such as water purification costs and sewage charges. When forest ecosystem service quality is transformed into value quantity, it conforms to the principles of "equivalent substitution" and "weight equivalent balance."



2.3 Principle and method for calculating the ecological compensation standard based on the HDI

2.3.1 Principle and method of the HDI

The HDI is a measure of the overall situation of human development in a region. Its computation incorporates measures of a region's average achievements in three main dimensions: health and longevity, knowledge acquisition, and standard of living (Klugman et al., 2011). HDI can be calculated using the equation:

$$HDI = (I_L \cdot I_E \cdot I_G)^{\frac{1}{3}},$$

$$I_L = \frac{(L_{ACT} - L_{MIN})}{(L_{MAX} - L_{MIN})},$$

$$I_E = \frac{(E_{ACT} - E_{MIN})}{(E_{MAX} - E_{MIN})},$$

$$I_G = \frac{(\ln G_{ACT} - \ln G_{MIN})}{(\ln G_{MAX} - \ln G_{MIN})},$$

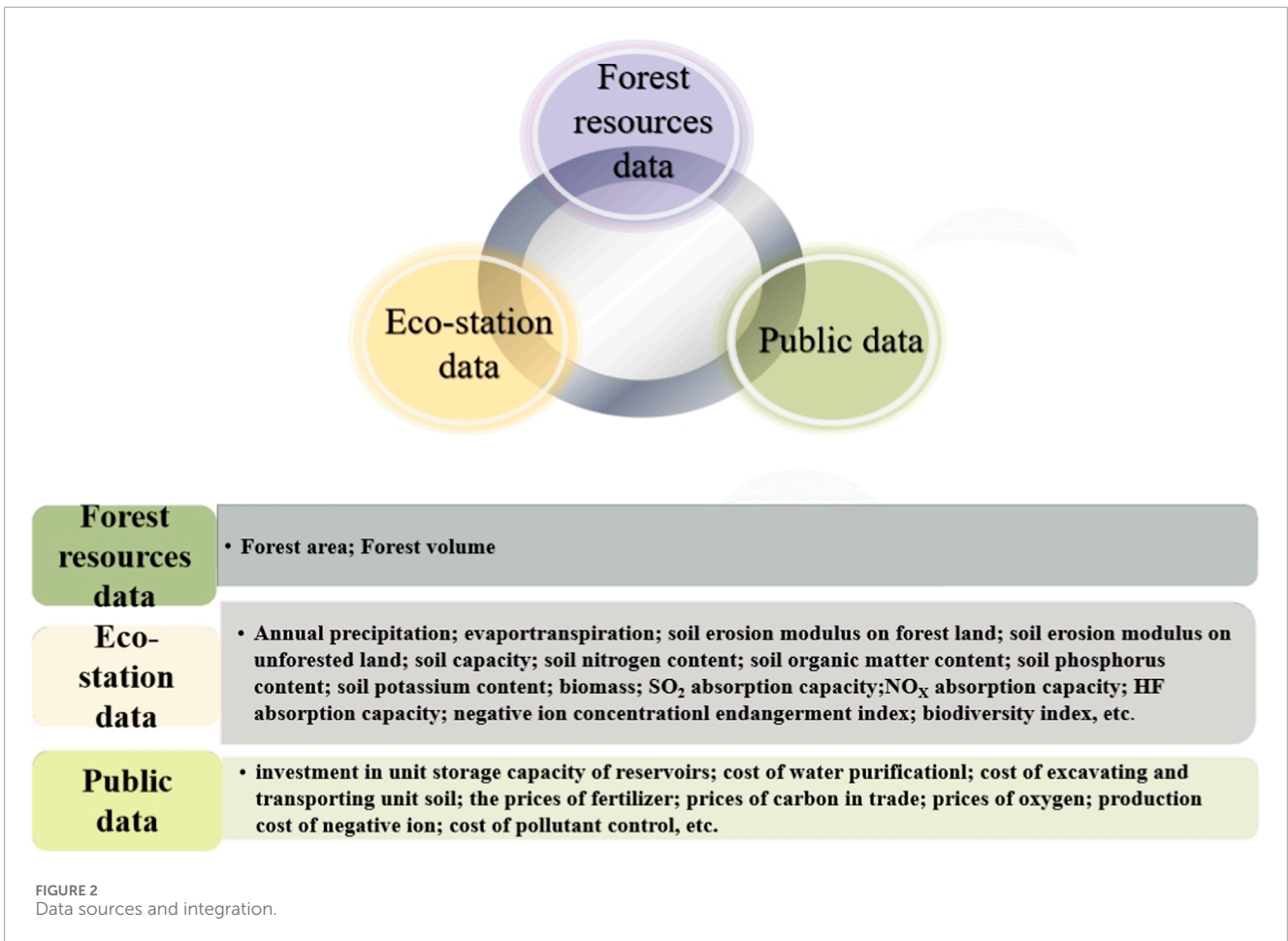
where HDI is the Human Development Index, I_L is the life expectancy index, I_E is the education index, and I_G is the gross national finance income (GNI) index. L_{ACT} , L_{MAX} , and L_{MIN} represent the actual value, maximum value, and minimum value of life expectancy, respectively. E_{ACT} , E_{MAX} , and E_{MIN} represent the actual value, maximum value, and minimum value of education, respectively. G_{ACT} , G_{MAX} , and G_{MIN} represent the actual value,

maximum value, and minimum value of the GNI per capital, respectively.

In addition, the dimension indicators related to the HDI happen to be basically consistent with human wellbeing factors such as health, basic material conditions for maintaining high-quality life, safety, and good social relationships. These factors are closely related to forest ecosystem services, and in economic statistics, these factors correspond precisely to a part of household consumption. Overall, the HDI is a parameter that is relatively easy to calculate, has a simple calculation method, can be calculated using readily available data, and is applicable to different social groups. HDI can also serve as an important indicator of social progress and development.

2.3.2 MQECS for forest ecosystem services based on HDI

The ecological compensation standard should be the embodiment of combining the information on both the beneficiary and the supplier (Yu et al., 2005). Integrating domestic and international theories and methods of compensation for ecosystem services, the multi-functional quantitative ecological compensation standard (MQECS) for forest ecosystem services is put forward based on the contribution of those services to dimensions of human wellbeing considered in the computation of the HDI. MQECS is a method that considers not only the multiple functions of the forest ecosystem but also the relationship between ecosystem services and human wellbeing, and the contribution of the beneficiary (the national and local governments' ability to afford) is also considered. So, the MQECS is applicable to the current situation of forest



ecosystem services in China's provinces (or cities). The specific method and process are introduced as follows:

$$MQECS_i = (SUNHDI_i \times BEFCI_i) \times \frac{V_i}{A_i},$$

where $MQECS_i$ is the multi-functional quantitative ecological compensation standard for forest ecosystem services in province (or city) i , RMB hm^{-2} ; $SUNHDI_i$ represents the contribution of the supplier of forest ecosystem services in a province (or city) i , %; $BEFCI_i$ represents the contribution of the beneficiary of forest ecosystem services in a province (or city) i , %; V_i represents the total value of forest ecosystem services in a province (or city) i , RMB; and A_i represents the forest area of a province (or city) i , hm^2 .

$SUNHDI_i$ is the basic consumption index of human development of a province (or city) i . It can be calculated by the following equation:

$$SUNHDI_i = \frac{(C_1 + C_2 + C_3)}{GDP_i},$$

where C_1 , C_2 , and C_3 represent total residential consumer food expenditure, healthcare expenditure, and cultural and educational entertainment products expenditure, respectively, RMB. GDP_i represents the gross domestic product of province (or city) i , RMB. These data can be obtained from the statistical yearbook.

$BEFCI_i$ is the finance compensation ability index of province (or city) i . It can be calculated by the following equation:

$$BEFCI_i = \frac{G_i}{GNI},$$

where G_i represents the gross finance income of province (or city) i , in RMB; GNI represents gross national finance income, in RMB. These data can be obtained from the statistical yearbook.

V_i includes the values of six distinct services, that is, water conservation, soil conservation, carbon sequestration and oxygen release, nutrient accumulation, atmosphere environmental purification, and biodiversity conservation (Niu and Wang, 2013). Moreover, the provision of these ecological services was evaluated using 11 quantitative indicators (Table 1), according to the "Specifications for assessment of forest ecosystem services" (SFA, 2020), and V_i can be calculated by the following equation:

$$V_i = V_R + V_W + V_S + V_F + V_C + V_O + V_T + V_A + V_P + V_D + V_B,$$

where V_R is the value for the quantity of water regulated per year; V_W is the value of water quality purification per year; V_S is the value of fixed soil per year; V_F is the value of fertility maintained per year; V_C is the value of carbon sequestration per year; V_O is the value of oxygen released per year; V_T is the value of N, P, and K accumulated in NPP per year; V_A is the value of anions produced per year; V_P is the value of pollutants absorbed per year; V_D is the

value of dust absorbed per year; and V_B is the total conservation value of species diversity per year. The data source is mentioned in Figure 2 and calculated with equations in Table 1.

In this study, we choose the forest ecological benefit compensation allocation coefficient to determine the total amount and the amount of compensation received by each city. The calculation formula for the distribution coefficient of forest ecological benefit compensation is as follows:

$$D_{ij} = \frac{V_{ij}}{V_i},$$

where D_{ij} , in %, represents the distribution coefficient of forest ecological benefits in province i , city j ; V_{ij} , in RMB/a, is the forest ecological benefits of province i , city j ; and V_i , in RMB/a, is the forest ecological benefits of province i .

From this, the total amount of $MQECS_{ij}$ in forest ecological benefits compensation that each region (city) should receive can be calculated as follows:

$$MQECS_{ij} = TMQC_i \times \frac{D_{ij}}{A_{ij}},$$

where $MQECS_{ij}$, in RMB hm^{-2} , is the multi-functional quantitative ecological compensation standard for forest ecosystem services in province i , city j ; $TMQC_i$, in RMB, is the total ecological compensation amount in province i ; D_{ij} , in %, represents the distribution coefficient of forest ecological benefits; and A_{ij} , in hm^2 , represents the forest area of province i , city j .

In our study, the $MQECS$ for forest ecosystem services were put forward based on the dimensions of the HDI . It is thus linked not only to human wellbeing but also to the financial income condition of each province (or city). In order to achieve the calculated $MQECS_i$ (the target compensation standard), a provincial (city's) government would have to take the measures necessary to promote the realization according to the calculated $MQECS_i$. The increase in investment necessary to close the gap between the calculated $MQECS_i$ and the current compensation amount of the provincial government is given as follows:

$$Y'_i = \frac{(MQECS_i - SC'_i)}{SC'_i},$$

where Y'_i , in %, represents the percentage of increased investment amount accounted for the current compensation amount; and SC'_i is the current compensation amount of the provincial government i in RMB hm^{-2} .

3 Results

3.1 Forest ecosystem services of Liaoning and Guangdong provinces of China

The value of forest ecosystem services in Guangdong province was 7031.28×10^8 RMB/a, and the value per unit area was 7.88×10^4 RMB/ hm^2 . Among them, water conservation accounted for 44.54% of the total ecosystem services, which was the highest

function, followed by biodiversity conservation, and the smallest function was nutrient fixation (Table 2).

The value of forest ecosystem services in Liaoning province was 2953.20×10^8 RMB/a, and the value per unit area was 6.57×10^4 RMB/ hm^2 . The sorting of various functions was consistent with that of Guangdong province. Water conservation, as the leading function, accounted for 39.37% of the total ecosystem services (Table 2).

3.2 $MQECS_i$ for forest ecosystem services in Guangdong and Liaoning provinces of China

Using the statistical yearbook data of Guangdong and Liaoning provinces, the basic consumption index of human development of a province (the $SUNHDI_i$), the finance compensation ability index of a province (the $BEFCI_i$), the $MQECS_i$, and the total ecological compensation amount ($TECA_i$) for forest ecosystem services in Guangdong and Liaoning provinces in 2012 were calculated.

The $SUNHDI_i$ and $BEFCI_i$ of Guangdong province were higher than those of Liaoning province in 2012 (Table 3), and the $MQECS_i$ of Guangdong province was approximately three times that of Liaoning province. The $TECA_i$ of forest ecosystem services of Guangdong and Liaoning provinces accounted for 1.83% and 1.01% of the provincial gross finance income (G_i), respectively. The $TECA_i$ of Guangdong province was approximately five times that of Liaoning province.

3.3 $MQECS_i$ for forest ecosystem services of different city levels within a single province

Using the $MQECS$ method, our study also explored the ecological compensation for forest ecosystem services of city levels within a single province. Therefore, the $MQECS_i$ and the $TECA_i$ for forest ecosystem services of different cities in Guangdong province (Table 4) and Liaoning province (Table 5) in 2012 were calculated. The $MQECS_i$ for forest ecosystem services of different cities in Guangdong province ranged from 456.86 to 985.37 RMB- hm^{-2} , with the highest standard for Zhaoqing and the lowest standard for Dongguan. The $MQECS_i$ for forest ecosystem services of different cities in Liaoning province ranged from 165.94 to 275.80 RMB- hm^{-2} , with the highest standard calculated for Benxi and the lowest standard for Chaoyang. The change trend of $TECA_i$ is consistent with that of the $MQECS_i$.

4 Discussion

4.1 $MQECS_i$ for forest ecosystem services at the provincial level

According to the relevant regulations of the two provinces, the compensation standard in 2012 was 240RMB/ hm^2 and 150RMB/ hm^2 , respectively. The government needs to increase

TABLE 1 Evaluation of the indicator system and formula of the assessment of forest ecosystem function.

Functional category	Indicator	Formula	Note
Water conservation	Water regulation	$V_R = 10C_R A(P - E - C)$	Here, V_R is the value for quantity of water regulated per year, RMB/a; C_R is the investment in unit storage capacity of reservoirs, RMB/m ³ ; A is the forest area, hm ² ; P is the amount of rainfall, mm/a; E is the evapotranspiration, mm/a; and C is the rapid surface runoff, mm/a
	Water purification	$V_W = 10C_W A(P - E - C)$	Here, V_W is the value of water quality purification per year, RMB/a; C_W is the cost of water purification, RMB/t
Soil conservation	Reduction of soil erosion	$V_S = C_S A(X_2 - X_1)/\rho$	Here, V_S is the value of fixed soil per year, RMB/a; C_S is the cost of excavating and transporting unit soil, RMB/m ³ ; X_2 is the soil erosion modulus in the forest area, t/(hm ² /a); X_1 is the soil erosion modulus in the non-forest area, t/(hm ² /a); and ρ is the soil bulk density, t/m ³
	Protection of soil fertility	$V_F = A(X_2 - X_1)(NC_1/R_1 + PC_2/R_2 + KC_3/R_3 + MC_3)$	Here, V_F is the value of fertility maintained per year, RMB/a; N , P , and K are the nitrogen, phosphorus, and potassium contents of the forest soil, %; C_1 , C_2 , and C_3 are the prices of di-ammonium phosphate fertilizer, potassium chloride fertilizer, and organic matter fertilizer, RMB/t; R_1 is the nitrogen content of di-ammonium phosphate, %; R_2 is the phosphorus content of di-ammonium phosphate fertilizer, %; R_3 is the potassium content of potassium chloride fertilizer, %; and M is the organic matter content of the forest soil, %
Carbon sequestration and oxygen release	Carbon sequestration	$V_C = C_C A(0.448B_C + F_C)$	Here, V_C is the value of carbon sequestration per year, RMB/a; C_C is the price of carbon, RMB/t; B_C is the net primary productivity of forest, t/(hm ² /a); and F_C is the soil carbon sequestration rate of forest, t/(hm ² /a)
	Oxygen release	$V_O = 1.19C_O AB_C$	Here, V_O is the value of oxygen released per year, RMB/a; C_O is the price of oxygen
Nutrient fixation	Accumulation of nutrients	$V_T = AB_C(N_T C_1/R_1 + P_T C_1/R_2 + K_T C_2/R_3)$	Here, V_T is the value of nutrient accumulated per year, RMB/a; N_T , P_T , and K_T are the nitrogen, phosphorus, and potassium contents of the forest plants, %
Purification of atmospheric environment	Anion supply	$V_A = 52.56 \times 10^{14} AHK_A(Q_A - 600)/L$	Here, V_A is the value of anions produced per year, RMB/a; L is the lifespan of negative ions; K_A is the production cost of negative ions, RMB/unit; H is the average height of the forest stand, m; and Q_A is the concentration of negative ions in the forest, unit/m ³
	Absorption of gaseous pollutants	$V_p = A(Q_S K_S + Q_N K_N + Q_F K_F)$	Here, V_p is the value of pollutants absorbed per year, RMB/a; K_S , K_N , and K_F are the cost of SO ₂ , HF, and NO _x control, RMB/kg; Q_S , Q_N , and Q_F are the annual absorption of SO ₂ , HF, and NO _x per unit area of forest, kg/(hm ² /a)
	TSP, PM _{2.5} , and PM ₁₀ retention	$V_p = A(Q_{TSP} K_{TSP} + Q_{PM2.5} K_{PM2.5} + Q_{PM10} K_{PM10})$	Here, V_p is the value of dust absorbed per year, RMB/a; K_{TSP} , $K_{PM2.5}$, and K_{PM10} are the cost of TSP, PM _{2.5} , and PM ₁₀ control, RMB/kg; Q_{TSP} , $Q_{PM2.5}$, and Q_{PM10} are the annual absorption of TSP, PM _{2.5} , and PM ₁₀ per unit area of forest, kg/(hm ² /a)
Biodiversity conservation	Conservation of species resources	$V_p = AS_B \left(1 + 0.1 \times \sum_1^x E_m + 0.1 \times \sum_1^y B_n + 0.1 \times \sum_1^z O_r \right)$	Here, V_B is the total conservation value of species diversity per year, RMB/a; S_B is the species conservation value of forest RMB/hm ² ; E_m is the rare and endangered index of species m ; B_n is the endemic species index of species n ; O_r is the age index of ancient trees for species r ; x is the number of rare and endangered species; y is the number of endemic species; and r is the number of ancient tree species

TABLE 2 Evaluation results of forest ecosystem services units: $\times 10^8$ RMB/a.

	Water conservation	Soil conservation	Carbon sequestration and oxygen release	Nutrient fixation	Purification of atmospheric environment	Biodiversity conservation	Total
Guangdong	3,131.41	400.99	1,260.17	96.18	582.97	1,559.56	7,031.28
Liaoning	1,162.71	349.69	422.19	59.06	151.11	808.44	2,953.20

TABLE 3 MQECS in Guangdong and Liaoning provinces.

	SUNHDI	BEFCi	TECA ($\times 10^8$ RMB)	MQECS (RMB·hm ⁻²)
Guangdong	0.95%	0.053	66.82	663.02
Liaoning	0.33%	0.022	13.67	225.27

TABLE 4 Coefficient and compensation amount of cities of Guangdong.

City	Ecosystem services ($\times 10^8$ RMB·a ⁻¹)	Partition coefficient (%)	TECA _i ($\times 10^8$ RMB)	MQECS _i (RMB·hm ⁻²)
Guangzhou	192.88	2.74	1.83	638.51
Shenzhen	48.66	0.69	0.46	610.86
Zhuhai	35.64	0.51	0.34	730.32
Shantou	39.26	0.56	0.37	617.12
Shaoguan	881.71	12.54	8.38	674.42
Heyuan	1017.84	14.48	9.68	861.65
Meizhou	733.78	10.44	6.97	630.12
Huizhou	450.04	6.40	4.28	647.23
Shanwei	178.93	2.54	1.70	747.51
Dongguan	37.81	0.54	0.36	456.86
Zhongshan	27.71	0.39	0.26	866.68
Jiangmen	223.48	3.18	2.12	515.05
Foshan	36.66	0.52	0.35	553.97
Yangjiang	258.52	3.68	2.46	595.23
Zhanjiang	119.73	1.70	1.14	469.91
Maoming	295.95	4.21	2.81	513.31
Zhaoqing	1032.48	14.68	9.81	985.37
Qingyuan	876.75	12.47	8.34	624.23
Chaozhou	111.39	1.58	1.06	594.48
Jieyang	166.42	2.37	1.58	584.93
Yunfu	265.64	3.78	2.52	521.41

TABLE 5 Coefficient and compensation amount of cities of Liaoning.

City	Ecosystem services ($\times 10^8$ RMB \cdot a $^{-1}$)	Partition coefficient (%)	TECA $_i$ ($\times 10^8$ RMB)	MQECS $_i$ (RMB \cdot hm $^{-2}$)
Shenyang	78.94	2.67	0.37	219.02
Dalian	228.26	7.73	1.06	226.43
Anshan	206.14	6.98	0.95	214.51
Fushun	418.79	14.18	1.94	251.88
Benxi	385.63	13.06	1.79	275.80
Dandong	540.22	18.29	2.50	260.49
Jinzhou	83.49	2.83	0.39	190.26
Yingkou	114.90	3.89	0.53	226.57
Fuxin	111.60	3.78	0.52	181.01
Liaoyang	97.05	3.29	0.45	253.36
Panjin	4.69	0.16	0.02	229.65
Tieling	210.61	7.13	0.97	218.36
Chaoyang	311.70	10.56	1.44	165.94
Huludao	161.08	5.45	0.75	192.64

investment per unit area by 176.25% and 50.20% (Yi) of the compensation amount in Guangdong and Liaoning provinces, respectively, to achieve the target quantitative compensation levels. These results indicate that improvements in the standard of living heighten the value of the contribution of forest ecosystems to the environmental quality (Gao et al., 2023). If the government can dedicate approximately 1% of the annual finance income to forest ecosystem service compensation in Guangdong and Liaoning provinces, the human wellbeing index can be improved accordingly. Moreover, the provincial governments can afford the TECA $_i$ for forest ecosystem services calculated by the MQECS method. So, the calculated ecological compensation results in Guangdong and Liaoning provinces not only consider the local government's ability to pay but also incorporate factors influencing human wellbeing and the valuation of distinct forest ecosystem services, and the MQECS method was reasonable and feasible. Since 2018, Liaoning province has implemented tending fund subsidies for ecological forests for the Grain for Green project, and the subsidy standard is 300 RMB/hm 2 . In 2024, Guangdong province provided a basic compensation of 585 yuan/hm 2 for non-commercial forests at or above the provincial level in general areas. At the same time, additional incentive compensation (60 RMB/hm 2 higher than the basic compensation standard) will be arranged for areas with high forest quality so that areas with good forest quality can receive higher compensation standards and prioritize the improvement of standards for this part of the region in future years. The policy compensation method does not differentiate between the contribution of the supplier and the contribution of the beneficiary (Kuai et al., 2024; Huang et al., 2023).

The MQECS method improves upon the deficiencies of some other compensation methods.

4.2 MQECS $_i$ for forest ecosystem services at the city level

The MQECS $_i$ was positively correlated with the total value of the forest ecosystem services (V_i) and negatively correlated with the forest area of the city (A_i). Obviously, this distribution of compensation was not consistent with the economic development standards of different cities in Guangdong province. According to the statistical yearbook data of Guangdong province in 2012, the gross finance income of Zhongshan, Zhuhai, Foshan, Dongguan, Shantou, and Shenzhen accounted for 44.86% of the total gross finance income of Guangdong province, but the gross finance income of these cities with higher TECA $_i$, such as Zhaoqing, Heyuan, Shaoguan, Qingyuan, Meizhou, and Huizhou, accounted for only 8.20% of the total gross finance income of Guangdong province. From these data, it can be seen that the cities with higher gross finance income are burdened with lower TECA $_i$ for forest ecosystem services in Guangdong province.

According to the statistical yearbook data of Liaoning province in 2012, the gross finance income of Shenyang and Dalian accounted for 56.68% of the total gross finance income of Liaoning province, but the cities with more TECA $_i$, such as Dandong, Fushun, Benxi, and Chaoyang, accounted for only 14.12% of the total gross

finance income of Liaoning province. These results were similar to those obtained for Guangdong province, and the $TECA_i$ for forest ecosystem services was related not only to the gross finance income of these cities but also to the total forest area and the total value of the forest ecosystem services. The results indicate that there is a certain degree of cost–benefit imbalance among cities in Liaoning and Guangdong provinces. Therefore, establishing a horizontal ecological protection compensation mechanism is crucial to alleviate this imbalance to a certain extent (Kroeger et al., 2019). One of the basic tasks of horizontal ecological compensation of forests is to determine reasonable and feasible compensation standards (Yu Y. Y. et al., 2023). In order to achieve a long-term stable and balanced state of horizontal ecological compensation and conservation in forests, it is necessary to calculate compensation standards that meet external forest conservation and internal environmental governance and take compensation actions (Norden et al., 2019). The MQECS method is suitable for calculating the horizontal ecological compensation for forests.

4.3 Implications and limitations

Forest ecological compensation is a policy tool to solve the contradiction between ecological environment governance and socio-economic development (Deng et al., 2020). The ecological compensation standard for forests should be higher than the relevant opportunity costs incurred during the planting process of forest land, thereby effectively improving the enthusiasm of the compensated subjects to protect the natural ecological environment (Engel et al., 2008). Establishing a reasonable forest ecological compensation mechanism is a practical need. This study explores a path that mainly focuses on vertical ecological compensation fiscal transfer payments and horizontal value exchanges, supplemented by market incentive mechanisms to enhance the enthusiasm of the public to participate in ecological compensation (Niu et al., 2024). China has a vast territory and needs to be studied from specific perspectives based on the actual situation in different regions. The current forest ecological compensation standards are mainly calculated from three perspectives: input cost, ecosystem service value, and compensation willingness. From the current situation, there is a problem of “one size fits all,” and the compensation standards are too low, which is not conducive to building a scientific ecological compensation mechanism. Such a method cannot fully mobilize the enthusiasm of forest managers. Other ecosystem services compensation mechanisms do not consider local governments' ability to pay or local levels of economic and social development and suggest compensation payments that are unaffordable (Ouyang et al., 2016). These mechanisms fail to achieve an appropriate compensation for forest ecosystem services. In contrast, the MQECS method takes the fiscal condition of the provinces and factors of human wellbeing into account; therefore, it is applicable to the present situation of forest ecosystem services compensation in China's provinces and cities.

The pursuit of material happiness by humans is neither equally important nor is it synchronous with the human wellbeing provided by ecosystem services (Zhou et al., 2024). There is a time gap between the two. Only when the happiness of human material life is satisfied will we begin to pursue the happiness brought by the ecological

environment. However, at present, this time difference cannot be expressed as a specific parameter in the calculation formula of the multi-functional quantitative compensation coefficient for provincial forest ecological benefits. This needs to be addressed as much as possible in the next step of work.

Ecosystems are unevenly distributed in space and have different flow rates, resulting in mismatched ecological services and their beneficiaries at the spatial and temporal levels (Yu et al., 2021), which requires ecological compensation. The value of forest ecosystem services is essentially a measure of the costs and benefits of traditional market spillovers. Through corresponding compensation, externalities are introduced into the decision-making process of economic actors, thereby achieving ecologically friendly behavior among different social entities (Yu H. Q. et al., 2023). There is a certain consistency between the theory of ecosystem service flow and the theory of ecological compensation (Du et al., 2023; Wang et al., 2024), which provides new technical support for the formulation of ecological compensation policies. Current forest ecological compensation is still mainly based on vertical transfer payments, which causes a series of problems such as low compensation standards, limited coverage, single funding channels, and high financial pressure (Deng et al., 2011). Using the MQECS method to rely on the ecological benefits of forests for reasonable compensation also realizes the transformation of ecological compensation from policy-based compensation to quantitative compensation based on the ecological function of forest ecosystem. Further exploration of inter-regional forest horizontal ecological compensation mechanisms is conducive to alleviating central financial pressure, promoting regional development equity, and establishing a relatively complete and reasonable ecological compensation mechanism to better promote the improvement of forest ecosystem quality and the enhancement of ecological product supply capacity.

5 Conclusion

This study puts forward the multi-functional quantitative ecological compensation standard (MQECS) for forest ecosystem services based on the HDI. The ecosystem services of six distinct forest ecosystem services (11 quantitative indicators) in Guangdong and Liaoning provinces were 7031.28×10^8 RMB/a and 2953.20×10^8 RMB/a, respectively. The MQECS for forest ecosystem services of Guangdong and Liaoning provinces in 2012 were $663.02 \text{ RMB}\cdot\text{hm}^{-2}$ and $225.27 \text{ RMB}\cdot\text{hm}^{-2}$, and the MQECS of Guangdong province was approximately three times that of Liaoning province. The MQECS of a single city in Guangdong province ranged from 456.86 to 985.37 $\text{RMB}\cdot\text{hm}^{-2}$, while in Liaoning it ranged from 165.94 to 275.80 $\text{RMB}\cdot\text{hm}^{-2}$. The economic development level of different provinces (or cities) has an important influence on the MQECS and TECA for ecosystem services.

Data availability statement

The original contributions presented in the study are included in the article/supplementary material; further inquiries can be directed to the corresponding author.

Author contributions

XN: conceptualization, methodology, project administration, and writing–review and editing. TX: conceptualization, methodology, and writing–original draft. BW: conceptualization, methodology, and writing–review and editing.

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