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# Gross Ecosystem Product (GEP) accounting for the ecological restoration of mine sites

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**Graphical abstract**

**Abstract**

This study developed a gross ecosystem product (GEP) accounting framework for small-scale mining areas and applied it to systematically evaluate the dynamics of ecosystem service values before and after ecological restoration in a typical karst mining region in Jinsha County, Guizhou Province. All monetary values are in Chinese currency (Renminbi, RMB) and are expressed in units of ten thousand yuan. The total regional GEP after ecological restoration increased significantly from 68.20 ten thousand yuan before restoration to 1212.90 ten thousand yuan, representing an increase of 1144.70 ten thousand yuan. Ecological regulating services were the primary contributors to this growth, with the soil conservation value increasing from 50.56 to 920.34 ten thousand yuan, providing the core driving force of GEP growth. An analysis of land use structure revealed that the proportional contribution of services from dry land within the GEP increased from 26.88% to 58.95%, becoming the dominant land type driving the growth of regional ecological economic value. Therefore, ecological restoration projects in karst mining areas effectively improve the quality of the regional ecological environment and also significantly enhance the value of ecosystem service functions. The study provides a quantitative basis and methodological support for the scientific transformation from lucid waters and lush mountains to invaluable assets, and for promoting the sustainable ecological management of small and medium-sized mining areas.

**Keywords:** Ecological restoration; Gross ecosystem product (GEP); Ecosystem services; Land use change

## 1. Introduction

Mineral resources are an important material foundation for national economic growth and social development. However, their large-scale exploitation, while supporting industrialization and urbanization, also inevitably has a profound negative impact on regional ecosystems. These impacts primarily manifest as vegetation destruction, soil erosion, terrain and landform degradation, loss of biodiversity, and various environmental pollution issues (Xu *et al.* 2025; Xu *et al.* 2025). The concept that lucid waters and lush mountains are invaluable assets highlights the need to align conservation with economic incentives. Historically, mining remediation has relied predominantly on end-of-pipe strategies targeting singular issues such as pollution control or vegetation restoration (Liu *et al.* 2022; Zhang *et al.* 2020). This fragmented approach has limited the ability to quantify comprehensive ecological benefits, obscuring practical pathways for value conversion and thereby weakening the intrinsic motivation for ecological preservation. Consequently, scientifically and comprehensively assessing the effectiveness of mine ecological restoration, translating abstract ecological benefits into concrete economic and social values, and thereby assigning a price to “lucid waters and lush mountains” have become urgent scientific challenges. Addressing these challenges is essential for advancing green, low-carbon development and the construction of an ecological civilization in the mining sector.

Gross ecosystem product (GEP) refers to the total economic value of all the products and services provided by ecosystems for human well-being and sustainable



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economic and social development. It is an important comprehensive indicator for measuring ecological benefits (Li *et al.* 2021). By establishing a rigorous GEP accounting system, it is possible to systematically quantify the key functions provided by ecosystems, such as provisioning services, regulating services, and cultural services, thereby providing a unified and comparable value basis for ecological benefit assessment, the design of ecological compensation mechanisms, and the formulation of green policies (Zhou *et al.* 2022). Recently, studies have conducted an extensive exploration of the theoretical framework and practical application of GEP accounting at the regional and global scales, providing an important foundation for the assessment of ecosystem service value (Li *et al.* 2021; Wu *et al.* 2021; Xie *et al.* 2018). However, most studies have focused on macro-scale systems, such as river basins and provinces, with much less attention given to ecological restoration projects in local contexts, such as small mining areas. Therefore, introducing GEP accounting into the field of mine ecological restoration will not only help to systematically trace the changes in ecosystem services during the restoration process, but will also provide a quantitative basis for coordinated decision-making on ecological protection and economic development in mining areas, facilitating a shift from the traditional model of prioritizing development over conservation to a green development model that prioritizes ecological benefits. In this context, conducting GEP accounting research on mine ecological restoration in typical mining areas and exploring the specific pathways for the conversion of ecological benefits into economic and social value are of significant theoretical and practical significance. Such studies would improve the evaluation systems used in mine ecological restoration and strengthen the internal drivers of ecological protection.

Based on this background, this study considered a typical mining ecological restoration area in the karst region of Guizhou Province as a case study, and constructed a GEP accounting system applicable to the project scale. The aim was to accurately quantify the value increment of small-scale restoration projects in terms of provisioning services, regulating services, and cultural services, determine their GEP structure and growth mechanism, and analyze how the functional contributions of different land types evolved before and after restoration at the micro-level. Additionally, the study clarified the pathways through which the ecological–economic pattern of small remediation projects is reshaped. By establishing a GEP accounting and analysis framework applicable to small scales, this research provides quantifiable and comparable evidence of ecological benefits for the ecological governance of small mining areas. It aims to enhance stakeholder confidence and provide scientific references and practical pathways for promoting the large-scale advancement of ecological restoration in small-scale mining areas.

## 2. Overview of the study area

The study area is a coal mine located in Jinsha County, Guizhou Province, in the southeast of Guizhou Province, China, situated approximately 40 km from the county seat of Bijie City. Its geographical coordinates range from 106°21′54″ to 106°23′37″ east longitude and 27°16′14″ to 27°17′24″ north latitude (Figure 1). The area has a subtropical humid monsoon climate, with an average annual temperature of 14.5°C and an average annual precipitation of 1126.71 mm, most of which occurs from May to September. This region is located in the transition zone from the central Guizhou plateau to the northwest Guizhou mountainous area. It is characterized by karst gully landforms, consisting of low and medium mountains formed by tectonic erosion and dissolution processes. The local hydrological system is part of the Liuguang River, a tributary of the Wujiang River in the upper reaches of the Yangtze River Basin. No major rivers have developed in the immediate vicinity. The soil is mainly yellow soil and lime soil, with a relatively thin layer generally ranging from 30 to 50 cm in thickness. The medium-sized mine started production in 2013, with a designed annual output of 450,000 tons. Long-term open-pit mining has caused strong human engineering disturbances, leading to significant geological and environmental problems, such as the large-scale exposure of coal gangue and the development of dangerous rock masses.

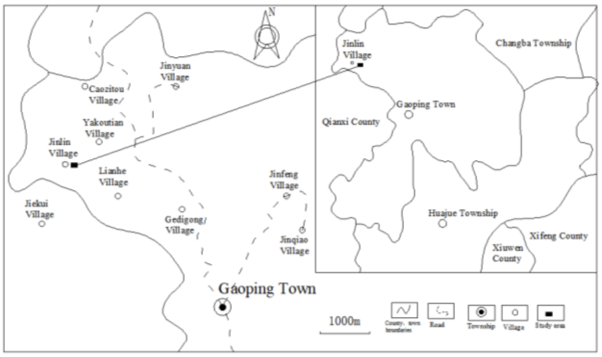


**Figure 1.** Location map of the project area.

In accordance with the requirements of the Bijie City Natural Resources and Planning Bureau for promoting the rectification of market-oriented mine ecological restoration projects, the coal mine initiated an ecological restoration project in 2022. A restoration strategy was adopted that combined ecological reconstruction with auxiliary regeneration. The project comprehensively restored 77.37 ha of damaged land. The restoration measures involved reshaping the terrain and landforms, constructing infrastructure, ecological restoration, and environmental protection projects. In terms of vegetation restoration, 20,550 trees were planted, and 2,413 kg of grass seeds were sown. In the cultivated areas, green manure (corn and rape) was planted, while in the forest areas, tree species were planted, including willow, privet, lindens, and osmanthus.

There was a significant change in the land use structure before and after the restoration (**Table 1**). Before the restoration, mining land accounted for 91.65% of the total area (70.91 ha), and the original industrial and mining land was mainly converted into dry land and forest land. The area of dry land increased by 40.47 ha, reaching 41.42 ha, becoming the dominant land use type; the area of forest land increased by 31.50 ha, reaching 34.07 ha.

**Table 1.** Changes in land use types before and after the ecological restoration project.

| Land types | Before restoration (ha) | Proportion (%) | After restoration (ha) | Proportion (%) | Variation (ha) |
|---|---|---|---|---|---|
| Mining Land | 70.91 | 91.65% | 0 | 0 | -70.91 |
| Dryland | 0.95 | 1.23% | 41.42 | 53.54% | 40.47 |
| Forest Land | 2.57 | 3.32% | 34.07 | 44.03% | 31.50 |
| Grassland | 1.11 | 1.33% | 1.88 | 2.43% | 0.77 |
| Construction Land | 1.83 | 2.47% | 0 | 0 | -1.83 |
| Total | 77.37 | - | - | - | - |

## 3. Accounting indicators and methods

### *3.1. Accounting indicator system*

The GEP accounting framework quantifies the status of the ecosystem from a value perspective. The *Technical Guidelines for Land Ecosystem Product GEP Accounting* (hereinafter referred to as the "guidelines") provide a scientific basis for conducting GEP accounting across various regions (Liu *et al.* 2022). According to the guidelines, the GEP accounting indicator system comprises three major service categories: provisioning services, regulating services, and cultural services. In this study, based on data availability and the applicability of assessment methods, as well as the ecological restoration status of the study area, eight indicators were selected for accounting: agricultural products, water source conservation, soil retention, air purification, carbon fixation, oxygen provision, climate regulation, and landscape value (**Table 2**). Different assessment methods were adopted for the different service categories: the value of provisioning services was mainly calculated using the market value method; the value of regulating services was mainly calculated using the substitution cost method; and because no standardized statistics were available for tourist attractions in this study area, the equivalent factor method was applied to directly calculate the value of forest cultural services. Notably, the functional quantity of cultural services was not quantified in physical terms. The specific accounting methods are summarized in **Table 2**.

**Table 2.** Physical and value measurement indicators system for the GEP of the restoration area.

| Service category | Accounting project | Physical quantity indicators | Value indicators (in ten thousand yuan) |
|---|---|---|---|
| Provisioning services | Agricultural products | Area (ha) | Value of agricultural products |
| Regulating services | Water conservation | Water conservation capacity ($m^3$/a) | Value of water conservation |
| | Soil conservation | Soil retention capacity (t/a) | Value of reducing sediment accumulation |
| | | | Value of reducing non-point source pollution |
| | Air purification | Reduce the amount of sulfur dioxide (t/a) | Value of sulfur dioxide purification |
| | | Reduce the amount of nitrogen oxide (t/a) | Value of nitrogen oxide purification |
| | | Absorbed dust volume (t/a) | Value of dust absorption |
| | Carbon fixation | Fixed carbon dioxide quantity (t/a) | Value of fixed carbon dioxide |
| | Oxygen supply | Oxygen supply quantity (t/a) | Value of providing oxygen |
| | Climate regulation | Oxygen provides value (kW·h/a) | Value of vegetation transpiration regulation |
| Cultural services | Landscape value | - | Value of cultural service products |

### *3.2. Accounting formula and data sources*

This study used multi-source data to support the calculation of ecosystem product value. Land use type data were obtained from the project's ecological restoration technical plan; precipitation and daily temperature data were provided by the local meteorological department; surface runoff volume was calculated based on the recommended surface runoff coefficient in the "Ecosystem Product Value Accounting Specifications (Trial)" (National Development and Reform Commission, National Bureau of Statistics, 2022) in combination with the measured rainfall. Parameters related to air purification were determined according to the same specification, while carbon sequestration and oxygen release parameters were obtained from the *Technical Guidelines for the Calculation of Land Ecosystem Product Value* (National Development and Reform Commission, National Bureau of Statistics, 2022). Other key parameters were determined through on-site investigations, soil sample analysis, and relevant literature references. For the accounting method, the price approach proposed by Ouyang *et al.* (2013) was adopted, in which the functional quantities of various ecological products and services are converted into monetary values. The final GEP of the project area was obtained by summing up the values of the products from provisioning services, regulatory services, and cultural services. The specific formulas and data sources used in the calculation before and after restoration are detailed in **Table 3**.

**Table 3.** Accounting formulas and parameter sources used for determining the GEP.

| Value category | Accounting project | Accounting method | Accounting formula | Parameter explanation | Data source |
|---|---|---|---|---|---|
| Value of provisioning services | Value of agricultural products | Market Value Method | $V_m = \sum_{i=1}^{n} E_i \times P_i$ | $V_m$ represents the value of ecosystem c (in yuan per year); $E_i$ is the output of the i-th type of ecosystem product (determined according to the measurement unit of the product, kg per year); $P_i$ is the price of the i-th type of ecosystem product. | The data on major crops, yield per unit area, unit price, cost per unit price, etc. were sourced from the local agricultural department. |
| Value of regulating services | Value of water conservation | Water balance method | $Q_{wr} = \sum_{i=1}^{n} A_i \times (P_i - R_i - ET_i) \times 10^{-3}$<br>$V_{wr} = Q_{wr} \times C_{we}$ | $Q_{wr}$ represents the water conservation volume (m³/a); $P_i$ represents the rainfall amou–nt (mm/a); $R_i$ represents the surface runoff volume (mm/a); $ET_i$ represents the evapotranspiration volume (mm/a); $A_i$ represents the area of type i ecosystem (m²); i represents the type of ecosystem, and n represents the total number of ecosystem types; $V_{wr}$ represents the water conservation value (yuan/a)； $C_{we}$ represents the market price of water resources transactions. | The rainfall data were obtained from the monitoring of meteorological stations; the required evapotranspiration data was obtained from the literature (Tan *et al.* 2023); the $A_i$ data was obtained from the project acceptance documents. |
| | Value of soil conservation | Revised Universal Soil Loss Equation | $Q_{sr} = R \times K \times LS \times (1 - C \times P)$<br>$V_{sr} = V_{sd} + V_{dpd}$<br>$V_{sd} = \lambda \times (Q_{sr} / \rho) \times c$<br>$V_{dpa} = \Sigma_{i=1}^{n} Q_{sr} \times C_i \times P_i \times a$ | $Q_{sr}$ represents the soil retention amount (tons per year); R is the rainfall erosion force factor; K is the soil erodibility factor, usually expressed as the soil loss caused by unit rainfall erosion force on a standard plot; LS is the slope length and slope gradient factor (dimensionless), C is the vegetation cover and management factor (dimensionless), P is the soil and water conservation measure factor (dimensionless). $V_{sr}$ represents the ecosystem soil retention value (yuan per year); $V_{sd}$ represents the value of reducing sediment accumulation (yuan per year); $V_{dpd}$ represents the value of reducing non-point source pollution (yuan per year); $Q_{sr}$ represents the soil retention amount (tons per year); c is the unit cost of reservoir dredging project (yuan per cubic meter); ρ is the soil density (tons per cubic meter); λ is the sediment accumulation coefficient; i | R represents the rainfall erosion force factor. The value was taken as the average annual rainfall erosion force in the Yangtze River Basin within Guizhou Province, and was 5823.42 MJ·mm/(hm²·h) (Zhu *et al.*, 2021). Before restoration, the values of K were based on literature values for loess soil in Guizhou (Gao *et al.*, 2022), and after restoration, they were 0.0336, 0.0544, and 0.0378 for forest land, cultivated land, and grassland, respectively (Tang *et al.*, 2016). The slope length and slope gradient factor were taken as an average value of 11.23 in the purple soil hilly areas of the southwest region (Yang *et al.*, 2013). C was combined with land use types. For dry land, it was 0.130, for forest land, it was 0.001 (Cai *et al.*, 2000), and for grassland, it was 0.040 (Ye *et al.*, 2021). The water and soil conservation measures factor adopted the assignment method. According to previous studies, the P factor was assigned for different land use types. For dry land, grassland, and forest land, the assignments were 0.4, 1, and 1, respectively (He *et al.*, |

| | | | |
|---|---|---|---|
| | | represents the quantity of nitrogen, phosphorus, etc. nutrients in the soil, i = 1, 2,..., n; $C_i$ represents the content of nitrogen, phosphorus, etc. nutrients in the soil; α is the coefficient for converting to fertilizer amount; $P_i$ is the fertilizer price. | 2023). The cost of the reservoir dredging project was 18.24 yuan/m³, referring to the official website of the Ministry of Water Resources of China. The pure content (%) of nitrogen and phosphorus and other nutrient elements in the soil was obtained from laboratory measurement, with values of 1.53 and 0.72 g/kg, respectively. The α values for nitrogen and phosphorus were 2.17 and 5.56, respectively, and the Pi values were obtained from market research with values of 1500 and 900 yuan, respectively. |
| Value of air purification | $Q_{ap} = \sum_{i=1}^{n} Q_i$ <br> $V_{ap} = \sum_{i=1}^{n} \left(Q_{api} \times C_i\right)$ | $Q_{ap}$ represents the actual amount of air purification; $Q_i$ is the emission volume of the i-th type of air pollutant; $Q_{api}$ is the purification volume of the i-th type of air pollutant (tons per year), where i represents the type of air pollutant; $C_i$ is the treatment cost of the i-th type of air pollutant (yuan per ton). | According to the "Norms for the Calculation of Ecological Product Value (Trial)", the amounts of sulfur dioxide, nitrogen oxides and dust absorbed by forests each year were 0.036, 0.0226, and 0.1076 tons per hectare per year; for dry land, the values were are 0.025, 0.0157, and 0.0841 tons per hectare per year; for grassland, the values are 0.0294, 0.0157 and 0.0847 tons per hectare per year, respectively. According to the pollution discharge charging standards issued by the National Development and Reform Commission, the charge for sulfur dioxide discharge is 1.2 yuan per kg, for nitrogen oxides it is 0.63 yuan per kg, and for dust it is 0.15 yuan per kg. |
| Value of fixed carbon dioxide | $Q_{tco_2} = M_{co_2}/M_c \times (FCS+GSCS+CSCS)$ <br> $FCS=FCSR \times SF \times (1+\beta)$ <br> $GSCS=GSR \times SG$ <br> $CSCS=CSR \times SC$ <br> $V_q = Q_{co_2} \times C_c$ | $Q_{tco_2}$ represents the total carbon sequestration volume (tons per year); FCS is the forest carbon sequestration volume (tons per year), GSCS is the grassland carbon sequestration volume (tons per year), CSCS is the farmland carbon sequestration volume (tons per year), $M_{co_2}/M_c$ represents the coefficient for converting C to $CO_2$. FCSR is the forest carbon sequestration rate (tons per year per hectare per square meter), SF is the forest area (ha), β is the forest soil carbon sequestration coefficient, GSR is the grassland soil carbon sequestration rate, SG is the grassland area (ha), CSR is the farmland soil carbon sequestration rate (tons per year per hectare per square meter), and SC is the farmland area (ha). $V_q$ is the carbon | According to the "Guidelines", in 2015, the carbon sequestration efficiency of forest vegetation and forest soil in Guizhou Province was 1.17 and 0.76 tC/(hm²·a), respectively, while the carbon sequestration efficiency of grassland was 0.02 tC/(hm²·a). From Tian *et al.* (2014), the carbon sequestration efficiency of dry land was 0.047 t/(hm²·a). |

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|---|---|---|---|---|
| | | | sequestration value (yuan per year), and $C_c$ is the carbon price (yuan per ton). | |
| | Value of oxygen release | $Q_{op} = M_{o_2} / M_{co_2} \times Q_{co_2}$ <br> $V_{op} = Q_{op} \times C_o$ | $Q_{op}$ represents the oxygen release rate (tons per year); $M_{o_2}/M_{co_2}$ is the coefficient for converting $CO_2$ into $O_2$, and $Q_{co_2}$ represents the carbon sequestration amount (tons per year). $V_{op}$ is the ecosystem oxygen release value (yuan per year); $Q_{op}$ is the ecosystem oxygen release volume (tons of oxygen per year), and $C_o$ is the industrial oxygen production price (yuan per ton). | From Cao *et al.* (2023), the manufacturing cost of oxygen in Guizhou Province was set at 1000 yuan per ton. |
| | Value of climate regulation | $Q_c = Q_p$ <br> $Q_p = \sum_{i}^{2} GPP \times S_i \times d/(3\,600 \times R)$ <br> $V = Q \times p$ | $Q_c$ represents the climate regulation function quantity (kW·h); $Q_p$ represents the total vegetation regulation function quantity (kW·h); GPP is the climate regulation function quantity per unit area of the ecosystem (kJ/hm$^2$); $S_i$ is the area of the i-th ecosystem type (hm$^2$); R is the air conditioning energy efficiency ratio; d is the number of days the air conditioning is open (d); V is the climate regulation value (yuan/a); p is the electricity price (yuan/[kW·h]) | From the literature, the amount of heat absorbed by the green space per unit area (1 hm$^2$) is 81100 kJ (Ouyang *et al.* 2013). The number of days when air conditioning is used was estimated based on the daily temperature data from 2009 to 2018 in Bijie City. The value of R was 3.0; in accordance with the *Implementation Opinions of the Development and Reform Commission of Guizhou Province on Innovating and Improving the Price Mechanism for Promoting Green Development*, the electricity price was taken as the first tariff level of the China Southern Power Grid, which was 0.45 yuan per kW·h. |
| Value of cultural service | | $V_i = \sum A_i \cdot S_i \cdot R \cdot P_a \cdot P_b$ | $A_i$ represents the unit area value equivalent factor of the aesthetic landscape function service provided by the i-th ecosystem in the | From Jiang *et al.* (2017), $A_i$ = 0.06 (for dry land), 0.82 (for forest land), and 0.56 (for grassland). |

study area; Si is the area ($hm^2$) of the i-th ecosystem in the study area in the current year; R is the ecological service value equivalent coefficient, which refers to the economic value of one ecological service equivalent factor provided by the natural ecosystem with no human intervention, and is taken as 1/7; $P_a$ is the market average price of grain in Jinsha County; $P_b$ is the average grain yield per hectare in Jinsha County ($kg/hm^2$), and the data is obtained from the local agricultural bureau.

**Table 4.** Comparison of the GEP calculation results before and after ecological restoration.

| Accounting project | Category | | Before restoration | | | After restoration | | |
|---|---|---|---|---|---|---|---|---|
| | | | Physical quantity | Value of Quantity/Ten thousand yuan | Total/Ten thousand yuan | Physical quantity | Value of Quantity/Ten thousand yuan | Total/Ten thousand yuan |
| Ecological provisioning services | Value of agricultural products | | 0.95/ ha | 0.71 | 0.71 | 41.42 ha | 42.47 | 42.47 |
| Ecological regulating services | Water conservation capacity | | 17414/($m^3$/a) | 4.18 | 4.18 | 191,860 /$m^3$/a) | 46.05 | 46.05 |
| | Soil conservation value | Reduction of sediment accumulation | 11529 /(t/a) | 3.36 | 50.56 | 218,953 /(t/a) | 23.90 | 920.34 |
| | | Reduction of nitrogen non-point source pollution | 287.73 /($m^3$/a) | 43.16 | | 5,465 /($m^3$/a) | 819.75 | |
| | | Reduction of phosphorus non-point source pollution | 40.95 /($m^3$/a) | 4.04 | | 681 /($m^3$/a) | 76.69 | |
| | Air purification | Purification of sulfur dioxide | 1.50 /(t/a) | 0.18 | 0.29 | 23.86 /(t/a) | 2.86 | 4.93 |
| | | Purification of nitrogen oxides | 0.90 /(t/a) | 0.06 | | 14.90 /(t/a) | 0.94 | |
| | | Purification of particulate matter | 3.29 /(t/a) | 0.05 | | 75.37 /(t/a) | 1.13 | |
| | Carbon sequestration value | | 19.62 /(t/a) | 0.76 | 0.76 | 264.80 /(t/a) | 10.22 | 10.22 |
| | Oxygen release value | | 14.27 /(t/a) | 1.43 | 1.43 | 192.60 /(t/a) | 19.26 | 19.26 |

| | | | | | | |
|---|---|---|---|---|---|---|
| | Climate regulation value | 218565/(Kw·h) | 9.84 | 9.84 | 3,660,246 (Kw·h) | 164.71 | 164.71 |
| Ecological cultural services | Aesthetic landscape | | | 0.43 | - | 4.92 | 4.92 |
| | Total | | 68.20 | | - | | 1212.90 |

**Table 5.** The composition of GEP value for different land use types before and after ecological restoration for each accounting project.

| **Accounting project** | **Category** | **Land types** | **Before restoration** | | **After restoration** | |
|---|---|---|---|---|---|---|
| | | | **Value of Quantity/Ten thousand yuan** | **Proportional contribution/%** | **Value of Quantity/Ten thousand yuan** | **Proportional contribution/%** |
| Ecological provisioning services | Agricultural products | Forest Land | 0 | - | 0 | 0.00 |
| | | Dryland | 0.71 | 1.04 | 42.47 | 3.50 |
| | | Grassland | 0 | - | 0 | 0.00 |
| Ecological regulating services | Water conservation capacity | Forest Land | 2.56 | 3.75 | 34.03 | 2.81 |
| | | Dryland | 1.39 | 2.04 | 9.64 | 0.79 |
| | | Grassland | 0.23 | 0.34 | 2.38 | 0.20 |
| | Soil conservation | Forest Land | 24.97 | 36.61 | 328.89 | 27.12 |
| | | Dryland | 14.05 | 20.60 | 571.57 | 47.12 |
| | | Grassland | 11.54 | 16.92 | 19.88 | 1.64 |
| | Air purification | Forest Land | 0.19 | 0.28 | 2.50 | 0.21 |
| | | Dryland | 0.04 | 0.06 | 2.32 | 0.19 |
| | | Grassland | 0.06 | 0.09 | 0.11 | 0.01 |
| | Carbon sequestration | Forest Land | 0.75 | 1.10 | 9.94 | 0.82 |
| | | Dryland | 0.006 | 0.01 | 0.28 | 0.02 |
| | | Grassland | 0.003 | 0.00 | 0.006 | 0.00 |
| | Oxygen release | Forest Land | 1.41 | 2.07 | 18.73 | 1.54 |
| | | Dryland | 0.01 | 0.01 | 0.52 | 0.04 |
| | | Grassland | 0.005 | 0.01 | 0.01 | 0.00 |
| | Climate regulation | Forest Land | 5.47 | 8.02 | 72.41 | 5.97 |
| | | Dryland | 2.11 | 3.09 | 87.80 | 7.24 |
| | | Grassland | 2.26 | 3.31 | 4.50 | 0.37 |
| Ecological cultural services | Aesthetic landscape | Forest Land | 0.32 | 0.47 | 4.35 | 0.36 |
| | | Dryland | 0.01 | 0.01 | 0.41 | 0.03 |
| | | Grassland | 0.10 | 0.15 | 0.16 | 0.01 |

## 4. Results and analysis

### *4.1. Changes in the value of different ecosystem service types before and after mine ecological restoration*

The preliminary accounting results of this project are presented in **Table 4** and clearly demonstrate the remarkable achievements of mine ecological restoration in enhancing the GEP. Overall, ecological restoration has driven a substantial growth in the GEP of the mining area. The total annual value after restoration reached 1212.90 (in units of ten thousand yuan), a net increase of 1144.70 ten thousand yuan compared to the 68.20 ten thousand yuan before restoration. Ecological regulating services constituted the largest portion of the overall value. Within the regulating services, the increase in soil conservation value after restoration was the most significant, rising from 50.56 to 920.34 ten thousand yuan. This finding aligned with Liu *et al.* (2020), who reported that soil conservation services contributed most significantly to GEP improvements after the ecological restoration of an abandoned mining area in Xingguo County, Jiangxi Province. The other key regulating services also showed varying degrees of improvement after restoration. The value of water conservation services increased from 4.18 to 46.05 ten thousand yuan, reflecting the positive regulatory effect of vegetation restoration on the regional water cycle. The significant growth in the values of climate regulation (from 9.84 to 164.71 ten thousand yuan) and oxygen release (from 1.43 to 19.26 ten thousand yuan) confirmed the contribution of the ecosystem to the regional environment and the carbon-oxygen balance through processes such as photosynthesis by vegetation. In terms of provisioning services, the value of agricultural products increased from 0.71 to 42.47 ten thousand yuan after restoration, which reflected the direct economic output of land reclamation and soil improvement. At the same time, the aesthetic landscape value as an ecological cultural service also increased from 0.43 to 4.92 ten thousand yuan, indicating that the landscape aesthetic function of the region began to emerge, creating conditions for potential ecological tourism development.

### *4.2. The composition of the GEP value for each land use type before and after ecological restoration*

The composition of the GEP values for each land use type before and after ecological restoration in the study area is shown in **Table 5**. Before restoration, the GEP value was highly concentrated within a few services, with a relatively simple structure. The soil conservation value was dominant, among which forest (36.61%), dry land (20.60%), and grassland (16.92%) together accounted for 74.13%, forming the cornerstone of the regional ecological service value. The proportion of all other service categories was less than 10%, indicating an imbalance in ecosystem functions.

Following restoration, this trend of centralization not only persisted but was further intensified and improved through a significant increase in total GEP value. The core position of the soil conservation service became even more prominent, with its proportional contribution to the total GEP value rising from 74.13% to 75.88%. A particularly notable change occurred within its internal structure: the proportion of the soil conservation service value attributed to dry land increased substantially from 20.60% to 47.12%, becoming the single largest component in the entire GEP system. This was likely due to the remarkable achievements of restoration projects such as slope farmland improvement and terraced field construction. Although the proportional contribution of the soil conservation service value in forests decreased from 36.61% to 27.12%, its absolute value increased significantly. Furthermore, the relative importance of some other services increased after restoration. The total proportion of provisioning services increased from about 1.04% before restoration to 3.50%, all due to service contributions from dry land, demonstrating the restoration project's role in promoting the coordinated development of ecology and production. The proportional contribution of climate regulation to the GEP value rose from 14.42% to 13.58% (remaining stable but with a large increase in absolute value), with the proportional contribution from services on dry land rising from 3.09% to 7.24%. This made it the third largest ecosystem service after soil conservation, highlighting the positive impact of vegetation restoration on the regional microclimate. Furthermore, although the absolute value of services such as water conservation, carbon sequestration, and oxygen release increased, their proportional contribution to the total GEP value decreased. This does not mean that their functions weakened, but rather that the growth rate of services such as soil retention became even greater, resulting in a reduction in their relative importance.

The ecological restoration project significantly increased the total value of GEP and reshaped the value structure in terms of individual services proportional contributions by altering the growth rates of different service types. The restored ecosystem formed a more efficient and stable value system with soil conservation as the absolute core, and climate regulation and provisioning services as important supplements. This marks a successful transformation of the regional ecosystem service functions from basic maintenance to enhanced efficiency.

### *4.3. Changes in the total GEP before and after ecological restoration of land use types*

The comparison of the total GEP values before and after ecological restoration for different land use types in the study area is shown in **Table 6**. In terms of land use structure, dry land replaced forest land as the primary contributor to GEP. Its GEP increased from 18.33 ten thousand yuan (accounting for 26.88% of the total) to 715.01 ten thousand yuan (accounting for 58.95%), significantly enhancing its dominant position. Although the value of forest land increased from 35.67 (accounting for 52.3%) to 470.85 ten thousand yuan, its proportional contribution decreased to 38.82%. Compared to dry land and forest land, the value of grassland increased slightly, but its proportional contribution significantly decreased from 20.82% to 2.23%, indicating that its contribution to the overall ecological value was relatively marginalized under this restoration model. Mining and construction land did not contribute to GEP both before and after restoration.

**Table 6.** Comparison of the total GEP values before and after ecological restoration for different land types.

| Land use types | GEP/Ten thousand yuan | Proportional contribution/ % | Rank | GEP/ Ten thousand yuan | Proportional contribution/ % | Rank |
|---|---|---|---|---|---|---|
| Mining Land | 0 | 0 | / | 0 | / | / |
| Forest Land | 35.67 | 52.3 | 1 | 470.85 | 38.82 | 2 |
| Dryland | 18.33 | 26.88 | 2 | 715.01 | 58.95 | 1 |
| Grassland | 14.19 | 20.82 | 3 | 26.97 | 2.23 | 3 |
| Construction Land | 0 | 0 | / | 0 | 0 | / |
| Total | 68.20 | / | / | 1212.90 | / | / |

## 5. Discussion

The calculation of GEP provides a powerful scientific tool for the quantitative assessment of ecological restoration effectiveness (Han *et al*. 2023). It converts abstract ecological benefits into tangible economic values, effectively promoting the practical transformation of the concept of "clear waters and green mountains are as good as mountains of gold and silver". This study conducted an empirical analysis in the ecological restoration area of a typical mining area, not only confirming the significant potential of ecological restoration to increase the total value of the ecosystem, but also clarifying the value transformation pathway that drives the appreciation of ecological capital from two aspects: service structure and land use type.

### *5.1. Identification of the mechanism driving the growth of GEP through ecological restoration*

The results showed that ecological regulating services, especially soil conservation, were the decisive contributors to the growth of GEP. The value of soil conservation services increased from 50.56 ten thousand yuan before restoration to 920.34 ten thousand yuan, accounting for over 70% of the total increase in GEP after restoration. This was a result of the combined effect of the specific ecological background of the study area and human intervention. Mining activities, especially open-pit mining and tailings accumulation, cause severe damage to regional ecosystems through the complete stripping of surface vegetation, the severe compaction of soil and destruction of its structure, and the alteration of topography and landforms. This can lead to extremely serious soil erosion and subsequent non-point source pollution (Wang *et al.* 2025), making soil retention capacity a key factor limiting regional ecological security (Zhang *et al.* 2025). The ecological restoration project in this mining area significantly enhanced the soil retention capacity of the ecosystem by restoring the surface vegetation cover and strengthening the soil's erosion resistance. The soil retention volume increased from 11,529 to 218,953 tons per year. Ecological restoration measures, such as reconstructing the vegetation root network (Hao *et al.* 2020) and improving the physical structure of the soil (Zhang *et al.* 2025), have resulted in the formation of a multi-level water and soil conservation system. This system also indirectly reduces the driving force of soil erosion through the interception of precipitation by vegetation and the reduction of surface runoff speed (Jin *et al.* 2021). At the same time, the enhancement of soil retention capacity further promotes the accumulation of soil organic matter and the cycling of nutrients, providing a favorable substrate for the continuous growth of vegetation. This is the main reason why ecological regulating services held a dominant position in the growth of GEP. The benefits of ecological restoration are neither uniform nor universal, but rather prioritize and significantly compensate for those ecological functions that have been most severely damaged and have the most significant constraints, thereby achieving maximum marginal benefits. In contrast, the significant improvement in the values of climate regulation and water conservation services was the result of a synergistic effect that emerged after the restoration of vegetation cover.

In addition to the core driving force of soil conservation, other ecological regulating services also exhibited significant synergistic growth. The value of water conservation increased more than ten times, reflecting the positive regulation of vegetation restoration and soil structure improvement on the regional water cycle. The significant increase in the value of climate regulation was mainly attributed to the recovery of vegetation biomass, which effectively reduces the surface temperature through transpiration and increases air humidity, thereby exerting a significant regulatory effect on the local microclimate of the mining area (Zhang *et al.* 2021). The growth in the value of carbon sequestration and oxygen release is a direct manifestation of the photosynthesis and biomass accumulation of vegetation, marking the successful transformation of the ecosystem from a carbon source to a carbon sink (Zhang *et al.* 2023).

### *5.2. Land use pattern transformation and value conversion of the dominant functional land use types*

Before the restoration, the ecological value of the study area was mainly supported by forests and drylands, and the functional structure was relatively simple, with soil conservation being the dominant ecosystem service. After the restoration, the proportion of GEP supplied from dryland increased from 26.88% to 58.95%. The restored dryland not only provided direct provisioning services through agricultural production (with the value increasing from 0.71 to 42.47 ten thousand yuan), but more importantly, it transformed into an efficient ecological regulation system. The value of soil conservation services contributed more half of the GEP of the entire area. This proves that through land leveling, contour planting, ecological ditches, and other methods, productive land can be simultaneously transformed into a powerful ecological infrastructure. Forest ecosystems have significant roles in soil retention, climate regulation, water resource conservation, oxygen release, and carbon fixation. This indicates that forest ecosystems are stable and resilient, and have a crucial role in maintaining regional ecological balance and biodiversity. They complement each other spatially and collaborate functionally, jointly forming a protective barrier for regional ecological security. In contrast, the value contribution of grasslands remains relatively marginal, suggesting that future restoration planning should reconsider their spatial layout and functional optimization. For example, integrating grasslands with forests and drylands through ecological corridor-style designs would enhance the connectivity and stability of the overall landscape.

### *5.3. Accounting application value and future development path*

This study demonstrates the critical role of Gross Ecosystem Product (GEP) accounting in ecological restoration. GEP precisely identifies restoration needs and quantifies the value of ecosystem services, moving beyond mere forest cover metrics to support targeted, functional restoration. Our results show a dramatic GEP increase post-restoration, largely driven by high-value agricultural land, proving sustainable land use is viable even in resource-scarce regions. Crucially, this value growth extends beyond ecological gains; it is fueled by socio-economic drivers like green finance. Research shows venture capital networks stimulate green innovation through knowledge sharing and market incentives (Lei and Xu, 2025). Thus, quantified ecological value (GEP) and market forces are synergistic. Integrating GEP into policies for eco-compensation and green credit can channel capital into restoration, creating a self-reinforcing cycle in mining areas.

There were several limitations to this study. First, the GEP accounting system is still in the development stage. Some important service values (such as the intrinsic value of biodiversity conservation and specific cultural service values) have not been fully incorporated into the accounting process due to limitations in the quantification methods and data availability, which may lead to a certain degree of underestimation in the value assessment. Second, this study mainly presents a static comparison before and after restoration, without identifying the dynamic evolution process of GEP over time. Future studies should conduct a time series analysis to track the accumulation and stability of ecological benefits. In the future, research should further investigate the efficiency of different restoration technologies (such as vegetation species configuration and the application of soil amendments) in enhancing the value of specific ecosystem services. It is also necessary to promote a deeper integration of GEP accounting results with market-oriented policy tools, such as ecological compensation and green finance, to stimulate the intrinsic motivation for ecological protection.

## 6. Conclusion

This study conducted a systematic calculation of the ecosystem gross product value for typical mine ecological restoration areas, quantitatively revealing the significant ecological and economic benefits generated by the ecological restoration projects. The research results showed that the total GEP of the restored area increased from 68.20 to 1212.90 ten thousand yuan. Moreover, this study found that the growth of GEP exhibited distinct structural characteristics. Ecological regulating services are the main driver of value growth, with the soil retention value serving as the core driving force. At the same time, ecological restoration has reshaped the spatial pattern of regional ecological value. The proportional contribution of services from dry land to overall GEP increased from 26.88% before restoration to 58.95%, surpassing forests to become the land use making the primary contribution to the overall value. This indicates that through scientific land reclamation and ecological management, a synergistic enhancement of economic output and ecological regulation functions can be achieved on productive farmland. Forests continue to play a diversified and stable regulatory role, complementing dry land to form an ecological security pattern with complementary functions.

This study advocates establishing GEP accounting as the core tool for ecological restoration projects. Future work must refine this system to capture more implicit values and enable long-term monitoring. Critically, the market translation of ecological value depends on specialized human capital. Research confirms that incentive policies (e.g., smart manufacturing pilots) can build a human capital foundation for green innovation through training and specialization, thereby improving environmental performance (Lei and Zhang, 2026). Therefore, a key pathway for deeply integrating GEP with policy tools like eco-compensation is to embed mechanisms for cultivating and assessing relevant professional capabilities within the policy design itself. Only through the “twin-engine drive” of accounting science and human capital development can quantified ecological value be robustly transformed into market signals that advance green development.

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