Ecological compensation in the Chinese coal resource-depleted cities based on the ecosystem service value

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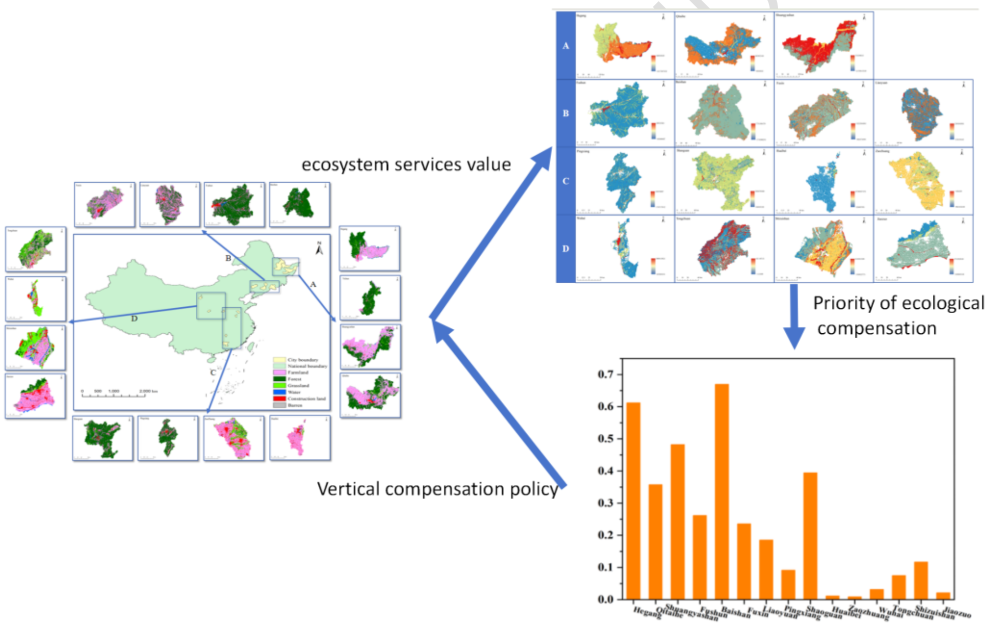
Graphical Abstract



Abstract

Ecological compensation of the Chinese coal resource-depleted cities (CRDC) aims to improve its ecological and environmental management capabilities after coal mining damage. Based on data on land-use changes in the CRDC from 2000 to 2020 (2000, 2010, 2020), this study used the equivalent factor method to assess the value of ecosystem services in the basin. Our research objectives include 15 prefecture level cities with coal resource-bases cities in China. The priority and amount of ecological compensation were determined for the CRDC. Results show that (1) the CRDC experienced various changes in land during 2000 to 2020, mainly leading to the conversion of arable land to forest land and a significant increase in construction land. (2) The total value of ecosystem services in the CRDC decreased from 236.04 billion yuan in 2000 to 230.57 billion yuan in 2020. Forest had the highest total ecosystem service value in 2020, accounting for 75.21%. (3) There are four ESV trends in the 15 cities of CRDC from 2000 to 2010 to 2020, which are caused by various factors such as coal mining and government policies. (4) The ecosystem service value and the economic development level of the cities in the CRDC are positively and negatively correlated with the priority of ecological compensation, respectively. Among them, the priority and amount of ecological compensation in the Northeast region are the highest, including Shuangyashan, Baishan and Hegang, with compensation priority exceeding 0.35 and ecological compensation amount exceeding 1 billion yuan. The findings of this study fill the gap in ecological compensation for CRDC and provide novel insights for improving transfer payments for CRDC.

Keywords: Chinese coal resource-depleted cities; Land use; Ecosystem service value; Compensation priority; Compensation amount;

1. Introduction

Metals, non-metals, and fossil fuels are indispensable to the global economic system (Dou et al., 2023). Since the Industrial Revolution, the global economy has demonstrated a long-term stability in its demand for natural resources (Henckens et al., 2019). The fate of these cities is inextricably linked to their natural resource wealth. In accordance with the laws governing the natural resource industry and resource-based city development, resource-based cities are destined to experience a cycle of construction, prosperity, decline, transformation, or extinction (Hou et al., 2020). For cities based on natural resources for development, the economic recession and ecological damage that come with the depletion of natural resources is an inevitable challenge. This situation is particularly evident in China.

In 2008, 2009 and 2011, China identified 69 typical resource-based cities (counties, districts) in three batches. These include 37 coal cities, 14 non-ferrous metal cities, 6 ferrous metallurgy cities, 3 oil cities and 9 other cities, with a total population of 154 million. These cities have developed in reliance on a single traditional industry and are now facing a situation of resource depletion and industrial decline because of long-term excessive development. Their future development prospects are therefore uncertain (Yu et al., 2016). For solving these problems, the Central Committee of the Communist Party of China made a transfer payment of 15 billion yuan to local resource-depleted cities in 2019. This was used to address historical legacy problems, including social security arrears caused by resource development, environmental protection, mining rights withdrawal, public infrastructure construction, and shantytown renovation in resource-depleted cities. Furthermore, the issues encountered by counties (cities, districts) where independent industrial and mining zones and coal mining subsidence zones are situated, including the relocation and redevelopment of shantytowns, the governance of subsidence zones, and the resolution of livelihood policy arrears (Ministry of Finance of the PRC, 2019), require attention. Nevertheless, there is currently a dearth of transparent and comprehensive compensation plans and associated financial provisions for ecological restoration in resource-based cities.

Ecological compensation is a system arrangement that aims to protect and sustainably utilize ecosystem services, primarily through economic means to regulate the interests of stakeholders, promote compensation activities, and mobilize the enthusiasm for ecological protection through various rules, incentives, and coordination (Yu et al., 2023). The rapid economic development and resource depletion that cause the contemporary era have a significant impact on the ecosystem, endangering the interests and well-being of local populations. In particular, the practice of surface and underground coal mining can result in a range of adverse effects on the surrounding environment, including surface subsidence, the drying up of rivers, a decline in soil fertility, and the overall degradation of the ecosystem (Kamanzi et al., 2023; Zhu et al., 2021). When mining 10,000 t of coal, it was anticipated that an area of land ranging from 0.2 to 0.33 ha would be affected by subsidence because of surface mining (Xiao et al., 2014). Coal mining seriously affects the supply of the mining ecosystem to human well-being. Therefore, it is necessary to carry out ecological compensation for cities with depleted coal resources.

Research on ecological compensation has diversified due to the use of different accounting methods, including the opportunity cost method (Ma et al., 2023; Yang et al., 2023). The willingness to pay method (Ren et al., 2024; Nie et al., 2023), ecological footprint method (Niu et al., 2024; Yu et al., 2021), and ecosystem service value assessment method (Zhou et al., 2022).

The opportunity cost method is a technique for estimating the cost of resource utilization in the absence of market prices. This is achieved by basing the estimation on the income derived from alternative uses that have been sacrificed. For instance, the protection of national parks and the prohibition of logging trees may be considered examples of such measures. Including the direct investment cost and development opportunity cost of ecological conservationists in the protection of the ecological environment. However, the lack of consideration for environmental dynamics results in a limited ecological compensation (Yang et al., 2019). The willingness to pay is evaluated by investigating the willingness of ecological conservationists to pay for ecological protection, but this method is too subjective, which can easily lead to significantly different evaluation results (Garau et al., 2021; Jiang et al., 2022). The ecological footprint method is a means of reflecting both ecological surplus and deficit. This is achieved by calculating the difference between the total supply and total demand of regional ecological footprints. This method employs the production and consumption of natural resources as the sole means of determining the cost of ecological compensation. It did not take into account the compensation capacity of each region and the willingness of both parties (Yang et al., 2019). Some researchers have also assessed regional ecological compensation through ecological risk assessment, but this method is less widely used and lacks universality (Xu et al., 2023).

Compared with the above methods, the ecosystem service value assessment method has obvious advantages. It covers comprehensive information such as land, climate, soil, socio-economic factors in the region, and can measure the level of coordination between regional economic development and ecosystems (Wang et al., 2021). It is easy to describe the differences in ecological benefits between different regions. At the same time, the evaluation results of ecosystem service value also have additivity, which is suitable for ecological compensation evaluation in large or extensive areas. Ecological compensation obtained by ecosystem service value can maximize ecological benefits, and is theoretically the best ecological compensation evaluation method (Yan et al., 2022; Zhou et al., 2022).

Ecosystem services (ES) are the benefits and well-being people obtain from ecosystems, which consist of services related to providing, regulating, supporting, and cultural aspects (Costanza et al., 1997). The value of ecosystem services is an important indicator for measuring regional economic development and ecological environment quality, and can provide a basis for sustainable development in policy formulation (Ouyang et al., 2020). This provides an important perspective for solving the ecological compensation problem in Chinese coal resource-depleted cities. Externalities in the value of ecosystem services are a theoretical foundation of ecological compensation (Liu et al., 2018).

Ecosystem service valuation methods mainly include ecosystem service functions, ecosystem service values, and market and preference-based methods. The ecosystem function method evaluates changes in ecosystem service function through various ecological models, and the market and preference-based methods include the conditional value method, travel cost method, etc. The most widely used method is the equivalent factor method for calculating ecosystem values to evaluate the value of ecosystem service (Gao et al., 2021). Since 2015, Xie et al. (2015) proposed a new approach to adjusting the total value of ecosystem services using socioeconomic coefficients. This adjustment has enhanced the reliability of estimating ecological compensation standards and has since been applied in numerous ecological compensation studies across China.

Ecological compensation research in China mainly focuses on forest and watershed areas, while research on mineral resource areas is almost blank, indicating that more attention is still needed for ecological compensation research in mineral resource areas (Wang et al., 2022). Since 2020, various Chinese coal resource-depleted cities have formulated several ecological restoration policies, including ecological restoration and management of mining areas, environmental restoration of mining areas, reclamation and comprehensive management of mining areas, and other ecological restoration policies (Table S1).These policies are helping to restore the capacity of cities with depleted coal resources to provide ecosystem services, but this also requires ecological compensation. Study on ecological compensation for coal resource-depleted cities can provide important basis for solving this problem.

In this study, we aim to use the 15 Chinese coal resource depleted prefecture level cities (CRDC) as the research object and explore ecological compensation in different areas of CRDC from the perspective of the ecosystem service value. This study has three objectives: (1) to assess the changes in land use and ecosystem service value of CRDC; (2) to determine the priorities for ecological compensation between regions in the CRDC; (3) to determine the amount of ecological compensation required for different CRDC regions. This provides an important basis for the formulation of sustainable development policies and ecological compensation strategies for CRDC.

2. Material and methods

2.1 Study area

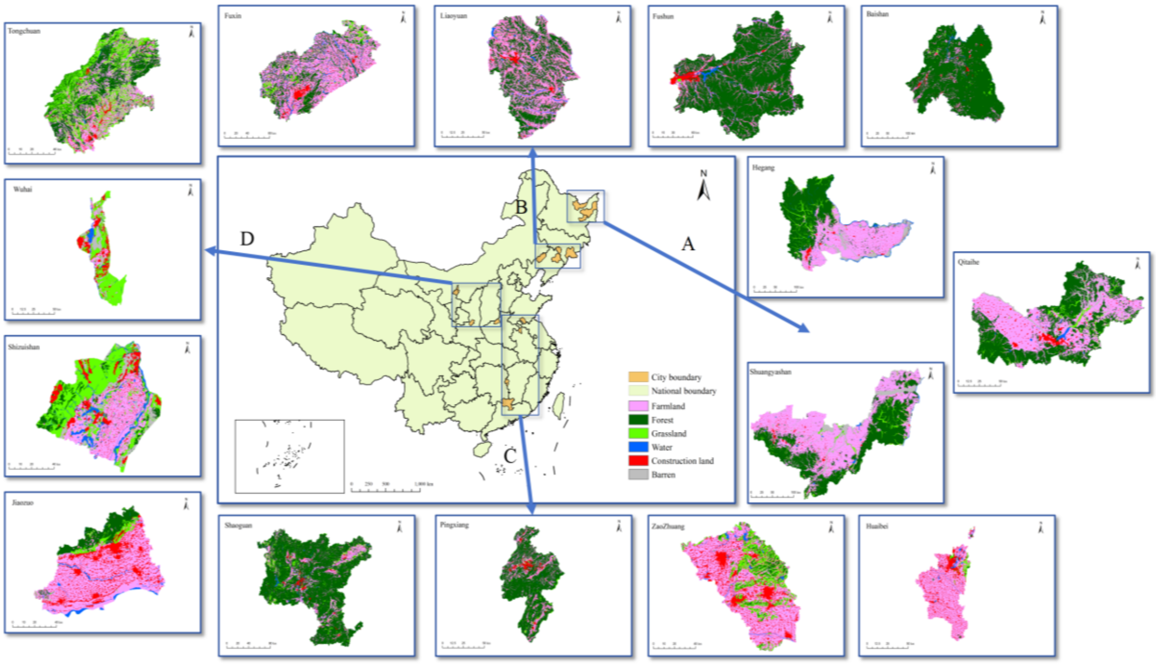


Fig 1. Location of Chinese coal resource-bases cities

This study selected 15 prefecture level coal resource depleted cities as the research objects (Fig 1), which are mainly distributed in the northern and northeastern regions of China, including region A: Hegang, Shuangyashan, Qitaihe. Region B: Fuxin, Fushun, Baishan, Liaoyuan. Region C: Shaoguan, Pingxiang, Zaozhuang, Huaibei. Region D: Jiaozuo, Shizuishan, Wuhai, Tongchuan. According to the results of seven population censuses, as of the end of 2020, the permanent population of the region was about 24 million, accounting for 17% of the total population of China. The total area of the region is, covering a wide range of land types including forest, farmland, grassland, water, and construction land. The farmland is 5121836.37 ha, forest is 8856799.29 ha, grassland is 1027505.61 ha, water area is 246032.73 ha, and construction land is 650049.75 ha.

2.2 Data sources

This study takes15 prefecture-level cities in the nine provinces (districts) through which the CRDC as the primary research unit flows and uses remote sensing, basic geographic information, and socioeconomic statistics from 2010 to 2020. Land-use and land-cover (LULC) data from the year of 2000, 2010, and 2020, the spatial resolution is set at 30 m. The date is provided by Date Center for Resource and Environment Sciences, Chinese Academy of Science (RESDC) (http: // www. Resdc.cn). It interpreted from the datasets of USGS Landsat 5 and 8 Surface Reflectance Tier 1. Including forestland (woodland, shrub forest, sparse forest), cultivated land (paddy field, dry land), grassland, water area (rivers, lakes, reservoir), construction land (urban , mining area). The combined accuracy exceeded 89%, with Kappa coefficients exceeding 0.85. Social and economic statistics were obtained from the Statistical Yearbook 2000-2020, Compilation of National Agricultural Product Cost Benefit Information 2000-2020.

2.3 ESV assessment

Costanza et al. (1997) firstly defined the scientific estimation principle and method of ESV, and estimated 17 ESV of 16 ecosystems in the world. Considering the shortcomings and reliable results of previous studies, Xie et al. (2017) used the questionnaire survey based on 200 Chinese ecologists, and made many improvements to methods employed in the study of Costanza et al. (1997). The ecosystem service function was divided into the providing service: food production, raw materials, water resource, regulating service: gas regulation, climate regulation, environmental purification, water regulation, soil retention, supporting service: nutrient cycling, biodiversity protection and cultural services: recreation and culture (Xie et al., 2015). According to the study of Xie et al. (2015), the ESV equivalent factor are equal to 1/7 of the average market value of grain production. Hence, using this foundation, this research reevaluated the economic worth of the ESV equivalent factor per unit of land area using the mean grain yield and the average market price of unprocessed grain declared by the respective governmental departments. The formula is as follows:

$$E_a = \frac{1}{7}\sum_{j=1}^{n}\frac{m_j p_j q_j}{M} \qquad (1)$$

Ea is the economic value of unit ecosystem in Yuan / (hm^2 a); *j* is food crop type; m_j is the average price of the *j* grain crops in the study area; the unit is Yuan / kg; P_j is the unit in kg/hm^2; q_j is the *j* planting area in hm^2; *M* is the total planting area of grain crops in hm^2 (Xiao et al., 2020). The results show that the economic value of the CRDC ecosystem service in the (Table S2).

The ecosystem services value is calculated as follows:

$$ESV = \sum_{i=1}^{n} A_i \times VC_i \qquad (2)$$

$$VC_i = \sum_{j=1}^{k} EC_j \times E_a \quad (3)$$

ESV is ecosystem service value, unit is Yuan / a; *i* is land use type; *j* is ecosystem service type; *Ai* is distribution area of land use type, unit is hm^2; VC_i is ecosystem service value equivalent per unit area of class i in Yuan / ($hm^2 \cdot a$); EC_j is ecosystem service value equivalent of item *j* of land use type; *k* is quantity of ecosystem service type; E_a is economic value of 1 unit ecosystem service, unit is yuan / ($hm^2 \cdot a$) (Xie et al., 2017).

2.4 Priority measurement for ecological compensation

According to Wang et al. (2010), the Ecological Compensation Priority Sequence (ECPS) effectively captures the pressing need in the area for receiving ecological compensation. Since the market already assigns monetary value to provisioning services like food and raw material production, the calculation specifically focuses on the non-market value of ecosystem services. This was calculated as follows:

$$ECPS = VAL_n / GDP_n \quad (4)$$

where *ECPS* is the priority for ecological compensation, VAL_n is the nonmarket value of the ecosystem services per unit area of the study area (yuan / hm^2), and GDP_n is the gross regional product per unit area of the study area (yuan / hm^2).

2.5 Accounting vertical ecological compensation

Vertical ecological compensation involves distributing funds from the central government to local governments. It aims to address pressing development needs in regions with lower GDP per unit area and mitigate the risk of rapid decline in ecological value. In order to effectively allocate compensation funds within limited capacity, emphasis is placed on prioritizing investments based on regional ecological compensation demand intensity and ecological value conversion coefficients, which account for variations in ecological compensation standards across different regions. The ecological value conversion coefficient was selected as 15% (Xin et al., 2019), and the specific calculation formula is as follows:

$$R_i = V_i \times k \times t_i \quad (5)$$

$$t_i = 2 \times arctan(ECPS) / \pi \quad (6)$$

where R_i is the total amount of ecological compensation in the study area (100 million yuan), *Vi* is the non-market value of the ecosystem services in the study area, k is the ecological value conversion coefficient, and t_i is the intensity coefficient of ecological compensation demand in the study area. The tangent function was used to normalize the ecological compensation priority.

3. Results

3.1 Spatial and temporal variation in land use and ecosystem service values in the Chinese coal resource-bases cities

3.1.1 Analysis of changes in the land use

Fig 2 Land use changes in the CRDC during 2000-2020 (ha)

Land use changes in the CRDC from 2000 to 2020 are shown in Fig 2. The land use in regions A and B is mainly dominated by forest and grassland, accounting for more than 80%, which are mainly concentrated in the northeast region with relatively high forest resources. Shaoguan and Pingxiang in region C are mainly forest, while Huaibei and Zaozhuang are mainly farmland, accounting for over 50% of the total. Grassland resources are abundant in region D, with grasslands in Wuhai, Shizuishan and Tongchuan accounting for over 30%.

From 2000 to 2020, there was no significant change in farmland in region A, with a decrease of 1-5% in forest and grassland, a decrease of 43% in water area, and an increase of 4% and 26% in construction land and barren land. Grassland in region B has decreased by 50%, while water and construction land have both increased by over 30%. Construction land in region C increased by 46%, water areas increased by 11%, and other land decreased by 5%. The land use change in region D is similar to region C, with an increase of over 20% in water and construction land, and approximately 3% in other land are

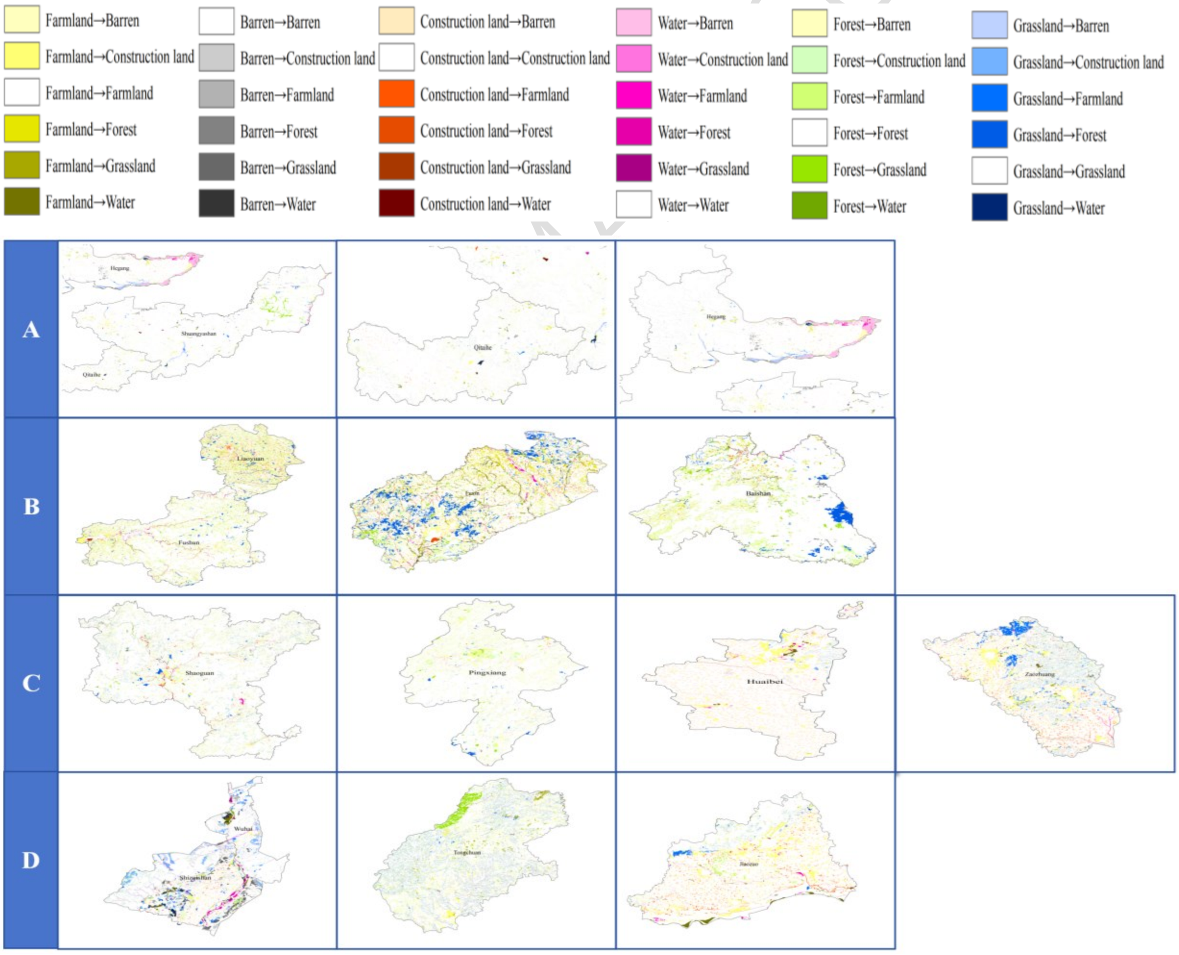


Fig 3. Spatial land use change in the CRDC during 2000-2020

The land spatial changes of the CRDC from 2000 to 2020 are shown in the Fig 3. The land use change in region A mainly occur in the changes of water area and grassland, which water area is mainly transformed into farmland and construction land. The land use change in region B is mainly characterized by grassland and farmland, with farmland mainly transformed into forest and construction land, and grassland into forest and construction land.

The land use change in region C is mainly concentrated in farmland and grassland, with farmland transformed into construction land and grassland into farmland. The land use change in region D is mainly dominated by forest land, grassland, and barren. Grassland is mainly transformed into construction land, forest is mainly transformed into farmland, and barren is mainly converted into grassland.

3.1.2 Analysis of changes in the value of ecosystem services

Using TableS2, ecosystem service value is calculated based on the value of different land types per unit hectare. We obtained the values of ecosystem services (Table 1) and the values of individual ecosystem service functions in the CRDC (Table 2) from 2000 to 2020. According to the table, the ESV of resource depleted cities in China showed a gradually decreasing trend from 2000 to 2020, decreasing from 236.03 billion yuan in 2000 to 230.5 billion yuan in 2020. Therefore, in the future, we should actively carry out ecological compensation for resource depleted cities in China. For restoring the protection and restoration of mountains, water, forests, fields, lakes, grasses, and sands areas should be promoted along with a reduction in soil erosion.

In the composition of ESV, the value of regulation services accounts for the highest proportion of 70%, followed by support services, about 20%, and product supply and cultural services account for about 0.05% (Table1). Among them, forest land provides the highest ESV, which accounting for over 70%. The proportion of ESV in water area and farmland is about 10%. The value of farmland first increases and then decreases, while the value of water is the opposite. The value of regulation services in cities with depleted coal resources in China showed a trend of first decreasing and then increasing, with a decrease of 4.1 billion yuan from 2000 to 2020. The value of other services showed a trend of first increasing and then decreasing. The value of product services, support services, cultural services decreased by 400 million yuan, 800 million yuan, and 300 million yuan, respectively.

Among various land types, the service value and proportion of forest land ecosystem are the highest, accounting for about 75%, and increasing year by year, followed by cultivated land and water area, accounting for about 12%. The value of grassland ecosystem services accounts for about 3%. The value of construction land and barren ecosystem services is relatively low, less than 1%.

The ESV composition of CRDC are similar (Fig 4), with regulating and support services accounting for over 60%, providing service and cultural service values being similar, accounting for about 10%. The regulating service has the greatest impact on the overall ESV, especially in region A and D, where the trend of ESV changes is consistent with the trend of its regulation service value.

Table 1 Value and proportion of the ecosystem services in CRDC (billion yuan).

	2000		2010		2020	
	ESV	(%)	ESV	(%)	ESV	(%)
Provisioning	13.02	0.06	13.88	0.06	12.67	0.05
Regulating	162.47	0.69	158.02	0.68	158.39	0.69
Supporting	50.43	0.21	50.68	0.22	49.61	0.22
Cultural	10.10	0.04	10.26	0.04	9.86	0.04
Total	236.03		232.85		230.56	

Table 2 Service value and the proportion of various ecosystems in CRDC (billion yuan)

Ecosystem type	2000		2010		2020		Rate of change in ESV(2000-2010)	Rate of change in ESV(2010-2020)
	ESV	(%)	ESV	(%)	ESV	(%)		
Farmland	26.48	11.22	29.03	12.47	25.94	11.25	1.26	-1.22
Forest	173.85	73.67	174.24	74.85	173.36	75.21	1.18	0.36
Grassland	6.96	2.95	5.65	2.42	5.42	2.35	-0.53	-0.07
Water	28.52	12.09	23.56	10.12	25.53	11.08	-1.97	0.96
Construction land	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Barren	0.22	0.09	0.36	0.16	0.32	0.14	0.06	-0.02

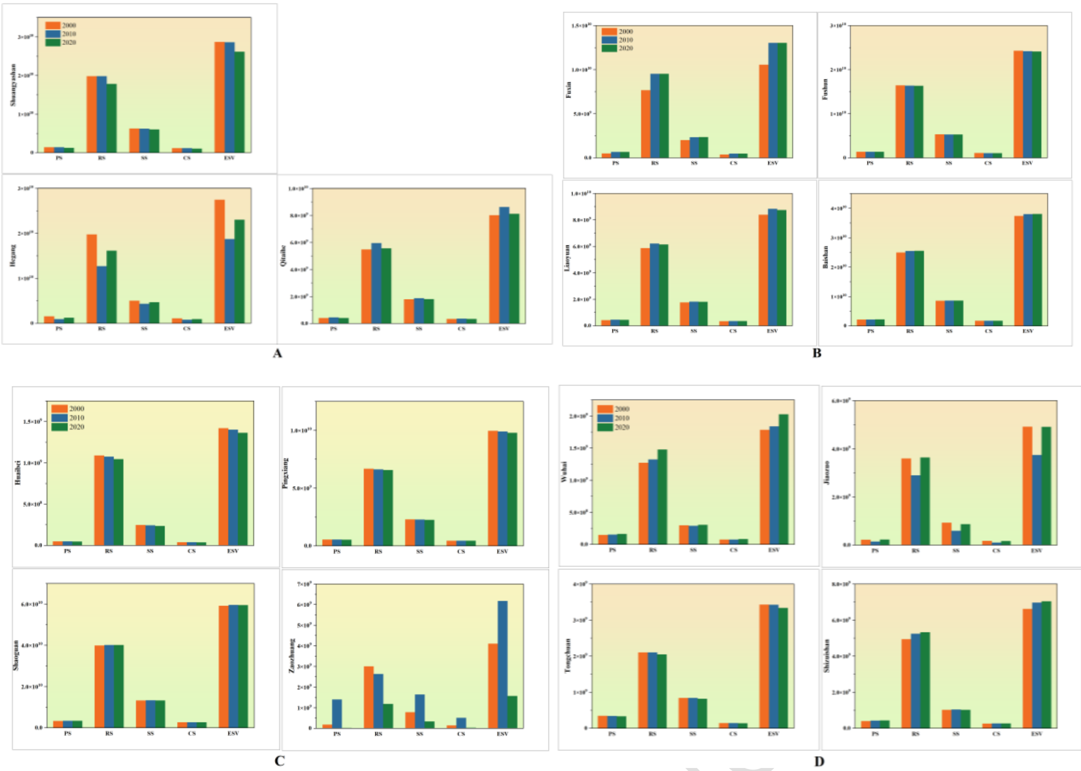


Fig 4 The ESV change of the CRDC during 2000-2020

The ESV change of individual CRDC is shown in the Fig 5. During 2000 to 2020, more than half of the cities showed a downward trend in ESV, including Jiaozuo, Tongchuan, Zaozhuang, Hegang, Pingxiang, Huaibei, Shuangyashan, and Fushun. ESV in Zaozhuang City showed a trend of first increasing and then decreasing, while ESV in Hegang City showed a trend of first decreasing and then increasing.

There were 7 cities show an increase in ESV from 2000 to 2020, including Wuhai, Fuxin, Shaoguan, Shizuishan, Qitaihe, Liaoyuan, Baishan and Shaoguan. Qitaihe Liaoyuan showed a trend of first increasing and then decreasing.

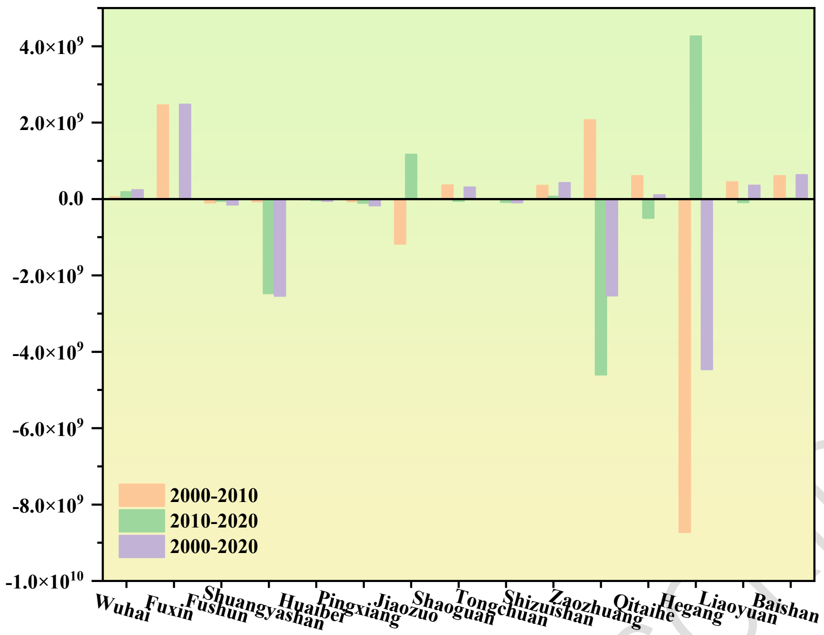


Fig 5 The ESV change of individual CRDC

The spatial change of ESV in the CRDC from 2000 to 2020 is shown in Fig 6. ESV has increased significantly in most areas of region A, such as Shuangyashan, Hegang, where over 60% of the ESV values are increasing. The spatial distribution of ESV changes in region B is scattered, such as Liaoyuan and Fuxin, the ESV increase and decrease is similar, about 50% of region B.

Over 90% of ESV in region C shows a decreasing trend, which the areas with increased ESV are only concentrated in the wetland and grassland areas of Pingxiang and Shaoguan. Only the forest ESV value in Huaibei city has increased, while the forest ESV value in other areas has decreased. The spatial ESV change of region D still shows a decreasing trend. The increase in ESV is mainly concentrated in the water areas of various cities, and the ESV in the grassland of Tongchuan and the farmland of Shizuishan are also showing an increasing trend.

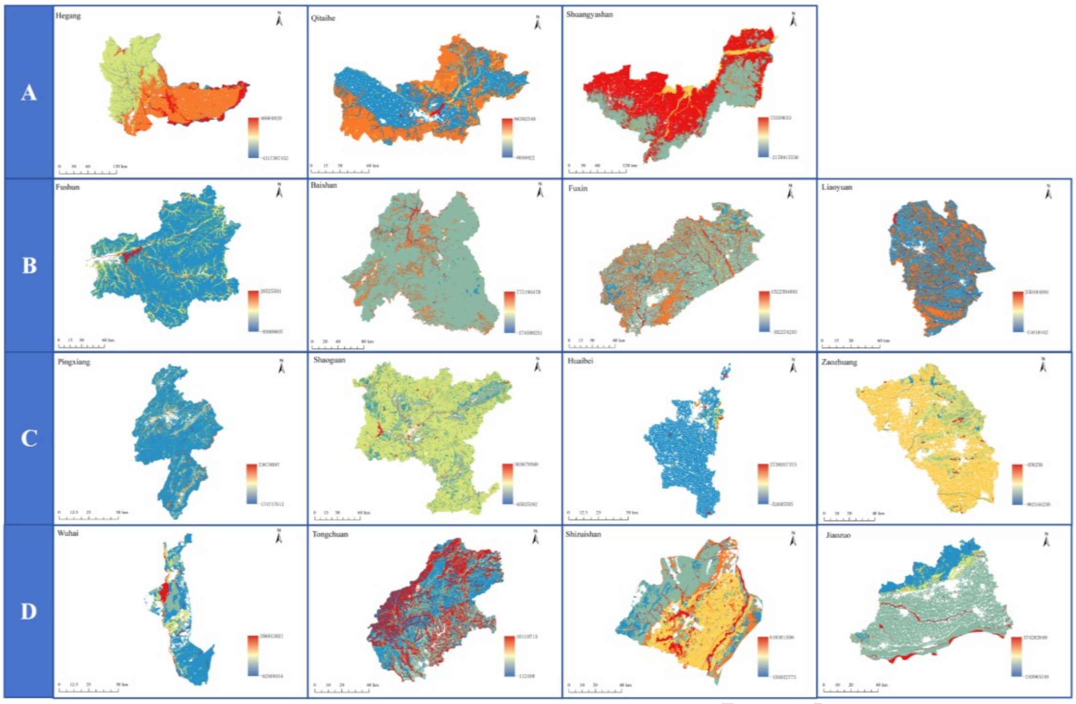


Fig 6 The spatial change of ESV in CRDC during 2000-2020

3.2 Ecological compensation in the CRDC

3.2.1 Prioritization of ecological compensation in the CRDC

The results of the ecological priorities are shown in Fig 7. There are two cities with an ecological compensation priority higher than 0.5, namely Baishan and Hegang, and three cities with an ecological compensation priority between 0.3 and 0.5, namely Shaoguan, Shuangyashan and Qitaihe. The ecological compensation priority for the other ten cities does not exceed 0.3, with 6 cities having an ecological compensation priority of 0.1 or less, including Pingxiang, Huaibei, Zaozhuang, Wuhai, Tongchuan, Jiaozuo.

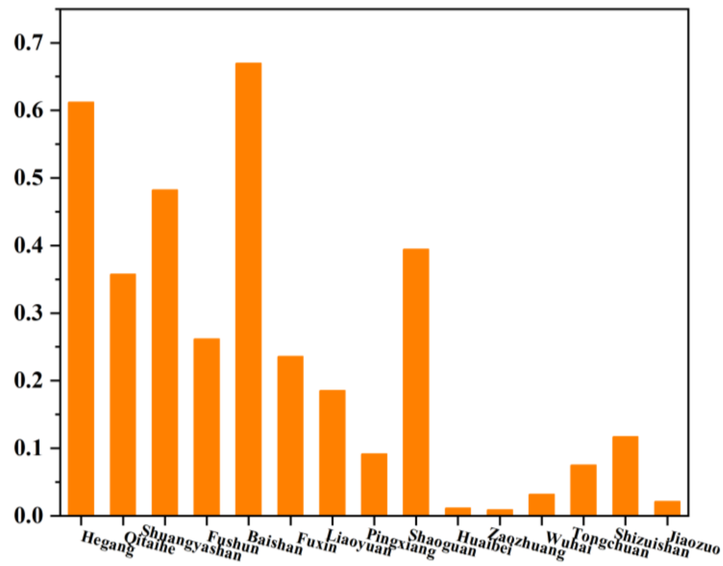


Fig 7 Ecological compensation priorities for the CRDC

3.2.2 The vertical ecological compensation of the CRDC

Table 3 Vertical ecological compensation and GDP in 2020 for each CRDC

City	Province	Amount of ecological compensation	Percentage of ecological compensation	GDP (billion yuan)	Percentage of GDP	Percentage of ecological compensation to GDP
Hegang	Heilongjiang	1.20	15.35%	34	2.81%	3.533%
Qitaihe	Heilongjiang	0.25	3.20%	20	1.70%	1.216%
Shuangyashan	Heilongjiang	1.09	13.93%	49	4.09%	2.206%
Fushun	Liaoning	0.54	6.90%	82	6.84%	0.653%
Fuxin	Liaoning	0.27	3.41%	50	4.17%	0.529%
Baishan	Jilin	2.15	27.45%	50	4.21%	4.219%
Liaoyuan	Jilin	0.14	1.79%	42	3.55%	0.327%
Pingxiang	Jiangxi	0.08	0.98%	96	7.97%	0.080%
Shaoguan	Guangdong	2.01	25.59%	135	11.20%	1.480%
Huaibei	Anhui	0.001	0.02%	111	9.26%	0.001%
Zaozhuang	Shandong	0.001	0.02%	173	14.34%	0.001%
Wuhai	Neimenggu	0.01	0.07%	56	4.66%	0.010%
Tongchuan	Shanxi	0.02	0.26%	38	3.15%	0.054%
Shizuishan	Ningxia	0.07	0.91%	54	4.48%	0.131%
Jiaozuo	Henan	0.01	0.12%	212	17.57%	0.004%
Total		7.82	100%	1208	100%	14.444%

The amount of vertical ecological compensation in the CRDC in 2020 was calculated using equations (5) and (6), and its relationships with GDP in different provinces were compared with the upper, middle, and lower reaches. The results are shown in Table 3.

The total value of ecological vertical compensation for coal depleted cities in China is 7.824 billion yuan, accounting for 14% of the total GDP. There are four high ecological vertical compensation cities, with compensation values exceeding 1 billion yuan. The compensation values from high to low are Baishan (2.148 billion yuan), Shaoguan (2.002 billion yuan), Hegang (1.201 billion yuan), and Shuangyashan (1.09 billion yuan), accounting for 4.21%, 11.20%, 2.81%, and 4.09% of the GPD, respectively.

The ecological vertical compensation values of Qitaihe, Fushun, Fuxin, and Liaoyuan cities are between 100 million and 1 billion yuan, corresponding to ecological compensation values of 2.51, 5.40, 267, and 140 million yuan, respectively, accounting for 1.70%, 6.84%, 4.17%, and 3.55% of GDP. The ecological vertical compensation values of seven other cities do not exceed 100 million yuan, namely Pingxiang > Shizuishan > Tongchuan > Hegang > Wuhai > Huaibei > Zaozhuang, with vertical compensation values of 77 million>71 million>21 million>09 million>0.05 million>014 million>0.012. The proportion of GDP is 4 - 17%.

4. Discussion

4.1 ESV change

This study starts from the perspective of ecosystem service value and explores the changes in ecosystem services in coal resource depleted cities based on land use in China. We consider the economic development levels of different CRDC and quantifies the urgency and compensation amount of ecological compensation for each coal resource-depleted city.

Land use change is an important factor affecting the ESV. From 2000 to 2010, the construction land of the CRDC significantly increased by 20%, which is one of the reasons for the decrease in ESV. Rapid economic development, urbanization, and ecological damage have reduced the value of ecosystem services (Zheng et al., 2024). That raises concerns about the sustainability of these ecosystems amidst industrial changes.

The reduction in farmland and the significant increase in forest are attributed to China's policy of returning farmland to forests proposed in 2000. More than half of the CRDC land changes show this trend, and the conversion of farmland to forest is mainly concentrated in the CRDC of A and B regions (Fig 4).

From 2010 to 2020, there was no significant change in the area of farmland and forest land, while the construction land area continued to increase by 20%. At the same time, the water area also decreased by 3000 hectares, which also had a negative impact on ESV. Despite the increase in grassland area, the ESV value provided by grassland is relatively low (Table 2). This reflecting the effect of both ecological recovery efforts and urban development pressures on ESV. The dominance of forest ecosystem services in 2020 (75.21%) indicates successful afforestation efforts, yet underscores the need for balanced development strategies that preserve ecological integrity.

In addition to the aforementioned factors of land use change, coal mining also has a negative impact on ESV in these cities. For example, from 2000 to 2010, although forest and water areas increased, ESV still decreased. Previous studies have also demonstrated the negative impact of coal mining on ecosystem services. On a national scale, the expansion of surface mining has resulted in the loss of ecosystem services, including solid and habitat quality (Xiang et al., 2021). Surface mining in the Qilian Mountains region can damage ecosystems, directly occupying and indirectly affecting neighboring ecosystems, leading to the loss of service value of surrounding ecosystems (Qian et al., 2018). However, the trend of ESV changes varies among different cities. From 2000 to 2020, 8 out of 15 cities showed negative growth in ESV, including Fushun, Shuangyashan, Huaibei, Pingxiang, Jiaozuo, Tongchuan, Zaozhuang, and Hegang. Fuxin, Shaoguan, Shizuishan, Qitaihe, Liaoyuan, and Baishan show an increasing trend in ESV.

Considering that the coal resources in most cities have been depleted around 2010, from 2000 to 2010 to 2020, there were four trends in ESV changes in CRDC. The cities with negative ESV growth during the two stages were Fushun Shuangyashan, Huaibei City, Pingxiang, Tongchuan and Zaozhuang. This shows that the coal mining in these areas has had a profound negative impact on the ecosystem service value, because most of the urban coal has been exhausted around 2010, and the mining output has decreased year by year.

The ESV of Baishan, Shizuishan, Fuxin, Wuhai show an increasing trend. Wuhai and Shizuishan are one of the main cities in the CRDC and one of the key areas for national ecological compensation and protection (Zhou et al., 2022). This is an important reason for their ESV value increasing trend, which is consistent with the research results of Zhou et al. Baishan has gone through a natural forest conservation project, while Fuxin City has gone through the process of returning farmland to forests (Wang et al., 2021), which can increase the ESV.

Jiaozuo Hegang shows a decreasing and then increasing trend, indicating that as the intensity of coal mining decreases, the ecosystems of these cities begin to gradually self repair. At the same time, the implementation of ecological protection policies will also increase ESV. Hegang has gone through NFCP, natural forest conservation project; GTGP, grain to green project policies (Mao et al., 2019). Jiaozuo City has implemented ecological protection policies for the South to North Water Diversion Project since 2010. Shaoguan and Liaoyuan first increased and then decreased. The reason for this ESV change is not yet clear, and it may be caused by the interaction of multiple factors. Because the impact of coal mining on ecosystems seems to be related to spatiotemporal variability, such as time lag, spatial spillovers, and cumulative spatiotemporal effects (Liu et al., 2022).

4.2 Ecological compensation

This study also evaluated the ecological compensation priority of coal resource depleted cities in China based on ESV and regional economic development. By filling a crucial gap in understanding ecological compensation needs in CRDC, the study offers valuable insights for improving transfer payments and ecological management strategies. Policymakers could benefit from these findings to implement more effective and equitable compensation systems. The ecological compensation priority of the five cities of Shuangyashan, Shaoguan, Qitaihe, Hegang, and Baishan is relatively high, all exceeding 0.3. Meanwhile, there are four cities with moderate compensation priority, including Shizuishan, Liaoyuan, Fuxin, and Fushun. The compensation priority is between 0.1 and 0.25, while other cities do not exceed 0.1.

High priority compensation cities are mainly distributed in region A and B. This is similar to the distribution of compensation quotas. Except for Shaoguan, the top 8 cities in the compensation quota belong to region A and B, accounting for 72%, which is consistent with national policies. In 2019, the top three provinces in China's resource depleted city transfer payment allocation table were also located in Liaoning Province, Heilongjiang Province, and Jilin Province in region A and B. The region A and B are located in the northeast of China, with abundant natural resources such as coal and oil, developed forestry and agriculture, and a forest coverage rate of over 40%. In the last century, it supplied China with coal and oil up to 50%. However, this has also damaged a large amount of ecosystems, so ecological compensation for these regions is urgent.

At the same time, we also found that the ecological compensation amount in some cities exceeded the national transfer payment allocation for resource depleted cities, such as 2.541 billion yuan in Heilongjiang Province and 2.278 billion yuan in Jilin Province, corresponding to transfer payment amounts of 1.25 billion yuan and 1.89 billion yuan respectively. The ecological compensation amount in other cities exceeded the transfer payment amount, indicating that the country should further improve the ecological compensation in the areas of Heilongjiang Province and Jilin Province in the future, including Baishan, Shuangyashan, Qitaihe, Hegang and Liaoyuan.

Cities with ecological compensation priority not exceeding 0.1 include Pingxiang, Tongchuan, Wuhai, Jiaozuo, Huaibei, and Zaozhuang. The ecological compensation amount in these cities is also relatively low, not exceeding 100 million yuan. The unit ESV in these areas is relatively low, but the economic level is relatively developed, so the demand for national vertical compensation may be lower because economically developed areas are more willing to carry out environmental protection policies. The relationship between ecosystem service value and economic development level is particularly noteworthy, revealing that higher economic activity does not necessarily equate to higher ecological value. This counterintuitive finding emphasizes the importance of prioritizing ecological health in policy decisions.

4.2 Policy recommendations

The ecological compensation system and policy of mining areas have been widely quoted in developed countries. In 1939, West Virginia issued the first law governing mining: Reclamation Law (Land Reclaim Law). Under the guidance of the law, the vegetation destruction of mining in mining areas in the United States was effectively controlled. Germany has formulated the principles of landscape ecological reconstruction and the distinction between the old and the new ones. According to the Federal Mining Law, the ecological compensation of mining areas in Germany is divided into two categories: first, the ecological environment damage caused by the newly developed mineral resources, and second, the ecological environment damage of the waste mining areas left by history, that is, the old account. While The valuable experience of German landscape ecological reconstruction and the principle of old and new distinction has a high reference significance for the ecological restoration and management of mining areas in China. In order to further standardize the ecological compensation behavior of mining enterprises, Australia implements the mine environmental impact assessment system. It requires mining enterprises to submit mine environmental impact assessment reports, and clarify in detail the specific countermeasures to compensate for the ecological environment damage caused by the mining process, so as the prerequisite for obtaining the mining license (Liu et al., 2023).

According to the existing international ecological compensation system and policies, combined with the actual development of journals in China, this paper puts forward the following suggestions.

For the national level, as an environmental and economic policy, ecological compensation mechanism involves the ecological environment, protection and construction of the interests of relevant parties. Therefore, we urgently need to carry out unified legislation on ecological compensation to meet the actual needs of ecological environment construction and resource-exhausted city transformation under the new situation. A complete legal system of ecological compensation fund compensation should be established, and the legislative principle of ecological compensation in coal mining areas should be determined. Based on the principle of "who develops who protects, who destroys who recovers, who benefits, who pays", and the principle of combining ecological and economic benefits. At the same time, we should speed up the special legislation of ecological compensation in coal mining areas and strengthen the unity of laws and regulations. At the same time, we should pay attention to the connection and cooperation with the Criminal Law, Environmental Protection Law, Tax Law and other existing laws and other departments and regulations, so as to ensure the unity and coordination between relevant laws and regulations (Wang et al., 2024; Xiong et al., 2020). For local region, regional compensation methods should be explored, compensation strategies should be refined, exploration and mining rights should be improved, by actively delegating some exploration rights and the approval and registration rights, we can save the labor and time cost, and adjust the mining right royalties to improve the future mining efficiency. Strict access and exit mechanisms should be formulated, It helps to reduce the ecological environment of the mining area Potential risk of quality decline. Lastly, the fund guarantee system should be improved, and the scope of funds should be defined (Li et al., 2019).

4.3 Limitations

This study still has many limitations. We conducted ecosystem service accounting based on large-scale data, so we failed to effectively measure the areas below the municipal level. Compared with the overall urban spatial area, the mining area is relatively small. Due to the large study area, we evaluated ecosystem services by equivalent factor method, and in the future, we should accurately describe and evaluate ecosystem services changes by model methods based on actual data (Jia et al., 2023). In addition, the content of our study is for the longitudinal supplementary study of Chinese resource-exhausted cities, in the future research should be considered in coal exhausted city transverse supplementary study, because the coal mining space spillover effect, should be based on the coal mining spillover effect associated between regional ecological supplement study, this is a key challenge to be solved (Fan et al., 2023).

5.Conclusions

The total ESV of the CRDC ecosystem services decreased from 236.053 billion yuan in 2000 to 230.565 billion yuan in 2020. In 2020, the value of forest ecosystem services was the highest, contributing 173.356 billion yuan, accounting for 75.21% of the total value, followed by arable land and water bodies, contributing about 25 billion yuan, accounting for 11% of the total value The regulation service value has the highest proportion, accounting for 69% of ESV, with a value of 158.396 billion yuan, followed by the support service value, accounting for 22%, with the value of 49.617 billion yuan.

The value of ecosystem services and the level of economic development have positive and negative relationships with ecological compensation priorities, respectively. The total ecological compensation amount is 7.824 billion yuan. High priority cities for ecological compensation are located in region A and B, with a relatively low level of economic development, making them cities in urgent need of ecological compensation. Including Shuangyashan, Hegang, Baishan, the priority of ecological compensation exceeds 0.45, with ecological compensation amounts of 21.48, 12.01, and 1.09 billion yuan respectively.

Statements & Declarations

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Competing Interests

The authors declare that there is no conflict of interest.

Author Contributions

All authors contributed to the study conception and design. Jiao Wang and Mingyou Wang were responsible for research funds and data. Yu Fan and Tongxin Sun were responsible for the text content of the article. Jiyang Liu for the model work.

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