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Evaluation and Policy Research on the Sustainable Development of China's Rare Earth Resources

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Abstract: As rare earth resources are indispensable raw materials for modern society, they have become strategic global reserve resources. Even though China is the world's largest producer and exporter of rare earth, the industry has low efficiency and severe problems with over-exploitation and environmental pollution; therefore, there needs to be a greater focus on the sustainable exploitation of rare earth resources. This paper establishes an innovative evaluation index system for the sustainable development of China's rare earth resources from six main aspects; economic development, social progress, environmental protection, technological innovation, rare earth development and utilization, and rare earth protection in which the indicators are assessed using an entropy method. Grey correlation analysis was used to evaluate China's rare earth sustainable development level from 2006–2016, from which it was found that sustainable development was poor from 2006–2010 and marginally better from 2011–2016. The main factor affecting rare earth sustainable development in China was found to be the lag in the development of environment protection system and rare earth protection system. Policy recommendations for improving China's rare earth protection, environmental protection, and technological innovation are proposed to guide government regulations and assist rare earth industry personnel.

Keywords: rare earth resources; sustainable development; evaluation index system

1. Introduction

The rare earth elements (REEs) represent a group of 17 chemical elements including 15 lanthanides (the lanthanide element is a general term for the elements from the 57th element to the 71st element of the periodic table), plus yttrium (Y) and scandium (Sc) [1]. Due to its unique physical and chemical properties, rare earth resources are widely used in new energy, new materials, energy conservation and environmental protection, aerospace, electronic information, and other fields [2]. As an indispensable raw material for modern high-tech technology and green innovation applications, REEs have become a strategic global resource [3]. The US Geological Survey's Mineral Commodity Summaries 2018 claimed in a recent report that at the end of 2017, there were about 130 million tonnes of proven rare earth resource reserves (rare earth oxides [REOs]) in the world, with possible total resources exceeding 2 billion tonnes in China, Brazil, Vietnam, Russia, India, Australia, Greenland, the United States, Canada, Malawi, and Malaysia (Figure 1) [4]. But The White Paper on China's Rare Earth Conditions and Policies issued by the State Council News in 2012 stated that "China's rare earth reserves account for about 23% of the world's total reserves". Currently, as China has more than 90% of the world's rare earth market with its 23% of global rare earth reserves [2], it has been predicted that China's rare earth element production will peak in 2040, with production slowly declining after that time [5]. Accordingly, as the world's largest producer, applier, and exporter of rare earths, the sustainable development and utilization of rare earth resources has been receiving close attention [6,7]. China's rare earth industry currently has serious development problems such as low efficiency, a long-term imbalance between supply and demand, large-scale raw materials exports, and environmental pollution [8–10]. Therefore, as China's rare earth resource industry faces many challenges, it is imperative that the government and industry work together to ensure rare earth industry sustainable development.

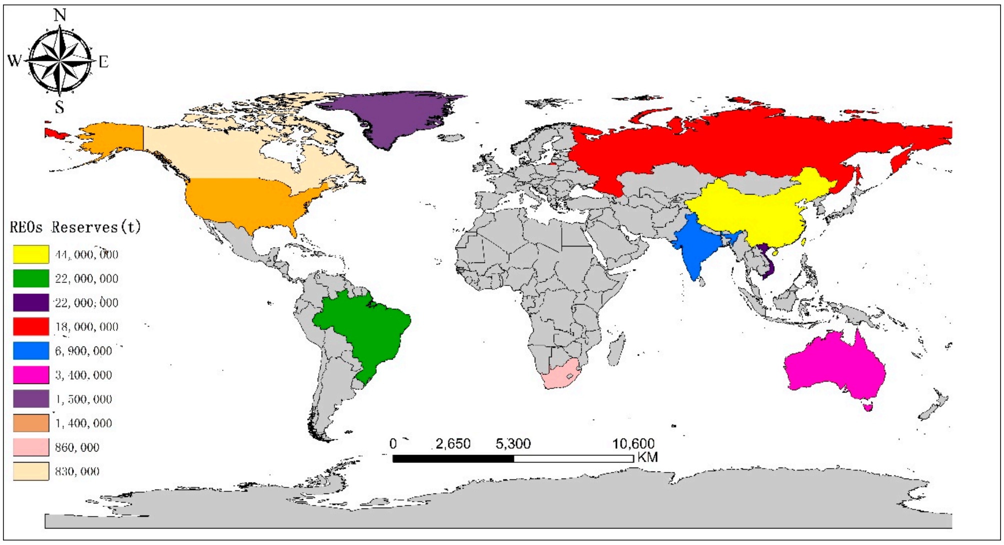

Figure 1. World REOs reserves distribution map.

The United Nations Sustainable Development Goal 7 is to achieve affordable, reliable, sustainable, and modern energy for all by 2030 [11]. Consequently, there has been increased research into the sustainable development of water resources [12,13], coal resources [14,15], power resources [16], land resources [17] and other energy resources [18]. However, even though rare earth reserves are nationally strategic resources, due to the difficulty in obtaining relevant data, there has been little research into the rare earth industry's sustainable development [1,5,19], with the little research available being primarily focused on the construction of sustainable indicator systems or on sustainable evaluation methods.

1.1. Construction of a Rare Earth Resource Sustainable Evaluation Index System

Mineral resource sustainability frameworks have been defined as "a state of dynamic interplay between the environment and society (in a broad sense) that ultimately contributes positively to indefinite human development and universal wellbeing whilst not overdrawing on natural resources or over-burdening the environment in an irreversible manner" [20,21].In 1980, the International Conservation Alliance's World Conservation Strategy stated that "[t]he basic relationships in the natural, social, ecological, economic, and natural resource processes must be studied to ensure global sustainability [22]". Therefore, previous research has attempted to establish evaluation index systems for sustainable rare earth resource development from the four aspects of resources, the economy, the environment, and the society [21,23]. As the material basis for rare earth development, resources have been the primary consideration when constructing sustainable evaluation index systems. The sustainable resource development levels have been evaluated by assessing the comprehensive utilization of resources and the comprehensive conditions for resource development [24]. The macroeconomic environment is identified as the most basic risk affecting world mineral resource development [25]. Research into the economics associated with rare earth sustainability has generally been focused on three key elements; the price on the market, supply restrictions by China, and the availability of non-Chinese deposits [21]. Ecological sustainability has also received some focused attention in recent years as environmental governance and environmental protection investment has tended to affect rare earth sustainable supply chain development [26].As a stable social system is the basis for the smooth operation of a circular economy, social indicators need to be included in any evaluation index system for rare earth resources sustainable development [27,28].While much previous research has only considered basic sustainable development objectives, as rare earth is a high-tech raw material, technological development and national policy guidance also affects rare earth industry development [29,30]. Further, rare earth sustainable evaluation systems have been proposed based on economic, social, environmental, technological, and policy issues [23]; however, these have not considered the most basic rare earth resources. Some research has also proposed that personnel systems have a strong interaction with the environment and resource systems, and have established structural sustainable development of the rare earth industry models that include rare earth, personnel, society, resources, and the environment [31]; however, the economic system that provides financial security was not considered. Therefore, while there have been some sound proposals, previous research has not comprehensively considered the rare earth sustainable evaluation subsystems and there has been a lack of empirical analysis from a system integration perspective.

1.2. Research on Sustainable Evaluation Methods

There have been many suggested evaluation methods for the sustainable development of rare earth resources. For example, the analytic hierarchy process (AHP) and fuzzy comprehensive evaluation method have been used to empirically analyze the sustainable development of the Baotou rare earth industry [27,32] and principal component analysis (PCA) and AHP have been used to evaluate the sustainable development level of metal mineral resources [33]; however, these methods have certain subjective judgments when determining the indicator weights. The DEMATEL (Decision Making Trial and Evaluation Laboratory) method has also been used in an empirical study on the factors affecting the sustainable development of China's rare earth industry [24]; however, as the expert decision-making had strong subjective randomness and was susceptible to a lack of knowledge by the decision makers, there was poor objectivity. To address these shortcomings, improved attribute reduction has been used to streamline existing index systems, with rough set attribute importance degrees being used to determine the index weights [34]. Although these methods effectively avoided the interference of subjectivity for the indicator selection, the methodology is complex and not universal. To overcome the above deficiencies, this paper proposes a combined entropy weight and grey correlation method for the comprehensive evaluation of rare earth sustainable development. Compared with the previously mentioned subjective valuation methods such as AHP and expert scoring, entropy weight methods have higher precision, are better able to explain the obtained results, are adaptable, and can be used in any process that needs weight determinations [35]. Grey relational analysis (GRA), which is a grey system with incomplete information, has been widely used in agriculture, industry, the economy, management, and other disciplines and has achieved good results [36–38]. GRA has a simple structure, a small amount of calculation, and the distribution data law does not need to be considered in the analysis [39]. Therefore, using the entropy weight method and the grey relational analysis method, subjective weighting and algorithmic complexity can be avoided.

Previous research has only considered economic, social, environmental and resource perspectives when constructing the rare earth resource sustainable development evaluation index systems and have omitted technological innovation, and the positive impact of state protection policies on rare earth mining and exports. Therefore, to overcome these omissions, this paper establishes an innovative systematic, comprehensive rare earth resource sustainable development evaluation index system from six perspectives; economic development, social progress, environmental protection, technological innovation, rare earth development and utilization, and rare earth protection. Further, as past research has tended to include subjective judgments when determining the indicator weights and have been complicated and difficult to operate, to ensure more objective and reasonable results, this paper applies a combined entropy weight and grey correlation method that offers both objectivity and universality when evaluating China's rare earth sustainable development from 2006–2016. From the evaluation results, policy recommendations to improve China's rare earth sustainable development are proposed to assist in the formulation of scientific rare earth resource exploitation policies. The rare earth evaluation index system and evaluation method proposed in this paper can be extended to the sustainable evaluation of other similar metal mineral resources.

2. Materials and Methods

As the influencing factors for the evaluation of China's rare earth sustainable development level are somewhat ambiguous and uncertain, in this paper, a grey relational analysis method combined with an entropy weight assignment is applied to ensure strong objectivity and rationality. The technical route for the evaluation in this paper is shown in Figure 2.

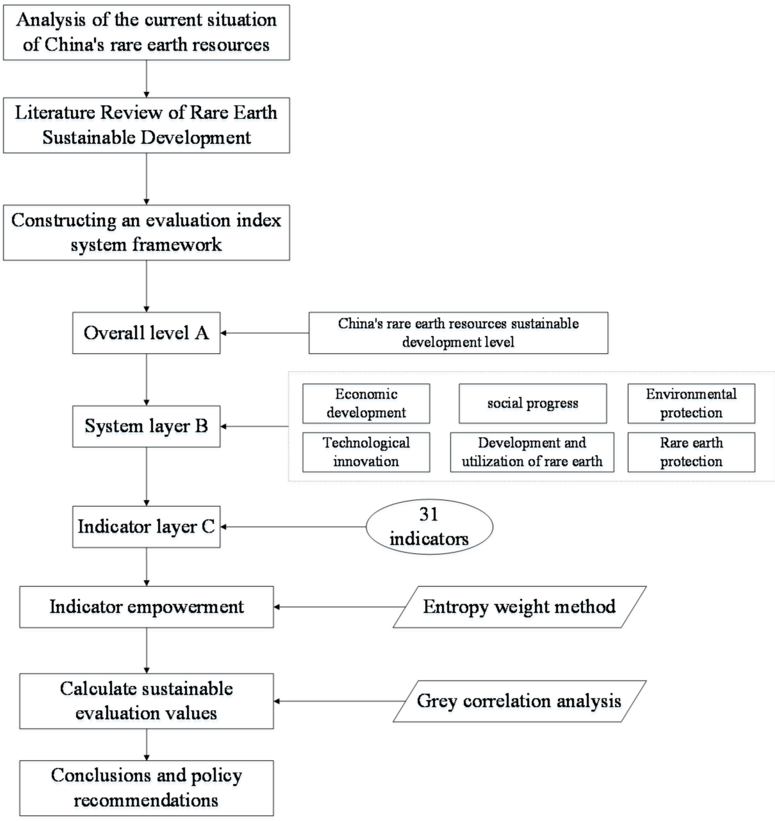

Figure 2. The technical route.

2.1. *Entropy Weight Method*

The entropy weight method is a method of determining the standard by using information entropy as the weight. Entropy is a thermodynamics concept first introduced into information theory by Claude Elwood Shannon, in which entropy is used to represent the measure of disorder in a system [40]. Information entropy can be used to measure the uncertainty of random variables; the smaller the information entropy of an indicator, the larger the amount of information provided by that indicator, the higher its importance in the indicator system, and the greater the weight. Using the entropy weight method to determine the weight of each level of indicators in an indicator system can reduce the influence of human factors on the indicator weights, thereby making the evaluation results more objective.

The index weight is determined using the entropy weight method as follows.

(1) Suppose there are m projects to be evaluated that together have n evaluation indicators; that is, the raw data $R = (r_{ij})_{m*n}$:

$$R = \begin{pmatrix} r_{11} & r_{12} & \cdots & r_{1n} \\ r_{21} & r_{22} & \cdots & r_{2n} \\ \cdots & \cdots & \cdots & \cdots \\ r_{m1} & r_{m2} & \cdots & r_{mn} \end{pmatrix} \tag{1}$$

where r_{ij} is the evaluation value of the i-th item in the j-th index.

(2) Calculate the proportion of the i-th item index value that is under the j-th indicator, p_{ij};

$$p_{ij} = r_{ij} / \sum_{i=1}^{m} r_{ij} \tag{2}$$

(3) Calculate the entropy weight e_j of the j-th indicator;

$$e_j = -k \sum_{i=1}^{m} p_{ij}.\ln p_{ij} \tag{3}$$

of which $k = 1/\ln m$;

(4) Calculate the entropy weight w_j of the j-th indicator;

$$w_j = (1 - e_j) / \sum_{j=1}^{n} (1 - e_j) \tag{4}$$

2.2. Grey Correlation Analysis

In 1982, the Chinese scholar Deng published the paper "Grey System Control Problems", which was the first mention of grey system theory [41] and further proposed the Grey Correlation Analysis (GRA) [42], in which grey relational order (GRO) was used to describe the strength and order of the relationships between factors. In fact, GRA is based on the analysis of the limited data columns in a grey system to identify the influences on the main target value and indicate the dynamic regular motion of the whole system [43]. The specific steps in GRA are as follows:

(1) Construct a standardized evaluation matrix, in which the original data is X and there are m indicators and n objects to be investigated:

$$X = \begin{bmatrix} X_{11} & \cdots & X_{1m} \\ \vdots & \ddots & \vdots \\ X_{n1} & \cdots & X_{nm} \end{bmatrix} \tag{5}$$

The reference sequence $X_0 = (X_{01} X_{02} \cdots X_{0n})$ is determined in which the reference value of the positive indicator is the maximum value and the reference value of the inverse index is the minimum value. The values, however, are very different because of the different dimensions in the original data in each index; therefore, to eliminate the original data dimensions, the data are first standardized.

(2) Calculate the absolute difference A_{ij}, which is the absolute value of the difference between the real value of the i-th object in the j-th indicator and the reference value. The absolute values then form the difference matrix:

$$A_{ij} = \begin{bmatrix} A_{11} & \cdots & A_{1m} \\ \vdots & \ddots & \vdots \\ A_{n1} & \cdots & A_{nm} \end{bmatrix} \tag{6}$$

(3) Calculate the correlation coefficient L_{ij} of object i with respect to index j for the reference sequence, in which ρ is the resolution coefficient.

$$L_{ij} = \frac{A_{min} + \rho^* A_{max}}{A_{ij} + \rho^* A_{max}} \tag{7}$$

The correlation coefficient for each reference sequence object constitutes a matrix:

$$L = \begin{bmatrix} L_{11} & \cdots & L_{1m} \\ \vdots & \ddots & \vdots \\ L_{n1} & \cdots & L_{nm} \end{bmatrix} \tag{8}$$

(4) Calculate the weighted correlation degree R, which is the weighted sum of the correlation coefficient values for each factor obtained using the grey correlation comprehensive evaluation model:

$$\mathrm{R} = W_i^* L_i \tag{9}$$

where R is the weighted correlation degree, L_i is the correlation coefficient of the i-th factor that reflects the interaction between the indicators, and W_i is the weight value of the i-th index, which reflects the intensity of the impact on the rare earth resource sustainability.

2.3. Data Sources

The more abundant REEs are in the lighter spectrum of lanthanides group, the so-called light REEs (LREEs) that include lanthanum (La), cerium (Ce), praseodymium (Pr), neodymium (Nd), and samarium (Sm). The remaining REEs form the heavy REEs (HREEs) group and include europium (Eu), gadolinium (Gd), terbium (Tb), dysprosium (Dy), holmium (Ho), erbium (Er), thulium (Tm), ytterbium (Yb), lutetium (Lu), and yttrium. Two elements are excluded from LREE/HREE classification: scandium, due to its unique properties and different occurrence, and promethium (Pm), due to its radioactivity [1]. 98% of China's total rare earth resources are distributed in Inner Mongolia, Jiangxi, Guangdong, Sichuan, Shandong and other regions and have the characteristics of "north light, south weight". LREEs are mainly distributed in the Bayan Obo mining area in Baotou, Inner Mongolia. Its rare earth reserves account for more than 83% of the country's total rare earth reserves, ranking first in the world. It is the main production base of LREEs in China. HREEs are mainly distributed in southern areas such as Jiangxi Yinzhou and Fujian Longyan. In particular, the Nanling area has become an important HREEs production base in China. The distribution of rare earth resources in China is shown in Figure 3.

The data in this paper were extracted from the 2007–2017 China Statistical Yearbooks, the 2007–2017 China Environmental Statistics Yearbooks, the 2007–2017 China Industrial Statistics Yearbooks, the 2007–2017 China Science and Technology Statistical Yearbooks, and the 2007–2015 China Nonferrous Metals Industry Yearbooks and the China Mining Yearbooks. Data were also taken from the China Rare Earth website, the China Industry Information Network, and the Ministry of Commerce website of the People's Republic of China.

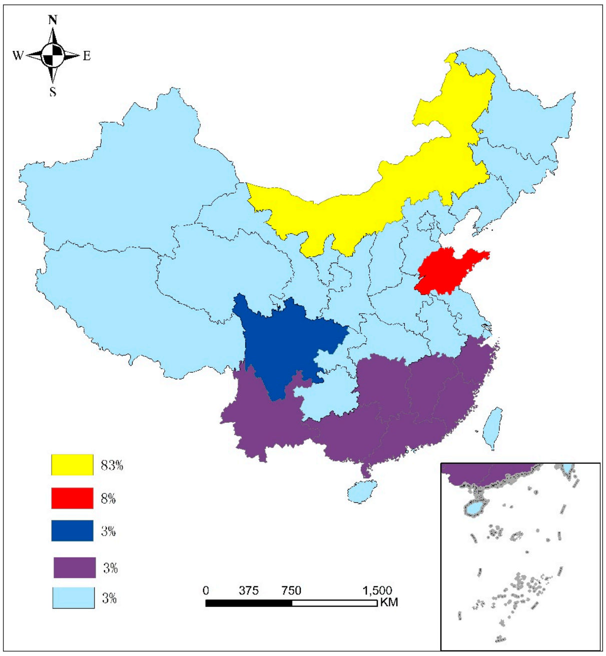

Figure 3. China's rare earth resource distribution map.

3. Evaluation of the China's Rare Earth Resource Sustainable Development

3.1. Evaluation Index System Construction

The rare earth sustainability was determined from the full RE lifecycle from extraction through to waste disposal and recycling. Therefore, 31 indicators were used to construct the sustainable rare earth resource development evaluation index system that covered economic development, social progress, environmental protection, technological innovation, rare earth development and utilization, and rare earth protection, as shown in Figure 4.

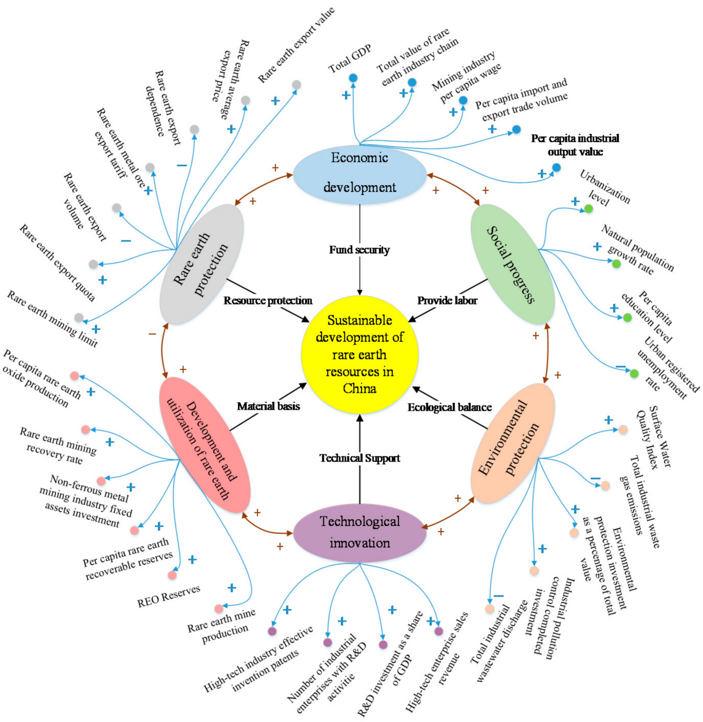

Figure 4. Evaluation index system for rare earth resource sustainable development.

(1) Economic Development Indicators

Economic development provides financial support for coordinated development and is an important driving force for rare earth sustainable industry development. The economic development indicators selected were: GDP, per capita import and export trade volumes, and per capita mining industry wages, all of which reflected the national industrial trade economic development level; per capita industrial output, which reflected the production results for certain sections of the rare earth metal mineral production base or the sustainable development level; and the total value of the rare earth industrial chain, which reflected the development, processing, and application across the entire industrial chain and indicated the rare earth resource development prospects on the resource market.

(2) Social Progress Indicators

Social progress refers to residential quality of life and reflects whether the environment is suitable for rare earth sustainable resource development as a stable society can support a sustainable environment. The selected social development indicators were; urbanization level, natural population growth rate, per capita education level, and the urban registered unemployment rate, the selection of which were based on the Index of Social Progress by Professor Estes of the University of Pennsylvania in 1984 [44] in which education, population, employment, and economic indicators were used to reflect societal progress.

(3) Environmental Protection Indicators

Environment is the carrier of resources, the level of environmental quality relates to the stock and quality of resources, and affects whether the rare earth industry can develop healthily and stably. The selected environmental indicators were environmental pollution and the environmental management of the rare earth bases. In the rare earth production process, annual waste emissions from the production bases and industrial water reuse affect sustainable development. Therefore, the environmental protection indicators [45] were: the surface water and ground water quality index, which reflected environmental water resource protection; total industrial waste gas emissions and total industrial wastewater discharge, which reflected the rare earth mineral resource production base environmental pollution sources; and the environmental protection investment proportion and total industrial pollution control investment, which reflected the state's investment in environmental protection and the emphasis placed on a sustainable resource production environment.

(4) Technological Innovation Indicators

China places importance on rare earth technological development and provides technical support for the sustainable development of rare earths [46]. Therefore, the selected technical innovation indicators were closely related to the Chinese Innovation Index (CII) [47] as follows; high-tech technology enterprise sales revenue, which reflected the innovation benefits and the impact of innovation on the economy and society; the R&D investment proportion in GDP, which reflected innovation investment and was the core indicator for the national science and technological input level; number of industrial enterprises with R&D activities, which reflected the manpower support given to innovation; and the number of valid invention patents in high-tech industries, which reflected the innovation output and market value and research and development competitiveness.

(5) Rare Earth Development and Utilization Indicators

China has the largest reserves of rare earth resources in the world; therefore, the development and utilization of rare earth resources is the material basis for sustainable development. The selected indicators for the development and utilization of rare earths [23,33] were: rare earth ore production and per capita REO production, both of which reflected the rare earth resource development level; REO reserves and per capita rare earth recoverable reserves, both of which reflected resource development conditions; the fixed asset investment in nonferrous metal mining, which reflected the comprehensive resource development mining utilization conditions; and the rare earth recovery rate, which reflected the percentage of actual rare earth ore reserves and the resource development and utilization benefits.

(6) Rare Earth Protection Indicators

China has introduced several rare earth policies covering mining, export, and taxation to reduce resource consumption, ensure rare earth sustainable resource development, and protect the rare earth resources. The selected rare earth protection index [48] indicators were: the rare earth mining quota, the rare earth export quota, and the rare earth metal ore export tariff, all of which reflected the state policy requirements for the protection of rare earths; the rare earth export volume, the average rare earth export price, and the rare earth export value, all of which reflected China's degree of rare earth foreign trade protection; and the rare earth export dependence, which reflected the proportion of China's rare earth exports to rare earth production. The high dependence on rare earth exports indicates that China lacks rare earth resource reserve protection measures.

3.2. Empowering the Evaluation Indicators

Because the 31 evaluation indicators all had different dimensions, it was necessary normalize each evaluation index. Using linear normalization, each indicator data x_i was unified into an interval $[0,1]$. From 2006–2016, the maximum indicator value was defined as maxx_i, with the evaluation value being 0.9, and the minimum value was minx_i, with the evaluation value being 0.1. The evaluation values were obtained using linear interpolation and the normalization formula is shown in Table 1 [49].

Table 1. Index normalization method.

Formula	Factors Affecting the Evaluation Value	Evaluation Range	Characteristics
$y_i = 0.1 - \frac{0.8(x_i - \max x_i)}{\max x_i - \min x_i}$	$x_i, \max x_i, \min x_i$	[0,1]	The evaluation value decreases as the index increases
$y_i = 0.9 + \frac{0.8(x_i - \max x_i)}{\max x_i - \min x_i}$	$x_i, \max x_i, \min x_i$	[0,1]	The evaluation value increases as the index increases

Using the entropy weight method, the weights for the 31 indicators were determined using Formulas (2)–(4), after which the weights for the six system layers were calculated by adding the weight values of the index layer. The specific weight values are shown in Table 2.

Table 2. Evaluation index weight allocation table.

Target Layer	System Layer	Weights	Indicator Layer	Weights
China's rare earth resource sustainable development level A	Economic Development B1	0.15094	Total GDP—C1	0.02693
			Per capita industrial output value—C2	0.02622
			Per capita import and export trade volume—C3	0.02662
			Total value of rare earth industry chain—C4	0.04624
			Mining industry per capita wage—C5	0.02493
	Social Progress B2	0.09660	Urbanization level—C6	0.02455
			Natural population growth rate—C7	0.03712
			Per capita education level—C8	0.02128
			Urban registered unemployment rate—C9	0.01366
	Environmental Protection B3	0.18775	Surface Water Quality Index—C10	0.03857
			Total industrial waste gas emissions—C11	0.04982
			Environmental protection investment as a percentage of total value—C12	0.02949
			Industrial pollution control completed investment—C13	0.03746
			Total industrial wastewater discharge—C14	0.03240
	Technological Innovation B4	0.14790	High-tech enterprise sales revenue—C15	0.03187
			R&D investment as a share of GDP—C16	0.02986
			Number of industrial enterprises with R&D activities—C17	0.04600
			High-tech industry effective invention patents—C18	0.04016

Table 2. *Cont.*

Target Layer	System Layer	Weights	Indicator Layer	Weights
	Rare earth Development and Utilization B5	0.17061	Rare earth mine production—C19	0.04224
			REO Reserves—C20	0.03839
			Per capita rare earth recoverable reserves—C21	0.02341
			Non-ferrous metal mining industry fixed asset investment—C22	0.03239
			Rare earth mining recovery rate—C23	0.01076
			Per capita rare earth oxide production—C24	0.02341
	Rare earth Protection B6	0.24620	Rare earth mining limit—C25	0.03300
			Rare earth export quota—C26	0.02403
			Rare earth export volume—C27	0.01965
			Rare earth metal ore export tariff—C28	0.02289
			Rare earth export dependence—C29	0.02821
			Rare earth average export price—C30	0.05844
			Rare earth export value—C31	0.05997

3.3. Evaluation Value Calculation

Under the principle of least information, $\rho = 0.5$,the specific results for the weighted relevance calculations for each indicator and the comprehensive weighted relevance are shown in Table 3, in which the grey weighted correlation degree was taken as the rare earth sustainable resource development score; the higher the score, the higher the rare earth resource sustainable development level.

Table 3. Evaluation value for rare earth resource sustainable development from 2006 to 2016.

Year	Economic Development	Social Progress	Environmental Protection	Technological Innovation	Rare Earth Development and Utilization	Rare Earth Protection	Comprehensive
2006	0.0503	0.0413	0.0986	0.0493	0.0932	0.1073	0.0797
2007	0.0542	0.0464	0.0894	0.0502	0.0801	0.1199	0.0801
2008	0.0578	0.0396	0.0926	0.0518	0.0828	0.1250	0.0825
2009	0.0573	0.0386	0.0821	0.0559	0.0879	0.1371	0.0848
2010	0.0687	0.0441	0.0937	0.0593	0.1180	0.1404	0.0957
2011	0.1107	0.0468	0.0731	0.0660	0.1042	0.2021	0.1122
2012	0.1038	0.0501	0.0854	0.0754	0.1007	0.1568	0.1035
2013	0.1265	0.0544	0.1007	0.0843	0.1034	0.1387	0.1075
2014	0.1256	0.0603	0.1197	0.0937	0.1323	0.1258	0.1147
2015	0.1248	0.0645	0.1054	0.1090	0.1380	0.0899	0.1067
2016	0.1287	0.0950	0.1215	0.1479	0.1168	0.0835	0.1138

Based on the reference sequence, the maximum reference scores for each subsystem and the comprehensive evaluation value were calculated, and are shown in Table 4.

Table 4. Evaluation values based on the reference sequence.

	Economic Development	Social Progress	Environmental Protection	Technological Innovation	Rare Earth Development and Utilization	Rare Earth Protection	Comprehensive
The optimal value	0.1509	0.0966	0.1878	0.1479	0.1706	0.2462	0.1790

A four-level evaluation level: very high, high, average, and poor; was determined as follows; 90% or more, 75% to 90%, 60% to 75% and 60% or less. The evaluation rating table is shown in Table 5.

Table 5. Rare earth sustainable development level evaluation scale.

Evaluation Level	Economic Development	Social Progress	Environmental Protection	Technological Innovation
very high	[0.1358,0.1509]	[0.0869,0.0966]	[0.1690,0.1878]	[0.1331,0.1479]
high	[0.1132,0.1358)	[0.0725,0.0869)	[0.1408,0.1690)	[0.1109,0.1331)
average	[0.0906,0.1132)	[0.0580,0.0725)	[0.1127,0.1408)	[0.0887,0.1109)
poor	[0.0151,0.0815)	[0.0097,0.0580)	[0.0188,0.1127)	[0.0148,0.0887)

Table 5. *Cont.*

Evaluation Level	Rare Earth Development and Utilization	Rare Earth Protection	Comprehensive
very high	[0.1536,0.1706]	[0.2216,0.2462]	[0.1611,0.1790]
high	[0.1280,0.1536)	[0.1846,0.2216)	[0.1342,0.1611)
average	[0.1024,0.1280)	[0.1477,0.1846)	[0.1074,0.1342)
poor	[0.0171,0.1024)	[0.0246,0.1477)	[0.0179,0.1074)

4. Results Analysis

4.1. Comprehensive Evaluation of the China's Rare Earth Resource Sustainable Development Level

A time series chart for the comprehensive evaluation of China's rare earth sustainable development level from 2006 to 2016 was plotted and is shown in Figure 5. Overall, China's rare earth sustainable development level was increasing from 2006–2016, and the capacity for sustainable development is getting stronger and stronger. Based on the shape of the curve, China's rare earth sustainable development level was divided into three stages.

The first stage was from 2006–2010. China's rare earth sustainable development level continued to grow relatively fast from 0.0797 in 2006 to 0.1122 in 2011, an average increase of 8%. The main reason for this growth was the promulgation of the "Rare Earth Industrial Industry Development Policy" and the "Rare Earth Industry Medium- and Long-Term Development Plan" in 2006. In 2007, rare earth production implemented a mandatory plan, rare earths were included in the catalogue of prohibited trade, and were subjected to export tariffs. Scientific development concepts were used to coordinate the economic and social development and various rare earth policies implemented to promote technological and environmental progress, all of which led to an increase in the rare earth sustainable development level.

The second phase was from 2011–2012, at which time the rare earth sustainable development evaluation value decreased from 0.1122 to 0.1035, which was mainly due to the sharp decline in the rare earth protection subsystem score. Because of the influence of the "raw material case", the sustainable development level fell sharply. The "raw material case" refers to the appeal filed by the United States, the European Union, and Mexico on the Chinese raw material export restriction measures to the WTO in 2009. The WTO ruled in 2011 that China's raw material export restrictions were in violation. In 2012, China seriously implemented the relevant WTO ruling after the loss of the raw materials case, and cancelled the export tax and export quotas applicable to the raw materials involved.

The third stage was from 2012–2016, during which time China's rare earth sustainability level had steady growth for two years; however, due to the termination of the rare earth export quota system management in 2014, China's rare earth sustainable development declined slightly. However, overall, the rare earth resource sustainable development level has grown steadily with the development of the economy, the society, the environment, and technology.

Based on the rare earth sustainable development level evaluation scale, a comprehensive evaluation from 2006 to 2016 was conducted, the results for which are shown in Table 6. It can be seen from Figure 5 and Table 6 that even though China's rare earth resource sustainable development level was rising from 2006–2010, the comprehensive evaluation value was poor. From 2011 to 2016, China's rare earth sustainable development level fluctuated greatly, and overall it improved compared with the previous five years. Except for the impact of the "raw materials case" and the termination of rare earth export quota management system in 2012 and 2015, the evaluation grade is "poor", and the other years are rated as "average".

Table 6. Comprehensive evaluation level of sustainable development level of rare earth resources in 2006–2016.

Year	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016
Grade	poor	poor	poor	poor	poor	average	poor	average	average	poor	average

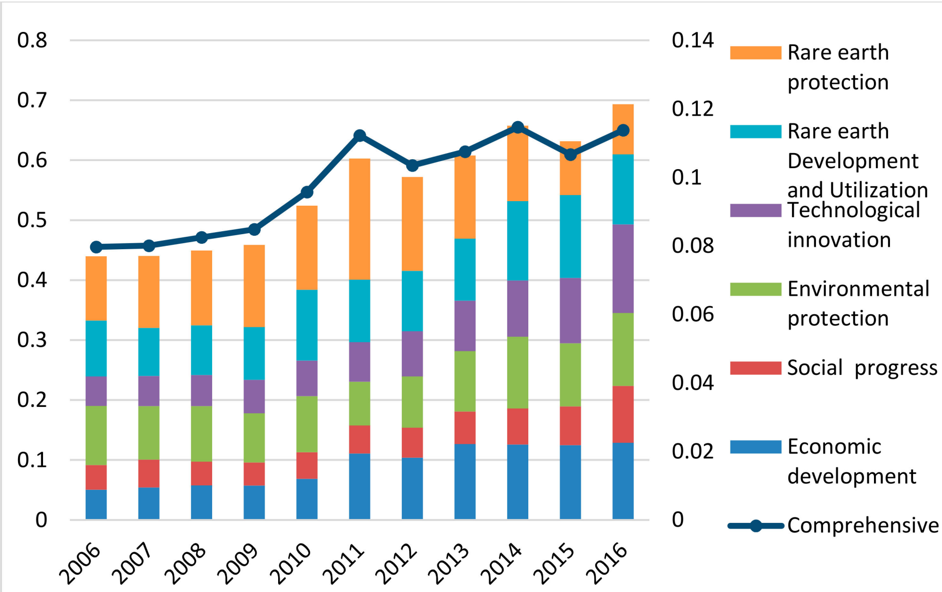

Figure 5. Time-series Gra about coordinated development of six subsystem during 2006–2016.

4.2. Subsystem Evaluation of China's Rare Earth Resource Sustainable Development Level

The time series for the six rare earth subsystem evaluation values from 2006–2016 are shown in Figure 6, from which it can be seen that the economic system, the technological system, and social system experienced rapid growth, while the environmental systems and resource development and utilization system growth rates were relatively slow, which was consistent with the overall comprehensive evaluation value trends. The rare earth protection system grew well from 2006–2011, and had a downward trend after 2011. The results show that the rapid development of the economic, social and technological systems was the most direct driving force for improving China's rare earth resource sustainable development, which was consistent with previous research [24]. However, due to the impact of "raw materials" case in 2011 and the "rare earth case" in 2012, the rare earth export quota system and export tariff policy were abolished. While exports increased substantially, international prices fell, and the rare earth resource protection system continued to decline from 2011. Therefore, it is necessary to pay attention to the protection of rare earth resources to ensure the continued sustainable development of China's rare earth resources in the future.

Based on the rare earth sustainable development rating scale, the sustainable development grades for the various rare earth resource subsystems from 2006 to 2016 were evaluated, as shown in Table 7, from which it can be seen that the level of sustainable development of the economic subsystem continues to rise, from the evaluation value of "poor" in 2006 to the "average" evaluation value in 2011 to "high" in 2013. The social subsystem and the technical subsystem have the same trend of sustainable development. The evaluation value in 2006–2013 is "poor", 2014 is "average", and 2016 is "very high". The environmental subsystems is rated as "average" in 2014 and 2016, and all other years are "poor". The trend of the development and utilization of rare earth subsystems is consistent with the comprehensive rating, and overall is developing in a good direction. Also because of the impact of policies and other factors in 2012 and 2016, the rating dropped to "poor" and "average". The rare earth protection subsystem is most noteworthy. Although it is known from Figure 6 that the evaluation value has increased year by year in the first five years, except for the evaluation grades of "high" and "average" in 2011 and 2012, the ratings for the other years are "poor". The evaluation results for each subsystem indicate that to improve China's rare earth resource sustainable development, it is necessary to pay attention to environmental protection of the rare earth resources and utilize rare earth resources rationally while developing social economic technology.

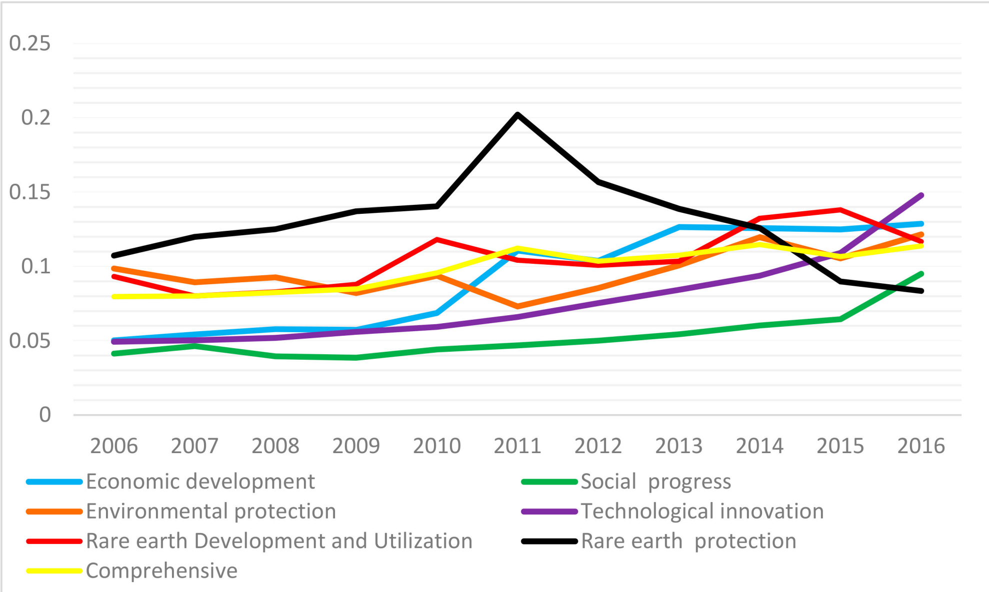

Figure 6. Evaluation value for the rare earth six subsystem sustainability from 2006–2016.

Table 7. Evaluation grade for rare earth resource subsystem sustainable development from 2006 to 2016.

Year	Economic Development	Social Progress	Environmental Protection	Technological Innovation	Rare Earth Development and Utilization	Rare Earth Protection
2006	poor	poor	poor	poor	poor	poor
2007	poor	poor	poor	poor	poor	poor
2008	poor	poor	poor	poor	poor	poor
2009	poor	poor	poor	poor	poor	poor
2010	poor	poor	poor	poor	average	poor
2011	average	poor	poor	poor	average	high
2012	average	poor	poor	poor	poor	average
2013	high	poor	poor	poor	average	poor
2014	high	average	average	average	high	poor
2015	high	average	poor	average	high	poor
2016	high	very high	average	very high	average	poor

5. Conclusions and Policy Recommendations

This paper constructed an index system for the evaluation China's rare earth resource sustainable development level from six perspectives; economic development, social progress, environmental protection, technological innovation, rare earth development and utilization, and rare earth protection. The entropy weight method was used to assign the values to each index, and Grey Correlation Analysis was used to evaluate China's rare earth resource sustainable development level from 2006–2016 on four levels.It was found that China's rare earth resource sustainable development level had a downward trend from 2011–2012 and from 2014–2015, but was steadily increasing in the other years. Even though, China's rare earth resource sustainable development evaluation level is not high, only in the four years of 2011, 2013, 2014 and 2016, the evaluation level is general, and the rest of the years are all poor. Through the analysis of the sustainable development of each subsystem, the results show that the main reason for the poor sustainable development level was the lag in the development of rare earth protection system and environmental protection system. Based on the above analysis and existing policies, the following policy recommendations are given:

(1) Strengthen Rare Earth Resource Protection

China needs to establish and improve the legal systems related to the production and export of rare earth enterprises, increase rare earth resource protection, and maintain rare earth sustainable development by restricting mining, prohibiting unlicensed mining, and eliminating excessive mining. Rare earth export protection needs to be moderately increased to change the rare earth export supply elasticity, which means that the export product structure needs to be adjusted to encourage the export of high value-added products and new rare earth materials, and to limit the export of low value-added raw material grade products and rare earth primary products. In addition, the integration of industry resources needs to be strengthened and the rectification of the rare earth industry accelerated to enhance rare earth industry concentration, control production capacity, promote healthy competition, and improve foreign price negotiation capabilities.

(2) Pay Attention to Environmental Protection when Developing and Utilizing Rare Earth Resources

To achieve rare earth resource sustainable development, it is necessary to improve the development and utilization rate of rare earth resources to achieve coordinated development and protect the ecological environment. First, source pollution needs to be controlled and the discharge of industrial wastewater and waste gas reduced, which would reduce environmental pollution and ecological restoration costs. Therefore, before any new rare earth resource project development, environmental impact assessments must be conducted to identify the pollution that may result from the rare earth resource exploitation, after which research and discussion based on the evaluation results need to be conducted to determine project viability. Second, increased investment in environmental governance is needed to develop new technologies and key equipment for green, efficient mining and smelting and for the separation of the rare earth resources. The optimization and upgrading of production technology and process equipment needs to be accelerated to further improve production and environmental protection technical levels.

(3) Promote the Development of Rare Earth Technological Innovation

Technological innovation is the driving force for improving China's rare earth industry and promoting industrial restructuring. Technological innovation can increase resource utilization, increase product added value, and contribute to environmental protection. The government needs to develop a reasonable talent attraction policy to encourage high-quality research teams and develop policies to encourage independent research and development into rare earth enterprises to create an innovative environment.In addition, it is necessary to increase investment in technological innovation to promote research and development into rare earth new materials and break the foreign high-end rare earth technological monopoly to raise China's status from the bottom of the industrial chain. At the same time, a patent early warning mechanism and a dispute response mechanism need to be established to protect innovation output.

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