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Which Factor Dominates the Evolution of Green Transformation System of Resource-based Enterprises? Evidence from China

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The green transformation of resource-based enterprises, as a complex systemic endeavour, has lacked in-depth exploration of the driving paths and evolutionary patterns of the system. Therefore, we analyse the formation mechanism and framework of the green transformation system of resource-based enterprises (GTSRE). Moreover, drawing on the practical experiences of representative provinces in central and western China from 2008 to 2019, the Haken model and evolutionary orderliness model are employed. The results show that the formation of GTSRE is a coupling and interactive behaviour that arises from the comprehensive consideration of the enterprises and the regions based on their respective development needs and capabilities. The evolution of the GTSRE does not have a completely consistent evolutionary process. Its evolution follows a driving path characterized by government regulation promotion–market green guidance–green technological innovation. The degree of influence of driving factors varies with the developmental stages. The evolution pattern of GTSRE in central and western regions shows significant gaps both within and between regions, and there is a further trend towards expansion.

Keywords: *Resource-Based Enterprises; Green Transformation System; Evolutionary Dynamics Mechanisms; Evolutionary Patterns; Haken Model.*

Introduction

The rapid development of traditional resource-based enterprises, characterized by high investment, high emissions, high pollution, and high energy consumption (referred to as the "four highs"), has significantly contributed to a notable decline in the sustainability of both these enterprises and the ecological environment in their respective regions. Particularly, resource-rich but underdeveloped regions in central and western China face more severe challenges. To break away from their economic disadvantages, these regions have actively sought to attract and accommodate the transfer and relocation of resource-based enterprises from the eastern regions, leading to a long-term overemphasis on economic development, a singular industrial structure, and an imbalanced development intensity. This situation has exacerbated the resource and environmental crisis in these central and western regions (Wang *et al.*, 2021; Wang *et al.*, 2022).

In recent years, resource and environmental issues have emerged as a significant concern for both the Party and the country, gradually rising to the level of a national strategic priority. The *Three-Year Action Plan to Win the Battle for Blue Sky Defence*, the *Energy Production and Consumption Revolution Strategy (2016–2030),* as well as the introduction of the "dual carbon" goal, have all provided a unified and comprehensive framework for promoting a healthy, stable, and green development of the national ecological civilization.

Green transformation, as an effective choice for aligning with a green economy and achieving sustainable development, is a development approach characterized by low resource consumption, minimal environmental pollution, high economic benefits, and rapid growth (Wang *et al.*, 2020; Yin *et al.*, 2022). Undoubtedly, by breaking free from the dual constraints of resources and the environment and achieving a magnificent transformation towards becoming environmental pioneers, green transformation will inevitably become the fundamental path for resource-based enterprises in central and western China.

In fact, due to the high complexity, high costs, high risks, and long cycles associated with green transformation, as well as the presence of "dual positive externalities", resource-based enterprises often find it difficult to engage in green transformation activities spontaneously (Li *et al.*, 2022). As a result, the academic community has conducted research on the driving factors of green transformation for resource-based enterprises. Early studies focused more on the impact of dynamic external environmental factors such as institutions and socioeconomics on the green transformation of resource-based enterprises (Qi *et al.*, 2020; Zhu *et al.*, 2021; Chang *et al.*, 2022). Most studies indicated that green transformation is a passive behaviour of enterprises adapting to changes in the external environment. However, even under the same external environmental conditions, enterprises do not demonstrate uniform transformation behaviour. Subsequently, scholars have shifted their focus to the meso-industry and micro-enterprise levels. At the meso-industry level, studies have mainly focused on dimensions such as industrial structure adjustment and value reconstruction of the industrial chain (Du *et al.*, 2021; Hirose & Matsumura, 2023). At the enterprise level, studies have explored the internal aspects of the enterprise, including resources, capabilities, and demands, demonstrating that the conscious fulfilment of corporate social responsibility, sound internal governance structures, and mature green dynamic capabilities can effectively promote green transformation (Zhou *et al.*, 2021; Yang *et al.*, 2021).

It is worth noting that, in the process of resource-based enterprises pursuing efficient resource utilization, vertical linkages are formed through resource consumption, while horizontal linkages are established through mutual support, creating interconnections within the industry. This intricate interplay gives rise to the green transformation system of resource-based enterprises (GTSRE). Therefore, green transformation is a multi-level and multi-stakeholder system engineering. Research on green transformation systems originated from the issue of green transformation in resource-based cities (Liu *et al.*, 2019; Lu *et al.*, 2023). With the increasing prominence of issues in resource-based cities, scholars have gradually realized that the macro-level understanding of green transformation in resource-based cities seems to overlook the specific development issues of numerous industries and enterprises behind them. Instead, it may impede the progress of green transformation in resource-based cities. This realization has led to more refined research on green transformation systems for industries and enterprises (Inigo & Albareda, 2016; Yin & Li, 2018; Yang *et al.*, 2022). In particular, Sun (2013) proposed that the ecological network system of green transformation in resource-based enterprises can be divided into a core layer, an auxiliary layer, and a peripheral layer, which laid the foundation for the preliminary construction of the structure model of GTSRE.

As the practice progresses, evaluating and recognizing the effectiveness of green transformation in resource-based enterprises has become another focal point for scholars. Relevant research has mostly focused on two aspects: evaluating green transformation schemes and assessing the degree of green transformation. From the perspective of evaluating green transformation schemes, Rui *et al.* (2018) focused on the development of oil sand resources in Canada. By analysing a large amount of historical data, they established a comprehensive evaluation model and collected data on 15 internal and external parameters of 35 oil sands projects in Canada. The comprehensive evaluation concluded that using steam-assisted gravity drainage technology for oil sands development is economically feasible with positive environmental effects. Zhou *et al.* (2019) utilized real options and scenario analysis methods to explore the optimal investment patterns and selection routes for enterprise green transformation technologies. From the perspective of assessing the degree of green transformation, several studies have aimed to accurately grasp the green transformation trends in resource-based enterprises by constructing comprehensive evaluation systems based on multiple indicators and dimensions or using input-output models (Mingaleva *et al.*, 2019; Xia *et al.*, 2020; Chen *et al.*, 2023).

In summary, the current research exhibits the following characteristics:

(1) Most of the aforementioned studies subjectively overlook the connections between the transformation subject and other individuals, lacking a systematic perspective to interpret the green transformation behaviour of resource-based enterprises. Few studies consider the GTSRE as a research premise, and there is a lack of beneficial discussions on how this system forms, as well as an integration and improvement of its framework.

(2) Although the aforementioned studies comprehensively explore the driving factors from macro to micro levels, providing a relatively systematic theoretical analysis framework for promoting the green transformation of resource-based enterprises, they tend to focus on exploring the quantity and categories of driving factors. They are often based on implicit assumptions of equal weights for various driving factors, while neglecting the inherent interrelationships among these factors and lacking an understanding of the mechanisms of interaction and impact among multidimensional factors.

(3) The above-mentioned studies mostly have limitations in terms of evaluating the effectiveness of green transformation in resource-based enterprises, as they often focus on short-term and static assessments. Specifically, when addressing the green transformation of resource-based enterprises at the system level, there is a lack of long-term tracking and identification of the system's evolving developmental level and dynamic characteristics, as well as in-depth analysis of the roots and evolution processes of various issues that arise during the transformation.

The current research status has limited guidance on the strategies and behaviour optimization for steadfastly promoting green transformation practices in a dynamic environment. To narrow the knowledge gap, this study is grounded in the practical field of resource-rich areas in the central and western parts of China and focuses on the perspective of GTSRE. Building upon the analysis of the formation mechanism and framework of this system, the study employs the Haken model to dissect the inherent interrelationships and "black box" effects of multi-dimensional factors in green transformation. Furthermore, the study integrates the evolutionary orderliness model to examine the dynamic evolution trends of GTSRE (Figure 1). Compared to the existing studies, the marginal contributions of this study are mainly in the following three aspects: (1) Revealing the formation logic of the system from the perspective of coupling of elements between resource-based enterprises and their respective regions, and refining its theoretical framework; (2) Breaking the limitations of the current analysis model that treats driving factors as independent and equally weighted, and emphasizing the interactive attributes of multidimensional factors. The study accurately extracts the driving chains and key paths of system evolution through stage-by-stage and regional refining; (3) Clarifying the long-term and orderly evolution trends and differences of GTSRE through multidimensional comparisons, and providing effective insights into the issues of evolutionary development. The primary objective of this study is to unveil the evolutionary dynamics mechanisms and levels of the GTSRE. It is also hoped that this study will provide a theoretical reference and decision-making basis to accelerate the development of green transformations in resource-based businesses in China and emerging economies globally.

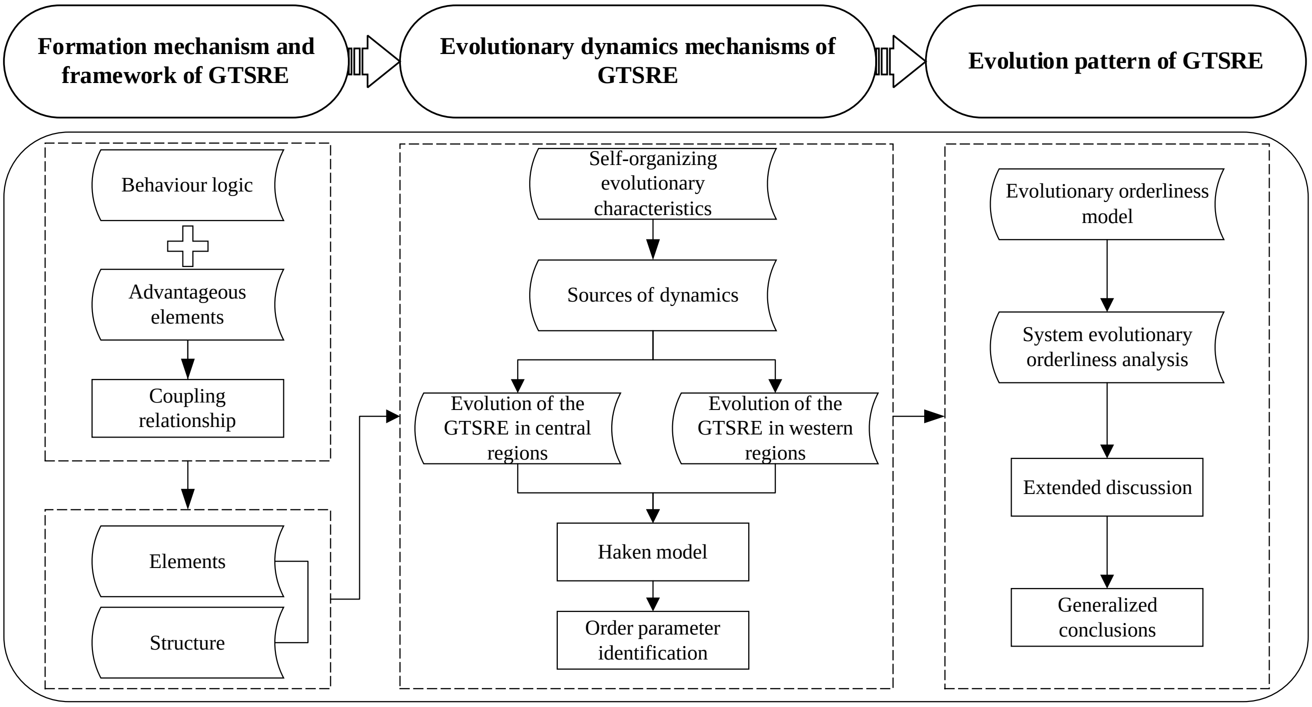


Figure 1. Research Framework

Methodology and Analysis

Formation Mechanisms and Structure of GTSRE

Due to the involvement of two major stakeholders, namely the decision-makers of resource-based enterprises and the decision-makers of the local government, the green transformation of resource-based enterprises is fundamentally an aggregation of interactive behaviours between decision-makers based on their respective value pursuits (Li *et al.*, 2020). Human behaviour tends to follow a logical chain of "demand-motivation-behaviour". Corporate decision-makers of resource-based enterprises, driven by the value pursuit of sustainable development, interact with the gravitational pull of external resources and the pressure of transformation risks, thereby generating the motivation for resource-based enterprises to seek cooperation in their respective regions. On the other hand, the decision-makers of the local government, in light of the value guidance for high-quality regional economic development and the full consideration of the development laws that entail mutual benefits and losses between the resource-based region and mineral resource development, are motivated to provide external support for the green transformation of resource-based enterprises. This motivation is driven by the gravitational pull of the diverse benefits in terms of economic, social, and ecological aspects brought about by the green transformation, as well as the pressure of regional economic losses caused by the failure of the transformation.

However, the transition from motivation to behaviour is not immediate. Through in-depth comparative analysis, both parties gradually clarify the complementary and coupling characteristics between the advantageous elements of resource-based enterprises (practical mining technology, abundant capital, mature management experience, complete human resources, etc.) and the supporting elements of the region (policy support, market support, technological innovation support, ecological support, etc.). Once the behaviour occurs and the coupling relationship is established, the resource-based enterprises and their respective regions can gradually transform into interdependent and symbiotic relationships through dynamic interaction mechanisms such as risk sharing, cooperation sharing, information transmission, and resource flow, using the complementary elements of both parties as a bridge. As a result, the GTSRE is formed (Figure 2). Specifically, for resource-based enterprises, actively participating in the construction of the system and the linkage of relationships can accelerate the enhancement of their own green transformation capability through complementary, spillover, and collaborative effects.

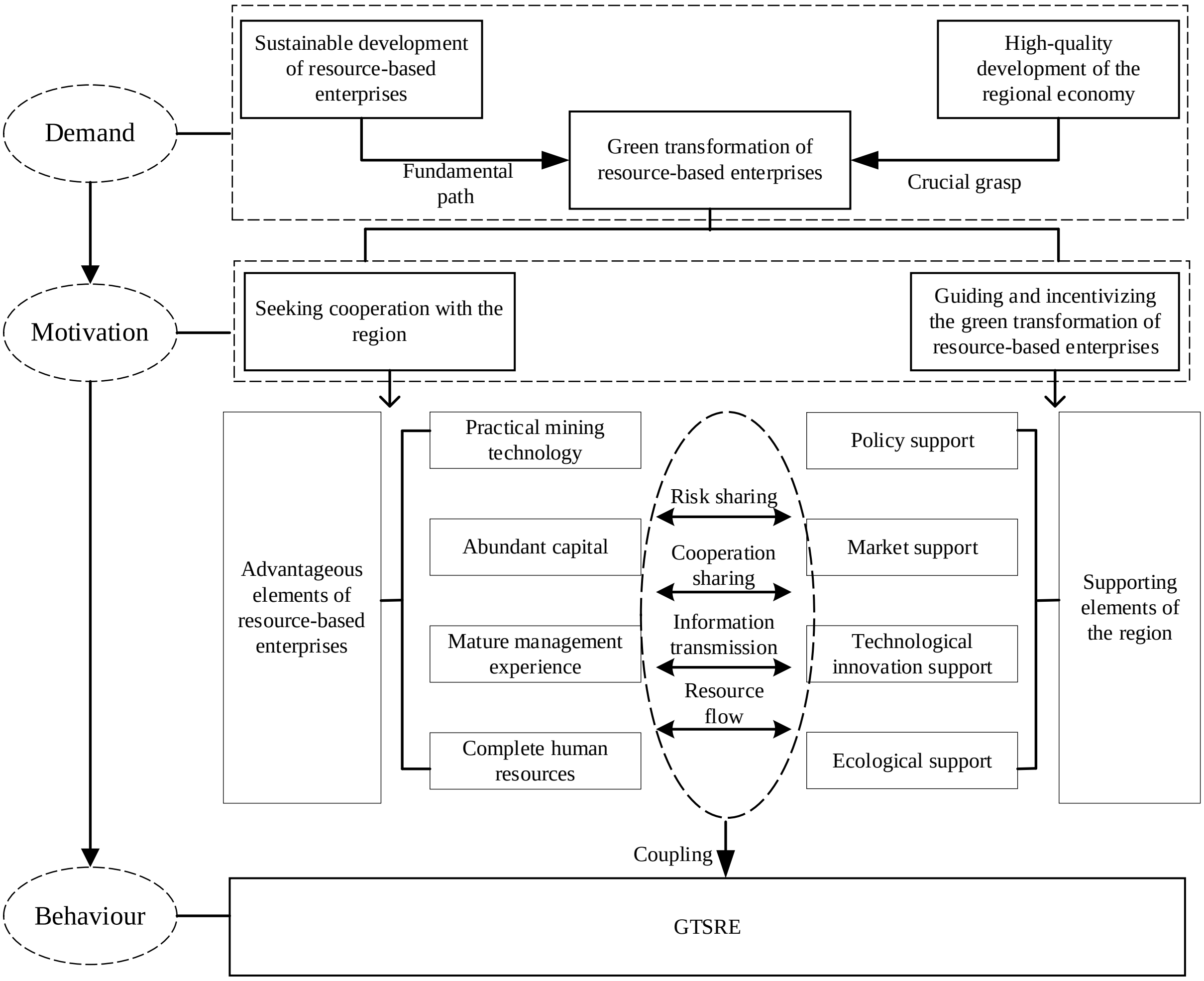


Figure 2. Formation Mechanisms of GTSRE

The GTSRE can be defined as a collection of various elements and their behavioural relationships that are involved in the green transformation of resource-based enterprises. Specifically, it is an organic whole of interconnection and interaction formed within a specific time and space scope by resource-based enterprises as the core, and uniting the governments of cities and provinces where resource-based enterprises are located, upstream and downstream enterprises in the industry chain, competing enterprises, service institutions, intermediaries, and other multiple subjects through the flow of green transformation resources.

In terms of hierarchical structure, the GTSRE can be divided into three levels, including the core layer, the auxiliary layer, and the peripheral layer, as shown in Figure 3. In the core layer, resource-based enterprises are the main implementers of green transformation. In the auxiliary layer, entities such as governments, industry associations, research institutions, financial institutions, etc., provide green transformation resources such as institutions, information, technology, and funding to the core layer, thereby guaranteeing, supporting, and catalysing green transformation activities. The peripheral layer is a collection of various environmental factors on which the survival and development of the green transformation subjects depend, which indirectly affects the behaviour of green transformation subjects.

In GTSRE, the core layer, the auxiliary layer, and the peripheral layer are all dynamically open to each other. With the continuous exchange of resource sharing, information transmission, material circulation, and energy flow between the layers, a complex, symbiotic whole of interrelated and interdependent entities is formed through value connection, promoting coordinated development and ultimately achieving the goal of green transformation of resource-based enterprise.

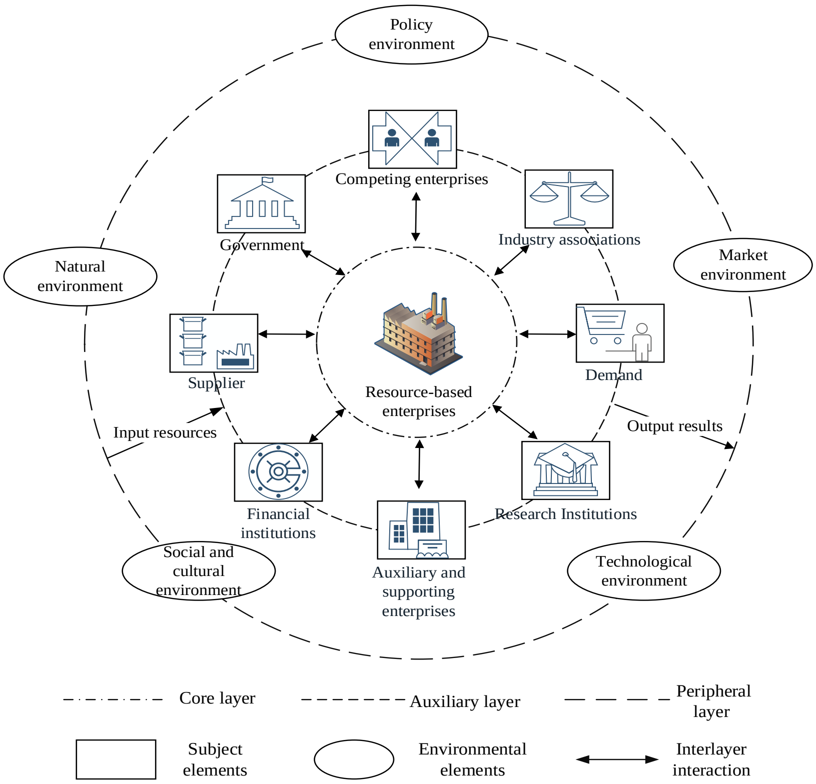


Figure 3. The Basic Structure of GTSRE

Analysis of the Evolutionary Dynamics Mechanisms of GTSRE

Self-organizing Evolutionary Characteristics of GTSRE

Self-organization (Haken, 1981) occurs when the subsystems within a system form an orderly structure through a mutually agreed set of rules, without external interference. The GTSRE is a collaborative and evolving system with self-organizing features. Firstly, the green transformation system of resource-based enterprises interacts dynamically with the external environment through openness. On one hand, the system outputs green technologies, green products, and green services to the outside through internal operations and transformations, thereby creating new benefits for businesses and society. On the other hand, the development of society further provides the green transformation system with more and better materials, energy, and information, thus forming a virtuous cycle. Secondly, the development levels of various entities within the system, as well as the distribution and flow of resources, are inherently imbalanced. Moreover, there exist nonlinear competitive relationships across multiple entities and hierarchical levels among the elements involved in green transformation. Leveraging various positive and negative feedback mechanisms, the GTSRE exhibits systemic and complex characteristics. Lastly, due to being an open dynamic system, the GTSRE is subject to the intertwined effects of internal and external factors, leading to the existence of random fluctuations. These fluctuations can arise from factors such as changes in government policies, breakthrough innovations in technology, and improvements in barriers within the resource industry. However, these fluctuations are random. Once random fluctuations occur under critical conditions of system instability, they can be amplified by the nonlinear mechanisms within the unstable system, resulting in significant fluctuations and causing the system to undergo abrupt changes. Overall, the evolution of GTSRE is a self-organizing process characterized by complexity and nonlinear interactions, continuously overcoming the increase in entropy and enhancing organizational order. During this process, the system undergoes dynamic transitions in its structures and states.

Sources of Dynamics for the Evolution of GTSRE

The theory of synergetic posits that self-organization within a system is a dynamic process of mutual competition and collaboration among its subsystems. In this process, the order parameter, acting as an "invisible hand," is initially generated through competitive and cooperative interactions among the subsystems. Subsequently, it controls and guides the interactions among the subsystems in a manner that governs or empowers them, thus dominating the ordered evolution of the system. Therefore, the order parameter is crucial in explaining the operation of system self-organization.

To this end, a literature review and quantitative analysis of studies related to the green transformation of resource-based enterprises are conducted by VOSviewer. Three major driving factors are identified at the macro, meso, and micro levels: government regulation promotion (GRP), market green guidance (MGG), and green technological innovation (GTI), as illustrated in Figure 4.

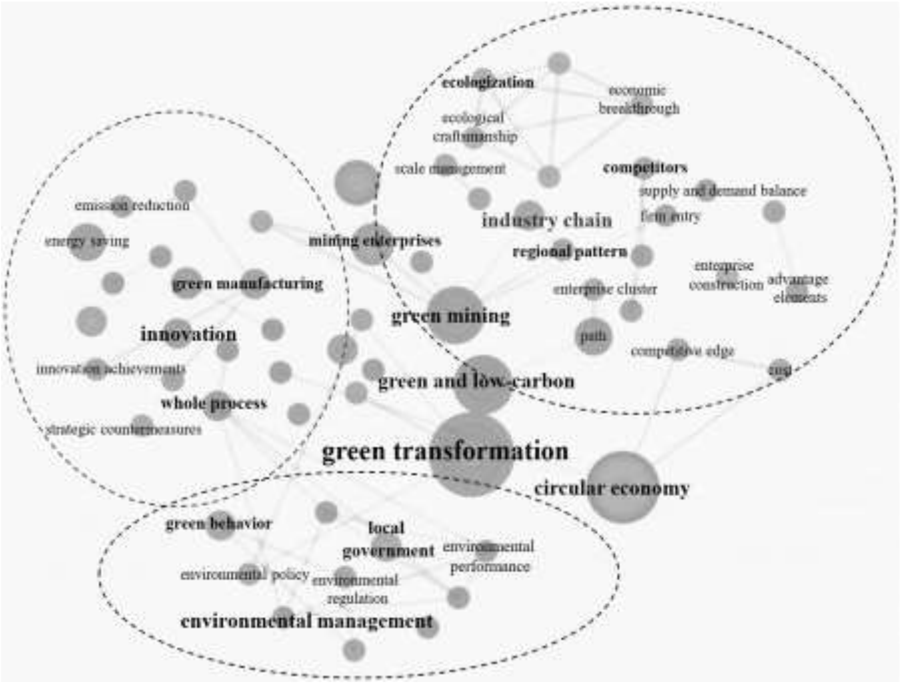


Figure 4. Literature Search on the Drivers of Green Transformation in Resource-Based Enterprises

(1) Government Regulation Promotion

Over the years, as a typical "four highs" enterprise, resource-based enterprises have short-sighted development visions, resulting in a lack of awareness of green development. With the fierce competition in the resource market, the reverse selection mechanism has accelerated the "black" development trend of resource-based enterprises. Therefore, for the GTSRE in the early stages of development, because the market mechanism and social awareness are still in a state of oppression (Guo & Zheng, 2011), the internal structural elements of the system are extremely incomplete. On the one hand, the number of green transformation subjects is small, presenting an irrelevant, loose state, and tending to develop disorderly. On the other hand, resources for green transformation are scarce, with a slow flow rate and low resource allocation efficiency.

In reality, under the political system and economic background from top to bottom in China, the government representing national and regional interests must first try to use administrative means to forcefully promote the establishment of internal order in the GTSRE (Zhang & Wang, 2023). As the government has an absolute advantage in setting goals and allocating resources, it can regulate the development behaviour of resource-based enterprises by formulating reasonable environmental regulations and standardized policies to internalize the external negative effects of environmental problems such as production and emission standards, resource utilization, and environmental pollution fees, thereby improving the efficiency of resource utilization of resource-based enterprises. In addition, the government can use industrial policies and fiscal incentives to stimulate the green behaviour of enterprises. With the help of comprehensive research and judgment, the government will lay out several forward-looking basic and common technologies in the region, take the lead in organizing scientific research institutes and universities to jointly conduct research and actively coordinate with financial institutions to build a financing matching platform for enterprise green transformation projects. In this process, green transformation resources and elements can break through the barriers between subjects to achieve emergence and aggregation, gradually break the scattered state of the system at its initial stage, and make the system structure clearer. Therefore, the stage of GRP is an important link to laying the foundation, and through GRP, it can provide necessary initial conditions such as the aggregation of green transformation resources and the coordination of green transformation subjects for the subsequent evolution of the GTSRE.

(2) Market Green Guidance

With the continuous release of policy dividends from the previous GRP mechanism, the green guidance of the resource market gradually emerged and replaced the dominant position of the government, leading the GTSRE into a new stage of evolution. The promotion of MGG on the evolution of the GTSRE is mainly reflected in green demand and green competition. Among them, the formation of green demand in the resource market mainly stems from two aspects. First, the widespread advocacy of green development concepts has strengthened the public's awareness of green consumption, and their purchasing preferences have also begun to shift toward low-carbon, green, and environmentally-friendly products (Huang *et al.*, 2023). Second, the government further leverages the green demand in the resource market by purchasing green resource products and services (Wang *et al.*, 2023). At the same time, the expansion of market green demand will attract more members to join, leading to the gradual optimization and improvement of the market competition mechanism.

As the starting and ending point of all activities arranged by resource-based enterprises, the market will inevitably give rise to green adjustments in production and operational strategies in response to green market demand. When green development permeates the market competition pattern, resource-based enterprises, to maintain their competitive advantage and continuously enhance their corporate reputation and image, will also actively assume social responsibility and strive to increase the "green" content of their production processes and products. In this process, considering the complexity and risk of green innovation, resource-based enterprises take the initiative to unite other subjects within the system and organically integrate the elements of government policies, research institutions' knowledge incubation, financial institutions' funds, and intermediaries' services through a clear division of labour and cooperation in the market, to finally cater to the market and realize the value co-creation of the GTSRE. Compared with the primary stage of the evolution of the GTSRE, the vitality of resource-based enterprises has been stimulated and their dominant position has been enhanced, the frequency of cooperation among subjects has been strengthened, and the allocation efficiency of resource factors has been greatly improved. This leads to a significant increase in the environmental adaptability, stability, and operational performance of the GTSRE, thereby driving the extension and expansion of the entire GTSRE. MGG plays an important role in the intermediate stage of the evolution of the GTSRE. It should also be pointed out that the role of the government has not disappeared when the MGG is exerted. At this time, the role of the government is more reflected in the supervision and maintenance of the operation of the resource market (He *et al.*, 2023).

(3) Green Technology Innovation

Under the regulation of MGG mechanisms, resource-based enterprises have successfully transformed their green innovation activities into economic value. However, the low-end locking of innovation still restricts the development of these enterprises (Ali *et al.*, 2019). On the one hand, this is manifested as a low-end locking of technological innovation, where resource-based enterprises remain largely in the imitation innovation stage. On the other hand, due to the low-end locking of technology, which constrains the product positioning of resource-based enterprises, these enterprises have been confined to a low level of market innovation. In this context of intense market competition, narrow profit margins, and low customer loyalty, the improvement of GTI is an important driving force for resource-based enterprises to break through their development bottlenecks during their green transformation period.

With the accumulation of certain technical capabilities in the earlier stages, resource-based enterprises have gradually replaced the single requirement of green product quantity output with the pursuit of green production efficiency, as well as the quality and variety of green products. This has led to a gradual increase in the coupling degree between R&D activities and the technical support requirements of resource-based enterprises within the system. This has significantly reduced the cost of R&D activities while enhancing the effectiveness of green technology innovation R&D activities. Moreover, it has facilitated the continuous implementation of GTI projects, bringing about a leap in the productivity of resource-based enterprises and the premium effect of green products through the autonomous control of core green technologies. In addition, GTI places greater emphasis on organic integration with market demand, rather than simple mechanized reflection (Yi & Dan, 2022). Concretely, GTI should not only meet the existing market demand, but more importantly, it should be able to identify brand-new application scenarios and break through the gap between R&D and commercialization by continuously stimulating and developing potential market demand. Through this, new markets are successfully created, opening up enormous profit margins and creating a constant source of driving force for the development of resource-based enterprises. GTI for resource-based enterprises is not a one-time event, but rather has a “Matthew effect”. In this process, heterogeneous resources emerge continuously within the system, and through the interaction and cooperation with other green transformation entities, resource-based enterprises effectively internalize external knowledge via "learning by doing", gradually forming their core GTI capabilities. Based on the coupling and coordination of multiple stages of green innovation activities over a long period, the distance between multiple entities within the system is further shortened, the flow channels of factors within the system are further opened up, and the effectiveness of resource allocation is significantly strengthened. Through collaborative operation and efficient integration among entities, the structure and function of the system are optimized and upgraded.

From a logical perspective, the government's decentralization of power continuously transforms government behaviour into market and enterprise practices. Therefore, GRP is the basis of MGG and GTI. Under MGG, the impetus for corporate GTI is born, making MGG the foundation of GTI. These three driving factors promote and rely on each other, utilizing a cycle of "competition-collaboration-competition" to achieve a spiral rise, promoting the entire GTSRE by the cycle path of "stability-instability-stability" to achieve evolutionary upgrades. Thus, a more logical, adaptable, and vital system functionality and structure are formed, as shown in Figure 5.

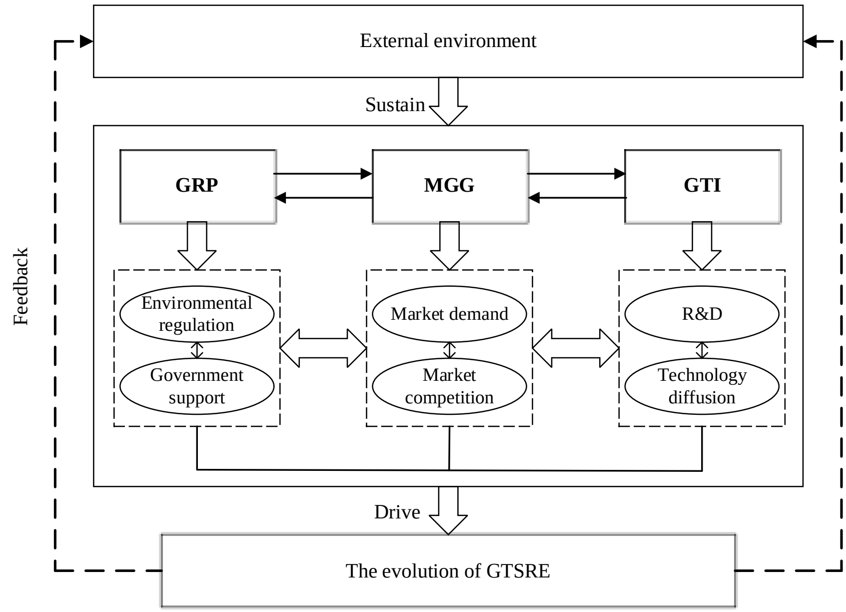


Figure 5. Conceptual Model of the Evolutionary Dynamics Mechanisms of GTSRE

Haken Model

Haken used the adiabatic principle in physics to investigate the interactions between different variables within a system, thus identifying the order parameter and determining the evolution equations and potential functions of the system. This method inspires examining the evolutionary dynamics mechanisms of GTSRE.

Assuming that in a certain motion system, there are two subsystems: one is the order parameter q_1, and the other is the variable q_2 that is governed by this order parameter. The motion equation satisfied by the system is

$$\dot{q}_1 = -\lambda_1 q_1 - a q_1 q_2 \tag{1}$$

$$\dot{q}_2 = -\lambda_2 q_2 + b q_1^2 \tag{2}$$

where λ_1 and λ_2 are the damping coefficients of the subsystems. If λ_1 (λ_2)>0, it indicates that negative feedback mechanisms have been established between subsystem q_1 (q_2). If λ_1 (λ_2)<0, it indicates that positive feedback mechanisms have been established between subsystem q_1 (q_2). a and b represent the strength of the interaction between subsystems q_1 and q_2, respectively. If $a > 0$, it means that q_2 impedes the growth of q_1, and vice versa. If $b > 0$, it means that q_1 promotes the growth of q_2, and vice versa.

To satisfy the adiabatic approximation assumption, it is necessary to have "$|\lambda_2| \gg |\lambda_1|$" (Haken, 1981). This means that subsystem q_2 changes and decays much faster with time than q_1. At this juncture, should q_2 be instantaneously withdrawn, it is inevitable that q_1 would fail to undergo the requisite transformation within the required timeframe. Let $\dot{q}_2$=0, then we obtain:

$$q_2 = \frac{b q_1^2}{\lambda_2} \tag{3}$$

Substituting this into equation (1), we can obtain the evolution equation of the order parameters, which is the evolution equation of the system:

$$\dot{q}_1 = -\lambda_1 q_1 - \frac{ab q_1^3}{\lambda_2} \tag{4}$$

The potential function equation of the system is obtained by integrating the opposite of $\dot{q}_1$:

$$v = \frac{1}{2}\lambda_1 q_1^2 + \frac{ab}{4\lambda_2} q_1^4 \tag{5}$$

The stable point of the potential function is determined by $\dot{q}_1$=0. For equation (5), it can be divided into the following two cases:

①If $a*b*\lambda_1*\lambda_2 > 0$, the evolution equation has only one solution q_1=0. At this time, the point (0, 0) is the only stable point, and the state of any point X in the system depends on the distance d between that point and the point (0, 0). The larger the value of d is, the more it deviates from the steady state, and the evolutionary orderliness of the system is lower, and vice versa.

②If $a*b*\lambda_1*\lambda_2 < 0$, there exist three solutions to the evolution equation: $q_1^* = 0$, $q_1^{**} = \sqrt{\left|\frac{\lambda_1\lambda_2}{ab}\right|}$ and $q_1^{***} = -\sqrt{\left|\frac{\lambda_1\lambda_2}{ab}\right|}$. In this case, q_1^* is an unstable solution, which is generally not considered in realistic analysis, and q_1^{**}, q_1^{***} are stable solutions. If the order parameter is a positive variable, then the point($q_1^{**}, v(q_1^{**})$)is a stable point of the potential function, at which time the state of any point X in the system depends on the distance d between that point and the point ($q_1^{**}, v(q_1^{**})$).

Since the Haken model is set up for continuous random variables, the following discretization is required when applying it to the analysis of GTSRE:

$$\begin{aligned} q_{1(t)} &= (1-\lambda_1)q_{1(t-1)} - aq_{1(t-1)}q_{2(t-1)} \\ q_{2(t)} &= (1-\lambda_2)q_{2(t-1)} + bq^2_{1\,(t-1)} \end{aligned} \quad (6)$$

Description of Research Subjects

The central and western regions of China are vast and rich in mineral resources as shown in Table 1. Among them, Shanxi and Henan in the central region are important energy and chemical bases in China. Around coal, coalbed methane, rock salt, gold, molybdenum ore, and other advantageous minerals, regional resource-based enterprises have gained rapid development. From 2008 to 2019, the average number of resource-based enterprises above a certain scale in Shanxi accounted for more than 70 % of the total industrial enterprises in the province, with their sales value on average accounting for over 85 %. Similarly, in Henan, there were an average of 7717 resource-based enterprises above a certain scale, ranking first among the six central provinces, with their sales value accounting on average for 50%. Overall, the absolute sales value of these enterprises in Henan and Shanxi in 2019 reached 21684.28 hundred million yuan and 17470.12 hundred million yuan, respectively, making these two provinces the leaders in resource-based enterprise development in the central region and key players nationwide (see Figures 6 and 7).

Meanwhile, the geological conditions in the western region are even better, with major reserves of coal, oil, natural gas, and other mineral resources. From 2008 to 2019, the average sales value of resource-based enterprises above a certain size in Shaanxi accounted for over 60% of the total industrial enterprises, with the absolute sales value reaching 14,208.50 hundred million yuan in 2019. While in Inner Mongolia, the average sales value of such enterprises was 75 %, with the absolute sales value reaching 13829.04 hundred million yuan in 2019. Moreover, relying on abundant mineral resources, the development momentum of resource-based enterprises in Xinjiang has been particularly rapid, with the number of such enterprises above a certain size rising nearly twofold from 936 in 2008 to 1848 in 2019, and in recent years, their sales value on average has accounted for 80 % of all such industrial enterprises, making resource-based enterprises the economic pillar of Xinjiang (see Figures 6 and 7).

However, as resource-based enterprises have become important growth engines for the economic development of these provinces, the resulting overreliance on such enterprises has brought inevitable economic and environmental problems to the regions (Wang *et al.*, 2021). Given this, considering the completeness and availability of research data and the generalizability of research results, this paper selects five central and western provinces, including Shanxi, Henan, Inner Mongolia, Shaanxi, and Xinjiang, which are more representative and exemplary, to conduct an empirical study to explore the evolutionary dynamics mechanisms of GTSRE.

Table 1

Distribution of Base Reserves of Major Mineral Resources by Region

Region	Oil (hundred million tons)	Natural gas (hundred million cubic meters)	Coal (hundred million tons)	Iron ore (hundred million tons)	Manganese ore (ten thousand tons)	Chrome ore (ten thousand tons)	Vanadium ore (ten thousand tons)
Midwest	15.22	46093.98	2252.76	100.21	294.28	4.03	9.37
Nationwide	35.01	54365.46	2492.26	201.20	310.34	4.07	9.52

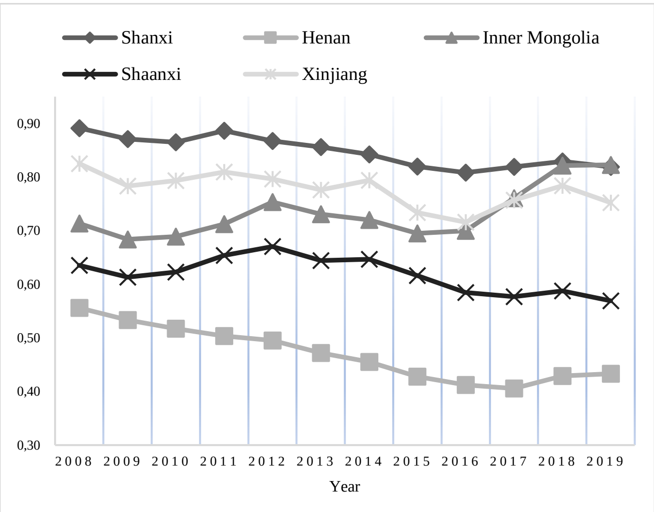


Figure 6. Trends in the Proportion of Industrial Sales Value of Resource-Based Enterprises above the Scale

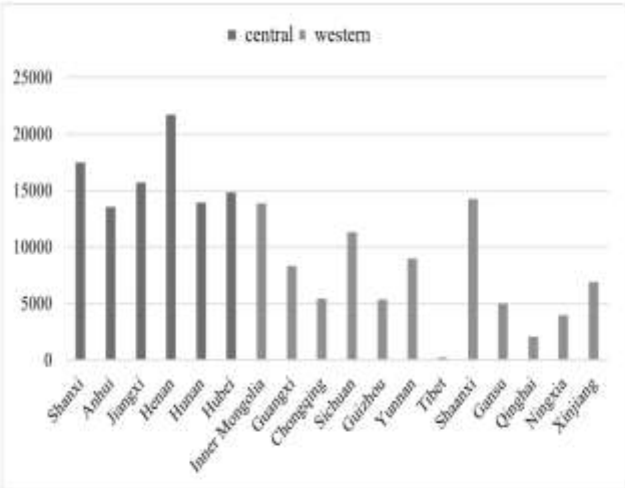


Figure 7. Industrial Sales Value of Resource-Based Enterprises Above the Scale in the Midwest (2019) (hundred million yuan)

Variable Selection

Government Regulation Promotion

GRP drives two dimensions, including environmental regulation and government support. In terms of environmental regulation, the academic community mainly follows several approaches to measure it: (1) the number of environmental regulatory policies, which is generally measured by the accumulation of effective environmental laws and regulations at the local level (Shen *et al.*, 2018); (2) the implementation intensity of environmental regulatory policies, which includes proxy indicators such as the number of environmental agencies, environmental staff, inspections and supervisions of business emissions by environmental agencies, and the number of environmental administrative penalty cases per capita (Cole *et al.*, 2008); (3) the effectiveness of environmental regulatory policies, which involves changes in pollutant emissions and compliance with standards, and business compliance willingness and status (Du *et al.*, 2019). Drawing on previous research and considering data availability, we adopt the two indicators of "cumulative number of effective local environmental laws and regulations (pieces)" and "the proportion of investment completed in industrial pollution control projects to the main business costs of scale-above industrial enterprises (%)" to comprehensively measure environmental regulation. As for government support, we choose government low-carbon subsidies as a proxy indicator. Government low-carbon subsidies are aimed at developing a low-carbon economy and helping businesses address various difficulties in obtaining low-carbon technologies, financing, investment, production and operation planning, and sales through various forms and means (Chang *et al.*, 2022). The specific indicator can be represented by the proportion of local fiscal energy conservation and environmental protection expenditures to total fiscal expenditure (%).

Market Green Guidance

MGG is considered from two aspects: market competition and market demand. Regarding market competition, the degree of competition in the resource market will directly affect the choice of green development strategy for resource-based enterprises. Referring to previous research (Yang & Yin, 2015), two indicators, namely the number of resource-based enterprises above a certain scale and the location entropy, are selected to comprehensively measure the degree of competition in the resource market. Among them, the number of resource-based enterprises above a certain scale reflects the degree of market competition positively, that is, the more companies there are, the greater the degree of market competition. Location entropy can not only measure the spatial distribution of factors but also effectively eliminate the adverse effects caused by differences in scale among regions, to a certain extent, reflecting the relative concentration of the resource industry in the region and indirectly reflecting the degree of market competition in resources. The formula for calculating the location entropy is as follows:

$$LQ = \frac{E_{ijt} / \sum_j E_{ijt}}{\sum_i E_{ijt} / \sum_i \sum_j E_{ijt}} \tag{7}$$

where E_{ijt} denotes the average annual employment of resource-based enterprises above a certain scale in region *i* at time *t*, $\sum_j E_{ijt}$ indicates the average annual employment of industrial enterprises above a certain scale in region *i* at time *t*, $\sum_i E_{ijt}$ represents the average annual employment of resource-based enterprises above a certain scale in the whole country at time *t*, and $\sum_i \sum_j E_{ijt}$ means the average annual employment of industrial enterprises above a certain scale in the whole country at time *t*. The higher the value of LQ is, the more concentrated the resource-based enterprises are in the region, and the more competitive the resource market will be, and vice versa.

Regarding the market demand, two indicators, namely the growth rate of the industrial sales output value of resource-based enterprises above a certain scale and the per capita disposable income of the region, are selected to comprehensively reflect the market demand situation. The industrial sales output value can directly reflect the market demand for resource-based enterprises' output products in monetary form, and the change in the growth rate of industrial sales output value can further reflect the guiding role of market demand on enterprise development. In addition, the per capita disposable income is proportional to the standard of living which means the higher the per capita disposable income, the higher the standard of living. While the improvement of living standards will, to a certain extent, bring about an increase in consumer awareness of environmental protection, and the consumers' willingness to pay for green products will become stronger, so the per capita disposable income will indirectly reflect the change of green demand in the market.

Green Technological Innovation

Previous studies have mainly measured GTI through input-based methods (Wang & Chen, 2018), output-based methods (Wang *et al.*, 2023), and efficiency-based methods (Dong & Li, 2023). Compared with direct indicators such as input and output, efficiency can better reflect the ability and level of GTI (Bai & Jiang, 2015), and has good explanatory power in measuring GTI.

The Super-SBM model can not only effectively solve the slack problem of input and output, but also fully considers and effectively resolves the unexpected output problem. Additionally, it can solve the identification and ranking problems of decision-making units (DMUs), effectively overcoming the defects of traditional data envelopment analysis (DEA) models. The model assumes that there are n DMUs in the production system, i.e. $DMU_j (j = 1, 2, \cdots n)$. For each DMU, $X = [x_1, \cdots, x_n] \in R^{m\times n}$, $Y^g = [y_1^g, \cdots, y_n^g] \in R^{s_1\times n}$ and $Y^b = [y_1^b, \cdots, y_n^b] \in R^{s_2\times n}$ representing m input indicators, s_1 expected output indicators and s_2 unexpected output indicators, respectively. The linear programming equation for the Super-SBM model is formulated as shown in Equation (8), where ρ is the target efficiency value, s^-, s^g

and s^b represent the corresponding slack values for input, expected output, and unexpected output, respectively, and k is the evaluated DMU, λ is the weight vector of the DMU.

$$\min \rho = \frac{1+\frac{1}{m}\sum_{i=1}^{m} s^- / x_{ik}}{1-\frac{1}{s_1+s_2}\left(\sum_{r=1}^{s_1} s_r^g / y_{rk}^g + \sum_{l=1}^{s_2} s_l^b / y_{lk}^b\right)}$$

$$s.t.\begin{cases} \sum_{j=1,\neq k}^{n} x_{ij}\lambda_j - s^- \le x_{ik}, i = 1,2,\cdots,m \\ \sum_{j=1,\neq k}^{n} y_{rj}^g\lambda_j + s^g \ge y_{rk}^g, r = 1,2,\cdots s_1 \\ \sum_{j=1,\neq k}^{n} y_{lj}^b\lambda_j - s^b \ge y_{lk}^b, l = 1,2,\cdots s_2 \\ \lambda_j, s^-, s^g, s^b \ge 0, j = 1,2,\cdots n \end{cases} \quad (8)$$

Regarding the selection of input and output indicators for GTI, previous studies (Zhou *et al.*, 2018; Dong & Li, 2023) are referred to from an input perspective to characterize capital and labour inputs. The perpetual inventory method is used to account for the R&D capital stock of resource-based enterprises above a certain scale as a proxy indicator for capital input, and the full-time equivalent of R&D personnel in resource-based enterprises above a certain scale is selected as a labour input. In terms of output, expected and unexpected outputs are considered separately. For expected output, the effective invention patents of resource-based enterprises above a certain scale and the sales revenue of new products of resource-based enterprises above a certain scale are selected to characterize knowledge creation and product output, respectively. For unexpected output, as GTI differs from general technological innovation with the aim of significantly reducing environmental pollution. Given that the dumping and disposal of industrial solid waste have greatly decreased in recent years due to its comprehensive utilization and storage, this paper intends to start from industrial wastewater and sulphur dioxide emissions, supplemented by the correction of the proportion of resource-based enterprises above a certain scale, to obtain industrial wastewater and sulphur dioxide emissions of resource-based enterprises above the scale. We then use the entropy method to obtain the comprehensive value of environmental pollution, which will be used to measure the unexpected outcomes of environmental pollution caused by the GTI of resource-based enterprises.

Considering the requirement of the DEA model for the number of DMUs, the entropy method is used to convert the output variables containing multiple secondary indicators. Additionally, due to the significant data gaps regarding GTI of resource-based enterprises in other central and western provinces, while ensuring data consistency, three additional provinces are added on top of the original five representative provinces in central and western China. Therefore, a total of eight DMUs (Shanxi, Henan, Hubei, Hunan, Inner Mongolia, Shaanxi, Yunnan, and Xinjiang) are selected. The relevant input-output data is then inputted into the MaxDEA 8 Ultra software for analysis and resolution.

Table 2 provides specific indicator systems for each variable, and objective weighting is uniformly applied using the entropy method.

Table 2

Indicator System for the Evolutionary Dynamics of GTSRE

Order parameter	**Criteria Layer**		**Indicator layer**	**Indicator weights/descriptions**
GRP	Environmental regulation		Cumulative number of effective local environmental laws and regulations (pieces)	0.282
			The proportion of investment completed in industrial pollution control projects to the main business costs of scale-above industrial enterprises (%)	0.486
	Government support		The proportion of local fiscal energy conservation and environmental protection expenditures to total fiscal expenditure (%)	0.233
MGG	Market competition		Number of resource-based enterprises above a certain scale	0.400
			Location entropy	0.231
	Market demand		The growth rate of the industrial sales output value of resource-based enterprises above a certain scale (%)	0.172
			Per capita disposable income of the region(yuan)	0.197
GTI	Input	Capital	R&D capital stock of resource-based enterprises above a certain scale (hundred million yuan)	
		Labor	The full-time equivalent of R&D personnel in resource-based enterprises above a certain scale (10,000 people/year)	
	Expected output	Knowledge	Effective invention patents of resource-based enterprises above a certain scale(pieces)	

Order parameter	Criteria Layer		Indicator layer	Indicator weights/descriptions
		product	Sales revenue of new products of resource-based enterprises above a certain scale (hundred million yuan)	Converted to composite index using entropy method
	Unexpected output	Water pollution	Total industrial wastewater discharge from resource-based enterprises above the scale (hundred million tons)	Converted to composite index using entropy method
		Atmospheric pollution	Total industrial sulphur dioxide emissions from resource-based enterprises above the scale (10,000 tons)	

Data Sources and Processing

According to *Industrial Classification for National Economic Activities* (GB/T4754-2017), resource-based enterprises originate from two categories, namely mining and washing industries and primary processing industries, comprising a total of 13 industries [a]. Due to the scarcity of data for "other mining activities", it is excluded. Therefore, this paper ultimately selects resource-based enterprises from 12 industries. It should be noted that the cumulative number of effective local environmental laws and regulations in the *China Environment Yearbook* has not been statistically updated since 2019. To ensure the accessibility and coherence of the data, the study period spans from 2008 to 2019. The relevant indicator data are obtained by searching and calculating from *China Science and Technology Statistical Yearbook*, *China Environmental Statistical Yearbook*, *China Environment Yearbook*, *China Industrial Statistical Yearbook*, *Industrial Enterprises Science and Technology Activity Statistical Yearbook*, *China Statistical Yearbook*, *China Financial Yearbook*, EPS database, China laws and regulations information system and other provincial statistical yearbooks and statistical bulletins during 2009 to 2020. All monetary variables are deflated using the corresponding price indices to eliminate the influence of price factors. Linear interpolation is employed to fill in missing data. Table 3 presents the descriptive statistical results for various variables.

Table 3

Descriptive Statistics

Varname	Indicator	Mean	Sd	Min	Max
GRP	Environmental regulation	0.268	0.099	0.092	0.517
	Government support	0.475	0.213	0.000	1.000
MGG	Market competition	0.246	0.086	0.089	0.405
	Market demand	0.164	0.087	0.006	0.352
GTI	Capital	184.106	141.850	21.357	615.950
	Labor	1.743	1.365	0.356	5.049
	Knowledge	1902.242	1781.788	134.382	7759.000
	Product	421.298	318.377	76.589	1365.140
	Water pollution	2.959	1.714	0.909	7.775
	Atmospheric pollution	50.575	30.488	1.257	114.780

Results and Discussion

Haken model identifies the order parameters through pairwise analysis of variables. In the context of the GTSRE, three variables-GRP, MGG, and GTI, have been verified by collinearity tests (VIF<<10).

The identification of order parameters within the GTSRE proceeds through the following steps:

(1) Formulation of a preliminary assumption regarding the order parameters, where GRP, MGG, and GTI are posited as the prospective order parameters respectively.

(2) Subsequent selection of pairs of variables for the construction of motion equations intrinsic to the model, culminating in the establishment of six distinct equation sets. Associated parameters are subsequently elucidated through the employment of regression analysis techniques.

(3) Evaluation of the validity of the proposed model assumptions facilitates the identification of the system's order parameters.

All pertinent calculations are facilitated via the use of Stata software.

Due to the long research period, the order parameters of the system may have changed during the evolution of the system. Therefore, we try to divide the system into two research phases: 2008–2012 and 2013–2019. The division is based on the consideration of profound changes in the external environment. In 2012, a blueprint for ecological civilization construction was comprehensively planned from a new historical starting point. A series of fundamental, forward-looking, and innovative new actions placed ecological civilization construction at an unprecedented strategic height, strongly demonstrating the determination of the party and the state to protect the ecological environment through drastic measures and indicating that resource-based enterprises will face a new environment for green transformation, and system development will enter a brand-new stage. However, the preliminary results of the model are not ideal, and the analysis suggests that the evolutionary process of GTSRE in the central and western regions may have exhibited significant differences during the study period. Therefore, this paper examines and compares the dynamics mechanisms of GTSRE in the central and western regions separately based on the two phases from 2008 to 2012 and 2013 to 2019.

Evolution of the GTSRE in Central Regions

Order Parameter Identification

According to the results in Table 4, *MGG* is identified as the order parameter of the GTSRE in central regions from 2008 to 2012, while *GTI* is the order parameter from 2013 to 2019.

Table 4

Identification Results of Order Parameters for the GTSRE in Central Regions

Year	Model hypothesis	Motion equation	Parameter estimation	Conclusion
2008-2012	$q_1=MGG$	$MGG_{(t)}=1.0102^{***}MGG_{(t-1)}-0.0359GRP_{(t-1)}MGG_{(t-1)}$	$\lambda_1=-0.0102$ $a=0.0359$	Motion equations hold; Satisfying the adiabatic approximation principle; *MGG* is the order parameter
	$q_2=GRP$	$GRP_{(t)}=0.2334^{***}GRP_{(t-1)}+0.7823^{***}MGG^2_{(t-1)}$	$\lambda_2=0.7666$ $b=0.7823$	
2013-2019	$q_1=GTI$	$GTI_{(t)}=1.1077^{***}GTI_{(t-1)}+0.0377GTI_{(t-1)}MGG_{(t-1)}$	$\lambda_1=-0.1077$ $a=-0.0377$	Motion equations hold; Satisfying the adiabatic approximation principle; *GTI* is the order parameter
	$q_2=MGG$	$MGG_{(t)}=0.7005^{***}MGG_{(t-1)}-0.0366GTI^2_{(t-1)}$	$\lambda_2=0.2995$ $b=-0.0366$	

*Notes: ***, **, and * denote the statistical significant levels of 1 %, 5 %, and 10 % respectively.*

System Evolutionary Orderliness Analysis

From the motion equations of the first stage and the second stage, the evolution equations and potential functions of the corresponding stages of the GTSRE in the central region can be obtained respectively, and then the stable solutions can be solved. Among them, the stable solution of the potential function in the first stage is $MGG^{**}=0.5277$, and the coordinates of the stable point are (0.5277, -0.0010); the stable solution of the potential function in the second stage is $GTI^{**}=4.8350$, and the stable point is (4.8350, -1.2024).

The distance between any state parameter point in the GTSRE in the central region and the stable point of the corresponding stage is determined by the state that the system is in. Thus, the evaluation function for system evolutionary orderliness status in the first stage is:

$$d=\sqrt{(MGG-0.5277)^2+(v(MGG)+0.0010)^2} \quad (9)$$

Similarly, the evaluation function for system evolutionary orderliness status in the second stage is:

$$d=\sqrt{(GTI-4.8350)^2+(v(GTI)+1.2024)^2} \quad (10)$$

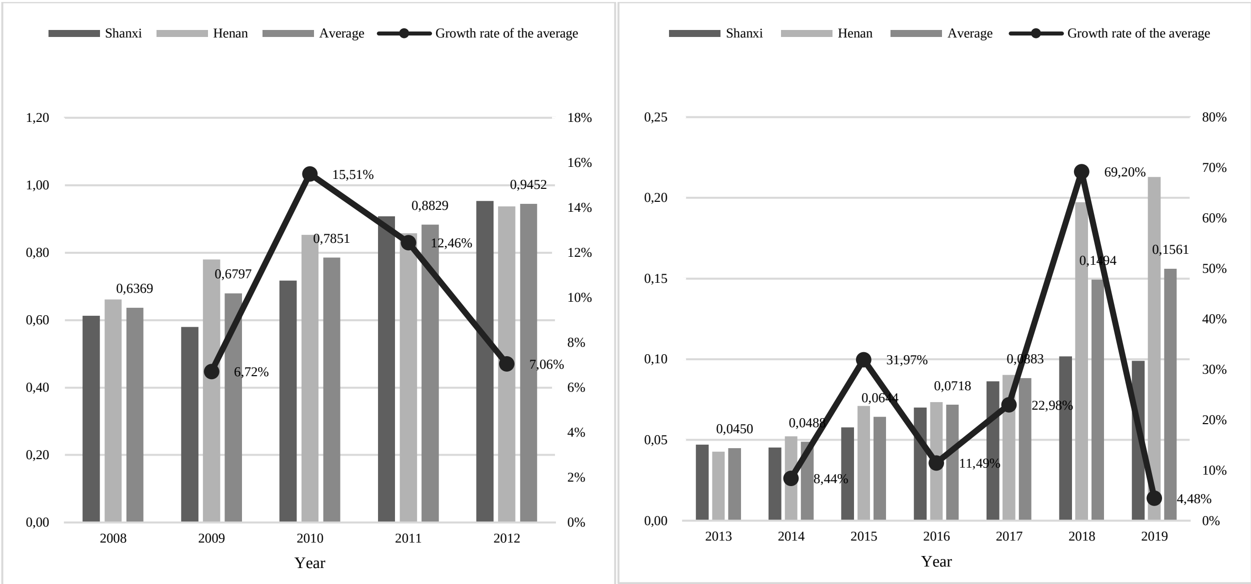
The *d*-value is a negative indicator used to measure the evolutionary orderliness status of the system. To facilitate comparison and analysis, the *min-max* normalization method is adopted to convert the *d*-value into positive indicators, from which the orderly evaluation score is derived. Following the processing method of relevant scholars (Gao, 2020), 1/2 of the orderly evaluation score is used to divide low orderliness and medium-low orderliness, and 1/4 of the orderly evaluation score is used to divide medium-low orderliness and medium-high orderliness, which is thus divided into the following three intervals, as shown in Table 5.

Table 5

Classification of the Evolutionary Orderliness Status of GTSRE

Score	Status
(0.0~0.5)	Low orderliness
[0.5~0.75]	Medium-low orderliness
(0.75~1.0)	Medium-high orderliness

According to equations (9) and (10), we calculate the orderly evaluation scores of the GTSRE in central China from 2008 to 2012 and from 2013 to 2019, as shown in Figure 8.



(a) 2008–2012

(b) 2013–2019

Figure 8. Trends in Orderly Evaluation Scores of GTSRE in Central China

During the first stage, the GTSRE in the central region achieved a leap in orderly development under the guidance of the MGG. The control parameter λ_1 =-0.0102<0, λ_2 =0.7666>0, indicating that the positive feedback mechanism of increasing MGG and negative feedback mechanism of decreasing GRP had been established within the GTSRE in the central region. The control parameter *a*=0.0359>0 shows that GRP has a negative impact on MGG. The market is the main force for factor allocation, and the government has not been able to respond sensitively to market changes or effectively maintain and supervise resource markets at this stage, thus partially suppressing the role of MGG. The parameter *b*=0.7823>0 represents that MGG has a positive effect on GRP, which is beneficial to reducing the cost of government regulation and improving efficiency. By 2012, the GTSRE in central China was in a highly orderly state (0.9452) and was close to the critical point of systemic mutation. Starting in 2013, it transitioned from an orderly state to a new disordered state, dominated by a new order parameter, highlighting the scientific and rationality of the division of development stages.

During the second stage, the GTSRE in the central region evolved under the dominance of GTI. The control parameter λ_1 =-0.1077<0, λ_2 =0.2995>0, indicating that the positive feedback mechanism of increasing GTI and negative feedback mechanism of decreasing MGG had been established. The control parameter *a* = -0.0377<0 means that MGG has a positive impact on GTI. The parameter *b*= -0.0366<0 denotes that GTI suppresses MGG, mainly due to the mean efficiency of GTI being only 0.4552 during this stage, and the level of innovation is relatively low, making it difficult to effectively stimulate the overall growth point of market green demand. From 2013 to 2019, although the degree of evolutionary orderliness of GTSRE in the central region showed an upward trend, the growth rate was reduced by 36.04 % compared to the first stage, and the average score in 2019 was only 0.1561, indicating a low level of orderly state. In terms of different provinces, the degree of orderliness in Henan increased by 30.66 % per year, while the degree in Shanxi increased by 13.16 % per year, and the gap between the two provinces is increasing year by year. Therefore, it can be seen that the GTSRE in the central region is far from the critical state of mutation, and there is still a lot of improvement in the orderliness degree. Taking into account the growth volume and rate of the orderliness degree, GTI will remain the main driving force for the evolution of the GTSRE in the central region in the future.

Evolution of the GTSRE in Western Regions

Order Parameter Identification

According to the results in Table 6, *GRP* is identified as the order parameter of the GTSRE in western regions from 2008 to 2012, while *MGG* is the order parameter from 2013 to 2019.

Table 6

Identification Results of Order Parameters for the GTSRE in Western Regions

Year	Model hypothesis	Motion equation	Parameter estimation	Conclusion
2008-2012	q_1=*GRP*	$GRP_{(t)}$=0.8194**$GRP_{(t-1)}$-1.3516$GRP_{(t-1)}GTI_{(t-1)}$	λ_1=0.1806 a=1.3516	Motion equations hold; Satisfying the adiabatic approximation principle; *GRP* is the order parameter
	q_2=*GTI*	$GTI_{(t)}$=-0.0741**$GTI_{(t-1)}$-0.7003***$GRP^2_{(t-1)}$	λ_2=1.0741 b=-0.7003	
2013-2019	q_1=*MGG*	$MGG_{(t)}$=0.9087***$MGG_{(t-1)}$-0.0128$GTI_{(t-1)}MGG_{(t-1)}$	λ_1=0.0913 a=0.0128	Motion equations hold; Satisfying the adiabatic approximation principle; *MGG* is the order parameter
	q_2=*GTI*	$GTI_{(t)}$=0.9061***$GTI_{(t-1)}$-0.1291**$MGG^2_{(t-1)}$	λ_2=0.0939 b=-0.1291	

System Evolutionary Orderliness Analysis

From the motion equations of the first stage and the second stage, the evolution equations and potential functions of the corresponding stages of the GTSRE in the western region can be obtained respectively, and then the stable solutions can be solved. Among them, the stable solution of the potential function in the first stage is $GRP^{**}=0.452$, and the coordinates of the stable point are (0.4527， 0.0078). The stable solution of the potential function in the second stage is $MGG^{**}=2.2777$, and the stable point is (2.2777， 0.1187).

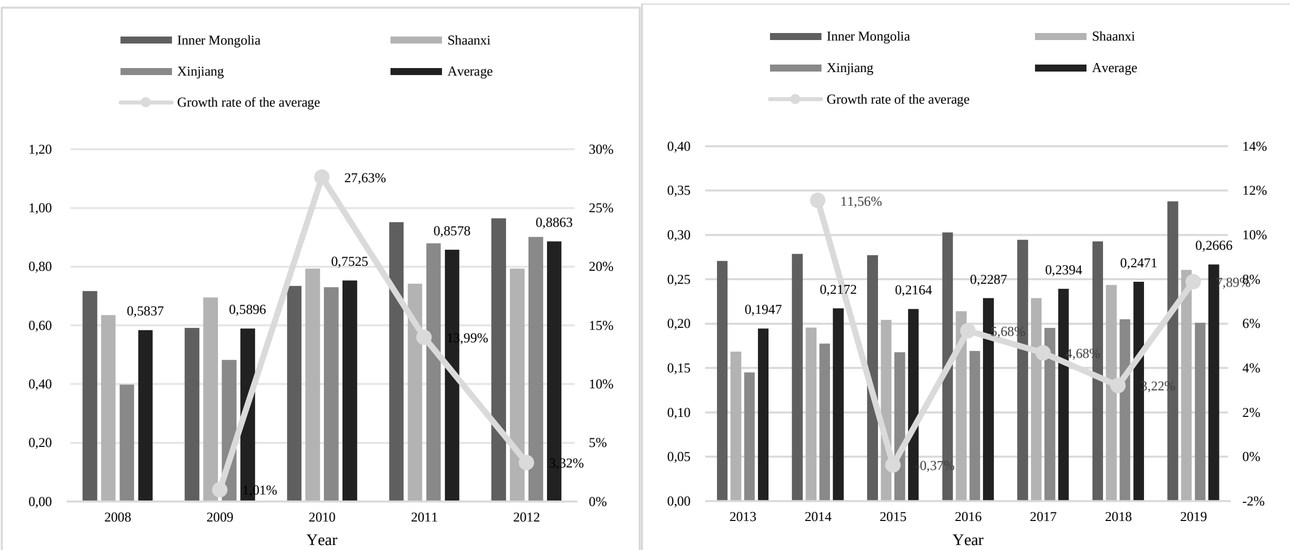
The distance between any state parameter point in the GTSRE in the western region and the stable point of the corresponding stage is determined by the state that the system is in. Thus, the evaluation function for system evolutionary orderliness status in the first stage is:

$$d=\sqrt{\left(GRP-0.4527\right)^2+\left(v(GRP)-0.0078\right)^2} \qquad (11)$$

Similarly, the evaluation function for system evolutionary orderliness status in the second stage is:

$$d=\sqrt{\left(MGG-2.2777\right)^2+\left(v(MGG)-0.1187\right)^2} \qquad (12)$$

Still following the treatment of *d*-values above, the orderly evaluation scores of the GTSRE in the western region for 2008–2012 and 2013–2019 are derived, respectively, as shown in Figure 9.



(a) 2008–2012 (b) 2013–2019

Figure 9. Trends in Orderly Evaluation Scores of GTSRE in Western China

During the first stage, the order parameter of the evolution of the GTSRE in western regions is GRP. The control parameters λ_1=0.1806>0, λ_2=1.0741>0 show that the positive feedback mechanism of GRP and GTI had not yet been established. The control parameters a=1.3516>0, b=-0.7003<0 express that GRP has a negative impact on GTI, while GTI hinders the effectiveness of GRP, further underscoring the importance and necessity of GRP in this phase. The strict environmental regulations imposed by local governments force resource-based enterprises to reduce emissions and increase "green" content, which will inevitably increase the cost of pollution control for these enterprises and may result in a "crowding-out effect" on R&D costs. Meanwhile, top-down administrative management by local governments focused mainly on the immediate effectiveness of environmental governance, with little adjustment and support for industrial and financial policies related to GTI, which hindered the development of such innovation. On the whole, under the influence of GRP, the overall mean value of the evolutionary orderliness of the GTSRE in the western region increased steadily, rising from 0.5837 in 2008 to 0.8863 in 2012 with an increase of 51.84 %. In different provinces, the evolutionary orderliness of the GTSRE in Inner Mongolia surpassed 0.9 for the first time in 2011, entering a highly orderly state, and continued to rise in 2012, approaching the system's critical mutation point. The most significant change in evolutionary orderliness occurred in Xinjiang, which evolved from 0.3982 in 2008 to 0.9014 in 2012, an increase of approximately 126 %, realizing a magnificent leap from low orderliness to high orderliness. In Shaanxi Province, orderliness showed a fluctuating upward trend, reaching a state of medium-high orderliness in 2010 and returning to such a state after a brief decline in 2011.

During the second phase, a shift occurred in the order parameter of the GTSRE in the western region, and the system evolution entered a more advanced new stage. MGG played an important driving role in the evolution of the system during this phase. The control parameters λ_1 =0.0913>0 and λ_2 =0.0939>0, indicating that the positive feedback mechanism of MGG and GTI had not yet been established. The control parameter a=0.0128>0 and b=-0.1291<0, representing that the synergic effect of MGG and GTI had not yet been formed, i.e., MGG had a negative impact on GTI, while GTI hindered the effectiveness of MGG. Since the current market demand for green products has not been fully stimulated, and as more resource-based enterprises continue to enter the resource market and share their resources, competition distortion will gradually weaken the enthusiasm for GTI and, in turn, inhibit market demand, forming a vicious cycle. From 2013 to 2019, under the domination of MGG, the evolutionary orderliness mean value of the GTSRE in the western region increased slightly, with an average annual growth rate of 5.38 %, but the increment was not considerable, with a maximum increment of only 0.0923. Meanwhile, there were significant differences among different provinces, with Inner Mongolia having an average evolutionary orderliness of 0.2935, much higher than Shaanxi (0.2165) and Xinjiang (0.1801). Overall, whether viewed holistically or by province, the GTSRE in the western region remains at a low level of orderliness and is still far from the critical mutation state, indicating that there is still a long way to go to increase the orderly evolution level, which will still be driven primarily by MGG.

Extended Discussion

This section intends to summarize and compare the evolutionary process and order parameters of the GTSRE in central and western China, aiming to extract general conclusions applicable both in China and in emerging economies globally.

The research period is selected from 2008 to 2019. However, it should be noted that the evolution of the GTSRE in the central and western regions did not start in 2008. In addition to the historical evidence (Tian *et al.*, 2008), the evolutionary orderliness of the GTSRE in some regions had already reached a moderate to high level of orderliness in 2008 (Figure 8(a)、9(a)), which can prove that even if the evolutionary process of the GTSRE cannot be completely restored during the research period, it is reasonable to believe that the GTSRE in central regions has gone through the evolutionary stage driven by GRP. Table 7 summarizes the comparative analysis of the evolutionary process and order parameters of the GTSRE in central and western China.

Table 7

Comparative Analysis on the Evolution of GTSRE in the Midwestern Region

Subject	Year	Region	Order Parameter	Evolutionary Process
GTSRE	Early Period	Central	GRP	Primary
		Western	GRP	Primary
	2008–2012	Central	MGG	Intermediate
		Western	GRP	Primary
	2013–2019	Central	GTI	Advanced
		Western	MGG	Intermediate

This comparative analysis yields several salient conclusions:

(1) Owing to disparities in regional resource endowments and the interplay of numerous ancillary factors, the evolution of GTSRE does not follow a singular trajectory. Examining Central and Western China illuminates this point. Given the nation's "east-high, west-low" tiered decline in economic development, notable discrepancies are evident across regions in terms of historical developmental remnants, prevailing developmental paradigms, and intended developmental goals. This heterogeneity engenders a considerable divergence in the provision of crucial components and substantive investments, which, under the impetus of assorted catalysts, ultimately precipitates irregularities in the efficacy of order parameters. Such variances underscore the differential progression in the GTSRE. Hence, for China and other swiftly ascending global economies, fostering efficacious green development in resource-based businesses requires a strategy that recognizes and accommodates the unique developmental characteristics of various internal regions, as opposed to overarching macro-level policy implementation which risks inefficiency and profligacy in resource allocation.

(2) The order parameters across the various evolutionary stages of the GTSRE are not uniform. In Central China, the evolution of the GTSRE appears relatively comprehensive, with each of the three phases of evolution being dominated by distinct order parameters. Overall, the evolution of the GTSRE follows a principle of progression driven by "GRP-MGG-GTI". Specifically, GRP acts as the order parameter in the primary stage of system evolution, while MGG serves as the order parameter in the intermediate phase, and GTI operates as the order parameter in the advanced stage. These three drivers synergistically contribute to the effective realization of an evolutionary upgrade in the GTSRE.

(3) The duration of each phase in the evolution of GTSRE depends on the attributes of the order parameter for that stage. Given that these parameters vary across different regions, this disparity influences the characteristics of system fluctuations and consequently leads to variations in the time required for system evolution. Examining the current state of GTSRE in Central and Western China, it is apparent that enterprises in the Central region are encountering a deficiency in the impetus for GTI, thereby constraining the pace of system evolution. Conversely, those in the Western region face a lack of MGG. In this regard, policies should be tailored based on the order parameter of the system's evolutionary stage, to foster a more advanced level of evolution in the GTSRE.

Conclusions and Future Works

Building upon the analysis of the formation mechanism and framework of GTSRE, this study focuses on the practical experience of green transformation in representative provinces of central and western China from 2008 to 2019. By utilizing the Haken model and evolutionary orderliness model, the evolutionary dynamics mechanisms of the system are explored, and a targeted analysis is conducted on the orderly evolution pattern of GTSRE in central and western China. The following conclusions are drawn:

(1) The formation of GTSRE is a result of the comprehensive consideration of the mismatch between the realistic development needs and capabilities of both the enterprises and their regions. It arises from a coupling interaction driven by a scientific logical chain of “demand-motivation-behaviour”, and its evolution is a self-organizing process of complex and non-linear effects that continually overcome the increase of entropy and enhance organizational orderliness.

(2) The evolution of the GTSRE does not have a completely consistent evolutionary process and driving mechanism. This primarily owes to the disparities in the order parameters inherent in system evolution, observable across disparate regions and varied phases within a singular region. Predominantly, the evolution of the GTSRE follows the driving law of "GRP-MGG-GTI". The three driving factors work together to promote the synergistic evolution upgrading of GTSRE.

(3) The GTSRE in the Central and Western regions have achieved breakthroughs in the evolutionary stages, but there is a significant disparity in the pace of evolution which appears to be widening further. Currently, the GTSRE in the central region is in an advanced stage of evolution, primarily driven by GTI, while the western region remains at an intermediate evolutionary stage where MGG serves as the main driving force. The evolutionary orderliness of the GTSRE in the central region increases by 23.06 % annually at the current stage, while the western region is only 5.38 %, and its latecomer advantage is clearly insufficient.

Given the different constraints facing the green transformation of resource-based enterprises in Midwest China, policy-making and implementation should be prioritized.

(1) The central and local governments should strengthen macroeconomic regulation and actively guide the interaction and cooperation between resource-based enterprises and regions, thereby accelerating the formation of GTSRE. The roles and functions of various green transformation entities within the system should be clearly defined, and the interests of all parties within the system should be coordinated to ensure ecological balance.

(2) The governments in the central regions should clearly support green technological innovation. They should continuously increase investment in green technological innovation and improve the feedback mechanism for green technological innovation. Subsidy levels and resource support should be dynamically adjusted in a timely manner based on the demand for green technological innovation, effectively enhancing the adaptability and practicality of policies. In addition, there should be a focus on strengthening green mode innovation in financial institutions and expanding financing channels for green technological innovation.

(3) The governments in the western regions should work to enhance the MGG. Firstly, efforts should be made to continuously improve and innovate the ways in which green resource products are promoted for consumption, gradually gaining consumer recognition of environmental labels, and energy efficiency labels. Secondly, subsidy policies and channels for the consumption of green resource products should be improved, fully safeguarding consumer rights in the consumption of green resource products. Thirdly, government green procurement systems should be improved, expanding the list of government green procurement items and gradually increasing the proportion of green resource products. Lastly, the government should strengthen normalized market supervision and special rectification, resolutely eliminate backward production capacity, and focus on breaking market monopolistic practices.

There are, however, several limitations of this study. Firstly, this study explores the driving mechanisms and evolutionary orderliness levels of green transformation from the perspective of GTSRE. The analysis of the formation mechanism of this system is limited to theoretical analysis, and future research should be supported and validated by rich typical cases. Secondly, due to restrictions on the availability of pertinent data, the study period has not been updated to the most recent years. Nonetheless, considering the incremental growth in system evolutionary orderliness and its velocity, the findings of this study remain applicable over the past five years. It is hoped that future endeavours, based on comprehensive data, could extend the study period to accurately validate the robustness of the research conclusions. Lastly, considering the heterogeneity in development across Eastern China and other emerging economies globally, future research expansion may yield more insightful and intriguing findings, which can further facilitate the deep sustainable development of resource-based enterprises.

Notes

These industries mainly include mining and washing of coal, extraction of petroleum and natural gas, mining and processing of ferrous metal ores, mining and processing of non-ferrous metal ores, mining and processing of non-metal ores, processing of petroleum, coal and other fuels, manufacture of raw chemical materials and chemical products, smelting and pressing of ferrous metals, smelting and pressing of non-ferrous metals, manufacture of metal products, production and supply of electric power and heat power.

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