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RESEARCH ARTICLE

Obstacle diagnosis of green competition promotion: a case study of provinces in China based on catastrophe progression and fuzzy rough set methods

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Abstract
As "green" and "sustainable" become the new themes of regional economic development, green competitiveness will undoubtedly become a new engine for regions to solve environmental, resource use, and other global problems to fit the new development themes. Unfortunately, the performance of regional green competitiveness is not always satisfactory due to various shortcomings. In this study, we abandoned the conventional research approach that directly explores the factors that promote regional green competitiveness and analyzed, instead, the obstacles to green competitiveness among provinces in China. The barrier degree was calculated for each obstacle using a catastrophe progression method and fuzzy rough set. Results showed that (a) resource and environmental problems have become increasingly prominent and have been the most common obstacles to promoting green competitiveness of provinces in China and (b) the obstacles to improving regional green competitiveness showed spatial differences and peculiarity according to the barrier degree. The outcome of the study can help policy makers to better understand and prioritize implementation strategies to develop effective action and policy interventions toward more successful construction of regional green competitiveness.

Keywords Barrier degree · Catastrophe progression method · Fuzzy rough set · Green competitiveness · Obstacle diagnosis

Introduction

Climate change, desertification, biodiversity loss, and ozone depletion are significant environmental problems that have become a global challenge to sustainable development, damaging the natural ecosystem and causing loss to economy and society. For example, outdoor air pollution could cost the world USD 2.6 trillion per year, or 1% of global gross domestic production (GDP), by 2060 according to the Organization for Economic Cooperation and Development (OECD). What is worse, air pollution could also cause as many as nine million premature deaths, leading to an expected increase in welfare spending to USD 25 trillion over the same period (Yan 2016).

China in particular, which is experiencing rapid economic development and urbanization, is faced with a more serious situation of environment and resource than many other countries. Data showed that 254 of China's prefecture-level cities (75%) failed to meet air quality standards in 2016 (NBSC 2016). According to a report from the World Bank (2016), China, which is already wrestling with severe general pollution, is expected to be affected especially badly by air pollution, as economic losses due to air pollution accounted for 10% of China's GDP in 2013. The World Health Organization (2010) also pointed out that the number of deaths attributable to 2.5-μm particulate air pollutants was as high as 1.2 million in China in 2010. Meanwhile, the resource crisis is becoming increasingly serious. China's net reduction in arable land area was 59,500 ha in 2016. The utilization rate of the Haihe River has surpassed 100%, and the utilization rate of the Yellow River and West Liaohe River has surpassed 70%, far exceeding the internationally recognized 40%

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security line (Yu 2014). In addition, national and regional economic competition, as well as competition between industries and enterprises, is becoming fiercer in the context of globalization, from the allocation of raw materials and capital dividends to policy support. There is no doubt that resolving resource and environmental crises and maximizing regional competitiveness have become urgent issues facing both the government and scholars.

Against this background, green competitiveness will undoubtedly become a new engine for regions in solving environmental issues, resource availability and utilization, and other world problems so as to achieve sustainable development. "Green competitiveness" means the ability to obtain market competitive advantage based on the green economic model of environmental protection, healthy ecosystems, and sustainable development (Porter 1991). Green competitiveness can be interpreted from two perspectives. The first is the "greenness" of regional competitiveness. That is to say, regional competitive advantage is based on efficient use of natural resource, ecological environment protection, and energy efficiency (Hart 1997; Shireman and Tachi 2002).

The second perspective refers to sustainable competitiveness. With the increasingly strict environmental regulations and the gradual transformation of the development model, a region that exhibits a high level of green competitiveness must embrace sustainable development; consequently, its economic and social development is bound to be more advanced and superior to that of other regions. Unfortunately, the performance of regional green competitiveness is not always satisfactory due to various shortcomings. On one hand, people have become accustomed to wasting resource and inefficient utilization of resource. On the other hand, people are always complaining about the shortage of resource and the deterioration of the ecological environment.

Thus, many obstacles exist in the promotion and achievement of regional green competitiveness. At the same time, due to unbalanced development, obstacles to green competition in different regions have different characteristics. These differences prompt several questions. How significant (i.e., what is the barrier degree) are these obstacles? How does a green competition obstacle evolve in a particular region? What kind of spatial characteristics does an obstacle to green competition have? These questions are significant for the regions working to adjust their development strategy and solve development problems, and urgently require further study and discussion.

Therefore, we diagnosed obstacles of regional green competitiveness using a catastrophe progression method, analyzing 30 provinces in China as a case study. We hoped that our study could provide a useful comparison for studies in other countries, and could inform related policies in similar areas. The objectives of our study were to carry out a multilevel decomposition of the green competitiveness of each province using a subtarget layer and criterion layer, and describe the evolution and spatial characteristics of obstacle factors based on calculated barrier degree. The subtarget layer consisted of the economic system, social system, and resource-environmental system. The criterion layer consisted of economic scale (ECS), economic efficiency (ECE), urbanization level (UL), scientific research and environmental protection investment (SEI), infrastructure (IFT), employment (EPM), natural resource (NR), green environment (GE), and pollution abatement (PA). Furthermore, to avoid the influence of human factors, we used a fuzzy rough set method to determine the relative importance of each index. The contribution of our paper is that we analyzed regional green competitiveness from a barrier diagnosis perspective, and made improvements in the techniques for obstacle diagnosis in empirical research. We used a catastrophe progression method and fuzzy rough set method to conduct a multilevel decomposition of the green competitiveness of each province, which not only included a dynamic diagnosis of different obstacles but also avoided redundant information and human factors when determining the importance of each indicator. In addition, the methods we used are versatile and can be used in other related studies, providing a new approach for barrier diagnosis and interdisciplinary research.

The remainder of this paper is organized as follows. The second section reviews and analyzes the related literature. The third section describes the material and methods. The fourth section provides the empirical results, and the fifth section presents an analysis and discussion of the results. The last section presents our conclusions and suggestions for policy implementation.

Literature review

Regional competitiveness

At present, there is not much discussion about regional green competitiveness, and what does exist is generally based on the study of regional competitiveness. The Lausanne International Institute for Management Development (IMD) considered productivity to be one of the performance indicators of competitiveness and evaluated national competitiveness from four aspects: economic performance, business efficiency, government efficiency, and infrastructure (IMD 2017). The World Economic Forum attached great importance to international competitiveness and considered lower-cost products and better service to be two key factors affecting competitiveness (World Economic Forum 2016). Porter (1990) proposed a diamond model that included production factors, demand conditions, corporate strategy structure, and peer competition to evaluate national competitiveness from the perspective of the value chain and industrial chain. In considering economic activities, OECD (2002) focused on environmental and resource productivity, natural resource, quality of life, economic opportunities and policy response, and socioeconomic background.

In addition, some scholars have conducted empirical research on regional competitiveness. Fernandez et al. (2013) developed a decision-making system based on a structural equation model and evaluated the competitiveness of the Mexican region using the final evaluation indicators. Guo et al. (2015) evaluated city competitiveness from the perspectives of environmental conditions, the extent to which the economy had been opened, economic development and people's quality of life. Taking several factors (including economy, firms, government, infrastructure, and people) into consideration, Charles and Zegarra (2014) constructed an indicator system to measure and rank regional competitiveness in Portugal. In general, the factors highlighted in these studies that affect regional competitiveness are economic output, efficiency, environment, natural resource, infrastructure, and people's quality of life.

Enterprise green competitiveness

Notably, scholars are involved in research about enterprise green competitiveness. Hart (1997) pointed out that when environmental protection becomes a part of an overarching strategy, enterprises can open the door to green competitiveness. Using ecology principles for business studies, Shireman and Tachi (2002) suggested that enterprises can enhance green competitiveness beyond environmental restrictions through innovation, replication, and improvement in the cycle of operational mechanisms. Some scholars have also carried out an empirical study on the green competitiveness of enterprises. Carraro and Galeotti (1997) used the WARM model to simulate the interaction between industry and the environment among countries in the European Union, finding that policies that stimulate research, development, and innovation can provide companies with the right incentives to avoid damage and keep businesses competitive in the market. Analyzing 110 manufacturing sectors in eight countries, Fankhauser et al. (2013) identified three success factors for green competitiveness at the sector level: the speed at which sectors convert to green products, the ability to gain and maintain market share, and a favorable starting point. Using a structural equation model to analyze a survey of 124 companies in eight industries in Taiwan, Chiou et al. (2011) found that it is necessary to encourage enterprises to implement a green supply chain and green innovation to improve environmental performance, so as to enhance the competitive advantage in the global economy. In general, the research on regional green competitiveness is still in the development stage, with more attention focused on the microenterprise level. Research mainly discussed the relationship between ecological environment protection and economic development, highlighting the role of environmental protection, scientific research, and innovation to enhance green competitiveness.

The existing barrier diagnosis model

Based on the evaluation model, the barrier diagnosis model is a mathematical model that identifies obstacles to the development of objects or achievement of objectives (Van Lamsweerde and Letier 2000). The existing barrier diagnosis models can be divided into the following four categories.

1. Obstacle diagnosis model based on the case study method. Taking typical cases as the study material, this model identifies the main obstacles by analyzing, decomposing, and making conclusions about information (obtained through a questionnaire, semistructured interview, network, literature, and newspapers and other information channels). To describe the influencing factors, Wolf et al. (2006) evaluated obstacles and success factors of pellet production in the forest industry using this model. In addition, based on the information acquired using a semistructured interview, Wong (2012) applied this obstacle diagnosis model to explore the key obstacles that constrain poor people from obtaining solar lighting. To achieve a successful implementation of smart energy city projects, Mosannenzadeh et al. (2017) classified and analyzed the barriers hindering implementation of a smart energy city. While this model has been proved effective, the generalization still remains unknown. Because this obstacle diagnosis model is based mainly on qualitative research, the research results cannot be extended to other situations.
2. Obstacle diagnosis model based on the analytic hierarchy process. This model identifies obstacles through empirical analysis and uses the analytic hierarchy process to calculate a weight for each obstacle and thus determine the main obstacle. Govindan et al. (2014) identified barriers to the implementation of green supply chain management based on this model. As to resource recycling, Hsu et al. (2010) used this model with a fuzzy Delphi method and analytic hierarchy process to find the factors hindering lubricant regenerative technology. Using the same method, Bouzon et al. (2016) studied reverse logistics barriers. Although widely used according to studies mentioned above, the limitations of this model cannot be ignored. In particular, the obstacle factors and the weights of obstacles are too subjective and easily produce subjective errors due to the use of the analytic hierarchy process.
3. Obstacle diagnosis model based on principal component analysis. After a related index for obstacles has been acquired through empirical or experimental analysis, this model extracts the principal barriers by principal component analysis, with the barrier degree determined by the

principal component coefficients. To find out about the application of waste cooking oil, Zhang et al. (2012b) analyzed the status, obstacles, and recommendations for the oil using this model. Although the model avoids subjectivity when determining index weights with analytic hierarchy process, the deficiency in the model is that the obstacle index must be obtained in advance. Furthermore, the computation is complex.

4. Obstacle diagnosis model based on regression analysis. After a related index for obstacles is acquired through empirical or experimental analysis, this model uses regression analysis to determine the barrier degree for each obstacle. The regression coefficients of each obstacle are considered as the barrier degree so that the main obstacle can be identified. Based on the rejections and registrations of samples in China, Xie et al. (2014) used regression analysis to identify the barrier to the implementation of clean development projects. From a micro perspective, D'Souza et al. (2014) diagnosed economic growth obstacles for privatized and de novo private firms. In addition, Souto and Rodriguez (2015) also focused on enterprises to find the innovation obstacles for environmentally involved firms. While all these studies proved the model to be well-founded, its limitation still cannot be neglected. This method is only applicable to a specific point in time. The model fails to achieve multilevel contradiction decomposition and lacks dynamic characteristics, thus giving rise to a deficiency in revealing qualitative change caused by mass quantitative change.

In summary, although the existing obstacle diagnosis models can explore obstructing factors, in practice, the models have some limitations, such as subjective influences, lack of dynamic characteristics, and high computational complexity.

Catastrophe progression method used in evaluation fields

Catastrophe theory is the basis for the catastrophe progression method and uses a mathematical model to describe the process of sudden interruption of continuous action (Cheng 1978; Chreiber et al. 1997; Raftoyiannis et al. 2006). Characterized by multilevel contradiction decomposition and dynamics, catastrophe theory is widely used in economics (Barkley Rosser 2007; Guastello 1995), resource and environmental evaluation (Wang et al. 2017; Wei et al. 2011) as well as psychology (Stewart and Peregoy 1983; Van and Molenaar 1992). Combining the catastrophe theory and fuzzy mathematics, Jin et al. (2013) built a new model to forecast rock-burst danger. The results showed that the method could produce highly accurate forecasts and had good practical value. Based on the landscape pattern, Cao et al. (2015b) studied land-use regionalization using rough set theory and the catastrophe progression method to avoid the subjectivity introduced by artificially determining factor weights. Besides, Zhang et al. (2013) evaluated the rural information dissemination level in four Chinese regions based on the catastrophe theory. The results are found to be in line with a priori expectations proving that the catastrophe progression method works well. In summary, we can see that the catastrophe progression method is widely used in many evaluation fields and has outstanding advantages, such as immunity to subjective influences, simple calculations, and richness in dynamic characteristics. Therefore, we established an obstacle diagnosis model based on the catastrophe progression method to overcome the limitations faced by other obstacle diagnosis models with the expectation to fully realize the diagnosis of regional green competitiveness obstacles.

Material and methods

Material

Sample data for 30 provinces (excluding Tibet, Hong Kong, Macao, and Taiwan) for the period 2005–2014 were used. The regional data were obtained from the China Statistical Yearbook, Environmental Statistics Yearbook, and China Energy Statistics Yearbook. Before diagnosing regional green competitiveness, it was necessary to analyze the positive indicators and the negative indicators separately to eliminate the problems associated with indicator data having different measurement units and a wide range of numerical values. So, nondimensional and nonnegative standardization were conducted according to the direction of the indicators. We used the range method to standardize different data. The process is described in Eqs. (1) and (2):

$$\textit{Positive indicators}: \quad X_{ij} = \frac{V_{ij} - \min\limits_{1\le i\le m}\left(V_{ij}\right)}{\max\limits_{1\le i\le m}\left(V_{ij}\right) - \min\left(V_{ij}\right)} \tag{1}$$

$$\textit{Negative indicators}: \quad X_{ij} = \frac{\max\limits_{1\le i\le m}\left(V_{ij}\right) - V_{ij}}{\max\limits_{1\le i\le m}\left(V_{ij}\right) - \min\left(V_{ij}\right)} \tag{2}$$

where X_{ij} denotes the standardized value of the j-th indicator of the i-th evaluation object, V_{ij} is the value of the j-th indicator for the i-th evaluation object, and m is the number of objects studied. Unless otherwise stated, standardized data for indicators are used in this paper.

Catastrophe progression method

Founded by the French mathematician Renethom in 1972, the catastrophe theory is a mathematical model to reveal a discontinuous change in natural phenomena and social activities by using the topological theory of dynamic systems. By describing and predicting the process of continuous qualitative interruption according to a potential function, the catastrophe theory is the only systematic theory to study mutations caused by gradients. In a catastrophic system, the variables of the potential function are divided into two categories: the state variable and the control variable. Among them, the state variable reflects the behavior state of the system, and the control variable influences the behavior state. Because state variables and control variables are two contradictory aspects, it is necessary to determine the importance of each control variable when a catastrophe model is established. Therefore, the important control variable is written first, and subsequent control variables are written in sequence according to decreasing importance. There are seven primary catastrophic systems, and the four most common catastrophe models are shown in Table 1.

Based on the catastrophe theory, the catastrophe progression method can be used to evaluate research objects in three steps. First, the evaluation objects are decomposed at different levels. Then, a fuzzy membership function can be acquired using catastrophe theory and fuzzy mathematics. In the last step, the total membership function is obtained by the comprehensive quantification operation of the normalized formula. In practice, the specific steps of the catastrophe progression method are as follows:

1. Establish the catastrophe evaluation index system.
2. Determine the catastrophe types at each level of the index system.
3. Derive the normalized formula using the bifurcation equation.
4. Evaluate the object with the normalized formula.

Two different principles should be considered when calculating the values of state variable according to each control variable. The first of these is the "noncomplementary" principle: If there is no obvious correlation between all control variables, the minimum value of all state variables should be used as the catastrophe progression value in the system. The second principle is the "complementary" principle: If there is an obvious correlation between all control variables, the average value of all state variables should be used as the catastrophe progression value in the system. We used the statistical software SPSS19.0 (IBM Corp., Armonk, NY, USA) to calculate the correlation coefficient between control variables. Then, a decision on whether to use the noncomplementary or complementary principle was reached by judging whether all the control variables were significantly correlated at the 0.05 level.

The research reviewed in "Literature review" section indicates that regional green competitiveness is mainly related to economic output, economic efficiency, environmental protection, natural resource, infrastructure, people's quality of life, and scientific research innovation. Taking data availability, comparability, and practicability into account, and on the basis of previous studies, we built a barrier diagnosis index system that utilized information from the economic system, social system, and resource-environmental system. Including 24 indicators (Table 2), the index system was expected to effectively evaluate the obstacles to regional green competitiveness when integrated with the obstacle diagnosis model based on the catastrophe progression method.

Obstacle model

Focusing on the factors that hinder regional green competitiveness, this study made a detailed diagnosis of green competitiveness among provinces in China and explored the barrier degree of obstacles. The obstacle diagnosis model was combined with the normalization formula in the catastrophe progression model.

First, the deviation of the indicator was calculated according to Eq. (3):

$$I_{ij} = 1 - X_{ij} \tag{3}$$

where I_{ij} denotes the deviation of the i-th indicator of the j-th province, and X_{ij} is the standardized value of the i-th indicator for the j-th province.

Then, the normalized formula in the catastrophe progression model was used to diagnose the obstacles that hindered regional green competitiveness. Since the normalized formula in the catastrophe progression model is essentially a multiobjective fuzzy decision method, the catastrophe progression value can be calculated according to the normalized formula. Furthermore, the catastrophe progression value can

Table 1 Catastrophe models in common

Catastrophe models	Number of control variables	Number of state variables	Potential function	Normalization formulas
Folding catastrophe	1	1	$V(x) = x^3 + ux$	$x_u = \sqrt{u}$
Cusp catastrophe	2	1	$V(x) = x^4 + ux^2 + vx$	$x_u = \sqrt{u}, x_v = \sqrt[3]{v}$
Swallowtail catastrophe	3	1	$V(x) = x^5 + ux^3 + vx^2 + wx$	$x_u = \sqrt{u}, x_v = \sqrt[3]{v}, x_w = \sqrt[4]{w}$
Butterfly catastrophe	4	1	$V(x) = x^6 + ux^4 + vx^3 + wx^2 + tx$	$x_u = \sqrt{u}, x_v = \sqrt[3]{v}, x_w = \sqrt[4]{w}, x_t = \sqrt[5]{t}$

Note: u, v, w, t are control variables; x_u, x_v, x_w, x_t are state variables

Table 2 Regional green competitiveness evaluation indicators

Target layer	Subtarget layer	Criterion layer	Index layer	Unit	References	
GC	Esys	ECS	Gross domestic production (GDP) per capita (X_1)	¥	Castro-Gonzáles et al. (2016), Guo et al.(2015)	+
			Per capita disposable income of urban residents (X_2)	¥	Herciu and Ogrean (2014), Thore and Tarverdyan (2016)	+
		ECE	Energy consumption elasticity coefficient (X_3)	–	Dou (2013), Zhang and Hao (2016)	–
			Per million GDP energy consumption (X_4)	Tonne/¥	Duan et al. (2016), Dou (2013)	–
			Ratio of tertiary industry to GDP (X_5)	%	Guo et al. (2015)	+
	Ssys	UL	Urbanization rate (X_6)	%	Duan et al. (2016)	+
		SEI	Research and development expenditure accounted for in the GDP (X_7)	%	Castro-Gonzáles et al. (2016), Fernandez et al. (2013), Herciu and Ogrean (2014), Jänicke (2012), Lau et al. (2013); Meiliene et al. (2015); Zhang et al. (2012a)	+
			Ratio of environmental expenditure to fiscal expenditure (X_8)	%	Herciu and Ogrean (2014), Jänicke (2012), Zhang et al. (2012a)	+
		IFT	Per capita road area (X_9)	m^2	Guo et al. (2015)	+
			Number of public transportation vehicles per 10 thousand persons (X_{10})	no.	Charles and Zegarra (2014), Duan et al. (2016), Guo et al. (2015), Singhal et al. (2013)	+
			Per million people have beds in hospitals (X_{11})	No.	Guo et al. (2015), Thore and Tarverdyan (2016)	+
		EPM	Proportion of employees in the tertiary industry (X_{12})	%	Castro-Gonzáles et al. (2016)	+
			Urban unemployment rate (X_{13})	%	Castro-Gonzáles et al. (2016), Guo et al. (2015)	–
GC	REsys	NR	Per capita arable land area (X_{14})	ha	Castro-Gonzáles et al. (2016), OECD (2002), Zhou et al. (2015)	+
			Per capita water resources (X_{15})	m^3	OECD (2002), Zhou et al. (2015)	+
			Forest cover proportion (X_{16})	%	OECD (2002), Thore and Tarverdyan (2016), Zhou et al. (2015)	+
			Ratio of wetland area (X_{17})	%	OECD (2002), Zhou et al. (2015)	+
		GE	Carbon dioxide emissions per capita (X_{18})	kg	Lau et al. (2013), Thore and Tarverdyan (2016), Yu et al. (2014)	–
			Ratio of air quality reaching level 2 to the average annual value (X_{19})	%	Guo et al. (2015)	+
			Equivalent sound degree of region in daytime (X_{20})	dB	Duan et al. (2016)	–
			Urban per capita green area (X_{21})	m^2	Guo et al. (2015), Zhang and Hao (2016)	+
		PA	Utilization rate of industrial solid wastes (X_{22})	%	Duan et al. (2016), Guo et al. (2015)	+
			Proportion of municipal waste appropriately treated (X_{23})	%	Duan et al. (2016)	+
			Urban sewage treatment proportion (X_{24})	%	Guo et al. (2015)	+

Note: "+" indicates that the indicator is a positive indicator, and the greater the value, the higher the level of green competition. "–" means that the indicator is a negative index, and the smaller the value, the higher the level of green competition

GC green competitiveness, *Esys* economic system, *Ssys* social system, *REsys* resource-environment system, *ECS* economic scale, *ECE* economic efficiency, *UL* urbanization level, *SEI* scientific research and environmental protection investment, *IFT* infrastructure, *EPM* employment, *NR* natural resources, *GE* green environment, *PA* pollution abatement be used as the barrier degree value in the upper layer of the index system after the value is standardized. Hence, the barrier degree of each level in the index system can be calculated by using the normalized formula repeatedly.

Fuzzy rough set model

When constructing the catastrophe progression model, fuzzy rough sets were used to determine the importance of the control variables so as to avoid the influence of subjective factors. Without the requirement for prior information, the fuzzy rough set method can accommodate the uncertainty problem objectively and scientifically (Ahn et al. 2000; Pawlak 1982). Therefore, the importance of each control variable can be determined according to the approximate quality of the classification reduction.

The fuzzy rough set model assumes that there is a fuzzy information system $\{U, C, V\}$, where $U = \{x_1, x_2, x_3 \ldots\ldots x_m\}$, which is a nonempty finite set representing a collection of objects, $C = \{c_1, c_2, c_3 \ldots \ldots c_n\}$ that comprise a conditional attribute set, and V is the range of the conditional attribute. We created a green competitive evaluation real-value information system using the fuzzy rough set model by treating each year as an evaluation object, by regarding each control variable as an attribute, and by taking the corresponding value of a control variable as the value domain. The following definitions were established.

Definition 1: U is the set of objects to be evaluated, $\forall O_s$, $O_t \in U$; and X_{ij} is the standardized value of the j-th indicator of the i-th evaluation object, $i \in [1, m]$. Based on the above definition, a fuzzy relationship (Eq. 4) can be described between O_s and O_t:

$$\mathrm{RS}(O_s, O_t) = \left\{ \left(O_s, O_t \in U \times U \left| \frac{1}{n} \sum_{i=1}^{m} \left| X_{sj} - X_{tj} \right| \leq \alpha \right. \right) \right\} \quad (4)$$

In Eq. (4), "$1-\alpha$" measures the similarity between O_s and O_t; thus, the larger the value of "$1-\alpha$," the greater is the similarity between O_s and O_t, indicating they can be categorized into the same class.

Definition 2: All evaluation objects having similarities with O_s that are greater than or equal to "$1-\alpha$" are called fuzzy analogy classes of O_s, denoted by FRS.

$$\mathrm{FRS}(O_s) = \left\{ O_s \in U \left| \frac{1}{n} \sum_{i=1}^{m} \left| X_{sj} - X_{tj} \right| \leq \alpha \right. \right) \right\} \quad (5)$$

Because the reduction resulting under the fuzzy rough set is determined by the inclusion relationship of the set, it is severely affected by "noisy" data. To solve this problem, Ziarko (1993) proposed a variable-precision rough set model and introduced the use of a classification error $\beta \in (0,0.5]$. After correction of this algorithm, An et al. (1996) proposed the corrected classification ratio of $\beta \in (0.5,1]$, which we used to establish the variable-precision rough set algorithm for evaluating green competitiveness.

Definition 3: Let $R(X)$ be the classification result of all evaluation objects. Then, $R(x_j)$ is the new classification result of all the evaluation objects after removing the j-th indicator. $R_\beta(x_j)$ is defined as this new classification result of all the evaluation objects after removing the j-th indicator, which can still reflect the information of the original $R(X)$ exceeding the critical value β. $R_\beta(x_j)$ is defined as Eq. (6):

$$R_\beta(x_j) = \cup \left\{ x \in U \left| \left| R(x) \cap R(x_j) \right| \div \left| R(x_j) \right| \geq \beta \right. \right\} \quad (6)$$

where ‖ represents the number of elements contained in the collection. β is error threshold, $\beta \in (0, 1]$. When $\beta = 1$, the two classification results are consistent; when $\beta = 0$, the two classification results are completely inconsistent.

Definition 4: $|R_\beta(x_j)|$ represents the number of objects in Eq. (6), and $|U|$ denotes the total number of evaluation objects. The approximate classification quality $\gamma_{R_\beta(x_j)}$ is defined as:

$$\gamma_{R_\beta(x_j)} = \left| R_\beta(x_j) \right| \div |U| \quad (7)$$

Definition 5: $\mathrm{Sig}(x_j)$ is the importance of the j-th control variable:

$$\mathrm{Sig}(x_j) = 1 - \gamma_{R_\beta(x_j)} \quad (8)$$

where $\mathrm{Sig}(x_j) \in [0, 1]$. In this study, a similarity of $\alpha = 0.3$ (Chi et al. 2012) and a precision of $\beta = 0.9$ (Beynon 2001) were selected as critical values according to previous studies. MATLAB R2012a software (MathWorks Inc., Natick, MA, USA) was used to solve Eqs. (4)–(8) and determine the importance of each control variable.

Results

Obstacle diagnosis for the criterion layer

Spatial distribution of obstacles

The barrier degree of the criterion layer for each province in China for the period 2005–2014 was calculated according to the catastrophe progression type identified in Table 1. Figure 1 shows the spatial distributions of the obstacles included in the criterion layer for 2005, 2008, 2011, and 2014.

Time evolution of obstacles

To clarify the changes in criterion-level obstacles in each province in 2005 and 2014, the barrier degree determined for 2005 was used as the ordinate, and the barrier degree for 2014 was used as the abscissa to establish a Cartesian coordinate system (Fig. 2). The auxiliary line in Fig. 2 is $y = x$, and for provinces located above this line, the barrier degree in 2014 was less than that in 2005. Furthermore, the farther away these provinces were located from the auxiliary line, the more obvious were the decreases in the barrier degree. Provinces below the auxiliary line were in a contrasting situation, i.e., the barrier degree in 2014 was greater than in 2005 and the obstacle was becoming more severe. Provinces that were plotted on the auxiliary line experienced the same barrier degree in 2014 and 2005, and the barrier degree did not change over time. According to the distribution and aggregation, the provinces in each obstacle distribution map were divided into three categories (I, II, or III).

Details of obstacles in each province

To clearly show the spatiotemporal evolution of obstacles, those for which the barrier degree exceeded 0.7 for each province in 2005, 2009, and 2014 were collated (Fig. 3 and Table 3). Each segment of the bars shown in Fig. 3 represents an obstacle for which the barrier degree exceeded 0.7. In addition, the length of each segment represents the barrier degree of a certain obstacle mentioned above. Thus, the total length of a bar in Fig. 3 represents the severity of obstacles faced in each province in terms of the number of obstacles with significant barrier degrees. Table 3 summarizes the frequency statistics of these obstacles for provinces in the eastern, central, and western regions of China.

Obstacle diagnosis for the subtarget layer

Time evolution of obstacles in the subtarget level

Based on the barrier degree calculated for the criterion layer, Eq. (1) was used to standardize the barrier degree value because all the criterion layers can be treated as positive indicators. The barrier degrees of the economic system, social system, and resource-environment system were calculated according to catastrophe progression models presented in

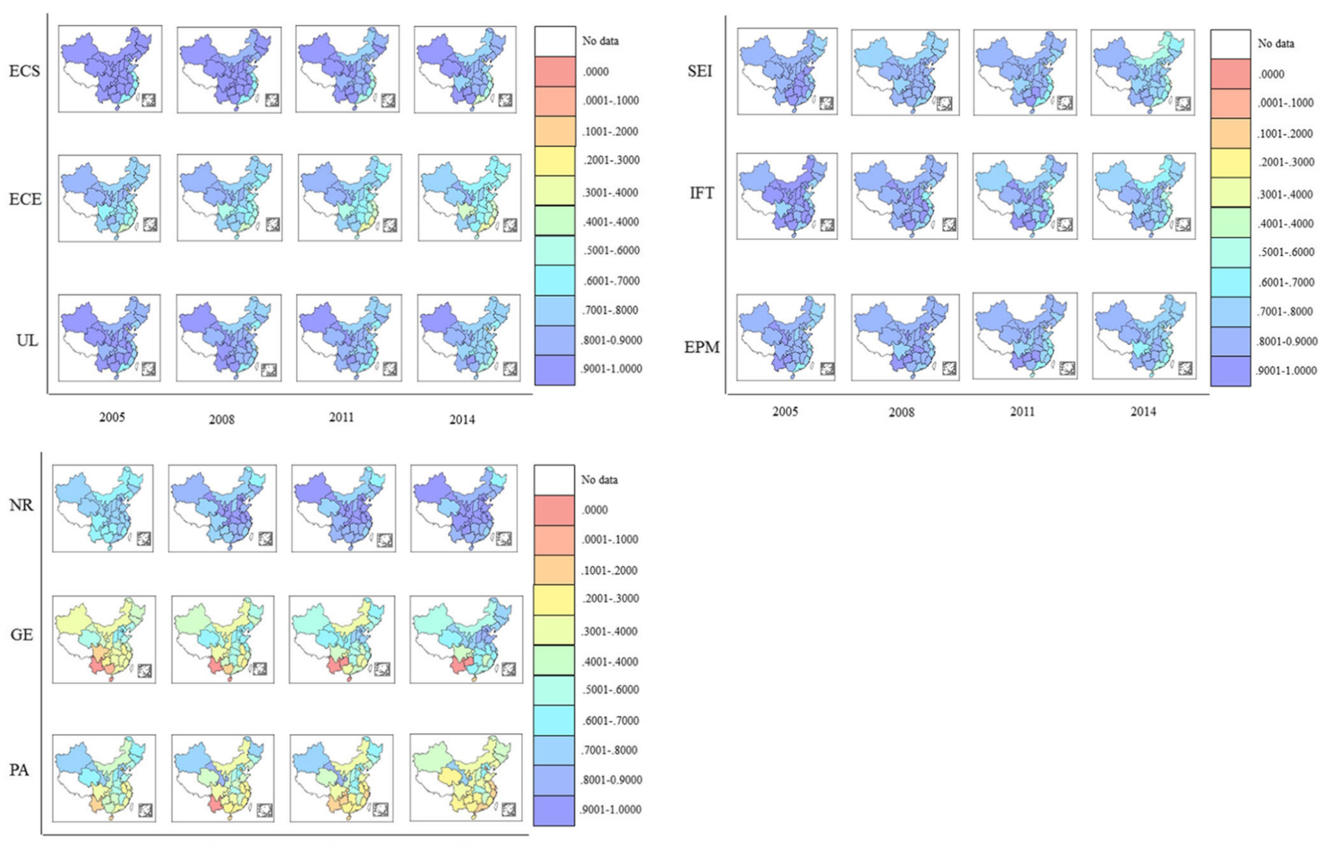

Fig. 1 Spatial distribution of obstacles included in the criterion layer for 2005, 2008, 2011, and 2014

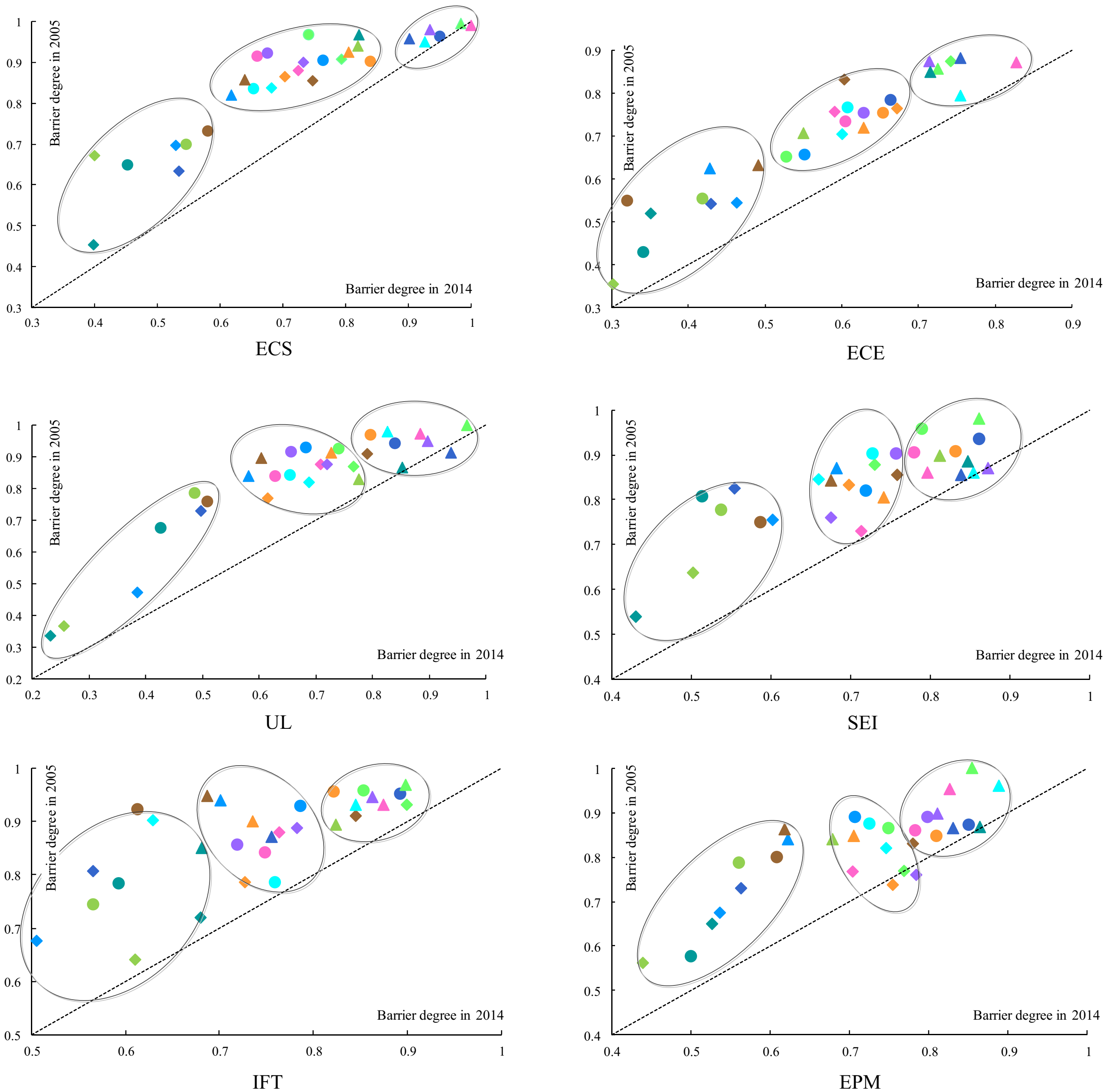

Fig. 2 Comparison of barrier degrees for obstacles between 2005 and 2014 among provinces in China

Table 1 for each province from 2005 to 2014, as shown in Fig. 4.

Comparison of barrier degrees in the subtarget level

To allow a better visual comparison of the barrier degrees for the economic system, social system, and resource-environment system, barrier data of the provinces for 2005, 2010, and 2014 were presented as rose diagrams (Fig. 5).

Discussion

Increasingly important resource and environmental problems

From Fig. 1, we can see that the barrier degree of obstacles to green competitiveness has been gradually reduced over time except for natural resource and green environment. Besides, comparing the barrier degree of criterion-layer obstacles in 2005 and 2014, we can see that the majority of provinces are plotted above the auxiliary line in Fig. 2 except for the

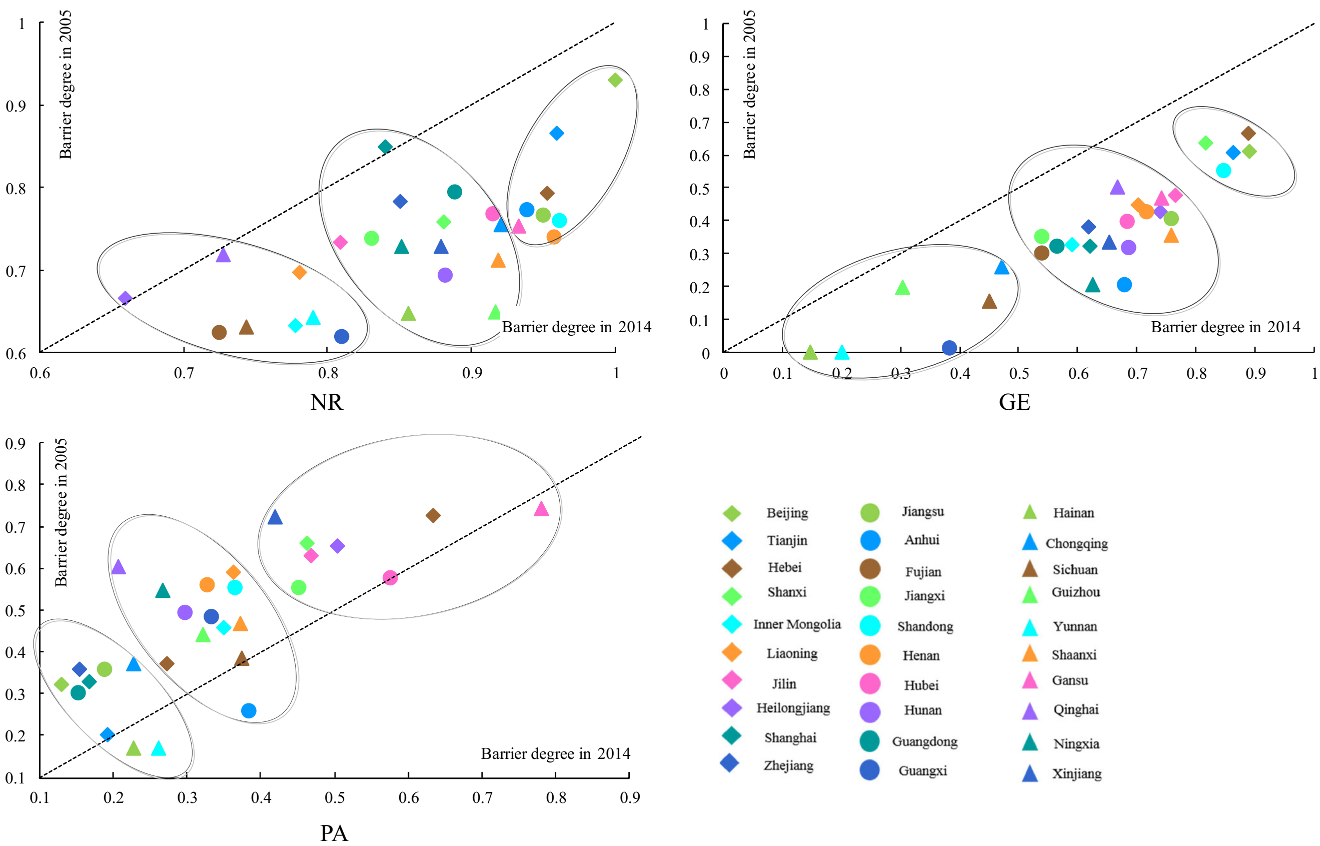

Fig. 2 (continued)

natural resource and green environment obstacles. Furthermore, provinces are plotted far from the auxiliary line in terms of natural resource and green environment obstacles, indicating that most provinces are restricted by natural resource and green environment and the barriers are becoming more severe over time in China, as shown in Fig. 2. The barrier degrees in the economic system and social system are decreasing year by year. On the contrary, the barrier degree of the resource-environmental system is increasing year by year, as shown in Figs. 4 and 5. Based on the analysis above, we can draw a conclusion that the resource and environmental problems cannot be underestimated in China, and resource and the environment have become the common obstacles to improving green competitiveness in China's provinces. This result is in accordance with many studies. Liu (2010) pointed out that China was facing environmental problems with most environmental conditions worsening and few improving during the past 60 years. Abramson (2006) and Cao et al. (2009) demonstrated that both economic growth and increasing urbanization had serious negative impacts on the environment in China, since neither was planned for or anticipated. In addition, Song et al. (2017b) concluded that China's ecological environment has been confronted with unprecedented threats combined with accelerating modernization. Furthermore, Cao (2011) and Streets et al. (2006) believed that China was facing both an environmental crisis and resource crisis mainly due to a labor-intensive economic model that used resource inefficiently. Geng and Zhang (2013), Wang (2013), Wang et al. (2015), and Zhang et al. (2012a) stated that China's environmental problems were not easy to solve and required the efforts of the state and all the residents to seek a win-win outcome between economic development and environmental protection.

The situation of resource and the environment is also becoming more serious on a regional basis. Figure 3 demonstrates the evolution of obstacles to promoting green competitiveness in Chinese provinces on a regional basis, i.e., eastern, central, and western China. As exhibited in Fig. 3 and Table 3, the obstacles in these regions had significant covariance with the development of economy and society. Obviously, resource and the environment have become the most common and obvious obstacle to improving green competitiveness in all regions. Similar findings were noticed in the studies conducted by Song et al. (2011) and Song et al. (2013). Indeed, according to Zhang et al. (2016), highly altered ecological states have been widely observed across China, from coastal regions in the east, to inland lakes and rivers, and to the grassland in the west. In other words, China's degraded environment has entered a new normal status. However, the eastern region is the most obvious and typical. Located along China's coast, the

Fig. 3 Obstacles having barrier degrees exceeding 0.7 in provinces in China for years 2005, 2009, and 2014

eastern region is the most dynamic and developed region in China. With the rapid development of economy and technology, the east has seen a rapid decline in the barrier degree of ECS, ECE, SEI, and IFT obstacles. However, the increased population and the accelerated urbanization have imposed a heavy strain on the environment and natural resource (Chen 2007; Wang et al. 2008), resulting in arable land reduction (Li et al. 2012), industrial pollution (Zhang and Da 2015), air pollution (Barbera et al. 2010; Huang et al. 2005), and water pollution (Bao and Fang 2007; Xian et al. 2007). Together, the environment and availability of resource has become the main obstacle to improving green competitiveness in the eastern region.

Table 3 Frequency of obstacles (barrier degree > 0.7) for provinces in the eastern, central, and western regions of China in 2005, 2009, and 2014

	The East			The Central			The West		
	2005	2009	2014	2005	2009	2014	2005	2009	2014
ECS	7	7	2	6	6	3	11	11	8
ECE	6	1	0	6	1	1	10	6	8
UL	8	5	2	6	6	2	11	10	7
SEI	10	8	1	6	6	5	11	11	8
IFT	11	8	0	6	6	5	11	10	6
EPM	9	10	4	6	6	5	11	11	7
NR	8	12	12	1	2	3	3	3	6
GE	0	0	8	0	0	2	0	1	2
PA	1	0	0	0	0	0	2	0	0

Rich in agricultural resource and energy, the central region has broadened many resource-based industries to develop the economy (Cao et al. 2015a), but this has brought serious environmental pollution problems at the same time, such as surface water pollution, solid waste generation, and automobile exhaust gases pollution (Wu et al. 2005). Moreover, Fang and Liu (2010) stated that the population and GDP scale in central China had exceeded the carrying capacity of resource and environment, and the sustainable development state was not

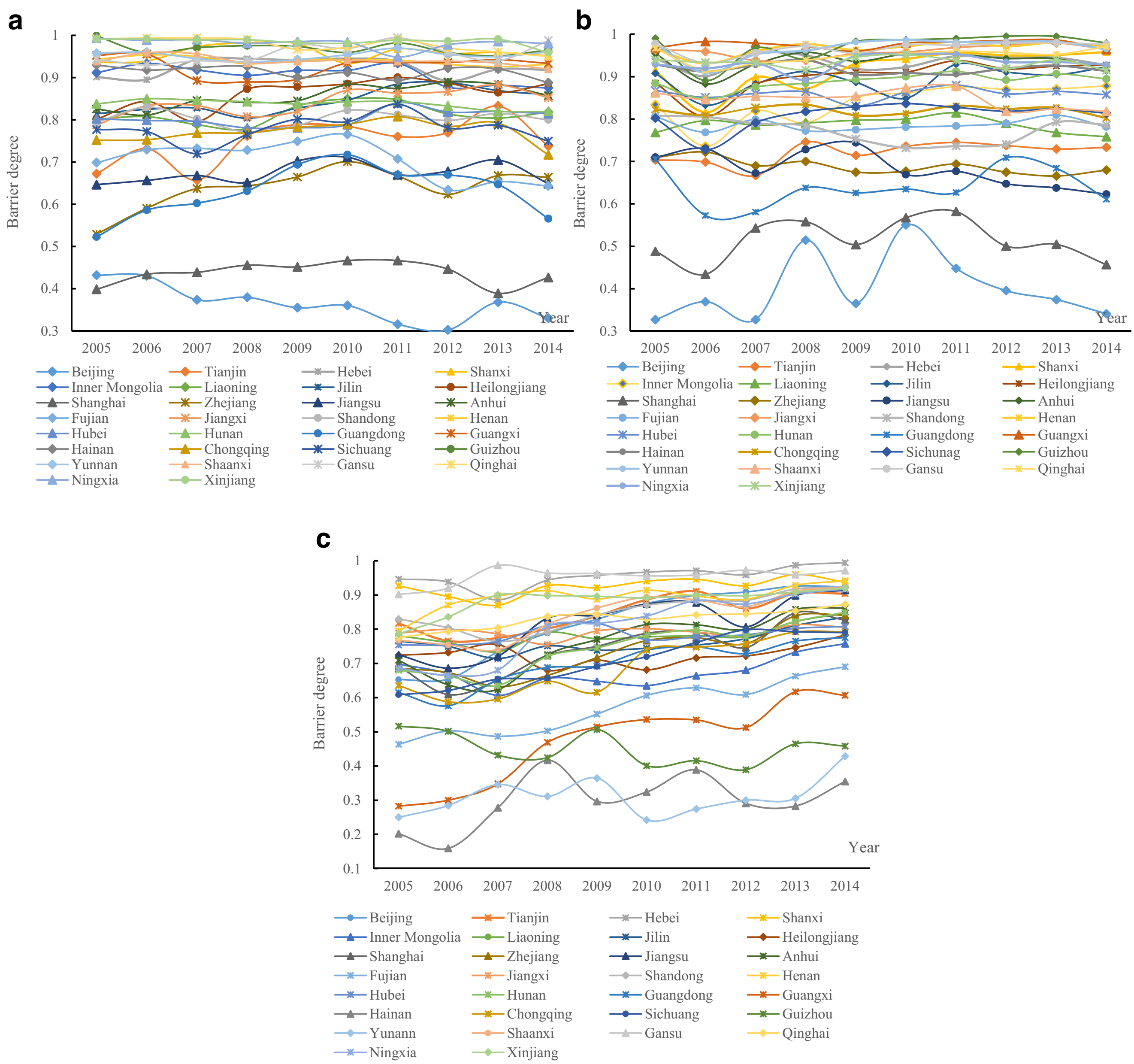

Fig. 4 Barrier degrees of the **a** economic system, **b** social system, and **c** resource-environmental system for provinces in China, 2005–2014

promising. It is easy to find that overreliance on natural resource and the absence of a reasonable environmental compensation mechanism have restricted the potential for the central region to achieve sustainable development. Similarly, the western region has relied on large-scale resource consumption and also faces a severe resource and environmental situation as indicated by the low resource utilization ratio and poor economy that is evident there. In other studies (Cao et al. 2015a; Hu et al. 2005), similar findings were mentioned about the environmental problems in the western region, such as land destruction, water pollution, solid waste pollution, and desertification.

Spatial heterogeneity of obstacle factors

Due to various factors such as history, geography, policy, and natural resource abundance, the obstacles to improving green competitiveness showed spatial heterogeneity.

As discussed in the "Increasingly important resource and environmental problems" section, the major obstacles to improving green competitiveness in the eastern region are natural resource and the green environment. Figure 2 shows that provinces in the eastern region were grouped in category I in terms of ECS, ECE, UL, SEI, IFT, EPM, and PA obstacles, indicating that the barrier degree of these obstacles was much

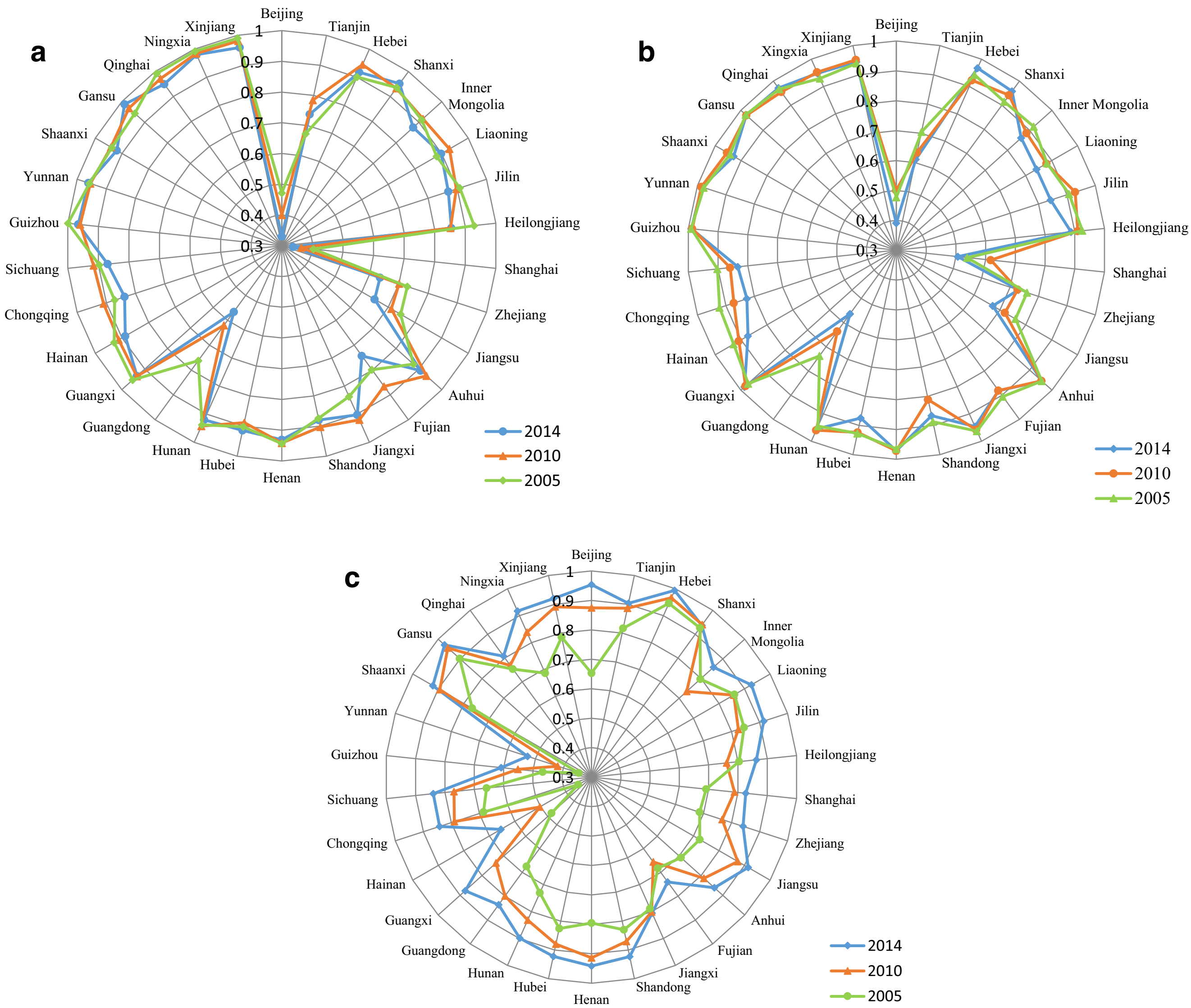

Fig. 5 Barrier degrees of the **a** economic system, **b** social system, and **c** resource-environmental system for Chinese provinces in 2005, 2010, and 2014

smaller for the eastern provinces than elsewhere, and the economic systems and social systems are very well developed. Besides, for these obstacles, most of the provinces were above the auxiliary line in Fig. 2, indicating that the barrier degree in 2014 was smaller than that in 2005. This outcome is consistent with those of Long et al. (2015), Wang et al. (2012a), and Wang et al. (2013), which highlighted the advantages of economic efficiency and technical efficiency in the eastern region compared to the central and western regions. However, as regards the obstacles NR and GE, most of the eastern provinces were gathered in category III, and the majority was below the auxiliary line in Fig. 2, showing that NR and GE were the main obstacles for the eastern provinces, and the barrier degree was continuing to increase over the period 2005–2014.

Figure 3 and Table 3 further show that provinces in the eastern region have experienced a decrease in the barrier degree of the ECS, ECE, UL, SEI, IFT, EPM, and PA, and the natural resource and environmental factors have become the biggest obstacles to promoting green competitiveness in this region. In recent years, driven by industrialization and better information technology, the eastern region has become an economic and social center in China by taking full advantage of its geographical condition, technological innovation, and knowledge-type talents. However, behind the rapid economic development is a series of devastating activities that violate the laws of nature, such as population growth, predatory resource consumption, and environmental pollution. Studies have shown that industrialization, urbanization, and rapidly increasing populations have accelerated environmental pollution and resource crises in the eastern region (Barbera et al. 2010; Chen 2007; Huang et al. 2005; Li et al. 2012; Wang et al. 2008). Industrial enterprises have expanded rapidly and grown sharply and have promoted the industrialization in the eastern region; however, these industries have also brought negative effects, such as air pollution and arable land reduction. City construction has accelerated the urbanization process but also triggered environmental contradictions at the same time. Population concentration, while increasing human capital, has also increased the already excessive demand for energy and resource. Consequently, natural resource and the green environment have become the most important barriers to promoting green competitiveness in the eastern region.

In the central region, the most important obstacles to improving green competitiveness are SEI and IFT. Figure 2 shows that provinces in the central region were grouped in category II, indicating that the barrier degree was greater than that in the eastern region for the ECS, ECE, UL, SEI, IFT, EPM, and PA obstacles and smaller than the eastern region for NR and GE obstacles. Previous studies also support our results and confirm the gap of technology efficiency and energy efficiency between the eastern region and the central region (e.g., Li et al. 2016; Long et al. 2015; Yang and Li 2017). The barrier degree of ECS and ECE in the central provinces decreased gradually in 2005–2014, and SEI as well as IFT became the most important obstacles to promoting green competitiveness, as described in Fig. 3 and Table 3, which is in line with findings of Wang et al. (2012b) and Wu et al. (2005). SEI includes two aspects: scientific-technological investment and environmental protection investment. On one hand, the lack of scientific and technological support not only delayed the change of growth mode but also restricted the full use of resource and the effective management of the environment, leading to a lack of potential development in the central region. On the other hand, low investment in environmental and resource management meant that enterprises and government were unable to concentrate financial funds on solving the natural resource and environment problems, thus resulting in a low level of green competitiveness. In addition, inadequate infrastructure construction, such as for water supply, gas supply, traffic and communication (Wu et al. 2005), and low efficiency of operations and management, as well as lack of infrastructure have become the main obstacles restricting green competitiveness in the central region.

The most important obstacles to improving green competitiveness in the western region are economy, scientific and environmental investment, and infrastructure. Figure 2 shows that provinces in the western region were grouped in category III, indicating that the barrier degree was greatest among all regions for the ECS, ECE, UL, SEI, IFT, EPM, and PA obstacles. Notably, some provinces such as Yunnan, Guizhou, Sichuan, and Guangxi were grouped in category I in terms of NR and GE obstacles, showing that the barrier degree for these obstacles was small in these provinces. From Fig. 3 and Table 3, we can see that the obstacles are diverse for the western region, among which the most important are ECS, ECE, SEI, and IFT. This conclusion is in conformity with that of Mei et al. (2015), Long et al. (2015), and Wang et al. (2012a) who showed the economic efficiency, technical efficiency, and environmental efficiency of the western region were far lower than those of the eastern and central regions. Because the western region is in the initial stage of industrialization and urbanization, there is a large opportunity and need for economic development. Faced with a low utilization of natural resource and a disorganized industrial structure, the western region must take full use of innovation and technology development to improve competitiveness (Song et al. 2017a). However, the lack of sufficient infrastructure is also a major obstacle to improving the green competitiveness in the western region.

The peculiarity of obstacle factors

When analyzing the obstacle factors of each province, we can find that each province has unique obstacle factors in addition to the universal obstacle factors in the region. We mainly analyzed the particularity of obstacle factors of some provinces in the criterion layer for the year 2014.

The major obstacles of green competitiveness for each province, defined by a barrier degree exceeding 0.7, can be seen according to Fig. 3. Apart from the two common obstacles of NR and GE, some provinces show unique obstacles in the eastern region. The EPM is also an obstacle of Liaoning, Jilin, and Heilongjiang, which are located in the old industrial base of northeast China. With industrial resource depletion and industrial structure transformation, the employment structure has also been changed greatly, resulting in the layoffs of employees in a large number of state-owned enterprises. Besides, the employment pressure is growing due to the decreasing proportion of heavy industry. A depressed heavy industry not only reduces the labor force but also hinders the transfer of the agricultural labor force to nonagricultural industries. In addition, the ECS and the EPM are also obstacles for Hebei province. On one hand, the economy is restricted by high energy consumption and industry strongly dependent on resource. On the other hand, the employment pressure has increased dramatically with industrial transformation in recent years.

For the central region, the ECS and EPM are also the main obstacles of Shaanxi, Jiangxi, and Henan to improving green competitiveness. The main reason is that these provinces are highly dependent on agriculture, and the industrial cluster has not yet formed because of the geographical position, putting great pressure on economic development and employment. As for the western region, with NR being the main obstacle, the most important work for Chongqing and Sichuan is to reduce the resource constraint by improving the resource use efficiency and taking full advantage of provinces rich in resource. Besides, UL and EPM are also important obstacles in most western provinces, such as Guangxi, Guizhou, Yunnan, Gansu, Qinghai, and Xinjiang. The low level of urbanization is mainly due to the underdeveloped economy and backward society. Besides, there are many reasons for the employment problems in the western region, including a backward economy, geographical disadvantage, unreasonable industrial layout, and lack of talented workers.

Conclusions, policy implication, and future research direction

The present studies mainly focus on the factors that influence and promote regional competitiveness or green competitiveness, and have not yet diagnosed factors that hinder regional green competitiveness. Hence, we developed an obstacle diagnosis model to explore the factors and their barrier degree that inhibited green competitiveness in Chinese provinces during the period 2005 to 2014. The following conclusions are justified by the results of this study.

1. Resource and environmental problems became increasingly prominent during the study period, and they are now the most common obstacle to promoting green competitiveness among provinces in China.
2. The obstacles to improving regional green competitiveness show spatial differences according to the barrier degree. The major obstacles in the eastern region are natural resource and the green environment, whereas the most important obstacles in the central region are scientific research and environmental protection investment, as well as infrastructure construction. The most important obstacles in the western region are economic development, scientific research and environmental protection investment, and infrastructure construction.
3. Specifically, some provinces have unique obstacle factors to improving green competitiveness in addition to the universal obstacle factors in the region. Employment is an important obstacle to Liaoning, Jilin, and Heilongjiang. Economic scale and employment are also the main obstacles of Hebei, Shaanxi, Jiangxi, and Henan. Additionally, urbanization and employment are also important obstacles in most western provinces, such as Guangxi, Guizhou, Yunnan, Gansu, Qinghai, and Xinjiang.
4. The empirical results are in accordance with China's actual development, indicating that the index system and the obstacle model are scientifically grounded and relevant, and can be used to explore the green competitiveness obstacles and their barrier degree in China.

Based on these conclusions, we propose a strategy for promoting and improving regional green competitiveness. The strategy is based on prioritizing resource and environmental quality, contains precision development, and encourages cross-regional cooperation. Our suggestions are as follows:

1. The resource and environment must be prioritized and solidified into the "redline" of economic growth. Meanwhile, efforts should be made to create a sustainable development path, focusing on efficiency and quality, and based on ecological as well as environmental principles.
2. Each region and province should improve green competitiveness by addressing the main obstacles they face. The eastern region should improve the efficiency and utilization of resource and properly address environmental pollution problems, such as water pollution and smog. The central region should accelerate innovation and construct infrastructure to create a dynamic and guaranteed atmosphere for development. The western region should perfect infrastructure and achieve sound and rapid economic development through crossover benefits in technical areas, policy support, and a skills-development strategy. Provinces that are faced with unique obstacles should focus on the specific problems and adjust development strategy in a timely way.
3. An information-sharing platform should be established to achieve regional coordinated development. Additionally, strategic alliances, including environment co-governance, resource sharing, infrastructure co-construction, and economic cooperation should be reached to improve regional green competitiveness.

Other topics can be further studied and discussed based on our work. These include finding the reason that may have led to the differences in obstacles, which would be useful in guiding strategies to address obstacles. Besides, the extension of our index system to consider more countries and more indicators is a logical next step for further research.

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