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Interaction characteristics and development pattern of sustainability system in BHR (Bohai Rim) and YRD (Yangtze River) regions, China

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ABSTRACT

The well-run structure, function and dynamics of complex regional sustainability system are critical for maintaining regional sustainability stability, so exploring the interaction characteristics and development pattern of the system should be considerably significant. Based on the new comprehensive index system of sustainability system, the indices of social, economic and eco-environmental dimensions and nine thematic indices are firstly presented for BHR (Bohai Rim) and YRD (Yangtze River) regions during the period 2001–2010, and then the regional sustainability changes are further tracked by regional sustainability index (RSI) and regional coordination index (RCI). Furthermore, we mainly focus on the dynamic interaction characteristics and propose green development index (GDI) to reflect the development pattern of BHR and YRD from the perspective of taking all indicators into account. The study results show that: the average annual growth rates of the indices of social, economic and eco-environmental dimensions of the BHR region are 10.00%, 19.11% and 0.37% during the study period, while the ones of YRD region are 7.32%, 20.25% and 0.46%, respectively, demonstrating that economic progress is the fastest-improving pillar for RSI of the two regions; the standard deviations of the indices of three dimensions that can construct a triangle diagram and the amount of that failed to construct are both decreasing from 2001 to 2012, showing that the RCI of two regions have made some progresses; BHR have stayed in some positions where eco-environmental level gradually decreases (from 0.50 to 0.45) with the progression of socioeconomic situations (from 0.20 to 0.50), while BHR in a position where eco-environmental level gradually increases (from 0.53 to 0.57) with the progression of socioeconomic situations (from 0.25 to 0.55), revealing dynamic interaction characteristics, and then in their evolution trajectories, YRD has been principally at the intermediate sustainable development stage while BHR always at the potentially unsustainable one; the green social or economic development degree, associated with the uneven resource utilization and eco-environment occupancy among provinces, should contribute most to regional development pattern. The study guides a direction where the policy makers need to improve in regional sustainability management.

1. Introduction

Sustainability science, gripped with the issue“that meets the present needs and aspirations without compromising the ability of future generations to meet their owns” (WCED, 1987), or “meeting fundamental human needs while protecting the life-support ecosystem” (Kate et al., 2001; Ostrom, 2009), has been emerging as a transdisciplinary effort for addressing the much-needed symbiosis between human activity and eco-environment (Rapport, 2007). It is also an attempt to link the environment with development (Giddings et al., 2002; Robinson, 2004). From the perspective of ecosystem health, to maintain the health or well-functioning of regional sustainability system, the interaction characteristics and development pattern of the dynamic complicated system should be the primary focus (Miller, 2013), which can help explore the structure, function and dynamics of sustainability system and provide insights into sustainability changes.

Such sustainability changes for the great majority of regions, as a matter of fact, often stem from human socioeconomic activities (Kajikawa, 2008; Li et al., 2012), which bring about poignant contradictions and foreseeable threats of our location: resources depression, environment deterioration and ecological disruption. Considering the essence of the issue, Schoolman et al. (2012) probed into the sustainability change research from three “pillars” of sustainability sciences (environmental, economic and social pillars) by using bibliometric data. The interaction characteristics between environmental change and socioeconomic development are highly meaningful to promote the researches of sustainability system, however, it seems to be hasty

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to make the researches relied solely on traditional Environmental Kuznets Curve (EKC) (Shahbaz et al., 2012; Wong and Lewis, 2013), because this interaction is always decided by multiple intertwined factors, such as population, economic scale and structure, science and technology level, and even human capital and policy change (Tsaliki, 2009). In practice, there has been considerable academic interest in the fields of modeling and analyzing the relation or interaction between economic growth and environmental pollution in many literatures (Brajer et al., 2011; Diao et al., 2009; Shahbaz et al., 2012), which commonly select a single indicator to reflect each subsystem, however, it is not great popularity of quantitative study on interaction characteristics between socioeconomic development and environmental change from the perspective of overall level for the two aspects so far. Therefore, the interaction characteristic among some subsystems, especially between socioeconomic and eco-environmental changes, deserves to be explored by synthesizing multiple temporal and spatial factors as all-round as possible.

What's more, the core issues of sustainability science (Ostrom, 2009), identified by Kates (2011), Kate et al. (2001) and Levin and Clark (2010), also cover how to make the modeling of dynamic interaction between human and environment and how to assess the sustainability in different trajectories. On the one hand, the dynamic interaction characteristics between human and environment need to be quantified in such a modeling way so as to observe the high intensity interactions and to identify their evolution trend in relation to the process of regional sustainable development. On the other hand, the two different trajectories of socioeconomic sustainability and environmental sustainability can first confine the coordinated development capability of regional sustainability system to a pessimistic level, and then can reflect the specific development pattern at each point. The two are not independent, but restrict mutually, play together.

Currently, a growing body of literatures has been conducted to achieve valuable results of dynamic change process of interaction between economic growth and eco-environmental quality, which largely conforms to a Kuznets curve (Wong and Lewis, 2013), and of interaction urbanization level and eco-environmental capacity, which largely conforms to a logistic curve (Wang et al., 2014). Nevertheless, the strand always focuses on how per capita GDP or income acts on a single indicator with each other, specifically on CO_2 emissions (Lin and Jiang, 2009), air pollution (Brajer et al., 2011), water pollution (Diao et al., 2009), and so on, and later greater attempts concentrate on more inclusive one, such as the interaction between Ecological Footprint and Human Development Index (Boutaud et al., 2006) and between Ecological Footprint and GDP (Caviglia-Harris et al., 2009). It may be still not enough. According to theoretical and practical analysis, this paper builds on a more inclusive analysis with a quadratic EKC model utilizing a time series of data on a theoretical framework incorporating society and economy subsystems into the overall socioeconomic level index and an aggregated measurement of eco-environment level index. In the evolution trajectory of socioeconomic and eco-environmental sustainability, five sustainability intervals are divided by virtue of the improved "sustainability barometer" framework, which can help display the specific development stage of each point in the whole trajectory.

Moreover, differing impact that human activities influence and occupy the state of the eco-environment will lead to uneven regional sustainability changes. How to assess the fairness and rationality of resource consumption or/and pollutant emissions under certain economic contribution for different regions aroused the researches' enthusiasm (Huang, 2012; Zhang et al., 2008), while previous studies primarily focused on evaluating the share of a single indicator, such as COD, SO_2 emissions or energy consumption, relative to the share of GDP in total for different regions according to Environmental Gini coefficient (Sun et al., 2010) to reflect the tradeoff between economic development and environmental protection. However, given the complexity of the equality issue in this topic, few studies were able to address it by taking all, including economic, social, and environmental, criteria into account. Meanwhile, structural decomposition analysis model (Liu, 2009; Yao et al., 2015) has been widely applied to explain the changes that occur in any variables over time or space. Therefore, we propose "green development index" to reflect this tradeoff so as to reveal the development pattern, and further explore the underlying driving forces of the changes of green development index by structural decomposition model.

The Bohai Rim (BHR) and Yangtze River Delta (YRD) regions of China, two of the leading economic zones in China as well as the political, economic and cultural center, show poignant linkage between human socioeconomic activities and eco-environmental change and uneven development among their provinces in recent years (Qi et al., 2013; Tan and Lu, 2015). Consequently, this paper will present such an interesting study that a detailed analysis of dynamic interaction characteristics and development pattern of sustainable development system of BHR and YRD regions from new insights. We track the interaction characteristics and regional development pattern and explore how and why regional sustainability system change when developing regional sustainability index (RSI), regional coordination index (RCI) and green development index (GDI), providing the policy makers with fundamental support for a regional sustainability direction.

2. Method

2.1. Data

Eight provinces, which belong to BHR (Beijing, Tianjin, Hebei, Shandong and Liaoning) and YRD (Shanghai, Jiangsu and Zhejiang) regions, are selected as the study area (Fig. 1). It is well known that the two regions are the central parts of Chinese economy, culture and policy; nevertheless, they harbor serious challenges for regional sustainable development. Therefore, the structure, function and dynamics of regional sustainable development system during the period 2001–2012 need to be explored at provincial and regional scales. And most of the data of selected regions origin from the statistical yearbooks of China and provinces from 2002 to 2013, compiled by the central government and subordinate ministries, with the national economy and society developed statistical bulletin and environmental bulletin replenished. Parts of population, economy, and education data are obtained from China Population and Education Statistical Yearbook of the corresponding year.

2.2. Index system

In accurately analyzing the interaction characteristics and development pattern of regional sustainability system, we first develop a comprehensive index system framework, which consisted of 3 dimensions, 9 thematic indices and 53 indicators (S1–S16, EC1–EC13 and EN1–EN14) (Table 1). Because challenges of eco-environmental protect policy not only come from the technical constraints (Energy structure, technology updating, etc), but also from the fact that there is a large regional development disparity in term of economic structure and benefit, policy change, technical constraints, human capital, physical geography, ecological endowment and pressure, environment conservation, lifestyles and so on (Dong and Liang, 2014; Valipour, 2014, 2015a, 2015b; Valipour et al., 2015). The index system particularly addresses the actual situation of BHR and YRD regions and constructs the evaluation index system in light of the science, maneuverability, hierarchical and dynamic properties. Among them, each thematic index (HLI, SPI, HCI, EGI, ESBI, STII, EEI, EPI and ERI) (see Table 1) is integrated by several corresponding indicators, respectively. The nine classified thematic index, followed the principle of "top to bottom" in establishing index system, form the basic indispensable structure of analyzing regional sustainability system, so it will be more accurate to determine the underlying indicators or variables. More specifically, the developed social dimension (SOC) contains three thematic indices and 16 basic indicators (variables).

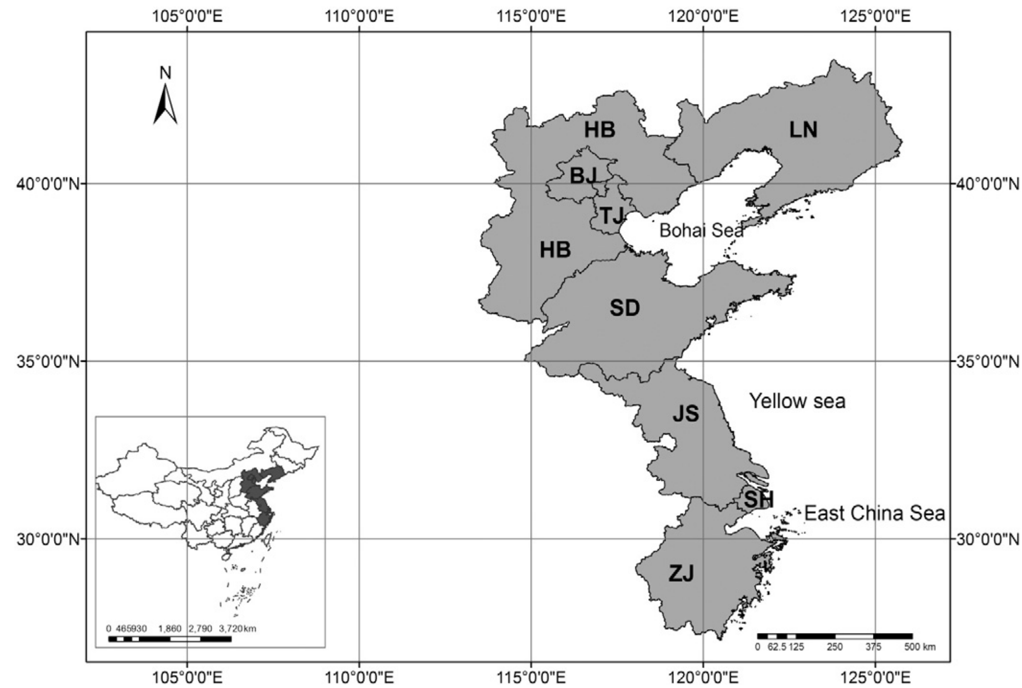

Fig. 1. The study area of BHR and YRD regions.

Economic growth index, Economic structure and benefit index and Science and technology innovation index are considered for economic dimension (ECO). The environmental dimension (ENV) includes four thematic indicators and 14 basic indicators. The selection of variables, the procedure of indicators construction, and the identification of the thematic index are well-suited to describe the context influencing the regional sustainability system.

It is worth mentioning that some indicators have been addressed according to Eq. (1) due to the inconsistent statistics caliber of urban and rural residents, such as S_1, S_2, which are computed on the basis of living area and per capita disposal income of urban and rural resident as weighted by the demographic data. In Eq. (1), S represent per capita value in overall, u_1, u_2 are separately the corresponding indicators of urban and rural, and P_1, P_2, P stand for the urban and rural population and total population, respectively. The average education level stems from the population of illiterates who are aged 15 or older and the total population who are aged 15 or older in the region. Besides, human resources quantities (HRQ) are calculated as Eq. (2), where EP and $P_{15\text{-}64}$ represent the employed population and the population who are aged 15 to 64 (Bian et al., 2012). As to the rest, it need not be explained in detail.

$$S = \frac{u_1 P_1 + u_2 P_2}{P} \tag{1}$$

$$HRQ = \frac{GDP}{EP} \times P_{15-64} \tag{2}$$

2.3. Data preprocessing with improved "max–min" normalized method

With the purpose of equal and feasible comparison for all different spatial and temporal data, we improved the traditional "max–min" normalized method (Eqs. (3) and (4)), which often manifests as selecting the maximum or minimum values in all spatial and temporal units for the normalized value of each indicator, while the traditional method often manifests as selecting the maximum or minimum values in all time units but the spatial units for the normalized value of each indicator. It is just the modified normalized method that should be a suitable computation basis for undertaking quantitative and qualitative analysis, which can also assist with identifying and weighting selection criteria to analyze the data.

$$x_{t,i,j} = \frac{x'_{t,i,j} - x'_{i,\min}}{x'_{i,\max} - x'_{i,\min}} \tag{3}$$

$$x_{t,i,j} = \frac{x'_{i,\max} - x'_{t,i,j}}{x'_{i,\max} - x'_{i,\min}} \tag{4}$$

Where $x_{t,i,j}'$ represents the original value of the *ith* indicator for the spatial unit j (a province or region in this study) in the year t; $x_{i,\max}'$ and $x_{i,\min}'$ are respectively the minimum and maximum values of the ith indicator in all temporal units for all spatial units; Eq. (3) is applied to an indicator which plays a positive role to regional sustainability while Eq. (4) is applied to an indicator which shows a negative role. Each normalized variable ranges from 0 to 1.

2.4. Developing the weight-determining method and composite index

To test the characteristics of the different indices with different weights, we built two weight scenarios based on Analytic Hierarchy Process (AHP) (subjective) (Valipour and Montazar, 2012; Valipour et al., 2012) and Entropy methods (objective methods) (Wang et al., 2014), and adopt the average values of the two as the final weights in order to exclude some differences brought by a single method. The two tables of Appendix. 1 present the detailed weights of all indicators of BHR and YRD regions and all provinces.

Once the weights of the basic indicators are determined, the values of nine thematic indices can be computed and subsequently the index level of the three subsystems (dimensions) and sustainable development system are presented, including the social level index (SLI), economic level index (ELI), eco-environmental level index (EELI) and regional sustainability index (RSI). As for regional coordination index (RCI), we develop a simple but vivid method to reflect the coordination level, and further quantify it by calculating the standard deviation of SLI, ELI and EELI of the three angles that can construct triangle diagram for each province or region.

Table 1
The index system of sustainability system in the BHR and YRD regions.

Dimensions	Thematic index	Serial number	Variables	Units	Direction
SOC	People living index (HLI)	S1	Per capita disposable income in whole society	Yuan	+
		S2	Per capita living space	m^2	+
		S3	Engel coefficient in whole society	None	−
		S4	Rate of per capita income of urban and rural resident	None	+
		S5	Per capita retail sale of consumer goods	Yuan	+
	Society progress index (SPI)	S6	Urbanization rate	None	+
		S7	Unemployment rate	None	−
		S8	Number of students in colleges and universities per ten thousand people	None	+
		S9	Number of hospital beds per ten thousand people	None	+
		S10	Per capita throughput of post and telecommunication	Yuan	+
		S11	Per capita highway mileage	km	+
	Human capital index (HCI)	S12	Human resources quantities	Yuan	+
		S13	Average education level	year	+
		S14	People health index	year	+
		S15	Per capita R&D investment	Yuan	+
		S16	Per ten thousand people Granted patent approval	None	+
ECO	Economic growth index (EGI)	EC1	Per capita GDP	Yuan	+
		EC2	Economic density	Yuan/m^2	+
		EC3	Per capita fiscal revenue	Yuan	+
		EC4	Per capita exports	Yuan	+
		EC5	Per capita fixed asset investment	Yuan	+
	Economic structure and benefit index (ESBI)	EC6	Labor productivity of whole society	Yuan	+
		EC7	Average wages of staff and workers	Yuan	+
		EC8	Proportion of primary industry output	None	−
		EC9	Proportion of tertiary industry output	None	+
	Science and technology innovation index (STII)	EC10	GDP energy consumption per ten thousand yuan	kg	−
		EC11	GDP water consumption per ten thousand yuan	kg	−
		EC12	Rate of R&D investment	None	+
		EC13	Rate of R&D population	None	+
ENV	Environment endowment index (EEI)	EN1	Per capita forest stocking volume	m^3	+
		EN2	Per capita water resource	m^3	+
		EN3	Rate of nature reserves to land area	None	+
		EN4	Per capita energy available supply	kg	+
	Environment pressure index (EPI)	EN5	Per capita wastewater discharge	kg	−
		EN6	Per capita waste gas discharge	kg	−
		EN7	Per capita emissions of COD	kg	−
		EN8	Per capita emissions of SO_2	kg	−
		EN9	Per capita emissions of solid wastes	kg	−
		EN10	Per capita energy consumption	kg	−
	Environment response index (ERI)	EN11	Industrial wastewater discharge compliance rate	None	+
		EN12	Industrial solid wastes comprehensive utilization ratio	None	+
		EN13	Rate of environment protection investment to GDP	None	+
		EN14	Rate of days of air quality reaching a minimum of Level II to a full-year	None	+

2.5. Interaction characteristics of SELI–EELI

The empirical studies of EKC started by Grossman and Kreuger (1995) and followed by Suri and Chapman (1998), Stern (2004) and Coondoo and Dinda (2008), all of which were inspired by the Kuznets' inverted U-shaped curve's meaning and encouraged environmental level improvement followed by the empirical results. Among the multiple models of such studies, the quadratic function of EKC is applied widely in various fields (Wang et al., 2014; Wong and Lewis, 2013), and Eq. (5) is the corresponding mathematical expression in the form of top point. However, the interaction characteristics of social–economic level and environment level are wanted to be explored from the perspective of taking all factors into account for the two aspects, rather than a traditional considering, such as GDP and pollutant emissions. Meanwhile, in order to vividly demonstrate the regional sustainability status, we simultaneously develop the improved “sustainability barometer” framework (Reed et al., 2006) to present the subcategorized sustainability intervals. Summarily, the development degree of a province or region during the twelve years can be displayed intuitively.

$$y = a - b(x - c)^2 \tag{5}$$

$$SELI = w_1 SLI + w_2 E^2 LI \tag{6}$$

Where x and y stand for socioeconomic level index (SELI) and EELI, respectively, and the former is integrated from SLI and ELI according to the corresponding weights (see w_1, w_2 and consider $w_1 = w_2 = 1/2$).

2.6. Regional development pattern with Lorenz curve and Gini coefficients

The Gini coefficient (Eq. (7)), a ratio between 0 and 1 based on the Lorenz curve, is a commonly economic measurement tool for income inequality or wealth distribution (Sun et al., 2010) and a prevailing method for processing regional inequality (Dong and Liang, 2014). The structure decomposition model (Liu, 2009) is commonly employed to explain the changes that occur in any variable over time or space. The model's logic allows us to analyze distinct patterns of regional development that might have their origins in differences in one or another of these components (Yao et al., 2015). To match our topic, thereby, from the perspective of “the green development index”, some modifications are made.

$$\text{Gini} = 1 - \sum_{i=1}^{n} (x_i - x_{i-1})(y_i + y_{i-1}) \tag{7}$$

Where, for the Lorenz curve of SELI–EPI, n is the number of groups; x_i is the cumulative share of EPI when come to group i; y_i is the cumulative share of SELI when come to group i.

(1) Structure decomposition model for Gini coefficient
Supported that:

$$G = \sum_{k=1}^{3}(f_k/f)G_k = \sum_{k=1}^{3} S_k G_k \quad (8)$$

Where f and f_k are the total output and the output of kth (k = 1, 2, 3) industry. And we can get the following by some simple mathematical transformations:

$$\begin{cases} \Delta G = G_{t+1} - G_t = \sum_{k=1}^{3}(S_{k,t+1}G_{k,t+1} - S_{k,t}G_{k,t+1}) \\ \Delta S_k = S_{k,t+1} - S_{k,t} \\ \Delta G_k = G_{k,t+1} - G_{k,t} \end{cases} \quad (9)$$

So we also get the specific decomposition as Eq. (10), which is divided into the effects from the changes of industrial structure, industrial concentration and the integration of the previous two.

$$\begin{aligned} \Delta G &= \sum_{k=1}^{3}(\Delta S_k G_{k,t} + \Delta G_k S_{k,t} + \Delta S_k \Delta G_k) \quad (10) \\ &= \sum_{k=1}^{3} \Delta S_k G_{k,t} + \sum_{k=1}^{3} \Delta G_k S_{k,t} + \sum_{k=1}^{3} \Delta S_k \Delta G_k \end{aligned}$$

Where S_k and G_k are the industrial proportion and their Gini values when $k = 1, 2, 3$ represent the first, second and tertiary industries, respectively; G is the total Gini value; ΔG, ΔG_k and ΔS_k stand for the changes of total Gini value, industry concentration level, the industrial proportion during the period t to t + 1, respectively.

(2) Structure decomposition model for green development index
With help of environmental Gini coefficient (EGC) (Sun et al., 2010) and the structure decomposition of traditional Gini coefficient, the green development index (GDI) model (Eq. (12)) and its decomposition are constructed as below when considering the corresponding weighted factors (f) for Green social development index (GSDI) and Green economic development index (GEDI) (see f in Table 2).

$$GDI = \sum_{j=1}^{5} S_j GDI_j \quad (11)$$

$$GDI_j = \frac{ELI_j/ELI_{BHR}}{EPI_j/EPI_{BHR}} \quad (12)$$

$$\Delta GDI = \sum_{j=1}^{5} \Delta S_j GDI_{j,t} + \sum_{j=1}^{5} \Delta GDI_j S_{j,t} + \sum_{k=1}^{3} \Delta S_j \Delta GDI_j \quad (13)$$

Where GDI_j is GSDI or GEDI and S_j is the proportion of each weighted factor (see f in Table 2) of jth province in whole BHR region when j = 1, 2, 3, 4, 5 stand for Beijing, Tianjin, Hebei, Shandong and Liaoning, respectively (there is a same process for YRD); ELI should be substituted by SLI when calculating GSDI and EPI (environmental pressure index), latter of which is one of the thematic indices mentioned above; and therefore ΔGDI, ΔGDI_j and ΔS_j stand for the total GEDI or GSDI changes, green social or economic development changes (which we can call concentration effect) and the changes of the proportion of f (which we can call structural effect) (see Table 3) from period t to $t + 1$, respectively.

Table 2
The set weighted factors in calculating GDSI and GDEI.

	Factor 1 (f_1)	Factor 2 (f_2)
GEDI	GDP	Secondary industrial (SI)
GSDI	Employment population (EP)	Human resources quantities* (HR)

* The Human resources quantities (S12) can be calculated in accordance with Eq. (2).

3. Results and analyses

3.1. RSI and RCI

3.1.1. RSI

We compute the correlation coefficients, which have been not presented for the sake of space, to show that the nine thematic indices in each dimension are independent with each other. Under this circumstance, the index level in the dimensions of regional sustainability system and its three subsystems are rationality to display the genuine change. Fig. 2 shows the sustainability change trend of the four during the period 2001–2012 when considering Beijing, Tianjin, Hebei, Shandong and Liaoning as BHR region and considering Shanghai, Jiangsu and Zhejiang as YRD region. The SLI, ELI and SDLI of BHR region, initially, have been invariably lower than YRD during the study period, except the EELI of the two regions seem to be cardinally identical, demonstrating the YRD region harbors a relative better sustainability status. It can also reveal that the regional sustainability improvement primarily attribute to the social and economic progress. Particularly, the average annual growth rates of SEL, ELI, EELI and RSI of BHR region are 10.00%, 19.11%, 0.37% and 5.78% during the twelve years, while the ones of YRD region are 7.32%, 20.25%, 0.46% and 5.86%, respectively, presenting the economic progress is the fastest-improving aspect. Furthermore, the more distinct and specific differences between two regions should depend more on the implied intra-regional gap.

More specifically, it can also be apparently noted that decreasing BHR-RSI in comparison with YRD-RSI after 2006, as a matter of fact, probably due to decreasing EELI and SLI of BHR in comparison with that of YRD. Further, the indicators' sequence by the effect of SLI is as follows: per capita R&D investment (S15), per ten thousand people granted patent approval (S16) and per capita disposable income in whole society (S1), and from 2007 to 2012 the average annual growth rates of S15, S16 and S1 of BHR are 24.06%, 18.48% and 13.25%, while that of YRD are 37.48%, 20.11% and 13.98%. Meanwhile, the indicators led to decreasing EELI of the two regions after 2006 or 2010 are mainly per capita forest stocking volume (E1) and per capita emissions of solid wastes (EN9).

3.1.2. RCI

The regional coordination index (RCI) can be determined by identifying whether the society, economy and environment subsystems develop coordinately with each other during a period. More specifically, the manifestation form should be judging whether the three indices' values (SLI, ELI, EELI) can construct one triangle, and the standard deviation of the three angles for each constructed triangle can further reflect the quantitative magnitude of RCI. In regard to the triangle diagram, each angle's value can be computed based on the Cosine Law with the three indices, the precondition of which is that the three indices can meet the basic requirements to a triangular diagram.

Table 3 shows the specific angles and their standard deviations of SLI, ELI, EELI that can construct triangle diagram and SLI, ELI, EELI that failed to construct triangle diagram in all the provinces and the two regions during the period 2001–2012 in details. The SLI, ELI and EEI of the provinces and regions that failed to construct the triangular diagram prove very poor coordination degree in the corresponding years. In Table 3, it can be easily observed that the amount of the provinces or regions that failed to construct a triangle is decreasing in the study period, showing that these provinces or regions have some progresses. So the conversion from incapable to capable construction in Table 3 can also

Table 3
The angles and standards deviations of SLI, ELI and EELI of BHR and YRD regions and the provinces during the period 2001–2012.

Year		BJ	TJ	HB	SD	LN	SH	JS	ZJ	BHR	YRD
2001	Angle (°)	44.91	23.49	-	-	-	52.05	-	-	-	-
		62.93	15.54	-	-	-	42.22	-	-	-	-
		72.25	141.06	-	-	-	85.82	-	-	-	-
	Standard deviation	6.55	33.13	-	-	-	10.78	-	-	-	
2002	Angle (°)	42.62	31.71	-	-	-	55.97	-	-	-	-
		66.9	20.83	-	-	-	47.54	-	-	-	-
		70.56	127.56	-	-	-	76.58	-	-	-	-
	Standard deviation	7.16	27.69	-	-	-	7.04	-	-	-	-
2003	Angle (°)	39.68	45.48	-	-	-	51.55	-	-	-	-
		61.64	29.38	-	-	-	48	-	-	-	-
		78.77	105.24	-	-	-	80.54	-	-	-	-
	Standard deviation	9.24	18.84	-	-	-	8.42	-	-	-	-
2004	Angle (°)	38.17	44.64	-	-	-	51.95	-	-	-	-
		63.06	29.68	-	-	-	52.91	-	-	-	-
		78.86	105.77	-	-	-	75.23	-	-	-	-
	Standard deviation	9.67	19	-	-	-	6.21	-	-	-	-
2005	Angle (°)	42.01	53.6	-	-	-	54.15	7.95	24.85	6.39	34.18
		75.92	37.85	-	-	-	58.23	5.59	19.88	5.55	26.63
		62.16	88.64	-	-	-	67.72	166.54	135.36	168.15	119.28
	Standard deviation	8.04	12.26	-	-	-	3.28	43.49	30.78	44.14	24.25
2006	Angle (°)	42.18	49.6	-	-	47.38	56.48	24.68	42.15	31.64	43.1
		79.7	36.94	-	-	25.53	61.17	19.48	34.22	26.09	35.14
		58.21	93.55	-	-	107.18	62.44	135.93	103.72	122.37	101.85
	Standard deviation	8.87	14.01	-	-	19.93	1.48	31.01	17.93	25.48	17.17
2007	Angle (°)	42.62	56.26	-	-	53.11	56.57	37.04	54.45	38.45	51.28
		84.03	43.86	-	-	30.68	64.79	28.85	40.59	31.96	40.59
		53.45	79.98	-	-	96.3	58.73	114.2	85.05	109.68	88.22
	Standard deviation	10.12	8.65	-	-	15.72	2.01	22.2	10.72	20.33	11.78
2008	Angle (°)	45.4	59.12	-	23.61	65.79	56.59	45.74	50.85	47.29	53.29
		83.81	50.41	-	18.44	38.45	65.94	36.97	38.21	40.08	42.64
		50.89	70.57	-	138.04	75.86	57.56	97.39	91.03	92.72	84.16
	Standard deviation	9.79	4.77	-	31.87	9.12	2.42	15.39	13	13.45	10.17
2009	Angle (°)	50.9	58.51	8.49	28.56	62.04	53.67	49.08	51.71	48.46	53.86
		81.33	53.48	6.79	22.58	41.59	69.2	43.65	40.66	42.7	46.45
		47.86	68.1	164.82	128.95	76.46	57.22	87.37	87.72	88.94	79.79
	Standard deviation	8.73	3.5	42.78	28.17	8.26	3.84	11.23	11.6	11.88	8.25
2010	Angle (°)	48.89	57.99	31.33	36.39	56.46	53.41	52.58	51.53	51.88	56.37
		82.5	60.85	25.23	29.93	44.23	73.62	49.38	42.04	48.64	49.65
		48.7	61.26	123.53	113.77	79.4	53.07	78.13	86.52	79.57	74.07
	Standard deviation	9.17	0.84	25.96	21.99	8.42	5.55	7.43	11.04	8.01	5.95
2011	Angle (°)	48.93	55.85	53.92	51.61	70.48	53.4	56.9	58.97	60.76	60.78
		88.41	70.81	42.7	41.04	56.1	75.53	57.52	48.59	59.64	55.3
		42.75	53.43	83.47	87.43	53.5	51.16	65.67	72.53	59.69	64.02
	Standard deviation	11.68	4.44	9.93	11.46	4.31	6.35	2.31	5.66	0.3	2.08
2012	Angle (°)	50.84	55.65	40.26	59.98	75.87	55.64	58.36	63.47	59.08	64.32
		86.23	73.42	34.39	46.79	59.6	84.59	62.02	51.43	61	58.61
		43.03	51.03	105.44	73.33	44.62	39.86	59.71	65.19	60.01	57.16
	Standard deviation	10.85	5.57	18.59	6.25	7.37	10.69	0.87	3.54	0.45	1.78

* The symbol "-" represents that SLI, ELI and EELI of regional sustainability system fail to construct any type of triangle due to without access to basic conditions for formation the shape, for instance, two sides of a triangular diagrams must be greater than the third and the difference of two side of a triangular diagram must be smaller than the third. "BJ, TJ, HB, SD, LN, SH, JS and ZJ" are the abbreviation of Beijing, Tianjin, Hebei, Shandong, Liaoning, Shanghai, Jiangsu and Zhejiang provinces, respectively. Meanwhile, each standard deviation refers to the coordination degree of three angles in the formed triangle for displaying the regional coordination index (RCI) from the perspective of system composition.

reveal the evolution trend of RCI for the provinces and regions. Furthermore, in terms of the constructed triangles' angels, the magnitude of standard deviations of the provinces and regions can reflect their RCI more quantitatively (the smaller standard deviation the smaller RCI is), and we can find that the provinces and the two regions in most years for gradually have smaller standard deviations as time goes on. Accordingly, we can seek out the determinate and detailed direction to adjust and control the distributions in the sustainable development management from both spatial and temporal perspective.

3.2. SELI–EELI

Apart from the coordination level among three subsystems, we can further dissect regional sustainability system from the perspective of interaction between SELI and EELI, the former of which stem from the integration of SLI and ELI and represent human activities level. The adjusted R-square and P values of those equations of nonlinearity fit curves can indicate a relative good fit (Wang et al., 2014). Figs. 3 and 4 show the nonlinearity fit curves and the actual curves of the 8 provinces and 2 regions, and five stages of sustainability intervals are set to manifest their own unique positions, which conform to the improved "sustainability barometer" framework despite differing in the matter of vertical axis. From the perspective of geographical locations, we find that there is a great difference among the five provinces of BHR, the embodiment of which in the sequence, according to the values of actual curves at provincial scale, followed by Beijing, Tianjin, Shandong, Liaoning and Hebei, while there is relative less difference in YRD. In terms of the sustainability level in the regional scale, in Fig. 4, YRD has been principally in the intermediate sustainable stage while BHR always in the potentially unsustainable one. Meanwhile, we also observe that the larger disparity of socioeconomic level and the less disparity of eco-environmental level for the eight provinces at the point of their horizontal axes.

The chart of SELI–EELI is available to validate the current interaction characteristics between socioeconomic and eco-environmental change. As shown in Fig. 3, all the provinces of BHR, except Beijing, have stayed

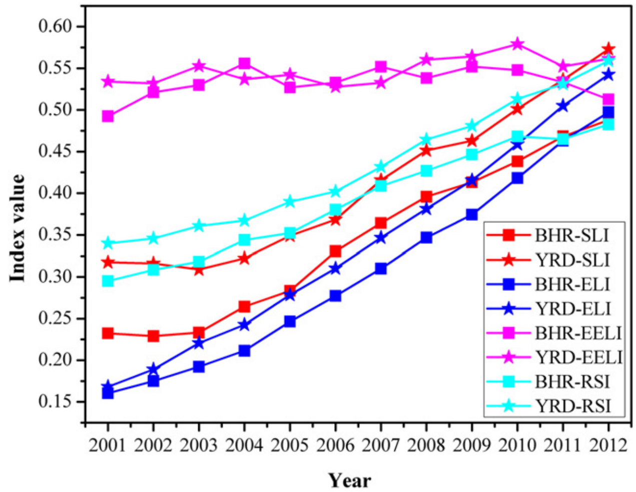

Fig. 2. The sustainability change trend of SEL, ELI, EELI and RSI in BHR and YRD regions during the period 2001–2012.

in some positions where eco-environmental level gradually decreases with the progression of socioeconomic situations, which just reveal that the relative high coordination between socioeconomic and eco-environmental dimensions in Beijing must depend on all forms of resources and energy occupancy and consumption provided by its surrounding provinces, and result in the position where BHR region is in. In view of the similar circumstance of YRD region, Shanghai and Zhejiang are both in a position where eco-environmental level gradually increases with the progression of socioeconomic situations, and thus YRD region harbor a minor monotonically increment for the study period.

3.3. Development equity and development pattern

3.3.1. Development equity with Lorenz curve and Gini coefficient

The Lorenz curve of SELI–EPI (Fig. 5), reflects that the regional development equity, is investigated for the eight provinces of BHR and YRD regions during the study period. In Fig. 5, we can find that the curve of Shanghai is the nearest to the ideal curve, which means the distribution of Shanghai is more equal by SELI than by EPI, and Beijing takes the second place. This can be explained by the fact that, as the largest city of China, most of the environmental pollution in Shanghai comes from the socioeconomic output process. Fig. 5 also reveals that, the greatest distribution inequity occurs in the Liaoning, followed by Hebei. The relative high Gini coefficients determine that the distribution of human activities level does not fit the natural condition very well.

To be specific, the Gini coefficients of SELI–EPI among Beijing, Tianjin, Hebei, Shandong, Liaoning, Shanghai, Jiangsu and Zhejiang are 0.1181, 0.1780, 0.2448, 0.2386, 0.3102, 0.0803, 0.2170 and 0.1788 respectively. It reflects that, on the one hand, the economy and society well-being is distributed unevenly. On the other hand, the environmental well-being is distributed unequally, either. Less developed areas,

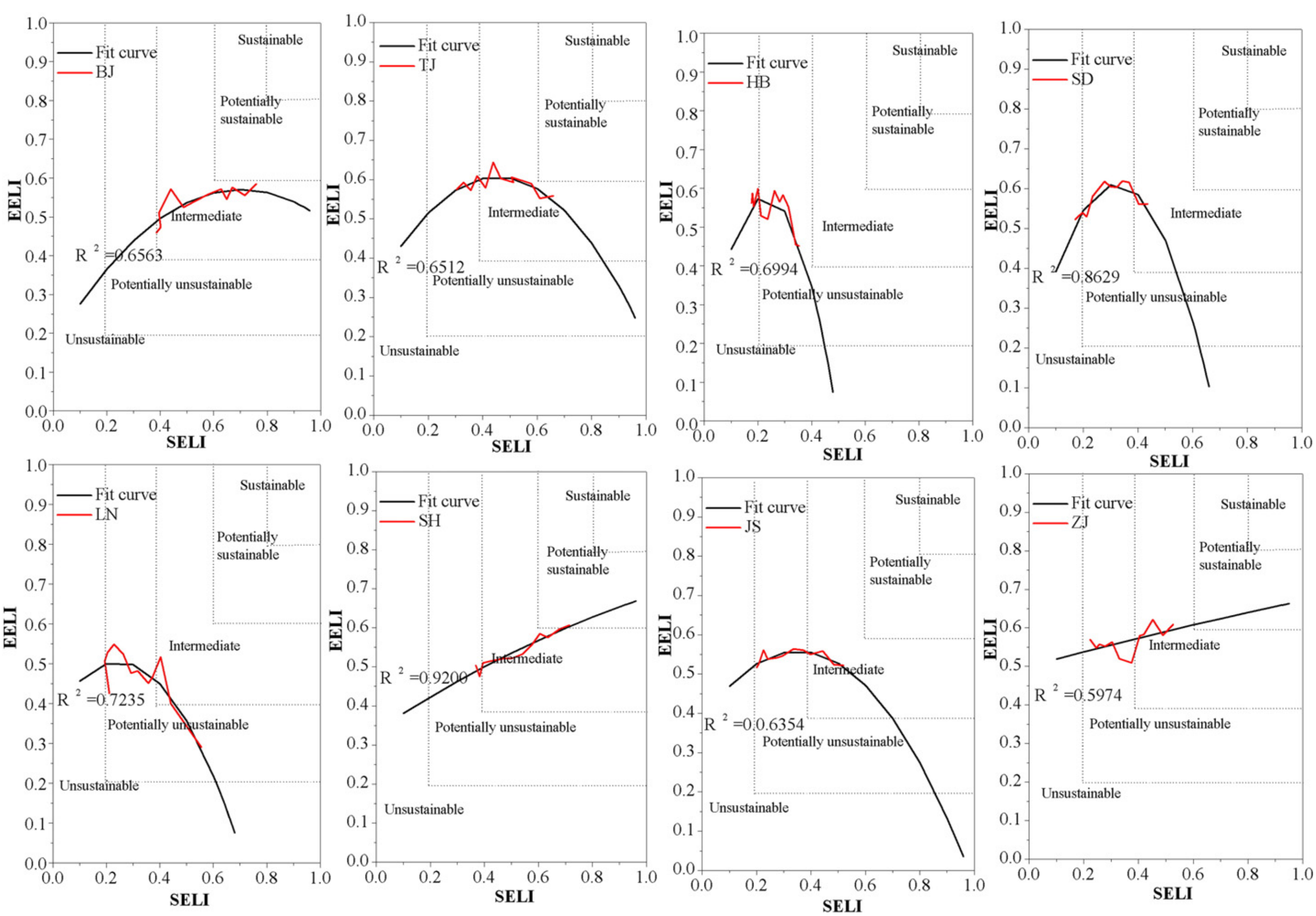

Fig. 3. The fit and actual curve of SELI–EELI and the sustainable intervals of all provinces in BHR and YRD. The two indices consist of a suite of indicators that are rated to give performance scores that are plotted as coordinates on a two-dimensional scale to yield a visual representation.

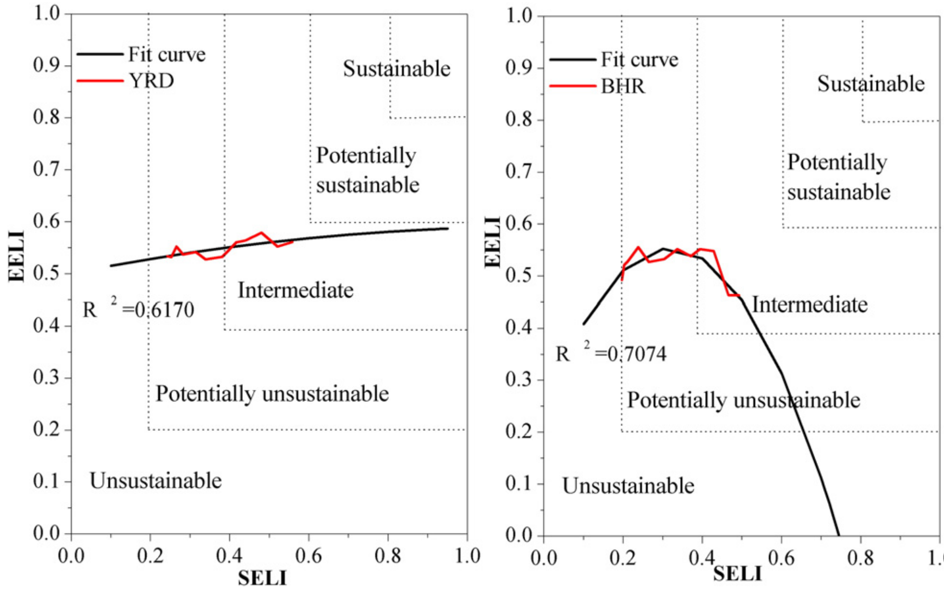

Fig. 4. The fit and actual curve of SELI–EELI and the sustainable intervals of BHR and YRD regions.

such as Hebei and Liaoning have higher pollution/economic level with lower economic level/capita, suffering from some external pollution.

3.3.2. Development pattern with GDI

In the context of Fig. 6, it is clearly observed that the changes of GSDI and GEDI are the most significant elements, where the negative values stand for the negative effects from the element to the total. Due to the structure decomposition model, we can get the underlying driving forces of total green development index. Thereby, Fig. 6 tells that the changes of green social or economic development index (concentration effect) are always larger than the changes of the proportion of *f* (structural effect) for each province no matter in BHR or YRD region. Furthermore, the structural and concentration effects are predominant at positive to the green development index, that is, the effects of all provinces are larger the regional development pattern is closer to green development level. With regard to the effective range, the two kinds of effects to the changes of GSDI and GEDI in YRD region are apparently smaller than in BHR, showing YRD region harbors a more stable eco-environmental level and better eco-environmental management system during the period 2001–2012.

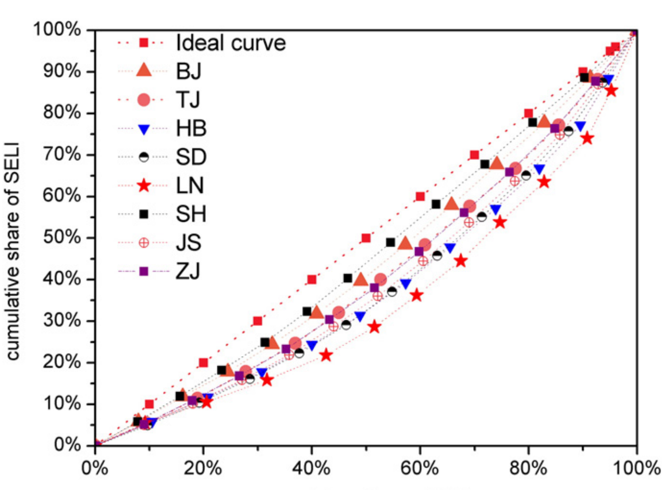

Fig. 5. The Lorenz curve of SELI–EPI of BHR region. BJ, TJ, HB, SD, LN, SH, JS and ZJ represent Beijing, Tianjin, Hebei, Shandong, Liaoning, Shanghai, Jiangsu and Zhejiang.

The green social or economic development degree, which should be associated with the uneven resource utilization and eco-environment occupancy among all provinces, should contribute most to the inequity development. In the sequence, according to the magnitude of three kinds of effects, they are followed by GSDI or GEDI, the weighted factor and common effect. More specifically, the variation of GDP has influenced more significantly than SI in green economic development changes, while that of HRQ more than EP in social development changes, which reveal the concrete influence factors for decision-making.

4. Conclusion and discussion

4.1. Main achievements

The well-run structure, function and dynamics of complicated regional sustainable development system provide a fundamental guarantee for maintaining regional sustainability stability. In this study, we presented a comprehensive view of social, economic and environmental dimensions of sustainability analysis from the perspective of interaction characteristics and development pattern in dynamic process for BHR and YRD regions at two scales, peering to these questions: How and why sustainability change of the provinces and regions? Is there a connection between socioeconomic and eco-environmental systems and how they influence each other? And is the development pattern healthy and what is the concrete form? To answer these questions, various quantitative and qualitative methods are developed in order to assess the changes of RSI and RSCI (structure and dynamics), to explore interaction characteristics between human and nature (structure, function and dynamics), to discern development patterns (function and dynamics), and to achieve sustainable development.

With two considerations of interaction characteristics and development pattern of regional sustainability system in dynamic process, the novel research framework is developed, composed of three modules in the concrete analysis. In the first module, SLI, ELI, EELI and RSI of BHR and YRD regions are computed and presented to explore the spatial and temporal changes. In the second module, the interaction and trend of socioeconomic and eco-environmental level are explored to display the interaction between subsystems through nonlinear fitting analysis and the identified sustainability intervals of each spatial position through sustainability barometer framework after previous module; in the third module, we focus on how the variations of green social or economic development level are.

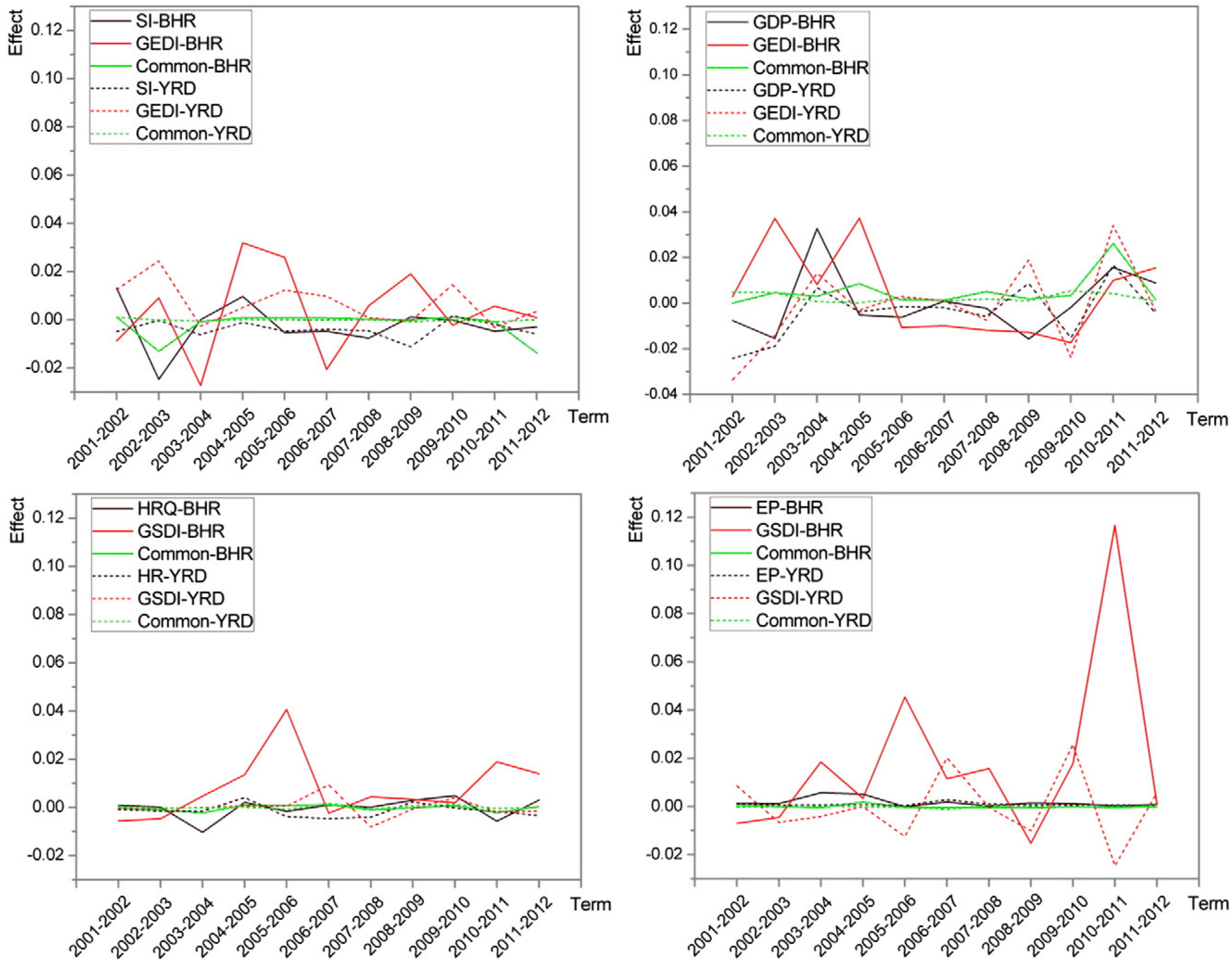

Fig. 6. The decompositions of green social and economic development index in BHR and YRD regions. Where GSDI and GEDI represent green social development and green economic development index, respectively, while GDP, SI, EP and HQR are all the weighted factors. And the red line in four sub-figures marked GEDI or GSDI represent the concentration effect and the black ones marked GDP, SI, EP and HQR represent the structural effect, while common is the effect from the common changes of the former two.

4.2. The structure, function and dynamics of regional sustainability system

The sustainability ideology comes from the concern over the environmental stressors from human activity, which not only influence the social and economic well-being and the occupancy of goods and services, but also harm the ecosystems to sustain human survival and life. Accordingly, transitioning to regional sustainability requires assessing and managing the extremely complicated human (social and economic pillars) and natural components (eco-environmental pillars) system (Ma and Wang, 1984). Up to the present, there are various efforts to assess the progress toward sustainable development (Dai et al., 2013; Jia et al., 2009; Mascarenhas et al., 2010; Singh et al., 2012), it seldom has systematic and embedded exploration of the structure, function and dynamics of regional sustainability system. Thereby, we study from these aspects with the aid of the mathematic properties of triangular diagram, sustainability barometer framework, structure decomposition model (Duro and Teixidó-Figueras, 2013; Liu, 2009), environmental Gini coefficient methodologies (Sun et al., 2010), and so on, and construct the feasible models to make the empirical research.

The main inhibitions distribution for sustainability progress is different in each dimension due to the adopted composite weight techniques, which are associated with improving the accuracy and veracity of RSI and RCI values for different spatial positions, and the detailed weight distribution can be found in the Appendix.1. Accordingly, the results of RSI and RCI exhibited fully and authentically regional sustainability change (Fig. 2) and system composition (Table 2), both of which can reflect that the structure and dynamics of sustainable development system of YRD are run better than of BHR, and it can also show the equity degree among three pillars, suggesting that problems should be mainly focused on the coordination level between the three in the emergence period.

Meanwhile, the results of fitting interaction analysis between human and nature profoundly reveal the development characteristics of each spatial position and the equity degree among the provinces, which can jointly reflect that the structure, function and dynamics of the sustainability system in YRD also run better in BHR, proposing that we should pay more attentions on regional sustainability disparity in the near future.

Furthermore, the section of green development index tells that the economic growth may be attributed to the availability of natural resources for the production of consumption goods and the environment condition (Kulig et al., 2010), or even sacrifice of social welfare. And decomposing the index by structure decomposition model help we locate where the problem occurred at each development stage. The less-developed provinces have higher eco-environmental pressure/human activities with lower socioeconomic level/capita than more-developed provinces, which is inimical to regional integration development in national plans, providing a direction where we need to improve. That is to say, the regional development pattern researches mirrored the function and dynamics of sustainable development system. Thereby, smart and intelligence development pattern should be advanced and the BHR region can imitate some specific aspects and examples of YRD region.

4.3. Limitations and recommendations

When computing RSI, SLI, ELI and EELI, although the average weight adopted from AHP and entropy methods, more particular considerations have not been given to data-weighting issues that are likely to have a certain impact on the result. What's more, RCI just presents as the standard deviation of SLI, ELI, EELI that can construct triangle diagram, however, we have not provided the specific index values, such as a range from 0 to 1, to directly compare the actual differences in various time point. It is also a flaw that we have not integrated a composite value for regional sustainability level and coordination level.

Regulating and unifying the sustainability study at regional and provincial scales in a holistic and comprehensive perspective can help in providing insights into the comparison for the regions like BHR and YRD. It has potential as a tool for raising community awareness about sustainability and the link between human activity and regional sustainability, so we attempt to fill a gap in sustainability science by providing an effective validation framework for assessing regional sustainable development stability. However, regional sustainability stability, in practice, should be relied heavily on the stability of change rate of RSI, SLI, ELI and EELI, that is, whether there is a stable upper and lower bounds for the corresponding changes is the important research topic in the near future.

Toward sustainability is the only way forward for human beings, requiring the involvement of not only policy makers and scientists, but also the public participation. Our decision-making should aim at tackling problems that such regional development faced, including over-exploitation, unreasonable structure and uncoordinated regional development. Therefore, human harmony development in all regions has to embrace sustainability in its core and goal. Indeed maintaining the structure, function and dynamics of sustainable development system is just the precondition of transition regional sustainability, and the journey moving toward sustainability has just begun.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at http://dx.doi.org/10.1016/j.ecoinf.2015.09.008.

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