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Rapid Assessment of Sustainability in Mainland China

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Abstract: This paper presents an approach for rapid assessment of sustainability for mainland China based on a multilayer index system. Efficient assessment is conducted with the basic mapping units at county and city levels. After evaluating a comprehensive Sustainable Development Index, *SDI*, for each unit, five rankings of sustainability are determined, and a zonation map produced. Regional characteristics and differences are interpreted through macro-analysis of the spatial variation in *SDI*. A sensitivity analysis is performed by which the weights of the sub-indices are altered by ± 20 %, and *SDI* re-evaluated; the resulting grades remain the same, thus confirming the robustness of the technique. Moreover, the accuracy of the proposed approach is indirectly validated by comparison with assessment results from an alternative systems analysis method. It is found that major conurbations such as Beijing have relatively high levels of sustainability, whereas provinces in central and western China require investment to improve their sustainability.

Keywords: rapid assessment; sustainable development index; sensitivity analysis;

mainland China

1. Introduction

There is international consensus that development should be sustainable, bearing in mind population, socio-economic and environmental considerations (Baumgartner and Zielowski, 2007; Hao et al., 2007; Streimikiene et al., 2007). An important definition of sustainable development was given by the Brundtland Commision (World Commission on Environment and Development, 1987), revealing connections between ecology, development and the achievement of basic human needs (Thorén, 2000). In recent years, the need for sustainable development has been widely recognized by the public and policy-makers, and incorporated in legislation, particularly with regard to natural resources (e.g. Fiorillo et al., 2007), energy (e.g. Hao et al., 2007), land-use (e.g. Espejel et al., 1999) and urban development (e.g. Jenerette and Larsen, 2006).

After undergoing unprecedented growth and profound economic, social and environmental changes, China is facing a crossroad of choices that will determine whether its goal of sustainable development can be achieved in the future (John, 2005). Important questions for China are how to cope with its environmental needs alongside a rapidly expanding economy and how to balance the regional disparities between the relatively affluent eastern provinces and the poorer western provinces. In 1994, the Chinese government made the strategic decision to move from a conservation policy to one of sustainable development (Zhang, 2001). Since then, great efforts have been made to attain sustainable development in China such as expressed by the concepts of "circular economy" and "abstemious society" (Barredo and Demicheli, 2003).

Measures of sustainability are difficult to define and quantify, and yet are vital in monitoring progress towards sustainable development (Walsh et al., 2006; Ness et al., 2007). Various studies have focused on the complex interactions between environmental, social and economic issues (Ravetz, 2000). Of the approaches taken, Function Analysis is of particular merit in that it could be used to facilitate the integrated assessment of the complex system and highlight conflict areas (see e.g. Cendrero and Fischer, 1997; Phillips et al., 2007). Much research effort has been dedicated to the development of sustainability assessment tools, their proper application, and reporting case studies (e.g. Devuyst, 2000; Rosenström and Kyllönen, 2007; Ioris et al., 2008). In a review article, Ness et al. (2007) categorized sustainability assessment tools under three umbrella headings: indicators and indices; product-related assessment tools; and integrated assessment. Mathematical models, such as artificial neural network (Buscema et al., 1998; Rowland et al., 2004) and genetic algorithm (Cai et al., 2001; Stafford, 2008) are being applied to quantitative sustainability assessment. These models are still at a relatively early stage of development and their applications have been limited to date to local, small scale regions. Compared with other approaches, indicators and indices are simple and flexible measures; for example, the economic, social and environmental state of a system may be represented by a quantifiable index. Unfortunately, current indicator and index approaches require complete data sets and the data collection is time consuming. Data scarcity often limits the applicability of such approaches.

This paper utilizes a rapid assessment approach to evaluate sustainability in mainland China. The approach has evolved from earlier incarnations where rapid assessment has been applied to soil erosion (Ni and Li, 2003; Ni et al., 2008) and abrupt mass movement hazard (Ni et al., 2006; Liu et al., 2006). When selecting reference sites and identifying matched groups for the test sites, the rapid assessment approach deals properly with data scarcity and is capable of handling a wide range of scales. These advantages are exploited in the present paper, with the aim of achieving efficient and reliable assessment of sustainability in mainland China.

2. Methodology

2.1 Background to the rapid assessment technique

Ni et al. (2006) developed the Rapid Zonation of Abrupt Mass movement Hazard (RZAMH) method based on the essence of Rapid Bio-Assessment (RBA) methods (see e.g. Clarke et al., 2003; Ni and Li, 2003). RZAMH comprises five steps: (1) identification of mapping units and multilayer indices; (2) establishment of a database according to basic sub-indices; (3) classification of reference groups based on mapping units with complete data; (4) identification of matching groups for mapping units with incomplete data; (5) evaluation of blank mapping units and the combination of sub-units. The method does not require units in the same group to be continuously distributed. By modifying the RZAMH approach proposed by Ni et al. (2006), a similar procedure can be applied to sustainability assessment. The hypothesis of the rapid assessment method is that two sites having similar values for sub-indices would have similar values for the upper layer index (Ni and Li, 2003; Ni et al., 2006). Furthermore, the rapid zonation method is based on classification of basic units, where units belonging to the same group are classified into disjunctive regions (Huang, 1959). Thus, the method can be used for rapid assessment of the discontinuous distribution of a given sub-index over the domain of interest without having to consider whether or not that sub-index in any given group is continuously distributed (Ni et al., 2006).

2.2 Sustainability indicator system for mainland China

In practice, many definitions have been proposed for sustainability (see e.g. Lynam and Herdt 1989, Pearce and Turner (1990), Kidd (1992), Goodland 1995, Costanza and Patten 1995) and sustainable development (following the World Commission on Environment and Development 1987). Likewise there are many methods suggested for measuring sustainability (see e.g. Costanza and Patten 1995, Harger and Meyer 1996, Bell and Morse (1999), Bossel 1999, Popp et al. 2001, and Barrera-Roldán and Saldivar-Valdés 2002). In the present paper, we define sustainable development as development that meets the competing social, economic and environmental needs of China, as these needs change over time. We use a systematic approach that places particular emphasis on stability of sustainable development in mainland China. The indicators are selected such that they (i) are simple, measurable, valid, reliable, comprehensive, and analytically sound (Harger and Mayer, 1996); (ii) are independent

Fig. 1

of each other; (iii) should reflect the structure of the system and be appropriate for decision-making purposes; and (iv) provide results that are reliable measures. Bearing this in mind, a four-layer sustainable development index system is developed based on a "top-down" or technocratic process. As shown in Fig. 1, a four-layer sustainable development index system was devised for mainland China. The index system contains a total of 44 indicators, of which 31 sub-indices are at the bottom level.

Following Ni et al. (2006), an arbitrary (sub-) index is denoted as $i_{m,n}$, where m is the layer number and n is the respective index in the m-th layer. The top-most (final) layer provides a unique Sustainable Development Index, $SDI = (i_{1,1})$. At the second layer, the sub-indices are System Development ($i_{2,1}$), System Coordination ($i_{2,2}$), and System Sustainability ($i_{2,3}$). The sub-indices of the third layer are: Economic Development ($i_{3,1}$), Social Development ($i_{3,2}$), Environmental Development ($i_{3,3}$), Socio-economic Coordination ($i_{3,4}$), Enviro-economic Coordination ($i_{3,5}$), Socio-enviro Coordination ($i_{3,6}$), Economic Sustainability ($i_{3,7}$), Social Sustainability ($i_{3,8}$) and Environmental Sustainability ($i_{3,9}$). There are 31 sub-indices in the 4th layer of the sustainable development indicator system (See Table 1).

Table 1

2.3 Data normalization and assessment process

To avoid problems arising from differences in magnitude of the raw indicators, modified min-max normalization is used to transform each basic indicator ($i_{m,n}$) of the mapping unit (S_x) onto a common scale, $I_{m,n}(S_x) \in [0,1]$ as follows:

$$I_{m,n}(S_x)=\begin{cases}0 & (i_{m,n}(S_x)\leq T_l(i_{m,n}(S)))\\ \dfrac{i_{m,n}(S_x)-T_l(i_{m,n}(S))}{T_u(i_{m,n}(S))-T_l(i_{m,n}(S))} & (T_l(i_{m,n}(S)<i_{m,n}(S_x)<T_\mathrm{u}(i_{m,n}(S))\\ 1 & (i_{m,n}(S_x)\geq T_\mathrm{u}(i_{m,n}(S)))\end{cases} \quad (1)$$

$$I_{m,n}(S_x)=\begin{cases}0 & (i_{m,n}(S_x)\geq T_u(i_{m,n}(S))\\ \dfrac{T_u(i_{m,n}(S))-i_{m,n}(S_x)}{T_u(i_{m,n}(S))-T_l(i_{m.,n}(S))} & (T_l(i_{m,n}(S))<i_{m,n}(S_x)<T_u(i_{m,n}(S))\\ 1 & (i_{m,n}(S_x)\leq T_l(i_{m,n}(S))\end{cases} \quad (2)$$

in which, $i_{m,n}(S_x)$ is the value of each sub-index ($i_{m,n}$) for mapping unit (S_x); $I_{m,n}(S_\mathrm{x})$ is the transformed value of $i_{\mathrm{m,n}}(S_x)$; T_u and T_l are the upper and lower limiting values in the group $i_{m,n}$(S) containing all the mapping units S_x. To reduce the side effects on data normalization of a few units with extremely high or low values, T_u and T_l are used here instead of the maximum and minimum values of $i_{m,n}$(S). Positive sub-indices are transformed using Eq. (1) whereas negative sub-indices are transformed using Eq. (2).

2.4 Weight of sustainable development indices

The analytic hierarchy process (AHP) is a systematic method that deals with decision-making problems using multiple criteria (Saaty, 1980). AHP firstly decomposes a complex problem into sub-elements based on an orderly hierarchical structure that includes goals, criteria, sub-criteria and alternatives. The elements are then sorted into clusters at various hierarchies (Szczypińska and Piotrowski, 2009; Zhang, 2009). Next, reciprocal matrixes are formulated by means of pair-wise comparisons and relative weights for all elements determined through an eigenvalue method (Saaty, 1980;

Ni et al., 2006). In the present paper, we use AHP to determine the weights of sub-indices with respect to the upper-layer index of sustainable development, noting AHP's proven advantages in multi-index evaluation in many research fields (Sambasivan and Fei, 2008; Lai et al., 2008; Korpela et al., 2007; Lee et al., 2007). In the present application, the detailed analytic process is as follows.

(i) Establishment of the hierarchic structure

According to expert advice, the evaluation system is divided into four levels – A, B, C, and D. Here, A denotes *SDI* in the 1st layer of sustainable development indicator system. B1, B2, and B3 denote three indicators in the 2nd layer of the sustainable development index system. C1 to C9 denote nine indicators in the 3rd layer of sustainable development indicator system in order. Similarly D1 to D31 denote the 31 indices in the 4th layer of sustainable development indicator system.

(ii) Construction of reciprocal matrix

The reciprocal matrix is constructed through pair-wise comparisons of each cluster at different levels. Experts with sustainable development related backgrounds are invited to estimate the relative importance of each factor in each cluster on a scale from 1 to 9.

(iii) Single ranking

The largest eigenvalue ($\lambda_{\max}$) and its corresponding eigenvector (W) are determined from

$$A_k \cdot W = \lambda_{\max} \cdot W \tag{3}$$

in which, A_k is a judgment matrix constructed in step (ii). Hence, the relative weights of each element to the upper-layer are obtained as W_1, W_2, $\cdots W_n$.

A consistency index (*CI*) is used to test the consistency of the judgment matrix, and is defined by

$$CI = \frac{\lambda_{\max} - n}{n-1} \tag{4}$$

where n is the exponent number of the judgment matrix. For complete consistency, $CI = 0$. The consistency ratio (*CR*) is defined as

$$CR = \frac{CI}{RI} \tag{5}$$

where the random index (*RI*) is an indicator of consistency randomly generated from reciprocal matrix and is used to eliminate the influence of the size of the reciprocal matrix (Saaty, 1980; Ni et al., 2006). The consistency ratio (*CR*) is used to measure the consistency of the reciprocal matrix. Normally, it is acceptable when $CR \leqslant 0.1$; otherwise, some or all of the matrixes have to be reconstructed.

(iv) Total ranking

According to the results of a series of simple rankings, the weights of all elements in a level relative to the topmost index of the hierarchy structure are calculated by multiplication according to the relative weight of the factor and that of the relevant factors at the upper levels.

2.5 Evaluation of sustainable development index (*SDI*) and its sub-indices

Values of the middle-layer sub-indices and the topmost index are calculated following linear weighted sum rules, as follows:

$$I_{m,n} = \sum_{j=1}^{k} w_j I_{m+1j}, \quad (I_{m+1j} \in C_{m,n}) , \tag{6}$$

in which $I_{m+1,j}$ are sub-indices of $I_{m,n}$ and $C_{m,n}$ is the corresponding group of sub-indices ($I_{m+1,j}$) of $I_{m,n}$.

Assessment of the sustainable development index, *SDI*, is associated with three groups of units: namely, units with complete data (S_c); units with incomplete data (S_i); and units with blank data (S_b). For S_c, *SDI* is computed directly from Eq. (6) based on the indicator system. For S_i, information for partial indicators is scarce and should be evaluated as follows. Firstly, units in S_c are classified into reference groups by *K*-means clustering. After clustering, the *K* reference groups have cluster centroids $Z_{m,n,j}$ (j=1, 2,…, k) whose eigenvalue $k_{m,n,j}$ is equal to the value of the sole sub-vector in the centroid or the sum of the sub-vector weighted values in multi-dimensional centroids. After that, the test unit is matched with a reference group based on the minimum Euclidean distance from the cluster centroid, omitting the missing information. The eigenvalues of the matched group are the evaluated values of the test unit. The (sub-)indices are evaluated in turn from the last to the first layer. For S_b, *SDI* could be roughly estimated from its neighboring regions as:

$$SDI = \sum_{j=1}^{k} SDI_j (A_j / \sum A_j) \tag{7}$$

Where A_j is the area of j^{th} neighboring region of the test unit in S_b, and SDI_j is the calculated or evaluated value of the sustainable development index.

3. Assessment of sustainability in mainland China

A total of 2339 counties or cities, determined according to the administrative division of mainland China in 1993, were selected as basic mapping units. Data from 2005 on the primary sub-indices were collected from statistical yearbooks and databases as follows. Socio-economic data were obtained from the China County Statistical Yearbook (Department of Rural Surveys of National Bureau of Statistics of China, 2006), the China City Statistical Yearbook (Department of City Surveys of National Bureau of Statistics of China, 2006) and the China Statistical Yearbook for Regional Economy (Department of Comprehensive Statistics of National Bureau of Statistics of China, 2006). Demographic data were extracted from the China Population Statistics Yearbook (Department of Population and Employment statistics of National Bureau of Statistics of China, 2006). Environment-related data were obtained from the China Environment Yearbook (China Environment Yearbook Editorial Board, 2006) and natural resources database (www.naturalresources.csdb.cn). Energy-related data were collected from the China Energy Statistical Yearbook (Department of Industry and Transport Statistics of National Bureau of Statistics and Energy Bureau of National Development and Reform Commission, 2006).

Data normalization was performed using Eqs (1) and (2), in which the upper limiting values (T_u) and lower limiting values (T_l) were given on the basis of frequency analysis of all values for each indicator; that is, T_u = 97.5% percentile and T_l =2.5% percentile (see Table 1). According to the analytic hierarchy process described above, reciprocal matrixes for the evaluation of indices at different levels of the hierarchy structure were constructed (see Table 2) and the weight of each evaluation index with respect to *SDI* was determined (see Table 3).

Table 3

Of the 2339 counties and cities, 1614 had complete data on all the basic sub-indices required to evaluate the system development sub-index ($i_{2,1}$), 1344 had complete data by which to determine the system coordination sub-index ($i_{2,2}$), 1823 had complete data required for the system sustainability sub-index ($i_{2,3}$), and 1249 had complete data for the top-most sustainable development index, *SDI* (= $i_{1,1}$). For counties and cities in S_c, *SDI* was directly computed using Eq. (6). Reference groups were classified by *K*-means clustering in turn from the lowest layer to the topmost layer. *K* was set to be 5, and thus five reference groups were classified. The grades of *SDI* were ranked in terms of the magnitude of eigenvalues of the centroids of the reference groups as 'very high', 'high', 'medium', 'low' and 'very low'. Table 4 lists eigenvalues of the centroids of the five reference groups for the 2^{nd}-layer sub-indices. Table 4 also gives the centroid eigenvalues of the five reference groups for the top-most *SDI*, and their ranks. Next, a reference group was identified for each test county and city in S_i. The centroid eigenvalues and degree rankings of *SDI* of the reference groups were then evaluated for each test county and city. No counties or cities belonged to S_b. Using this approach, the *SDI* value and its grade were estimated for each of the 2339 counties and cities in mainland China. Table 4 also lists the number of units that have different grades of *SDI* according to the ranking system.

Table 4

4. Results and Discussion

4.1 Spatial variation of sustainability in mainland China

Fig. 2 presents a zonation map whereby the mainland of China has been classified

Fig. 2

into five zones according to the grading of *SDI* as ‘very high’, ‘high’, ‘medium’, ‘low’ and ‘very low’. These degrees indicate relative levels of sustainability, rather than absolute. The zonation map is useful for identifying areas that have similar levels of sustainability. In mainland China, about 8%, 14%, 31%, 16% and 31% of the land area corresponds to ‘very high’, ‘high’, ‘medium’, ‘low’ and ‘very low’ levels of *SDI*.

Regions of ‘very high’ and ‘high’ grades of *SDI* are mostly located in eastern China, and are contained 642 units distributed from the north-east to the south-east coast of China. Of these, ‘very high’ grade *SDI* is mostly located at the three major economic centers of Beijing-Tianjin, the Yangtze River Delta and the Zhujiang River Delta. Economic growth based on the knowledge economy and high technology industries has given these areas greater potential to become sustainable compared with other regions in China, although they presently lag behind certain large cities in developed countries. Regions of ‘medium’ *SDI* are found in the south-east plain, the North China Plain and far west areas, such as Xinjiang and the west of Inner Mongolia. A total of 616 counties or cities are located in these regions. For the south-east plain and North China Plain, economic growth is directed by high consumption and highly polluting traditional manufacturing industries. ‘Low’ and ‘very low’ *SDI* regions mostly occur in west and south-west provinces, such as Chongqing, Guangxi, Guizhou, Shaanxi, Sichuan, Tibet, and Yunan, containing 1081 counties and cities. These areas are either under development or have economic growth directed towards the consumption of non-renewable resources. In general, the characteristics of the mode of economic growth vary according to the *SDI* level.

4.2 Differences among provincial and regional sustainability levels

To investigate differences in sustainability, area-averaged (or 'provincial') values of *SDI* have been calculated for all the 27 provinces and 4 municipalities that are directly under central government control, including Beijing, Shanghai, Tianjin and Chongqing. Fig. 3 shows the distribution of the provincial *SDI* values and their associated relative grading. Fig. 3 indicates that regional differences in *SDI* are enormous. The relative grades of *SDI* obtained for three municipalities, Beijing, Shanghai and Tianjin, are much higher than other provinces. Chongqing lags far behind due to its traditional industrialization and fragile ecological and geological conditions.

Fig. 3

The provinces and four municipalities may be grouped geographically according to their sustainability as follows: Region A with 'very high' and 'high' levels of *SDI*, comprising three of the municipalities and eastern China; Region B of 'medium' level *SDI* in central China, including Chongqing; and Region C with 'low' levels of *SDI* in western China. Table 5 lists the area-averaged values of *SDI* and its sub-indices $i_{2,1}$, $i_{2,2}$, and $i_{2,3}$ for Regions AM, AP, BM, BP, and CP, where M refers to Municipality and P refers to Province. It is clear that the regional *SDI* values follow the approximate order AM > AP > BP > BM > CP, which suggests that *SDI* increases from western to eastern China. For Region BP, the values of *SDI* and its sub-indices lie close to the national area-averaged value of *SDI*. Fig. 4 shows the average distances between the *SDI* values of the provinces and municipalities in Region A (Fig 4(a)), the average distances

Table 5

between the *SDI* values of the provinces in Regions A and B (Fig. 4(b)), and the average distances between the *SDI* values of the provinces in Regions B and C (Fig. 4(c)). Fig. 4 also shows the corresponding average distances for the sub-indices of *SDI*. The municipalities of Beijing, Shanghai, and Tianjin, could be viewed as demonstrations of relative sustainable development in mainland China, due to the higher distances of *SDI* and its sub-indices in Fig. 4(a) compared to those in Figs 4(b) and 4(c). Even so, these cities still face many environmental problems, including traffic congestion, urban pollution, and scarcity of certain key resources (such as water). Development is a primary task for most regions of mainland China, as indicated by the higher value obtained in Fig. 4(a) for the distance of the system development sub-index ($i_{2,1}$) than for the other sub-indices. The distance of the sub-index of system coordination ($i_{2,2}$) remains significant throughout Figs 4(a), 4(b) and 4(c), indicating wide variations in $i_{2,2}$ in all the Regions A, B, and C. For the purpose of balanced regional development, it is therefore vital that the economic, social, and environmental system be better coordinated. Pressure on resources remains the major constraint on the sustainable development of eastern China, whereas skill shortages and low technology hamper the sustainable development of western and central China.

Fig. 4

4.3 Differences in urban sustainability

Following industrialization, the proportion of urban area to the total land of China is about 40 % at the time of writing and is estimated to reach 65 % by 2020 (Chinese Academy of Sciences Research Group on Sustainable Development, 2005). Along with the centralization of wealth and population, urban development causes multiple impacts on the environment related to excessive population density, depletion of natural resources, and ecological deterioration. Fig. 5 presents the results of frequency analysis applied to (a) 58 major cities and (b) 2339 counties and cities, arranged as a histogram of percentage of the number of cities divided by the total number against *SDI*. The histograms are different; in Fig 5(a) the histogram appears to fit a Lorenz curve, whereas that in Fig. 5(b) appears to follow an exponential decay curve. Of the 58 major cities, 81 % have $SDI > 0.5$, whereas of the 2339 counties and cities only 13 % have $SDI > 0.5$. These results suggest great inequality between city and county development. Furthermore, Fig. 5(a) also indicates that *SDI* varies widely among the 58 major cities. Most cities in eastern China have $SDI > 0.6$, with Beijing having the highest value. For the majority of cities in central China, $SDI \in [0.5, 0.6]$. For most cities in western China, $SDI \in [0.3, 0.5]$.

To further investigate the disparities of *SDI* among cities in different regions of China, four case cities are selected: Beijing municipality which is a highly-developed city in eastern China, with $SDI = 0.77$; Jinan whose $SDI = 0.67$, representative of a typical medium-developed city in eastern China; Hefei whose $SDI = 0.58$ is representative of a typical medium-developed city in central China; and Yinchuan, representative of a typical city in western China with a low value of $SDI = 0.40$. Fig. 6 presents radar charts related to the 2nd and 3rd layer sub-indices of *SDI* for these four cities. From Fig. 6(a), it may be seen that the spatial disparities between the sub-index values are mainly due to differences in system development and system coordination. Cities in western China are the least sustainable according to the sub-indices, whereas cities in central China are more like their eastern counterparts regarding sustainability. This is because cities in the different regions are experiencing different urban development paths. Most conurbations in western China have experienced haphazard urban development of poor quality, uncontrolled pollution from industries, and great economic disparity between urban and rural communities. Cities in central China are mainly situated along transportation corridors or river basins, and are characterized by industrial clusters with problems of agglomeration diseconomies (Higano, 1999). Certain cities in eastern China such as Shanghai have grown to become megalopolises (i.e. networks of metropolises) due to the huge expansion of regional social-economic activities (Chinese Academy of Sciences Research Group on Sustainable Development, 2005). The radar chart in Fig. 6(b) highlights the differences in the 3rd layer sub-indices of *SDI* for the four representative cities. In all cases, the sub-index of environmental development has a consistently low value confirming the great environmental pressure on cities in mainland China. The radar structure of the sub-indices is similar regarding the economic and environmental development of cities in eastern China and central China, whilst central cities have lower values of the social related indices. Cities in western China appear to have the highest capacity for environmental development due to their abundance of natural resources and low population density. However, the relatively low levels of economic related indices suggest that these cities would benefit from

Fig. 6

sustainable economic development.

4.4 Sensitivity analysis

A sensitivity test has been undertaken to check the reliability of the rapid assessment approach to sustainability in mainland China, given that uncertainty is introduced during the weighting process by AHP (Ni et al. 2006, 2007). The sensitivity analysis involved changing the weights by ± 20 % of each of 2nd layer sub-indices of *SDI* and investigating the effect on the resultant *SDI* values. As shown in Table 6, absolute values of the eigenvalues for each group change slightly with the ± 20 % alteration to the weights, while the orders of the magnitude of the eigenvalues and the rankings of reference groups remain almost unchanged. In all cases, the present rapid assessment approach is found to be reliable, and the resultant gradings of *SDI* remain stable in spite of the changes to the weights.

Table 6

4.5 Validation and discussion

To validate the rapid assessment approach for sustainability, the resultant province-averaged *SDI* values are compared with results obtained by the Chinese Academy of Sciences using systems analysis (Chinese Academy of Sciences Research Group on Sustainable Development, 2005). The absolute values of province-averaged *SDI* evaluated by the two approaches are normalized (SDI_i/SDI_{max}) to [0, 1] to eliminate scaling effects. As shown in Fig. 7, the normalized values of *SDI* obtained by the two approaches are consistent. Similarity of the normalized results by the two approaches is investigated using Pearson correlation and Cosine correlation. Table 7 compares the various attributes of the two approaches; in particular the Pearson coefficient is 0.957 and Cosine coefficient is 0.998, demonstrating the close agreement between the assessment methods. The table also shows that the 31 basic indices used by the rapid assessment approach are sufficient.

Table 7

Fig. 7

To compare the sustainable development indicators presented in this paper with other sets of indices used in China and in other countries, the following indicator systems are chosen:

(i) An indicator system of sustainable development including 15 groups and 90 indicators for Shandong province by the Institute of Geography, Chinese Academy of Sciences (Mao, 1996).

(ii) A five-level indicator system with 47 indicators and 231 basic indices for 31 provinces in mainland China (Chinese Academy of Sciences Research Group on Sustainable Development, 2005).

(iii) An urban sustainable development indicator system including 52 indices for Jinning City in Shandong Province by Research Center for Eco-environmental Sciences, Chinese Academy of Sciences (Li et al., 2009).

(iv) Sustainable development indicators in Southeastern Europe (Golusin and Ivanović, 2009).

(v) Sustainable development indicators in Scotland (Russell and Thomson, 2008)

The indicators developed in the present paper have been widely applied in other studies in China. In all cases related to China, the indicators have been based on a systematic hierarchical method for describing the sustainability of the complex system of social, economic and environmental issues through a top-down process. The indicators in the present paper have been selected on the grounds of simplicity and sensible representation in order to facilitate straightforward data collection, and hence improve measurement efficiency. Indicators commonly used in China, Southeastern Europe, Scotland, and elsewhere, include GDP per capita and growth of GDP. Compared with sustainable development indicators in Southeastern Europe and Scotland, the indicators used in China put particular emphasis upon development, such as the proportion of tertiary industry production, per-capita public finance revenue, and investment in terms of fixed assets. Instead, indicators in Southeastern Europe and Scotland are rather more related to the quality of life issues, such as numbers of homeless people, the percentage of children living in low-income households, life expectancy, and political freedom.

5. Conclusions

A rapid assessment approach for sustainability has been applied to investigate regional sustainable development in mainland China. Although the approach is not intrinsically new, the authors believe this is the first time rapid assessment has been used in the context of sustainable development. The rapid assessment approach has the advantages that data preparation can be accomplished relatively quickly and the solution procedure is computationally very efficient. Moreover, this approach is designed to cope with data scarcity, and so can be applied to sustainability assessments using fine scale but incomplete information.

Using the rapid assessment approach, sustainable development indices have been determined throughout mainland China for its counties, representative municipalities, and all provinces. China has been classified into five zones according to the magnitude of *SDI* as 'very high', 'high', 'medium', 'low' and 'very low'. About 47 % of China's land area corresponds to a relatively 'low' degree of sustainability, 31 % corresponds to 'medium' sustainability, the remainder being of 'high' sustainability. The area-averaged *SDI* values for the municipalities of Beijing, Tianjin and Shanghai are all higher than any of the province-averaged *SDI* values. Provinces in eastern China, central China, and western China appear to have 'high', 'medium' and 'low' levels of sustainability, respectively. After examining the frequency analysis results, and the 2nd layer and 3rd layer sub-indices in the sustainable development indicator hierarchy, it seems that the central cities of China need further improvement regarding social related issues, whereas cities in western China would benefit from appropriate sustainable economic development through increased investment. Further socio-economic research is required in order to identify how best to develop the central and western regions of China. To enhance the accuracy of the present assessment approach, it is recommended that secondary influence factors such as coastal areas and tourism be incorporated in future studies.

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List of Tables and Figures

Table 1 Sub-indices in the 4th layer of sustainable development indicator system and their upper and lower limits

1st layer	2nd layer	4th layer	Units	Upper limits (T_u)	Lower limits (T_l)
SDI ($i_{1,1}$)	System Development ($i_{2,1}$)	Per-capita GDP ($i_{4,1}$)	RMB	47216.55	2381.25
		Proportion of Tertiary Industry Production ($i_{4,2}$)	%	56.46	17.57
		Per-capita Public Finance Revenue ($i_{4,3}$)	RMB	51.14	3691.27
		Telephones per 1,000 People ($i_{4,4}$)	Household/10^3 people	682.12	33.01
		Hospital Beds per 1,000 People ($i_{4,5}$)	Bed/10^3 people	6.75	0.75
		Books in Public Library per 100 People($i_{4,6}$)	List/10^2 eople	123.55	6.01
		Numbers with Secondary Education per 100,000 People ($i_{4,7}$)	person	14515.46	1912.40
		Per-capita Land Area ($i_{4,8}$)	Hm^2	0.75	0.01
		Per-capita Water Resource ($i_{4,9}$)	m^3	16176.90	102.20
		Forest Coverage ($i_{4,10}$)	%	62.96	2.94
	System Coordination ($i_{2,2}$)	Proportion of Research and Education Expenditure to GDP ($i_{4,11}$)	%	5.25	0.92
		Per-capita Public Finance Expenditure ($i_{4,12}$)	RMB	4734.56	410.91
		Proportion of Rural Population ($i_{4,13}$)	%	100.00	0.00
		Energy Consumption per 10,000 Yuan GDP ($i_{4,14}$)	Ton of standard coal /10^4 RMB	4.14	0.79
		Industrial Waste Water Discharge per 10,000 Yuan GDP ($i_{4,15}$)	t/10^4 RMB	35.73	1.86
		SO_2 Discharge per 10,000 Yuan GDP ($i_{4,16}$)	kg/10^4 RMB	68.62	0.80
		Industrial Solid Waste Discharge per 10,000 Yuan GDP ($i_{4,17}$)	t/10^4 RMB	2.68	0.03
		Implementation of Environmental Impact Assessment ($i_{4,18}$)	%	100.00	96.10
		Implementation of the "Three at the Same Time" Policy of the Chinese Government ($i_{4,19}$)	%	100.00	72.00
		Proportion of Industrial Wastewater Drainage within Standard ($i_{4,20}$)	%	99.60	44.60
		Proportion of Industrial Exhaust Gas Treatment within Standard ($i_{4,21}$)	%	100.00	52.70
		Solid Waste Utility Efficiency ($i_{4,22}$)	%	98.30	1.40
	System Sustainability ($i_{2,3}$)	GDP Growth Rate ($i_{4,23}$)	%	24.00	9.30
		Per-capita Balance of Saving Deposits ($i_{4,24}$)	RMB	33177.26	752.5
		Investment on Fixed Assets ($i_{4,25}$)	%	24004.03	1350.83
		Population Growth Rate ($i_{4,26}$)	%	11.76	0
		Gender Ratio ($i_{4,27}$)	-	107.62	100.00
		Old-age Dependency Ratio ($i_{4,28}$)	-	16.24	7
		Natural Disaster Indicator ($i_{4,29}$)	%	11.58	0.00
		Coal Consumption Indicator ($i_{4,30}$)	%	98.14	2.52
		Clean Energy Indicator ($i_{4,31}$)	%	7.20	1.20

Table 2 Reciprocal matrixes for evaluation indices in different levels of the hierarchy structure

A (*CR*=0)	B1	B2	B3		B1 (*CR*=0)	C1	C2	C3	
B1	1	1	1		C1	1	1	1	
B2	1	1	1		C2	1	1	1	
B3	1	1	1		C3	1	1	1	
B2 (*CR*=0)	C4	C5	C6		B3 (*CR*=0)	C7	C8	C9	
C4	1	1	1		C7	1	1	1	
C5	1	1	1		C8	1	1	1	
C6	1	1	1		C9	1	1	1	
C1 (*CR*=0)	D1	D2	D3		C2 (*CR*=0)	D4	D5	D6	D7
D1	1	1	2		D4	1	1/2	1/2	1
D2	1	1	2		D5	2	1	1	2
D3	1/2	1/2	1		D6	2	1	1	2
					D7	1	1/2	1/2	1
C3 (*CR*=0)	D8	D9	D10		C4 (*CR*=0)	D11	D12	D13	D14
D8	1	1	2		D11	1	2	2	1
D9	1	1	2		D12	1/2	1	1	1/2
D10	1/2	1/2	1		D13	1/2	1	1	1/2
					D14	1	2	2	1
C5 (*CR*=0)	D15	D16	D17	D18	C6 (*CR*=0)	D19	D20	D21	D22
D15	1	1	1	1/3	D19	1	3	3	3
D16	1	1	1	1/3	D20	1/3	1	1	1
D17	1	1	1	1/3	D21	1/3	1	1	1
D18	3	3	3	1	D22	1/3	1	1	1
C7 (*CR*=0)	D23	D24	D25		C8 (*CR*=0)	D26	D27	D28	
D23	1	1/2	1/2		D26	1	1/2	1/2	
D24	2	1	1		D27	2	1	1	
D25	2	1	1		D28	2	1	1	
C9 (*CR*=0)	D29	D30	D31						
D29	1	1/2	1/2						
D30	2	1	1						
D31	2	1	1						

Table 3 Weight for each evaluation index to *SDI*

First level	Second level	Weight	Third level	Weight	Fourth level	Weight
A	B1	0.333	C1	0.111	D1	0.044
					D2	0.044
					D3	0.022
			C2	0.111	D4	0.019
					D5	0.037
					D6	0.037
					D7	0.019
			C3	0.111	D8	0.044
					D9	0.044
					D10	0.022
	B2	0.333	C4	0.111	D11	0.037
					D12	0.019
					D13	0.019
					D14	0.037
			C5	0.111	D15	0.018
					D16	0.019
					D17	0.019
					D18	0.056
			C6	0.111	D19	0.056
					D20	0.018
					D21	0.019
					D22	0.019
	B3	0.333	C7	0.111	D23	0.022
					D24	0.044
					D25	0.044
			C8	0.111	D26	0.022
					D27	0.044
					D28	0.044
			C9	0.112	D29	0.022
					D30	0.045
					D31	0.045

Table 4 Eigenvalues of centroids for *SDI* and its 2nd-layer sub-indices

Class (j)		1	2	3	4	5
System Development Sub-index ($i_{2,1}$)	Eigenvalue ($k_{2,1,j}$)	0.40	0.66	0.21	0.27	0.52
	Number of Units in reference group	226	29	600	709	50
System Coordination Sub-index ($i_{2,2}$)	Eigenvalue ($k_{2,2,j}$)	0.34	0.57	0.62	0.77	0.43
	Number of units in reference group	59	903	213	63	106
System Sustainability Sub-index ($i_{2,3}$)	Eigenvalue ($k_{2,3,j}$)	0.66	0.39	0.50	0.41	0.59
	Number of units in reference group	74	198	993	501	57
Sustainable Development Index ($i_{1,1}$)	Eigenvalue ($k_{1,1,j}$)	0.60	0.43	0.39	0.51	0.35
	Number of units in reference group	148	566	151	187	197
	Ranking	‘Very high’	‘Medium’	‘Low’	‘High’	‘Very low’
	Number of units	266	616	603	376	478

Table 5 Area-averaged *SDI* and its sub-indices for different classes of provinces and municipalities in mainland China

Regions	Provinces & municipalities	*SDI*	System Development Sub-index ($i_{2,1}$)	System Coordination Sub-index ($i_{2,2}$)	System Sustainability Sub-index ($i_{2,3}$)
Region AM Municipalities	Beijing, Shanghai, Tianjin	0.66	0.58	0.84	0.64
Region AP Eastern China	Zhejiang, Guangdong, Fujian, Heilongjiang, Shandong, Liaoning, Jiangsu, Jilin	0.49	0.33	0.66	0.52
Region BM Municipality	Chongqing	0.43	0.26	0.59	0.44
Region BP Central China	Xinjiang, Hainan, Anhui, Hubei, Hebei, Henan, Hunan, Jiangxi, Inner Mongolia	0.43	0.30	0.51	0.51
Region CP Western China	Shaanxi, Qinghai, Sichuan, Guangxi, Gansu, Shanxi, Ningxia, Yunnan, Tibet, Guizhou	0.37	0.26	0.40	0.49
National level	27 provinces & 4 municipalities	0.41	0.29	0.49	0.50

Table 6 Sensitivity of *SDI* to ± 20% changes to the weights assigned to 2nd layer sub-indices

Weights	Sub-indices of *SDI*			Eigenvalues and rankings for each reference group of $i_{1,1}$				
	$i_{2,1}$	$i_{2,2}$	$I_{2,3}$	$k_{1,1,1}$	$k_{1,1,2}$	$k_{1,1,3}$	$k_{1,1,4}$	$k_{1,1,5}$
Initial	0.333	0.333	0.334	0.60 V[a]	0.43 III	0.39 II	0.51 IV	0.35 I
1.2W$i_{2,1}$	**0.400**[b]	0.300	0.300	0.60 V	0.43 III	0.38 II	0.51 IV	0.33 I
1.2W$i_{2,2}$	0.300	**0.400**	0.300	0.60 V	0.43 III	0.38 II	0.52 IV	0.35 I
1.2W$i_{2,3}$	0.300	0.300	**0.400**	0.60 V	0.43 III	0.41 II	0.52 IV	0.35 I
0.8W$i_{2,1}$	**0.266**	0.367	0.367	0.60 V	0.43 III	0.40 II	0.52 IV	0.35 I
0.8W$i_{2,2}$	0.367	**0.266**	0.367	0.60 V	0.43 III	0.40 II	0.51 IV	0.33 I
0.8W$i_{2,3}$	0.367	0.367	**0.266**	0.60 V	0.43 III	0.40 II	0.51 IV	0.33 I

[a] I ~V represent ‘very low’, ‘low’, ‘medium’, ‘high’ and ‘very high’ rankings of *SDI*.

[b] highlighted values are the weights changed by ±20%.

Table 7 Comparison between applications of rapid assessment of sustainability and systems analysis (Chinese Academy of Sciences) to sustainability in mainland China

Approaches		Rapid assessment of sustainability	Systems analysis by Chinese Academy of Sciences (2005)
Mapping units level		Counties and cities	Provinces
Sum of mapping units		2339	31
Pearson coefficient	Rapid assessment	1.00	0.957
	Systems analysis	0.957	1.00
Cosine coefficient	Rapid assessment	1.00	0.998
	Systems analysis	0.998	1.00
Number of basic indicators		31	231
Dealing incomplete information		Yes	No

Figures:

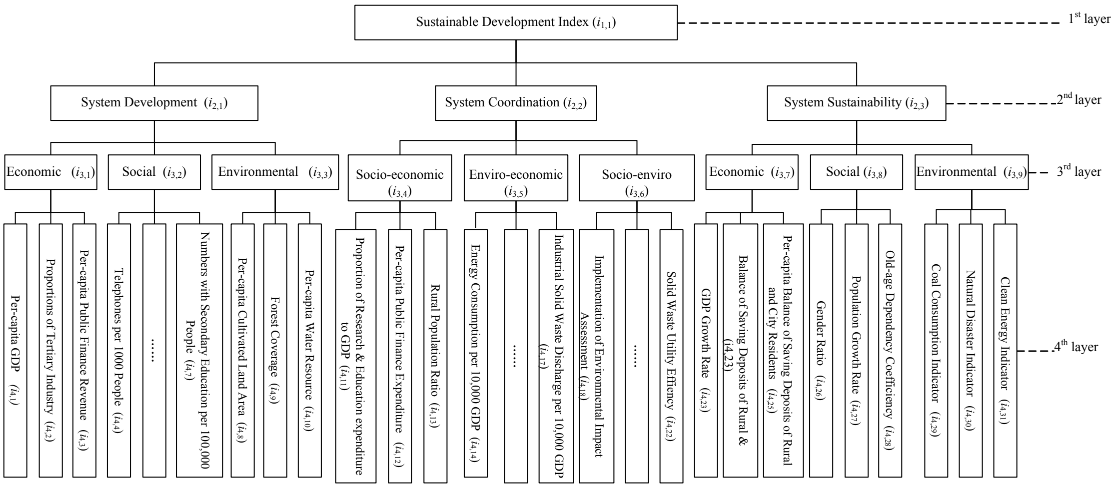


Fig. 1 General structure of sustainable development index system for China

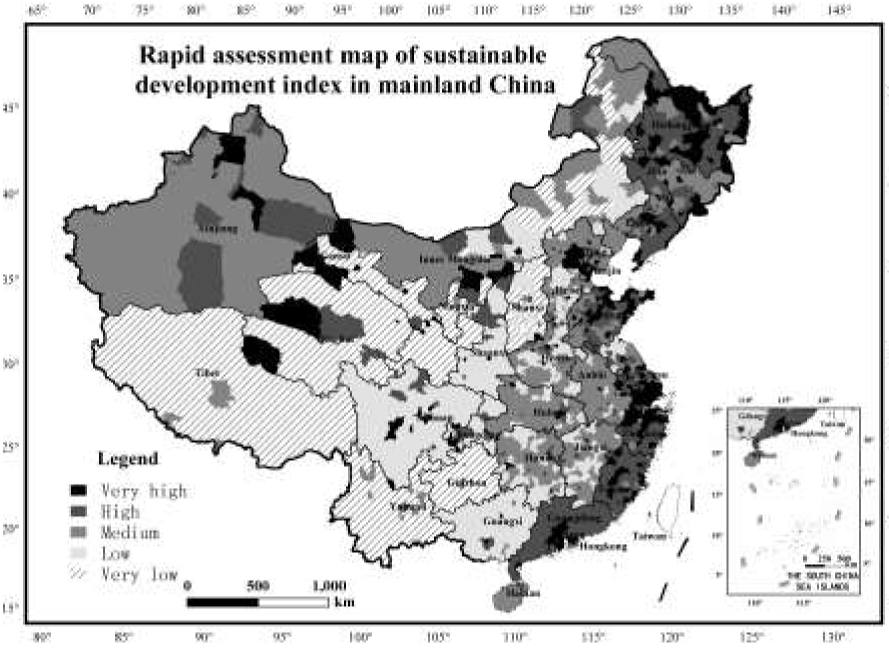


Fig. 2 Rapid assessment map of sustainable development index (*SDI*) in China

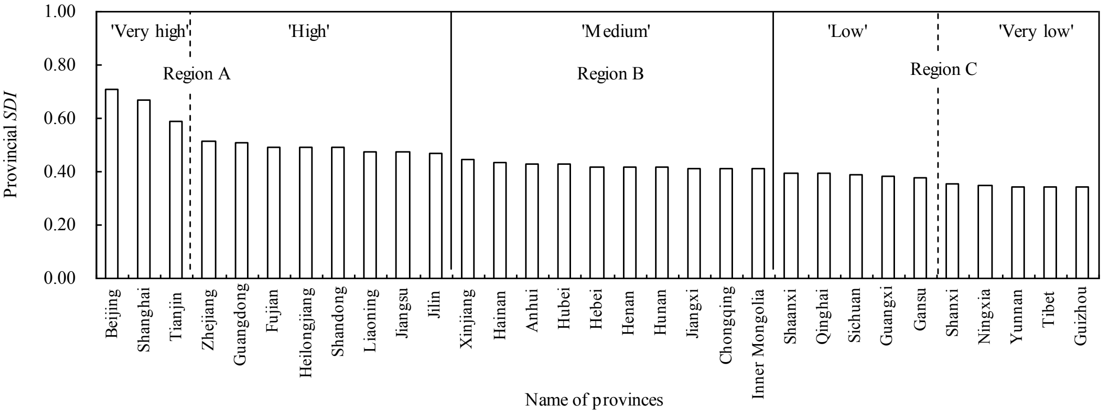
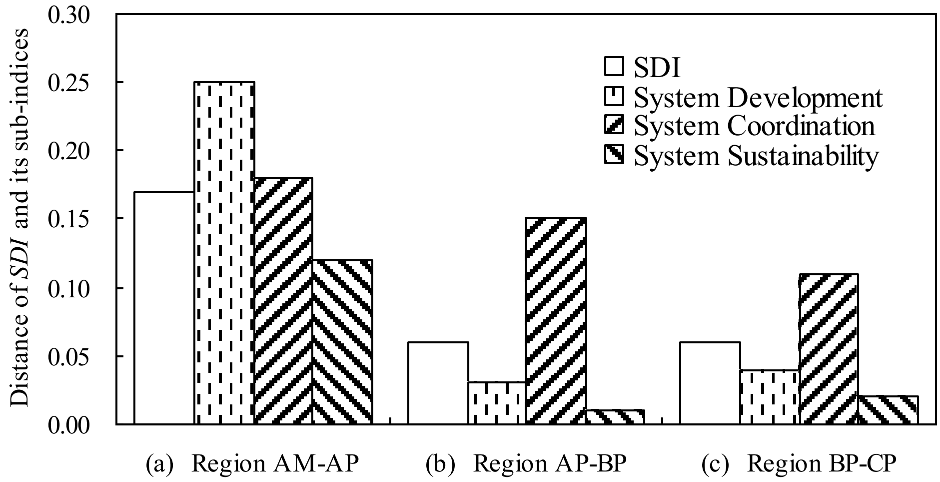
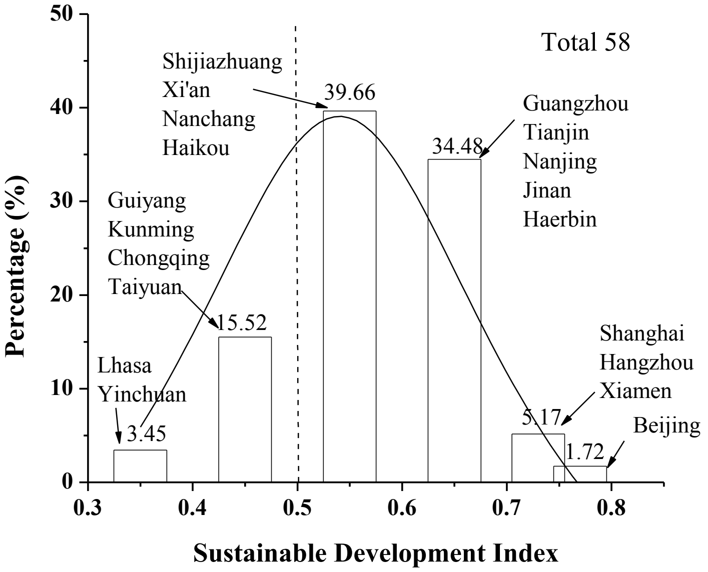


Fig. 3 Provincial *SDI* and its grading for 27 provinces and 4 municipalities

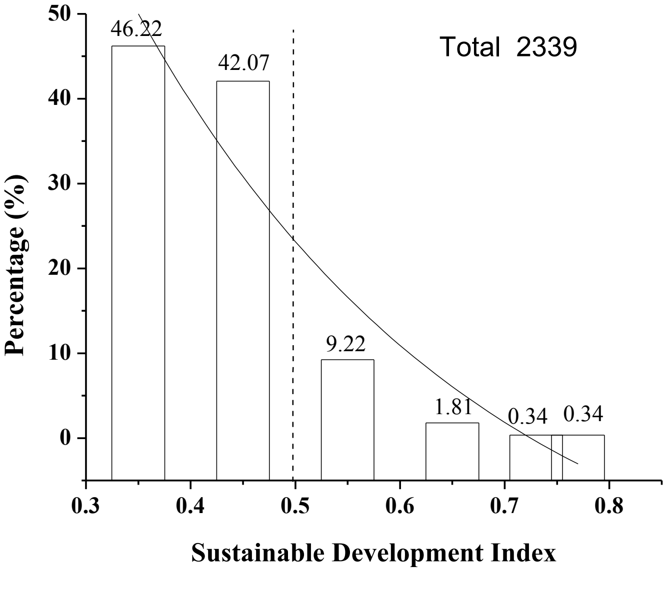


(a) Region AM-AP means comparison of AM and AP
(b) Region AP-BP means comparison of AP and BP
(c) Region BP-CP means comparison of BP and CP

Fig. 4 Regional disparities of *SDI* and its sub-indices

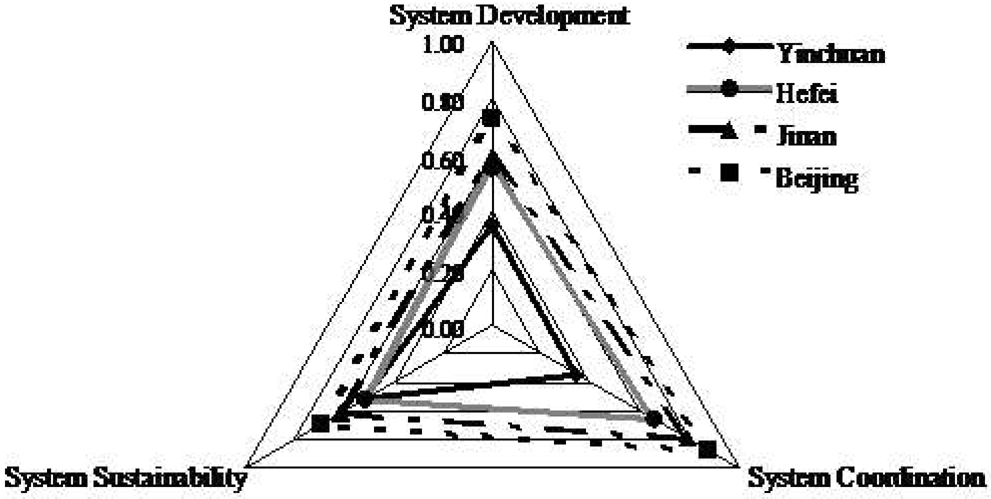


(a) 58 major cities

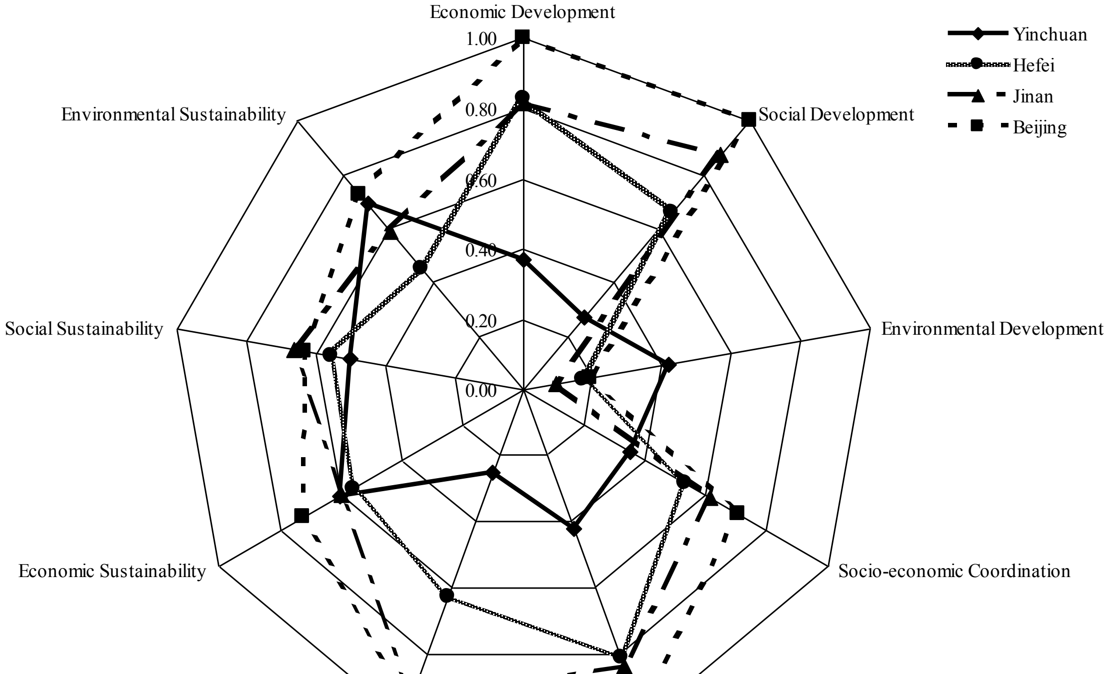


(b) 2339 counties and cities

Fig. 5 Frequency analysis histograms and curve fits for *SDI*



(a) 2nd-layer sub-indices



(b) 3rd-layer sub-indices

Fig. 6 Radar diagrams for 2nd-layer and 3rd-layer sub-indices of *SDI* for representative cities in different regions of China

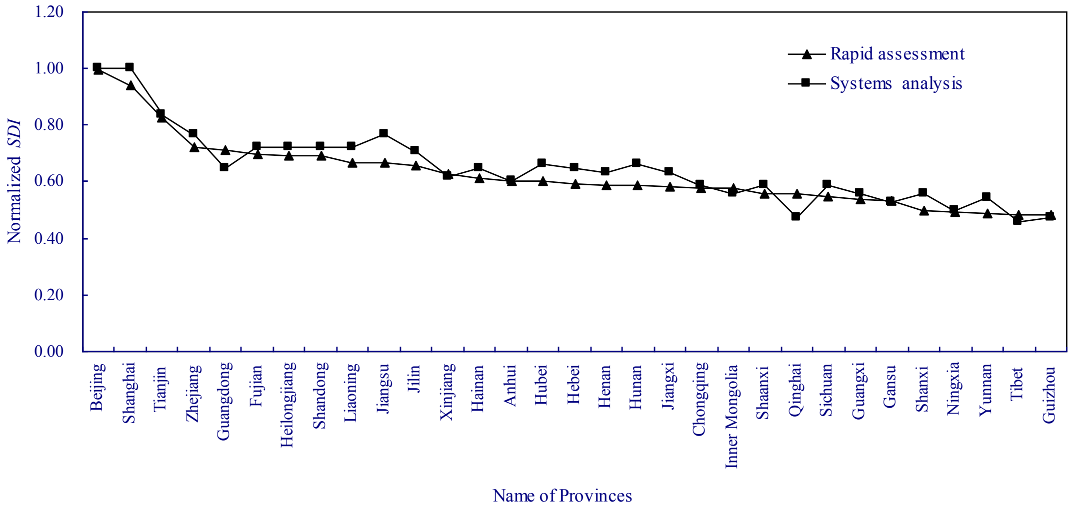


Fig. 7 Comparison of normalized values for *SDI* obtained using the present approach and a systems analysis method used by the Chinese Academy of Sciences