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A new approach of deriving indicators and comprehensive measure for ecological environmental quality assessment

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ABSTRACT

The key indicators' identifications and assessments of ecological environmental quality (EEQ) are very important for management policies and strategy. In this paper, founding upon the facts that the key indicators of EEQ from the experts' selections are hidden in and improved by the constantly additions of new publications, a new approach of deriving indicators and comprehensive measure for ecological environmental quality assessment (EEQA) is developed from dynamic co-word network. We elaborate the new approach and the modeling construction roadmap: the key indicators of EEQ emerge from the dynamic co-word network; basing on clustering and K-core analysis of the co-word network domains, four levels of indicators for EEQA are deduced; based on the similarity or relatedness between the indicators in the co-word network, nodal degrees are introduced to calculate indicators' weights and derive a comprehensive measure for EEQ, finally forming a rigorous co-word network model of EEQA. This model is applied to some typical cases of EEQA (a town, a city and two specific cases from Chongqing and Beijing) and the reasonable assessment results are obtained. The results are compared with other models to show the features of the model. The co-word network model for EEQA is a potential and universal function derived from traditional co-word methods of bibliometrics. Beyond the EEQA, the assessment of many other complex phenomena can be similarly conducted in terms of the given technical roadmap.

1. Introduction

With the rapid economic development and the increasing human living needs, energy depletion, environmental pollution and ecological damage have currently been rather serious. The accurate grasp of ecological environmental quality (EEQ) and their intrinsic key indicators (i.e., influential factors) is of great importance to management policies and strategy. Ecological environmental quality assessment (EEQA) has ever been a prerequisite of guiding us to take any specific intentional actions, which has attracted more and more public attentions.

During past decades, many works on EEQA have been conducted in available literature. EEQA includes indicator selection and assessment model. At present, in much available research, EEQA has extremely diverse and controversial connotations, which is divided into single indicator assessment and comprehensive indicator assessment. The studies of single indicator assessment, for example, included air quality assessment using sulfur dioxide emissions and particulate matters as indicators (Merlevede et al., 2006; Dasgupta et al., 2006). Ferrat et al. (2003) used aquatic plants as a biological indicator of EEQ to study the protection of coastal ecosystems. Vrscaj et al. (2008) discussed soil functions, soil quality indicators, soil functions and urban soil quality, and proposed a specific assessment system for urban soil quality. As for comprehensive indicator assessment studies, for example, the target system was established and assessment function was constructed for Swedish national EEQ (Larsson and Hanberger, 2015). Robati et al. (2015) introduced a comprehensive indicator for urban EEQA. Biondi and Colosi (2005) analyzed the landscape EEQA by calculating plant landscape indicators. Ma and Shi (2016) investigated the county-level administrative area using ecological environment indicator, in which the objective weighting method was invoked to determine the importance of each indicator and then evaluate the EEQ of economic zone. Besides much research on indicator selection, many models of EEQA were also proposed, which included comprehensive indicator model (Liu et al., 2015), principal component analysis model (Skrbic and Durisic-Mladenovic, 2007), analytic hierarchy process model (Li, 2007), and fuzzy assessment model (Wang et al., 2012), gray assessment model (Tian et al., 2011), neural network model (Kosiba, 2009), and so on.

Up to today, by developing many indicator selection avenues and

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assessment models, many achievements of EEQA have been made in available literature. However, it is also clear that, most available indicator selections and models are usually subjective, and the qualitative but not quantitative characteristics are usually emphasized, which can be attributed that the models are lack of rigorous theoretical foundations. To give an objective indicators system, and then to establish a precise scientific assessment model of EEQA with rigorous theoretical basis are still lack and very urgent up to today. To fill this gap and face the challenge, some new thoughts and breakthroughs should be highly needed.

Experts' selections for assessment are important. The applications of 'experts' selections appeared in many related research areas. For example, by combining experts' opinions on the likelihood and expected development of complex systems, the experts' selections were applied in many scopes, especially those related to business forecasting (Shankar and Schroeder, 1977). The experts' selections were also successfully used as an open-ended public-private sector approach to identify the most urgent challenges for their regional ICT-for-development eLAC Action Plans. Further applications came from the use of computer-based (and later web-based) Delphi conferences (Glenn and Gordon, 2009). In addition, considering the experts' selections have traditionally aimed at a consensus of the most probable future by iteration, experts' selections related to the policy Delphi have instead been used as decision support methods aiming at structuring and discussing the diverse views of the preferred future (Seker, 2015). In this study, we tend to introduce a new avenue. Since indicator selection and assessment methods of EEQA are conducted by experts in the subject of EEQ, the opinions of experts can be well reflected by their publications. The keywords in the publications written by experts in various fields of EEQ embody the core ideas or opinions of the publications, definitely hiding the key indicators or factors of EEQ that experts hold. By constantly issuing new publications, experts follow information from available publications, and responses are collected and analyzed. They have thus constantly improved their knowledge on EEQ during the development process of the subject, which are further reflected in the keywords of the new publications. The process would continue towards building a consensus on EEQ. The evolutionary co-occurrence of keywords (i.e., co-word) over a long period (i.e., many rounds of responses or feedbacks) would finally generate the key indicators or factors of EEQ. In other words, as the key components of the knowledge system, the coupled dynamic keyword network emerges a suitable indicator skeleton of EEQ. Thus, we hold a logical deduction that we may rigorously build a new approach of deriving indicators and comprehensive measure for EEQA from the co-word network, resolving the subjective or even unsound problems met by indicator selection and EEQA models in available literature.

The layouts of the paper are organized as follows. After the introductory part, the second part describes the methodological foundation. The third part elucidates the new approach of deriving indicators and comprehensive measure for EEQA, showing the modeling construction roadmap of EEQA. The fourth part uses the model to assess several cases. Lastly, the summary is provided.

2. The methodological foundation

Keywords, as the important parts of publications, carry and condense the core contents of topics, being fundamental elements of a subject. The appearance of a keyword and another keyword in the same publication, i.e., co-word phenomena, reflects the true internal topical relationship in a subject. The co-word network approach for bibliometrics has popularized since it was proposed by Callon et al. (1983). It is generally thought that co-word network could go directly into literature and observe the development of a subject. In this way, in the historical mainstream of bibliometrics, it is a consensus that co-word network can reveal the history, indicate situation and future development trend of any specific subjects. So far, along this mainstream, co-word network method has been applied in many fields such as polymer chemistry (Callon et al., 1991), bibliometrics (Courtial, 1994), information retrieval (Ding et al., 2001), renewable energy (Romo-Fernández et al., 2013), the Internet of Things (Yan et al., 2015), and so like.

Here, beyond available understanding, in our opinion, co-word network should have more potential implications or functions, which can yield an assessment model of any subjects (e.g., EQQ) by self-emerging the indicators of the subjects. Our detailed thoughts are as follows. The publications are written by experts in various fields of a subject who have knowledge on the subject, hiding the reasonable core ideas or opinions of experts on the key indicators or factors of this subject. The keywords from the publications, as the reflection of core ideas or opinions of the publications, must conceal the key indicators or factors of a subject. The initial ideas, opinions and comments on the indicators of subjects from some experts are collected and reflected in the keywords appearing in the publications. The more and more experts constantly process the information and filter out irrelevant contents from available publications, issuing more and more new publications. That is, by constant new publications, many experts follow available information and present their new responses and views. Responses are collected and analyzed, which are further reflected in the keywords of the new publications. Then, common and conflicting viewpoints are identified during the process. The process continues through more and more publications, gradually approaching towards synthesis and consensus formation. Thus, the evolving coupled keyword networks, which come from constantly increasing publications during the knowledge system development, are actually suitable the developing indicator skeletons of subjects. The dynamic co-occurrence of keywords (i.e., co-word network) over a long period of time (i.e., many rounds of feedbacks) can build up a subject in which all key indicators or factors can be identified. Thus, as a strongly-coupled network that evolves through interactions, co-word network reveals not only the evolution of "research trends" about a subject, but also reveals the agreed consensus on the subject and constructs indicators systems of assessing the subject.

In summary, we would like to reach a logical conclusion that we may rigorously assess EEQ from co-word network, achieving a potential function development beyond traditional co-word methods of bibliometrics. Co-word network will solve the hard problems of indicator selection in available models, which can help to find key indicators and build a new assessment model with rigorous theoretical foundations. In details, we consider that the node/vertex of the co-word network is the keyword ($K_{1,t}$, $K_{2,t}$ …) and the link/edge of the node is the occurrence of two words in the same publications ($P_{1,t}$, $P_{2,t}$ …). By calculating the number of co-occurrences of two keywords in the same publication in Gephi software, a co-word matrix is obtained. With the constant entrance of new publications, new keywords will add. According to the new co-occurrences, we go to build new links between them and re-set relationship weights. In this way, we obtain sequential co-word network by dividing publication sets according to time slice. That is, we can accordingly obtain a dynamic co-word network. The relationship between co-word network patterns can be visualized. This dynamic co-word network reflects how the original opinions incorporate new information, feedback or revision and finally approach correct indicators of the complex phenomena resulted from the experts' selections hidden in the constantly addition of new publications. It shows a structural information flow to a consensus on the indicators of the complex phenomena. Co-word network is a structured approach that aggregates diverse opinions from groups. By group or structural judgments emerged from individual judgments, it yields the correct key indicators, their weights and the associated comprehensive measure for EEQA by the network structure.

Up to now, we elaborate the methodological foundation of the model (let us call it co-word network model). By analyzing why we can use co-word network to build a rigorous theoretical EEQA model, the implications or functions of co-word network are extended beyond the traditional co-word methods of bibliometrics.

3. The modeling construction of EEQA

Now, we clarify the new approach of deriving indicators and comprehensive measure for EEQA, showing the modeling construction roadmap of EEQA.

3.1. The emergence of key indicators system

For EEQA, TS = "environment* quality" is chosen as the retrieval term to search the WoS database including scientific citation index (SCI), scientific citation index extension (SCI-E), social science citation index (SSCI), and conference proceedings citation-science (CPCI-S), yielding 6819 articles and 15668 keywords. Firstly, the keywords such as + s form, + ing form, + ed form and abbreviation are processed and unified. Then, the data is checked by the Bibexcel software for accuracy.

To show the dynamic emergence of key indicators system of EEQ from the experts' selections hidden in the constantly addition of new publications, we extract the keywords from different years (1998; 1998–2002; 1998–2006; 1998- 2009; 1998–2012 and 1998–2015) to construct the dynamic co-word network. Here the top 100 nodes (keywords) are selected to visualize the dynamic co-word network. As shown in Fig. 1; with the enlarging size of the nodes (keywords); the links between the nodes are increasing. In the dynamic evolution of EEQ's indications system; many small groups are gradually clustered to be some large groups. From the topological pattern with different colors; we intuitively see a shift from the original small groups with dozen different colors to some big groups with only three colors. This shows that; with the joining of new keywords; the stable indications system has been gradually formed by the self-organizing process. This process self-organizes constantly until a consensus emerged; which vividly reflects a trend of converging towards accurate indications system of EEQA.

By comparing the top 100 nodes (keywords) in each period, we can calculate the number of the changing keywords, reflecting the changing indicators of EEQ in each period with the evolution of the knowledge system. A comparison of 1998 and 1998–2002 shows that 50 keywords among the top 100 have changed. Until 1998–2009 and 1998–2015, a comparative analysis shows that only 4 keywords among the top 100 have changed. With the number reduction of changing keywords among the top 100 keywords, it ensures that the co-word network has gradually generated the stable indicators of the knowledge system by a self-organized dynamic process, emerging the key indicators of EEQA. In other words, corresponding to Fig. 1, by calculating the change of keywords, here we further reveal the indicators of EEQA emerged from the self-organized dynamics.

As shown in Fig. 1, the main key indicators shown in the three-color groups are pollution (dominated by various factors of EEQ), heavy metals, models, sediments, management, water quality, soil, impact, health, economy, policies, emissions, and so on. By comparing the cases of 1998 and 1998–2015, we find the single study is replaced by integrated approaches and technologies such as dynamics, GIS and remote sensing. The indicators such as soil degradation, herbicides, maize and hormones are converted into industrial sediments, indoor environmental quality, land use and energy. Without surprise, it clearly states that the indications system of EEQ is dynamically related to changing situations during past two decades. The overall environment or certain aspects of the overall environment, the survival and multiplications of human, the society-economic development and the specific requirements of human have all gradually been included in the indicators of EEQ. Especially, by adding more factors to the human satisfaction, perception and comfort, a wide spectrum of key indicators related to EEQ has been reached. The dynamic co-word network that reflects the experts' selections hidden in the constantly addition of new publications, can accurately emerge the wide range of key indicators of EEQ. That is, by the dynamic co-word network process that can be stopped after a predefined stop criterion (e.g. number of rounds, achievement of consensus, stability of indicators) that is here determined by the ascertained publications within 1998–2015, the indicators system of the final rounds determine the standards of EEQA. Up to now, we clearly verify why and how the complete indicators of EEQ can be emerged from dynamic co-word network, underpinning the foundations of establishing EEQA model.

3.2. Construction of the assessment model

Above section gives a description on the dynamic emergence of key indicators system of EEQ by a process of self-organized information flow in the dynamic co-word network. To construct the model, we need a clearer clustering on the converged stable domains of indicators system in the co-word network. We use Gephi software modularization to do cluster analysis on the domains as shown in Fig. 1. Modularity is built on the theory of community discovery or detection. A community is a sub-graph containing nodes that are linked more densely to each other than to the rest of the graph. A graph has a community structure if the number of links within specific sub-graphs is higher than the number of links between those sub-graphs (Newman and Girvan, 2004). Gephi's community discovery algorithm uses the Fast Unfolding algorithm program (Blondel et al., 2008). Because keywords are enormous and play different roles in the EEQ, we extract the keywords with frequency over 10 from Fig. 1, and cluster the EEQ into five different colors by Fast Unfolding algorithm, as shown in Fig. 2.

Then we extract the five aspects of indicators in terms of the different colorful clusters, and analyze them respectively. In cluster 1 with 32.6% of total keywords, major keywords have pollution, heavy metal, sediment, soil, metal, pesticides, toxicity, PAHs, water framework directive, biomarker, and so on. Cluster 2 accounts for 29.2%, which primarily includes keywords such as sustainability, environment, china, sustainable development, climate change, energy, public health, policy, economic growth, environmental Kuznets curve, and so on. In cluster 3 (18.6%), the main keywords have water quality, monitoring, agriculture, watershed, model, land use, nutrients, wastewater, runoff, phosphorus, and so on. Cluster 4 accounts for 12.3%, in which the main keywords have indoor environment quality, health, indoor air quality, schools, green building, thermal comfort, ventilation, housing, survey, and so on. In cluster 5 (7.2%), the main keywords have air pollution, biomonitoring, biodiversity, air quality, lichens, PM10, and so on. In summary, based on the above keywords, five aspects (clusters) of indicators are recognized as soil quality, sustainable development, water quality, indoor environmental quality and air quality. In this way, by a clear clustering, we get an underlying structure for indicators of EEQA, which can facilitate the indicators construction of EEQ. We can use the above five aspects to establish the indications system of EEQ.

By K-core analysis of co-word network, a multi-level of indications system of EEQA can be constructed. The K-core is the remaining subgraphs after the repeated removal of nodes with degrees less than or equal to K (Gaertler, 2004). The number of nodes can denote the depth of the node in the network. According to the definition of K-core, the K-core can be obtained by repeatedly removing the nodes (degrees are less than K) and the edge connected with it until the degrees of all nodes in the remaining graph are greater than or equal to K. Therefore, we can analyze the network from outer layer to inner layer by K-core analysis until the innermost layer, revealing the hierarchical structure of the network. As shown in Fig. 3, by taking the K-core value of 10, we can well get the deepest core layer of EEQ. In general, the indications system of EEQA is divided into four layers: (1) The target layer. Here the EEQ can be taken as the overall target level. (2) The standard layer. Here human activity indicators and natural environmental indicators are summarized as the standard layer. (3) The factor layer. We here ascertain the indicators (e.g., indoor environment quality, socio-

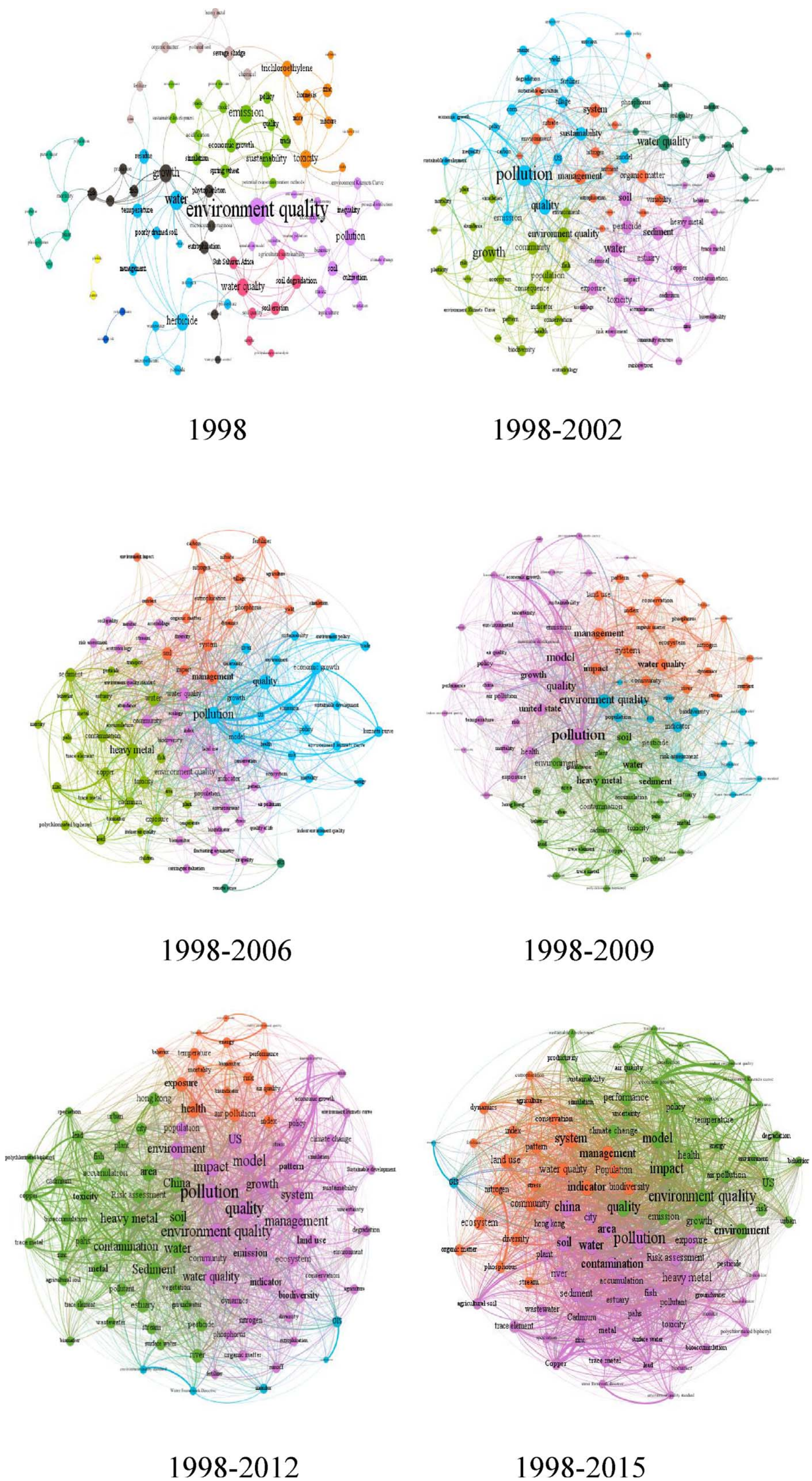


Fig. 1. The dynamic emergence of key indicators of EEQ from co-word network.

economic development, water resources, soil resources and air resources) as the factor layer. (4) The micro-indicator layer. The micro-indicator layer is composed of various representative indicators that can be directly measured. It is the preliminary-level of indicators system of EEQ. Here there are 66 preliminary-level indicators (X1-X66). In fact, of course, by increasing the value of K, one can also build two layers, three layers, four layers and ever more. This study constructs four layers of indicators system. The above four levels of indicators together constitute the indicators system of EEQA, as shown in Table 1. It should be noted some keywords that cannot be used as indicators are here

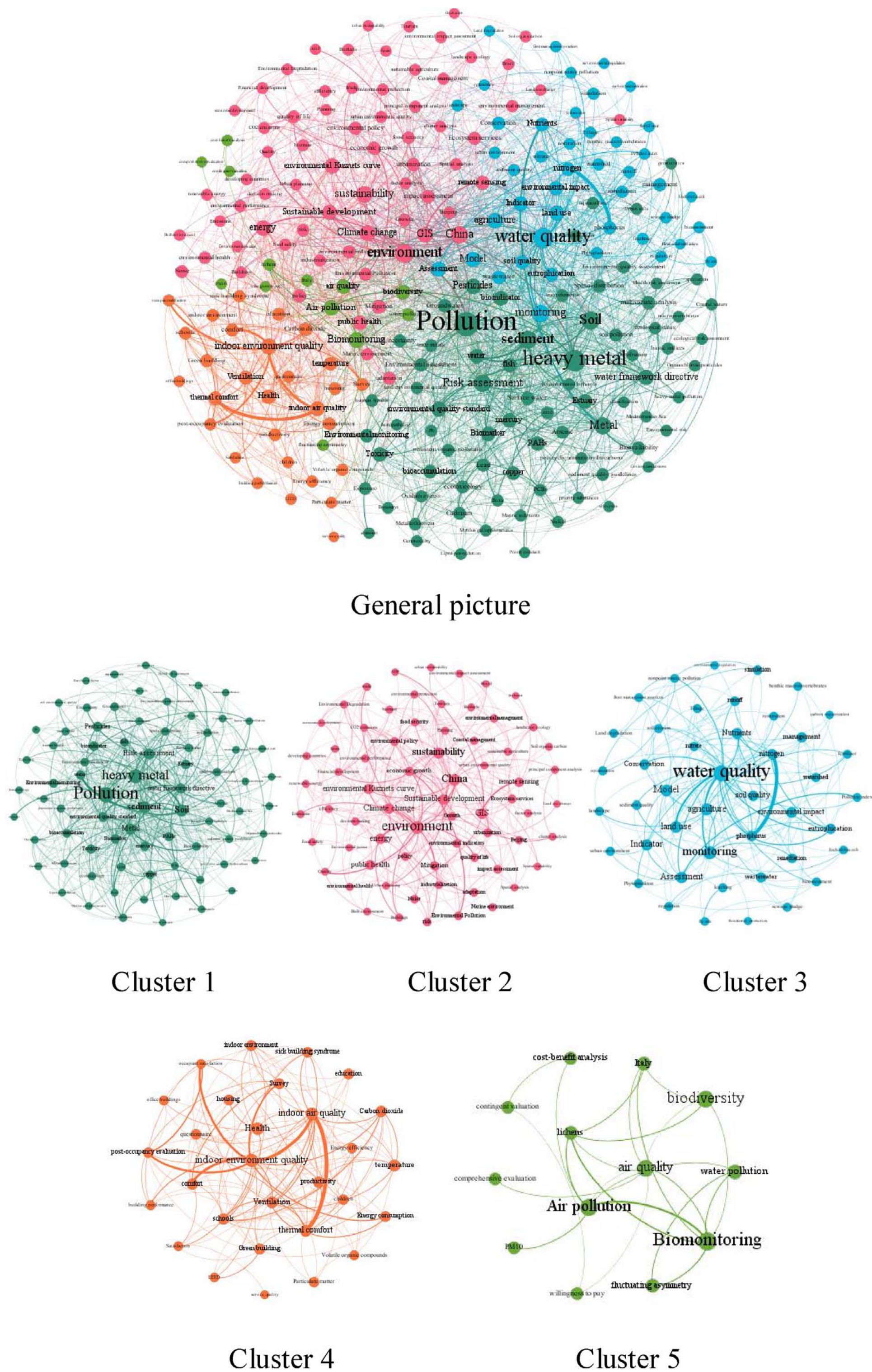


Fig. 2. The clustering on the converged stable domains of indicators in EEQ.

removed from the co-word network. The reservation of keywords in the paper follows the following principles: (1) The retained indicators can fully reflect the intrinsic mechanisms of EEQ, and the concept of indicators must be clear and can reflect the characteristics of the environment. (2) It should be able to comprehensively reflect and measure all aspects of environmental capacities, not only including the resource, environment, population, economic, social and other indicators of the system development, but also highlighting the above systems of mutual synergetic indicators. (3) The indicators should have characteristics such as relatively independence, accuracy, accessibility, testability and comparability. (4) The indicators should hold completeness, simplicity, representativeness and integrality. Based on these principles, we finally select the indicators system for EEQ as shown in Table 1.

Table 1 also gives the degrees of all micro-indicators in the micro-indicator layer. In the co-word network, the links between any two nodes reflects the distance between them, which fairly embodies the similarity or relatedness between them. In this way, the weights of the indicators (nodes) can be determined by the degrees of the nodes in the co-word network. The degree is simple and important concept. The

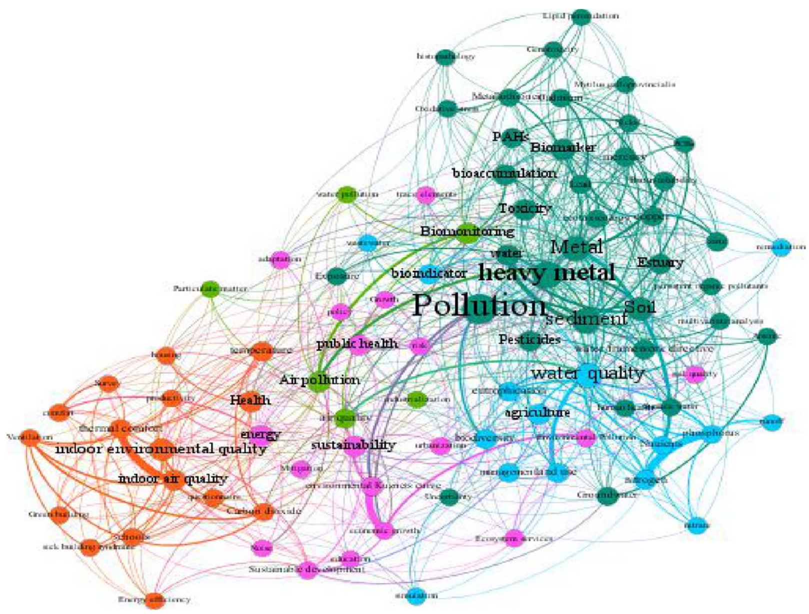


Fig. 3. The diagram of EEQ's indicators system by co-word network with K-core = 10.

neighbors' number k_i of node i is the degree in the network. The greater degree of an indicator in the co-word network means this indicator is more important in EEQA. Thus, the definition of the indicator weight from the perspective of degree is very appropriate. In this way, the indicator weights are calculated by

$$\alpha_i = \frac{k_i}{\sum_{i=1}^{n} k_i}. \tag{1}$$

Through the indicators system of EEQ, we can obtain the comprehensive measure ξ by

$$\xi = \sum_{i=1}^{n} \alpha_i x_i. \tag{2}$$

Here x_i are the empirical values of indicators. The comprehensive measure ξ can be used to determine the overall level of EEQ. In this connection, dynamic co-word network provides a new method of EEQA, which yields a new EEQA model. Up to now, after deriving indicators and comprehensive measure for EEQA, a general and rigorous model of EEQA is completely formulated.

Of course, the above technique roadmap of modeling construction is universal. Beyond the case of EEQA, the technique can be widely and conveniently applied to other cases of assessing complex phenomena by our readers.

4. The verifications and applications of the EEQA model

Any models of EEQA will require scientific validation based on the real data in order to judge their advantages and disadvantages in application cases, so that revision and improvement can be made. Here, to check the co-word network model and simultaneously resolve engineering problems, we give some typical application cases of EEQA.

4.1. EEQA of Dushan Town: a case of town

First, Dushan Town is used as a case of town for analysis.

(a) Indicators system of EQ for Dushan Town

Dushan Town is located in Chengxi New District of Ezhou City, China. Dushan town has 68 square kilometers of land area. With 106 villagers' groups and the total population of 32,200, the total area of agricultural land is 2681.5 ha. Since 2005, the fiscal revenue of the town has rapidly increased. With flat terrain, convenient transportation, superior location, it is the developing main town, being a typical case of town. All the nodes and edges connected with the keywords of "ecological environmental quality" are extracted from the co-word network constructed by all keywords of EEQ. We get 482 nodes (keywords) and 524 edges (links between keywords), as in Fig. 4(a). Following the scientific, feasible, simple, independent, complete and accessible principle of indicator selection, we finally get all related indicators for the EEQ of Dushan Town, as shown in Fig. 4(b). Based on Fig. 4(b), by using the clustering and K-core analysis of co-word network, we can get the indicators system of EEQ in Dushan Town, as shown in Table 2. Through the value of the nodal degree, using Eq. (1), we get the weight of each indicator.

- EEQA results of Dushan Town.

Based on the actual data of annual reports from the "Statistical Yearbook of Hubei Province", "Hubei Economic Yearbook", "Yearbook Ezhou", Province Statistical Information Network and other statistical data in 2006, we obtain the standardized data of the determined 21 indicators x_i of EEQ in Dushan Town, as shown in Table 3.

By multiplying the indicator weight α_i and the measured value x_i, the comprehensive measure ξ of the EEQ for Du Town is obtained by Eq. (2). As shown in Fig. 5, the quality of Keying Village is the best, followed by Dushan Village. Both Xudong Village and Xiawang Village have good quality, while the quality of Fandun Village is the weakest. To verify the reliability and accuracy of the assessment results from the co-word network model, we compare the results with those from analytic hierarchy process, principal component analysis and BP artificial neural network models. As shown in Fig. 6, the results of all the assessment models show that the quality of Keying Village is the best, followed by Dushan Village. The results of the co-word network model are similar to those of the AHP model. In general, the results of the co-word network model are reasonable. Of course, there are also some obvious differences in the quality grades of other villages, especially for Xudong Village and Fandun Village. At present, the co-word network model is at its preliminary stage. The weight error (that may usually be caused by the unification of the keywords' format, the combination of the indicators and the obtained empirical data) needs to be further modified.

Table 1
The overall indicators system of EEQ.

Target layer	Standard layer	Factor layer	Micro-indicator layer	Degrees (k_i)
Ecological environmental quality (EEQ)	Human activity indicators	Indoor environmental quality indicators	Thermal comfort: X1	216
			Indoor air quality: X2	192
			Health: X3	127
			Energy efficiency: X4	107
			Temperature: X5	105
			Carbon dioxide: X6	99
			Productivity: X7	88
			Energy consumption: X8	81
			Green building: X9	72
			Noise: X10	66
			Housing: X11	57
			Sick building syndrome: X12	53
			Natural ventilation: X13	51
			Building performance: X14	47
			Schools: X15	46
			Office buildings: X16	35
		Socioeconomic development indicators	Sustainability: X17	385
			Environmental Kuznets curve: X18	177
			Quality of life: X19	150
			Energy: X20	149
			Economic growth: X21	144
			Environmental protection: X22	129
			Public health: X23	94
			Management: X24	90
			Biomass: X25	81
			Urban planning: X26	76
			Renewable energy: X27	66
			Policy: X28	56
			Education: X29	56
			Tourism: X30	54
			Economic development: X31	52
			Trade: X32	48
	Natural environmental indicators	Water resources indicators	Biodiversity: X33	209
			Agriculture: X34	199
			Eutrophication: X35	164
			Land use: X36	163
			Nitrogen: X37	130
			Phosphorus: X38	130
			Nitrate: X39	64
			Runoff: X40	62
			Phytoplankton: X41	49
			Coastal waters: X42	46
			Watershed: X43	45
			Waste water: X44	10
		Soil resource indicators	Pollution: X45	397
			Sediment: X46	270
			Heavy metal: X47	256
			Soil: X48	221
			Pesticides: X49	185
			Water: X50	151
			Toxicity: X51	147
			Surface water: X52	121
			Groundwater: X53	117
			Mercury: X54	113
			Estuary: X55	112
			PAHs: X56	112
			Cadmium: X57	98
			Arsenic: X58	97
			Lead: X59	92
			Copper: X60	85
			Zinc: X61	66
			PCBs: X62	62
			Nickel: X63	48
		Air resources indicators	Air pollution: X64	208
			Particulate matter: X65	47
			Industrialization: X66	44

4.2. EEQA in Tianjin: a case of city

Now we select a case of city for analysis. Situating in the northeast of the North China Plain, Tianjin is the national center city and the largest open coastal city in north China. The terrain is mainly plain. The area of the plain is 11,192.7 square kilometers, accounting for 93% of the total area of the city. Since 1990s, Tianjin has fully been positioned as an international port city, northern economic center and eco-city, being a typical case of city. With Tianjin city as a case, the urban EEQA is here conducted by the co-word network model.

(a) Indicators system of EEQ in Tianjin

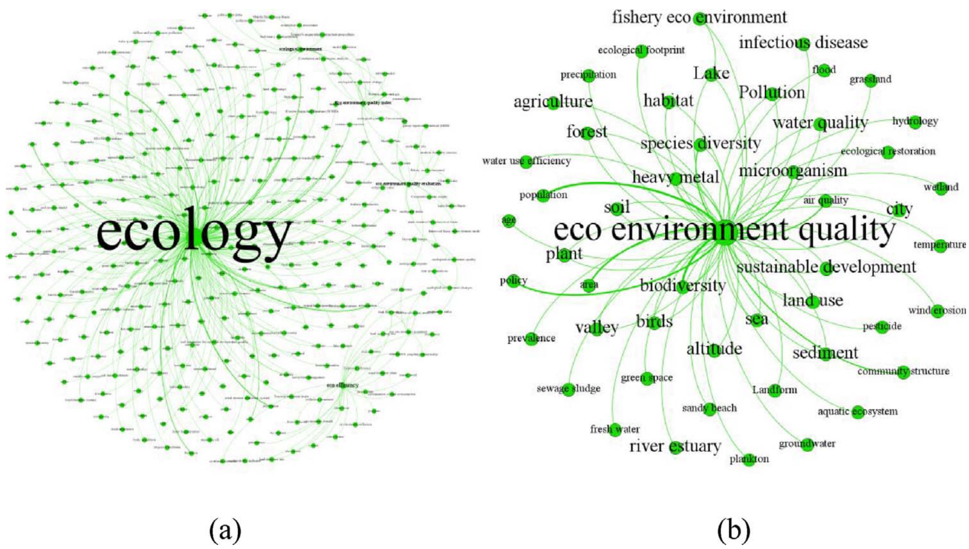


Fig. 4. Indicators system of EEQ from the perspective of ecological aspect.

Construction methods for indicators system of EEQ in Tianjin is: (1) From the co-word network, we extract keywords linked to "urban environmental quality" from all nodes, a total of 55 nodes (keywords) and 68 edges (links between keywords) are obtained as in Fig. 7(a). (2) By culling indicators that do not meet scientific, feasible, simply, independent, complete and accessible standards, we obtain the indicators of the urban EEQ, as shown in Fig. 7(b). (3) By clustering and K-core analysis of the co-word network, we finally obtain the indicators system of EEQ in Tianjin combining with the urban characteristics, as shown in Table 4. In terms of the degree of each node in the co-word network, we also obtain the weight α_i of each indicator by Eq. (1), as listed in Table 4.

- The results of EEQA in Tianjin.

After determining the indicators system of EEQ in Tianjin, to compute the comprehensive measure ξ, we need also the empirical data x_i of indicators. The empirical data is from the "Tianjin City Statistical Yearbook", National Bureau of Statistics, China's economic development statistical database, Tianjin Statistical Information Network, and other statistics. Here we focus on the assessment of five-year (2007–2011). The standardized empirical data is listed in Table 5.

The comprehensive measure ξ of EEQ in Tianjin in 2007–2011 is calculated by Eq. (2) according to the indicator weight α_i in Table 4 and the indicator value x_i in Table 5. As shown in Fig. 8, the value of ξ increases from 0.981 in 2007–1.025 in 2011. The value of ξ is increasing every year, which indicates that the level of EEQ in Tianjin is getting better and better. In order to verify the reliability and accuracy of the results of the co-word network model, the comprehensive measure is compared with the results from the MIE (maximum information entropy) model. The comparisons are shown in Fig. 8. As two different models, the measures of the two models cannot be directly compared. However, the development trends of EEQ deduced from two models are basically same. In specific, from the beginning of 2007, Tianjin's level of EEQ has gradually approached to a good level. Compared with the MIE model and actual situations, we may ensure that the assessment results from the co-word network model are reliable.

4.3. EEQA from the perspective of air: a case of the single factor

Above gives two cases of EEQA by providing the assessment from all aspects of environment. Of course, our model is also applicable to EEQA

Table 2
Indicators system of EEQ for Dushan Town.

Target layer	Standard layer	Factor layer	Micro-indicator layer (unit)	Indicator weight (α_i)
Dushan town's EEQ indicator	Human activity indicators	Indoor environmental quality indicators	Industrial structure: X1	0.054
			Clean energy penetration (%): X2	0.053
			Road accessibility: X3	0.053
			Sound environmental quality: X4	0.046
		Socioeconomic development indicators	Population density (%): X5	0.047
			Education level: X6	0.051
			Income of residents: X7	0.051
			Engel coefficient(%): X8	0.057
	Natural environmental indicators	Water resources indicators	Water resources abundance (%): X9	0.062
			Penetration rate of tap water: X10	0.031
			Domestic sewage treatment rate(%): X11	0.033
			Wastewater discharge intensity: X12	0.041
		Soil resource indicator	Per capita arable land: X13	0.051
			Irrigation guarantee rate (%): X14	0.059
			Domestic waste disposal rate (%): X15	0.028
			Comprehensive utilization of crops: X16	0.025
			Vegetation coverage (%): X17	0.055
			Fertilizer application: X18	0.047
			Pesticide application: X19	0.048
			Biomass (B): X20	0.047
		Air resources indicators	Air pollution indicator (μg/m3): X21	0.061

Table 3
Standardized data of the indicators of EEQ in Dushan Town.

Indicators (x_i)	Donggang Village	Dushan Village	Fandun Village	Keying Village	Lukou Village	Xiawang Village	Xiantai Village	Xudong Village
X1	0.648	0.400	0.515	0.654	0.591	1.000	0.449	0.558
X2	1.000	0.500	0.250	0.583	0.167	0.083	0.167	0.150
X3	0.700	0.800	0.500	0.500	1.000	0.600	0.800	0.900
X4	0.700	0.600	1.000	1.000	0.500	0.800	0.800	0.700
X5	1.000	0.808	0.779	0.891	0.577	0.772	0.602	0.556
X6	0.670	0.890	0.380	0.897	0.430	0.780	1.000	0.670
X7	0.920	0.977	0.856	1.000	0.888	0.966	0.951	0.908
X8	0.670	0.897	0.578	1.000	0.596	0.781	0.678	0.631
X9	0.131	1.000	0.556	0.139	0.280	0.227	0.343	0.368
X10	0.000	0.734	0.000	0.673	0.413	0.000	0.000	1.000
X11	0.400	0.200	0.200	0.600	0.100	0.100	0.800	0.300
X12	0.944	0.556	0.944	0.889	1.000	0.556	0.889	0.667
X13	0.796	0.600	1.000	0.901	0.591	0.745	0.742	0.846
X14	1.000	0.786	0.959	1.000	0.971	1.000	0.887	0.985
X15	0.500	0.500	0.500	0.250	1.000	0.500	0.250	1.000
X16	0.556	0.944	0.889	1.000	0.889	0.889	0.667	0.944
X17	0.071	0.379	0.365	1.000	0.000	0.182	0.033	0.027
X18	0.169	0.143	1.000	0.227	0.148	0.720	0.203	0.788
X19	0.662	1.000	0.764	0.481	0.318	0.474	0.774	0.643
X20	0.175	0.059	0.034	0.188	0.017	1.000	0.535	0.098
X21	0.980	0.940	0.930	0.960	1.000	0.970	0.990	0.980

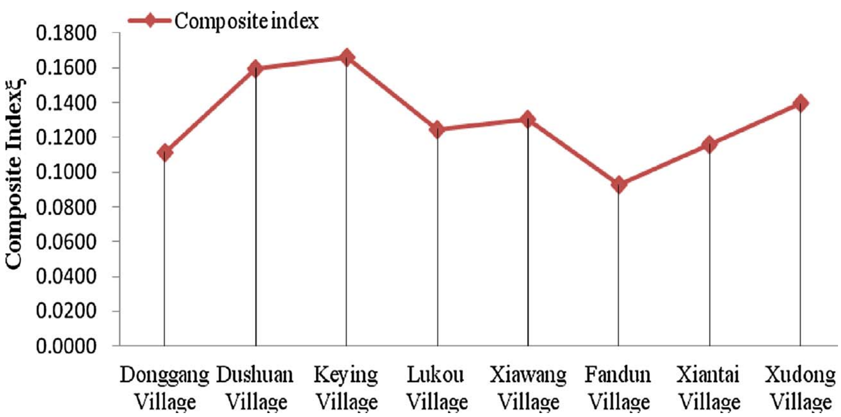


Fig. 5. The results of EEQA of 8 villages in Dushan Town.

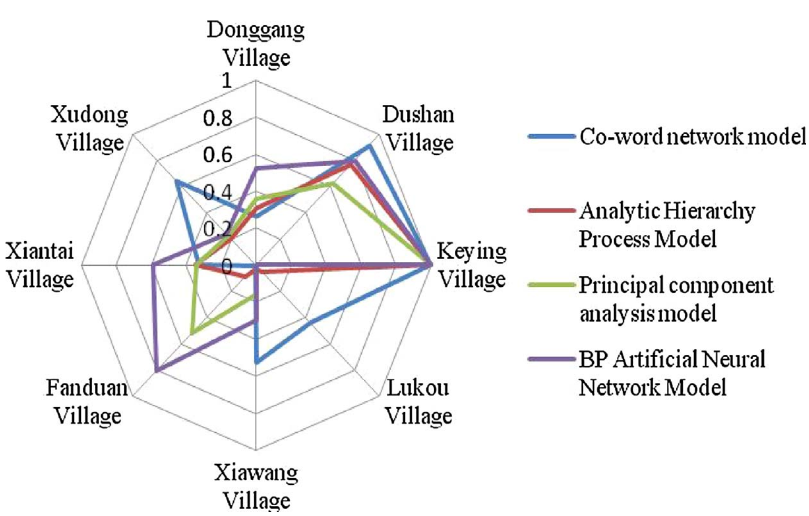
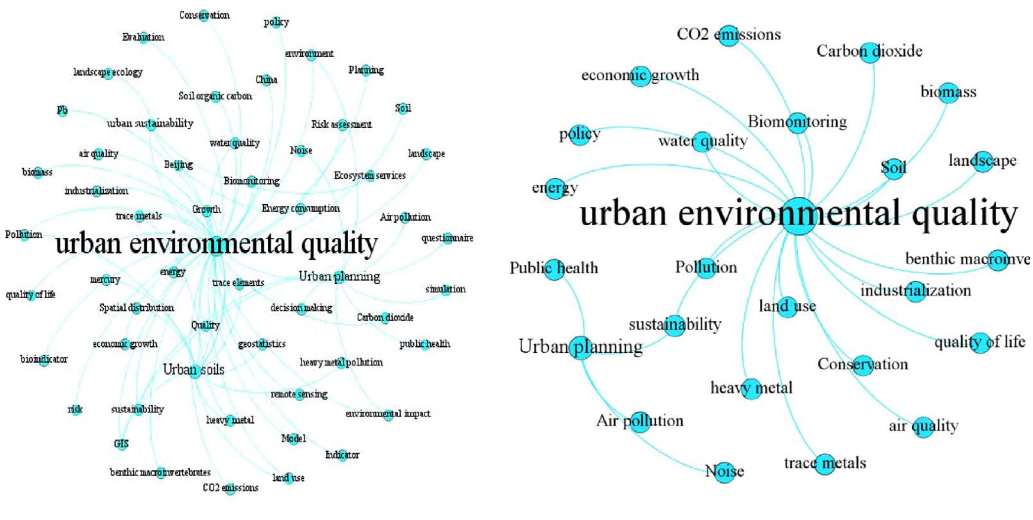


Fig. 6. The comparisons between the co-word network model and other models.

from the single aspect such as air, water, soil and so on. Currently, air quality is one of the most important aspects of EEQ. To timely and accurately denote the EEQ from the perspective of air is very necessary. Here we conduct EEQA from the perspective of air, providing an application case of the single factor in using the model.

(a) The indicators system of air EEQ

To construct the indicators system of air EEQ, as in the previous two cases, we extract the keywords linked to "air quality" from all nodes in the co-word network, as shown in Fig. 9(a). Culling unfit keywords, we finally get a total view of indicators system of air EEQ, as shown in Fig. 9(b), which widely includes 215 indicators such as PM_{10}, allergens, formaldehyde, asthma, ozone, ventilation, acid rain, $PM_{2.5}$, SO_2, ammonia, mercury and so on. Although the indicators we here get are very



(a) (b)

Fig. 7. Indicators system of urban EEQ based on the co-word network.

Table 4
Indicators system of EEQ in Tianjin.

Target layer	Standard layer	Factor layer	Micro-indicator layer (unit)	Indicator weight (α_i)
Tianjing EEQ indicator	Human activity indicators	Indoor environmental quality indicators	Unit GDP energy consumption (tons of standard coal/ million): X1	0.0774
			Mean value of environmental noise in urban area (dB): X2	0.0630
		Socioeconomic development indicators	Engel coefficient (%): X3	0.0048
			Percentage of added value of tertiary industry in GDP (%): X4	0.0019
			Urban per capita housing area (m^2/person): X5	0.0038
			Research and development fund as a percent of GDP (%):X6	0.0048
			Urban per capita disposable income (yuan): X7	0.0029
			Urban − rural income ratio (%):X8	0.0067
			The number of public transport vehicles per 10,000 people in urban areas (units): X9	0.0325
			Investment in public equipment management (billion yuan): X10	0.0048
	Natural environmental indicators	Water resources indicators	Industrial water recycling rate (%): X11	0.0029
			Sewage treatment rate (%): X12	0.0344
			City water quality compliance rate (%): X13	0.5654
		Soil resource indicators	Vegetation coverage (%): X14	0.0067
			Domestic waste treatment rate (%): X15	0.0029
			Industrial solid waste comprehensive utilization rate (%): X16	0.0181
		Air resources indicators	Air quality good days ratio (%): X17	0.1671

Table 5
The data of indicators of EEQ in Tianjin.

Indicator layer	2007	2008	2009	2010	2011
X1	0.840	0.902	1.020	1.032	1.207
X2	0.998	0.998	0.998	1.000	1.004
X3	1.026	0.971	0.992	1.010	1.001
X4	0.960	0.962	1.014	1.029	1.034
X5	1.169	1.041	0.929	0.931	0.931
X6	0.935	1.016	0.976	1.016	1.057
X7	0.755	0.896	0.987	1.121	1.242
X8	1.014	0.963	0.960	0.981	1.082
X9	0.927	1.004	1.025	1.046	0.997
X10	0.358	0.784	1.145	1.372	1.340
X11	1.013	0.977	1.007	1.001	1.001
X12	0.897	0.989	0.990	1.044	1.081
X13	1.000	1.000	1.000	1.000	1.000
X14	0.993	0.993	1.005	1.005	1.005
X15	0.970	0.972	0.980	1.039	1.039
X16	0.999	0.997	0.998	1.000	1.006
X17	1.015	1.021	0.973	0.977	1.015

comprehensive, some indicators and statistics are currently unable to be monitored. Therefore, the indicators system should be further reduced to be able to be obtainable under the real conditions. In this connection, in Tables 6 and 7, for example, the indicators systems of air EEQ for Chongqing 2008–2012 and Beijing on October 23- October 29, 2013 are selected. The empirical data of indicator x_i comes from the monitoring results released by “China Statistical Yearbook” and Beijing Municipal Environmental Protection Monitoring Center. The weights of the indicators are obtained by Eq. (1), as listed in Tables 6 and 7.

- The results of air EEQA.

Basing on x_i and indicator weights α_i listed in Table 6, the level ξ of air EEQ for Chongqing can be obtained by Eq. (2). As shown in Fig. 10, the value of ξ decreases from 0.079 in 2008–0.061 in 2012, which indicates that level of air EEQ in Chongqing is getting better and better. The results from the co-word network model are compared with those from fuzzy comprehensive evaluation and comprehensive pollution indicator evaluation model. As shown in Fig. 10, the development

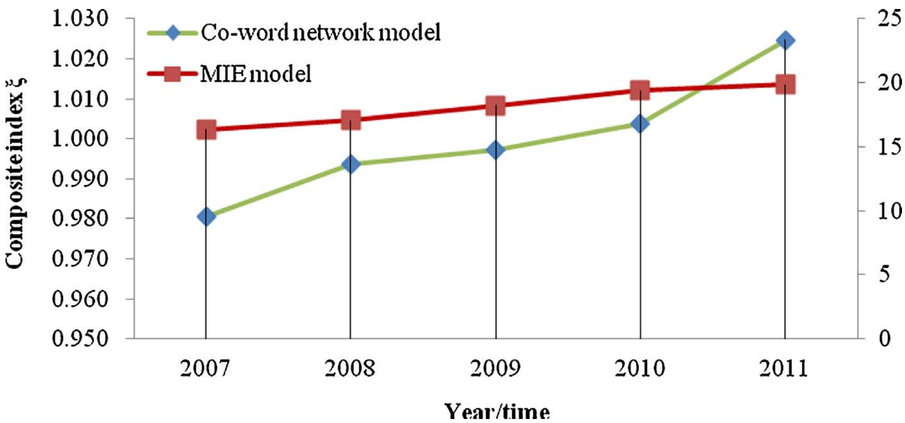


Fig. 8. The comparisons between co-word network model and MIE model for Tianjin.

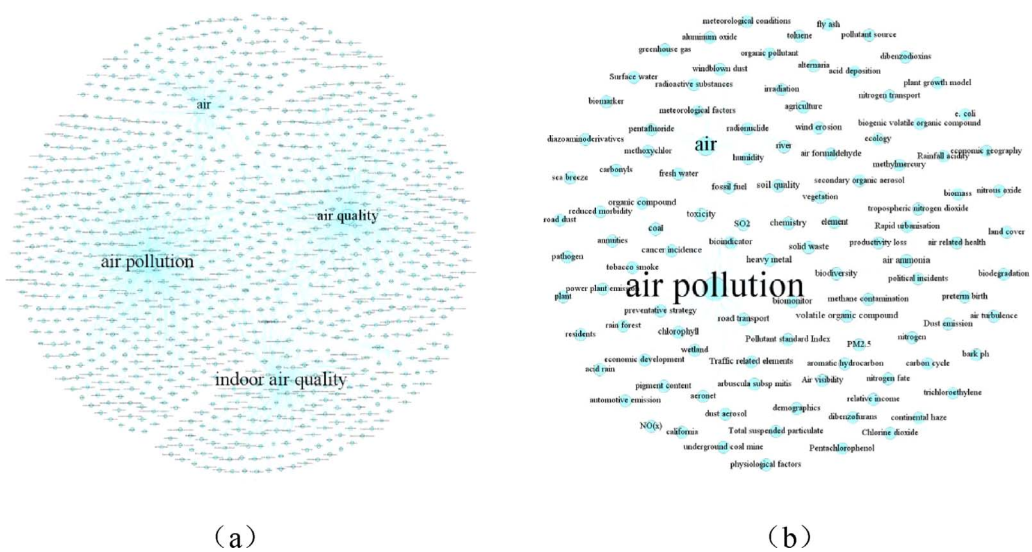


Fig. 9. Indicators system of air EEQ based on co-word network.

Table 6
The indicator data of air EEQ for Chongqing between 2008 and 2012.

Indicator	2008	2009	2010	2011	2012	Weights (α_i)
SO_2	0.063	0.053	0.048	0.038	0.037	0.337
NO_2	0.043	0.037	0.039	0.031	0.035	0.194
PM_{10}	0.106	0.105	0.102	0.093	0.090	0.469

Table 7
The indicator data of air EEQ for Beijing between Oct. 23-Oct. 29 in 2013.

Time	$PM_{2.5}$	PM_{10}	SO_2	NO_2	O_3	CO
2013 – 10-23	0.238	0.216	0.040	0.196	0.187	0.122
2013 – 10-24	0.190	0.127	0.029	0.146	0.345	0.162
2013 – 10-25	0.244	0.159	0.033	0.232	0.220	0.111
2013 – 10-26	0.272	0.142	0.034	0.330	0.147	0.075
2013 – 10-27	0.420	0.192	0.035	0.220	0.035	0.099
2013 – 10-28	0.468	0.195	0.034	0.158	0.067	0.078
2013 – 10-29	0.318	0.151	0.038	0.231	0.120	0.142
Weights (α_i)	0.201	0.231	0.166	0.095	0.216	0.090

trends of air EEQ shown by ξ values of the different composite measures are basically same. From the beginning of 2008, the level ξ of air EEQ in Chongqing is gradually approaching to a good direction. The comparisons with other models provide a good check for the co-word network model.

The level of air EEQ in Beijing from October 23 to October 29 in 2013 is shown in Fig. 11. Our composite measure ξ value reaches a peak on October 28, and October 26 is the lowest point, which indicates that the level of air EEQ at October 26 is relatively good and October 28 is relatively poor in the week. We compare our results with those from fuzzy comprehensive evaluation, as shown in Fig. 11, both basically showing the same development trends, except that the results of fuzzy comprehensive evaluation for October 23 to October 26 almost keep no changes. We may draw the results of the co-word network model are relatively more reasonable.

4.4. The future applications of EEQA

Ecological environmental systems are typical open complex systems made of multifaceted agents and are affected by multiple factors from physics, chemistry, biology, economy and society. EEQA can give a general evaluation model. By reasonably simplifying ecological environmental systems as networks made of agents x_i. Then we have a reasonable structural parameter ξ for specific ecological environmental systems. By numerically resolving Eq. (2), we can assess the evolutionary structural feature and interactions between the agents for specific ecological environmental systems. Some instructions on regulation or prediction of agents' behaviors can be provided, which can further guide us to make a decision related to policies, legislation, etc. EEQA provides an opportunity for ecological environmental management.

In fact, EEQA can find much wider applications for ecological environmental systems. For example, after we obtain the dynamic structural results of ecological environmental systems, i.e., the variations of ξ with the behaviors of the agents x_i (the correlation between ξ and x_i). In term of the expected x value, and the values of the agents can then be

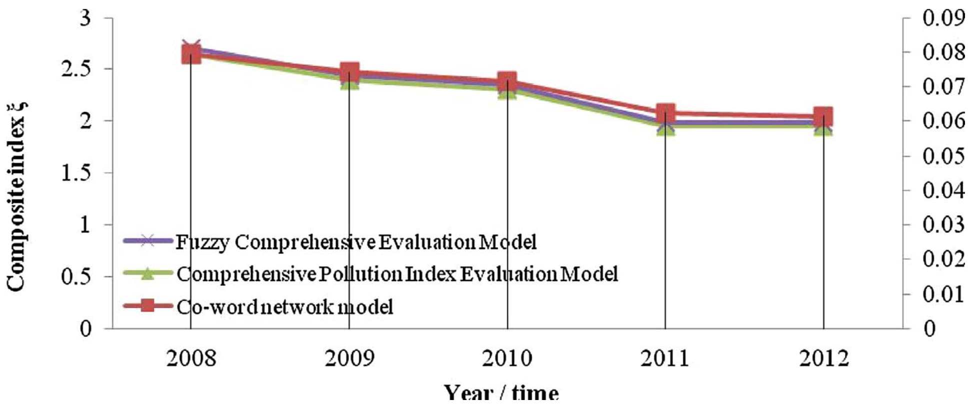


Fig. 10. The comparisons of the co-word network model and other models for air EEQ in Chongqing from 2008 to 2012.

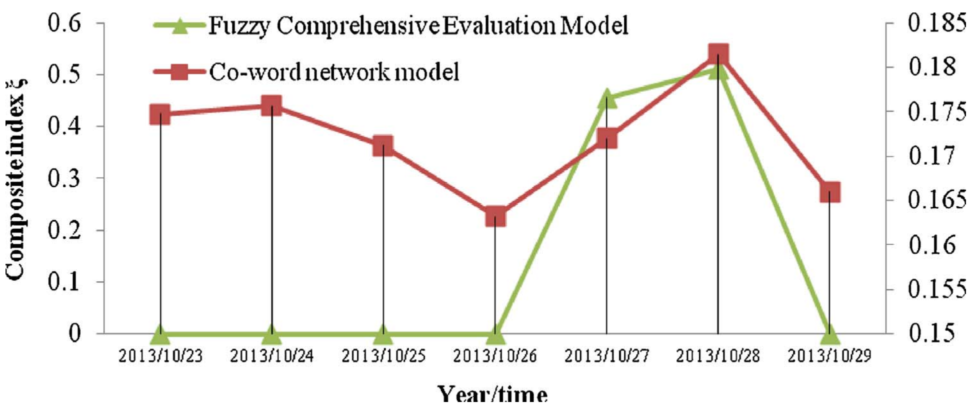


Fig. 11. The comparison between co-word network model and fuzzy comprehensive assessment model for Beijing.

predicted according to the corresponding ξ-x_i. The prediction of agents' behavior is important for us to make a decision in ecological environmental engineering. In this connection, EEQA is operational in predicting or managing some aspects of our ecological environmental systems.

In a word, EEQA model has provided a renewed perspective on the application of managing our ecological environmental systems. Though the present analyses are still preliminary, we hope they would act as catalysis for the further application research in the future in both ecological environmental systems and other complex systems.

5. Conclusions

For the first time, basing on the facts that the key indicators of EEQ from the experts' selections are hidden in and improved by the constantly additions of new publications, we verify that the indicators system can be emerged from the dynamic co-word network of knowledge system. Founding upon the new approach of deriving indicators and comprehensive measure for EEQA, a rigorous theoretical model (i.e., co-word network model) of EEQA is proposed. By the detailed analyses, the main conclusions can be summarized as follows.

(1) Through the visualized dynamic co-word network for EEQ, we find that the key indications of EEQA such as pollution, heavy metal, model, sediment, management, water quality, soil, influence, health, economy, policy and emission are emerged from the experts' continuous publications on EEQ by a self-organized process.
(2) The Fast Unfolding algorithm is invoked to cluster the domains of the co-word network. Five aspects of indicators are recognized, namely soil quality, sustainable development, water quality, indoor environmental quality and air quality, which provide the underlying structure for the indicators of EEQA and facilitate the indicator construction of EEQA.
(3) By invoking the K-core analysis, four levels of indicators for EEQA are deduced. In terms of the similarity or relatedness between the indicators in the co-word network, we propose the concept of nodal degrees to describe the indicators' weights and deduce the comprehensive measure ξ for EEQA, finally forming a rigorous theoretical model of EEQA (i.e., co-word network model).
(4) The model is applied to EEQA of Dushan Town. We compare the assessment results with those from analytic hierarchy process, principal component analysis and BP artificial neural network models. In general, ignoring the weight error caused by the unification of the keywords' format and the combination of the indicators, the assessment results from the co-word network model are reasonable.
(5) With Tianjin city as a case, the urban EEQA is conducted by the model. The increasing values of the comprehensive measure ξ indicate that the level of EEQ in Tianjin is getting better and better. By comparing the comprehensive measure with the results obtained by the MIE model and actual monitoring, the assessment results from our model are verified to be reliable.
(6) The cases of air EEQA for Chongqing and Beijing are analyzed. The results from our model are compared with those from fuzzy comprehensive evaluation and comprehensive pollution indicator evaluation models. It is found the assessment results of the co-word network model are relatively more reasonable.

The co-word network model of EEQA is a potential function derived from traditional co-word methods of bibliometrics. As a new method with rigorous theoretical foundations, the co-word network model can build objective indicators system of EEQ and directly yield accurate indicators' weights, and obtain reliable comprehensive measure of EEQA. Beyond the EEQA we here provide as a specific case, the new model, which gives an universal approach of deriving indicators and comprehensive measure for any subjects, has universal merits. By opening a corner of an iceberg, we wish our present modeling construction roadmap and operational applications, which can be widely and conveniently used to assess many other complex phenomena, could act as catalysis for further promising research from our readers in the future.

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