The Evaluation and Prediction of Urban Ecological Security: a Case Study of Dongguan, China

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Abstract. A rational evaluation of the current impacts of urban industries is a prerequisite for their transformation and upgradation. Integrating the classical pressure-state-response (PSR) framework with the technology-resource-environment (TRE) perspective, we constructed a PSR-TRE urban ecological security index system for this study. Using the weights of different indicators for information entropy, we applied the weighted sum method to calculate a comprehensive urban ecological security index for Dongguan. We subsequently formulated five categories for assessing the security levels of the urban ecology. We also established a learning vector quantization neural network model to predict levels of urban ecological security in Dongguan under different scenarios. The results indicated that the urban ecological security level for Dongguan gradually increased during the period 1999–2015, showing the following progression: critically safe → relatively safe → safe. To a certain extent, this transformation indirectly reflects a successful process of industrial transformation and upgradation in Dongguan. We recommend a continued managerial emphasis on industrial transformation and upgradation within urban development planning. Moreover, reasonable guarantees should be provided to ensure the smooth progress of industrial upgrading.

1. Introduction

Industrial upgradation constitutes the foundation of eco-city construction [1], promoting mutual and coordinated development of the three pillars of the economy, society, and environment. It leads to improved efficiency of production and the advancement of the social economy, while simultaneously contributing to a reduction of pollutant emissions and the protection of the eco-environment. The impacts of industrial transformation and upgrading are thus manifold. However, there is still a lack of scientific evaluation of industrial transformation and upgrading, while most of studies focus on the necessity of industry transformation, the advantages and obstacles, the thinking and countermeasures, and the mode of transformation [2]. We believe that given its comprehensive characteristics, ecological security can serve as an evaluation tool for assessing the security of industrial transformation and upgradation. Ecological security refers to a state in which people do not experience any threats relating to their lives, health, basic rights, and sources of life security. Moreover, in this state, there is an absence of threats to necessary resources, the social order, and

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societal adaptation to environmental changes. Thus, ecological security reflects the overall level of ecosystem integrity and health [3]. Existing studies on ecological security have focused mainly on the construction of index systems [4-5] for evaluating ecological security, evaluations of the eco-environment (e.g., sensitivity assessment, vulnerability assessment and quality evaluation), assessments of ecosystem health (e.g., structural and functional evaluations, stability and sustainable evaluation) [6], as well as evaluation of ecological service functions and ecological risks [7].

As ecological systems with high population densities, urban ecosystems are particularly vulnerable in terms of their security [8]. Security in the context of urban ecological systems means that the environment and resources of an urban area can meet the requirements for sustainable development of the associated human society and economy. Moreover, in a secure urban ecological system, the eco-environment is not threatened, or is not seriously threatened, by economic and social adjustments implemented within it [9]. Most of the existing studies conducted on urban ecological security have focused on overall evaluations of urban ecological security [10], applying evaluation models and index systems relating to urban ecological security. Prevailing research methods for assessing urban ecological security, such as the fuzzy comprehensive method [11], system dynamics, the ecological footprint method, and the landscape pattern method have entailed largely static evaluations, evidencing some limitations in their ability to make predictions. A more accurate method of predicting early warning analysis entails modifying the learning vector quantization (LVQ) neural network method [12] by incorporating self-learning interactions between neurons and the outside world, which allows for nonlinear correlations between the indexes [13].

2. Research method

2.1. Construction of the index system

Table 1. Urban ecological security indicators.

Objective	Item	Factor	Index		
			Evaluation Indicator	Unit	Direction
Urban ecological security	Pressure	Technology pressure	Pt_1/ Non-high-tech enterprises account for the total number of enterprises	%	-
		Resources pressure	Pr_1/Population density	10^4 /km^2	-
			Pr_2/Annual precipitation	mm	+
			Pr_3/Land area per capita in a built-up area	10^4 /km^2	-
		Environment pressure	Pe_1/Industrial output value of industrial waste water per 10,000 yuan	t/10^4 yuan	-
			Pe_2/Emission of industrial waste residue per 10,000 yuan	t/10^4 yuan	-
			Pe_3/Industrial waste gas emission per 10,000 yuan of industrial output	m^3/yuan	-
	State	Technology state	St_1/Education and health expenditure accounting for a proportion of fiscal	%	+
			St_2/The total output value of new and advanced technology	10^8yuan	+
		Resources state	Sr_1/Rate of green coverage of the built-up area	%	+
			Sr_2/Forest coverage	%	+
		Environment state	Se_1/ Acid rain frequency	%	-
	Response	Technology response	R_{t1}/Tertiary industry accounting for a proportion of the GDP	%	+
			Rt_2/Research and development expenditure	10^4yuan	+
			Rt_3/Investment ratio in scientific research and in a technology service industry	%	+
		Resources response	Rr_1/Park area	m^2	+
		Environment response	Re_1/The comprehensive utilization rate of industrial solid waste	%	+
			Re_2/Standard rate of automobile exhaust emissions	%	+

We constructed the framework of a PSR evaluation index system, which was then divided into three sets of factors relating respectively to technology, resources, and the environment. Thus, we created a PSR-TRE urban ecological security assessment system comprising 18 indexes, as shown in Table 1.

2.2. Calculation of the urban ecological security index

Standardization of the index: To eliminate differences within each evaluation index unit, and in the levels and nature of their quantities, it was necessary to standardize the data.

For positive indicators: $$y_{ij} = \frac{x_{ij}}{x_{\max}} \tag{1}$$

For negative indicators: $$y_{ij} = \frac{x_{\min}}{x_{ij}} \tag{2}$$

In the above formulas, x_{ij} denotes the original value of j index in i year, x_{max} denotes the maximum value in m year, x_{min} denotes the minimum value in m year, and y_{ij} denotes the standard value after y_{ij}.

To determine the weight of the indicator, we applied the entropy weight method. We first calculated the entropy value of the e_j index as follows:

$$e_j = -k\sum_{i=1}^{m} y_{ij} \ln y_{ij} \tag{3}$$

where K = 1/lnm and y_{ij} denotes a standardized indicator data. The weight of index J was calculated as follows:

$$w_j = \frac{d_j}{\sum_{j=1}^{n} d_j} \tag{4}$$

In the above formula, $d_j = 1-e_j$ denotes the difference coefficient of the index y_j. A reduction in entropy corresponds to the increasing difference and importance of the index.

Exponential computation based on the weighted summation method: The weighted summation method is widely used in ecological security assessments. The computation is performed as follows:

$$A = \sum_{j=i}^{n} w_j y_{ij} \tag{5}$$

Where y_{ij} denotes the value of the i year j index, w_j denotes the weight value of the j index, and n denotes the index number. To obtain the comprehensive contribution value of n, the contribution value of $w_j y_{ij}$ to the ecological security index is added to the sum of any n items. A higher composite index of the comprehensive index calculation and evaluation corresponds to a higher security level.

2.3. Determination of the level of urban ecological security

Considering the influence of various factors, and referring to previous research findings [14], we designed a 5-level classification system comprising the following categories: quite unsafe, unsafe, critically safe, relatively safe and safe, as shown in Table 2:

Table 2. Urban ecological security classification system.

Comprehensive coefficient	< 0.25	0.25–0.40	0.40–0.60	0.60–0.75	> 0.75
Security description	quite unsafe	unsafe	critically safe	relatively safe	safe
Security level	1	2	3	4	5

2.4. Construction of a learning vector quantization neural network

Basic principles of LVQ neural networks: The LVQ neural network comprises an input layer, a hidden layer, and an output layer. These three layers are closely connected, with each neuron in the output layer connected to neurons from different groups in the hidden layer. The connection weights between the neurons in the hidden layer and those in the output layer are fixed at a value of 1. In the course of network training, the weights between neurons in the input and hidden layers are modified. When an input pattern is incorporated into the network, neurons within the latent layer in the closest mode win the competition because of the excitation, thus prompting their production of a value of 1, whereas the other neurons that are suppressed are forced to produce a value of 0. The neurons in the output layer that are connected to the neurons in the hidden layer containing the winning neurons also produce a value of one, whereas other neurons in the output layer produce a value of 0.

Neural network algorithm of LVQ: The basic steps for performing the LVQ algorithm are as follows:

(1) Network initialization: The initial value of weights between the input and hidden layers is set as a small random number.

(2) Addition of vector input: The input vector $x = [x_1, x_2, x_3, \ldots, x_n]^T$ is added to the input layer.

(3) The distance between the weighted vector in the hidden layer and the input vector is calculated from the neurons in the hidden and the input vector, which is the same as the self-organization mapping:

$$d_j = \sqrt{\sum_{i=1}^{n} (x_i - w_{ij})^2} \tag{6}$$

(4) Selection of the neurons closest to the weighted vector: The smallest neurons in the input and weighted vectors are computed and selected as the winning neurons, recorded as j*.

(5) Updating of the connection weight: If the winning neuron is consistent with a predetermined classification, called the correct classification, this is called an incorrect classification. The correct and incorrect classifications of the weight of the adjustment are obtained using the following formula:

$$\Delta w_{ij} = \begin{cases} +\eta(x_i - w_{ij}) \\ -\eta(x_i - w_{ij}) \end{cases} \tag{7}$$

(6) To determine whether the maximum number of iterations meets the preset, when the algorithm is completed, or return steps (2), into the next round of learning.

Construction of an urban ecological security LVQ model: The LVQ neural network method is an effective method for predicting urban ecological security. The procedure for predicting urban ecological security using this model comprises two steps as follows. In the first step, some index data are randomly extracted as training samples, and the remaining samples are tested to verify the accuracy of the model. In the second step, the index data for each year of the study period are used as training samples to predict the result.

2.5. LVQ neural network prediction

Network training: After creating the neural network, we set up its training parameters at 1,000 times. The training target was 0.05 and the learning rate was 0.01. The data input network was randomly selected from all of the samples during the study period as samples for training the network. The network input was the index value of the sample in the city, and the network output was a sample of the urban ecological security grade. The five urban ecological security grades numbered 1, 2, 3, 4, and 5 corresponded respectively to the following categories: extremely quite unsafe, unsafe, critically safe, relatively safe, and safe.

Detection of the LVQ neural network: After the network training was completed, the remaining samples were used as simulation test samples, and the simulated test was performed within a trained neural network to obtain the actual output security level of the samples. Because each operation entailed re-establishing a neural network, the accuracy varied for each one. To reduce errors and avoid contingency, the average number of run verifications was applied in this study.

3. Results and discussion

3.1. Changes in ecological security during the process of industrial transformation and upgradation in Dongguan

Table 3 and Figure 1 show changes in the levels of ecological security in Dongguan during the period 1999—2015. The values indicate a gradual increase in Dongguan's ecological security from critical safe to relative safe and finally safe during the respective periods 1999–2006, 2007–2011, and 2012–2015.

Table 3. Urban ecological security values for Dongguan during the period 1999–2015.

Year	1999	2000	2001	2002	2003	2004	2005	2006	2007
Security value	0.479	0.475	0.488	0.496	0.495	0.459	0.514	0.553	0.606
Year	2008	2009	2010	2011	2012	2013	2014	2015	
Security value	0.653	0.642	0.688	0.653	0.698	0.755	0.785	0.910	

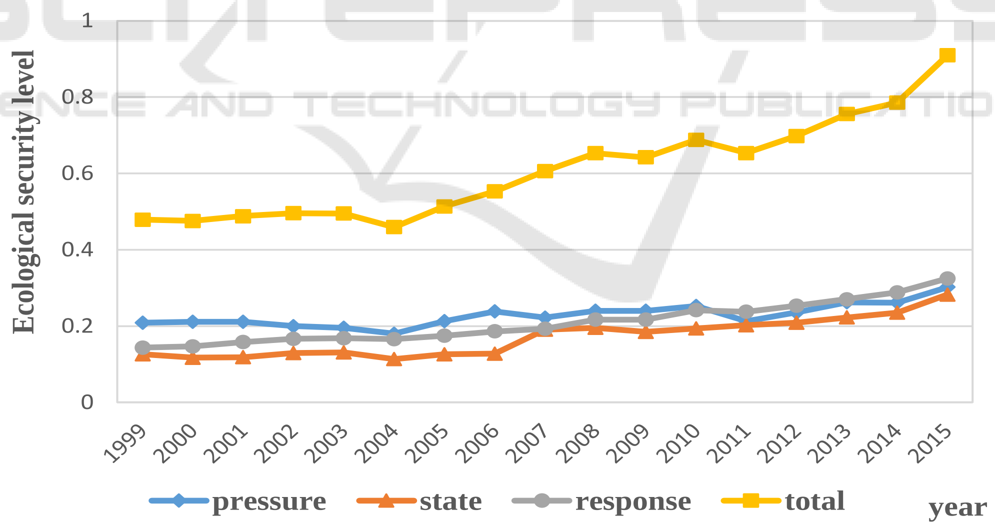

Figure 1. Changes in the ecological security level for Dongguan during the period 1999–2015.

3.2. Analysis of bottleneck factors constraining Dongguan's ecological security

Pressure layer: As shown in Figure 2, the indicators with the most impact on the pressure layer were the industrial production value per 10,000 yuan industrial waste, waste water, and exhaust gas. Although emissions of pollutants in Dongguan have been reduced, the government should pay attention to the environmental pressure layer, continuing to make efforts to reduce industrial waste residues, waste water, and the exhaust emission index value of every million industrial output value.

Moreover, alternatives to the "three high" enterprises should be sought and efforts should be made to improve production efficiency.

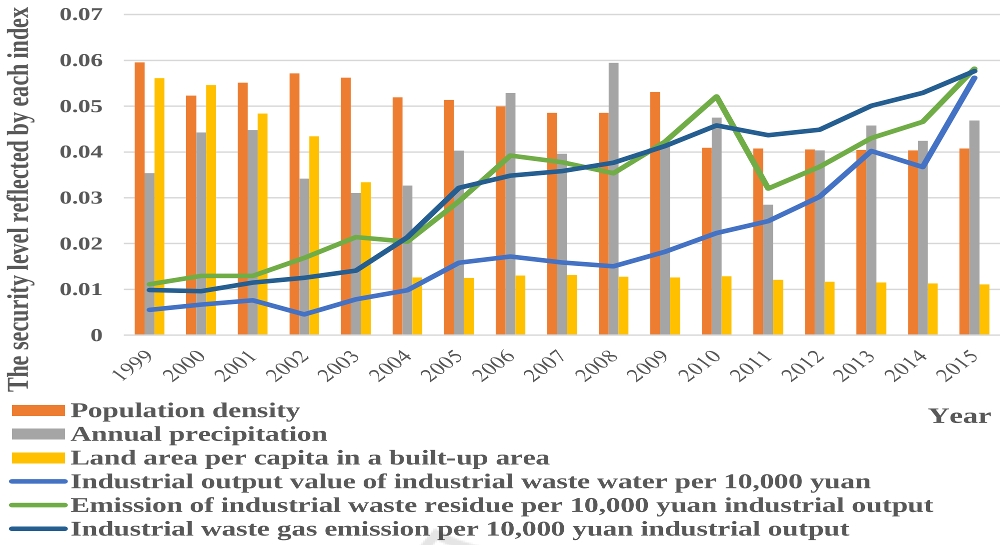

Figure 2. The security level reflected by each index at the pressure layer.

State layer: As shown in Figure 3 shows, the two index levels of education and health expenditure accounting for a proportion of fiscal, accounted for the total output value of new and advanced technology were relatively high and on the rise in terms of their technical status, with small fluctuations evident during the middle period. Therefore, the focus should be on the technical state layer, with supplementary efforts made to improve the resource state layer. Investments in science and education should continue to increase, and the urban area's core creation level should be increased.

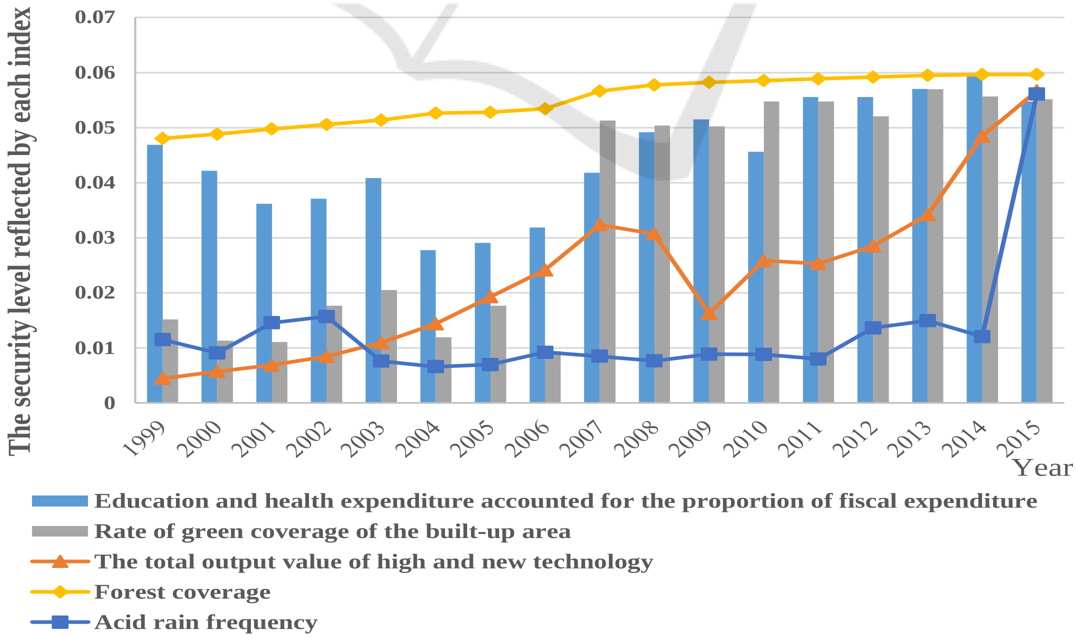

Figure 3. The security level reflected by each index at the state layer.

Response layer: As Figure 4 shows, the park area, research and development expenditure and investment ratio in scientific research and in a technology service industry are the main influencing factors. The government should provide strong support for the development of scientific research projects and increased investments in scientific research to further promote the transformation of industry in a positive direction. Simultaneously, more parks should be created to provide more recreational venues for the public, while improving the environment and reducing ecological risks.

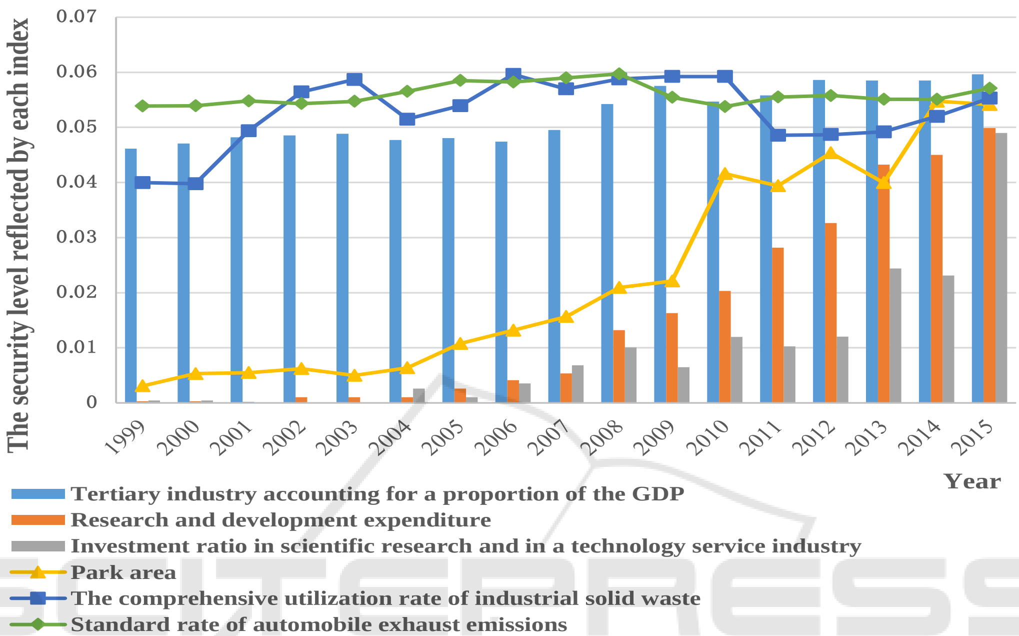

Figure 4. The security level reflected by each index at the response layer.

3.3. Analysis of LVQ prediction results in 2020

As shown in Table 4, the index data inputted into the LVQ model for each scenario was derived from the corresponding security level.

Table 4. Prediction results obtained with the learning vector quantization model in 2020.

Scenario levels	Basis of scenario setting		Security level
Low	Failed mode of industrial transformation	The industrial development pattern is still extensive, resource consumption and the intensity of pollutant emissions are high, and other industries have reached the anticipated targets	Safe
	Failed mode of industrial upgrading	High-end industries have suffered setbacks. The development of high-tech industries is not ideal, with other aspects having reached the anticipated targets	Relatively safe
	Mode of environmental protection missing	Industrial transformation and upgradation have been implemented to achieve the anticipated goals. However, necessary policies on environmental protection have been neglected and are not in place.	Safe
Normal	Industrial transformation and upgradation have been implemented to achieve the desired goal. A variety of implemented policies are relatively established, producing enhanced results		Safe
High	Industrial transformation and upgradation are highly successful. Various countermeasures have been implemented and are established with outstanding results.		Safe

From the prediction results shown in Table 4, it can be seen that the security levels for the outcomes of the normal and high-level scenarios in 2020 are categorized as safe. In 2015, the ecology of Dongguan was categorized as safe. For the low-level scenarios in 2020, only the scenario entailing the failure of industrial upgradation was associated with a decline in the security level of the urban ecology, with the scenario outcomes for failed industrial transformation and failed environmental protection both remaining safe. In the absence of environment protection, environmental pollution at the source is greatly reduced by the rational industrial structure and fine industry. This compensates for the government's unfavorable policy-related influence on environmental protection. The situation regarding industrial upgradation is directly related to urban ecological security for all aspects of the impacts of various factors. Consequently when formulating urban development plans, the government should focus on the situation regarding industrial upgradation and develop a mechanism for achieving rational industrial upgradation and environmental protection.

4. Conclusions

It is necessary to comprehensively evaluate the effect of urban industrial transformation and upgrading after a few decades' implementation. Considering the fact that there is a lack of scientific evaluation method for industrial transformation, we introduced ecological security in this paper as an useful evaluation tool.

Taking Dongguan as a case study, we first proposed a new PSR-TRE evaluation index system using the weighted summation method to calculate and analyze changes in the urban ecology's security levels associated with the process of transforming and upgrading Dongguan's industry. Moreover, we applied the LVQ neural network method with self-learning ability to predict the change trend of Dongguan's urban ecological security for better planning in the future. The results of the analysis indicated that the level of ecological security in Dongguan rose gradually during the period 1999–2015, progressing from critically safe to relatively safe and then to safe. This progression to some extent reflects the success of Dongguan's industrial transformation and upgradation process. The prediction results revealed that the urban ecological security levels for all of the scenarios were categorized as safe, with only one scenario entailing failure of industrial upgradation being categorized as relatively safe.

Although ecological security provides a helpful evaluation tool of urban industrial transformation, a lot of improvement can be conducted in the future, especially considering the underlying uncertainties caused by the limitations of data quality, determined weights of each index, and the grading standards of security levels.

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