Urban Ecological Security Measure Model and its Application based on Symbiosis Theory

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ABSTRACT

The calculation and prediction of urban ecological security have a great significance to a city’s sustainable development. So this paper constructs the socioeconomic-natural L-V symbiosis mode in the basis of the Lotka-Volterra symbiosis model. Through analyzing the coefficient of the competition and cooperation in the model, we divide the urban ecological security into five regions: healthy region, sub-healthy region, risky region, high risky region and dangerous region. Then we predict the future ecological security of the city by solving the stable equilibrium point of the model. Finally, in order to evaluate the model’s practical significance, it is used to measure the ecological security of Xi’an, and the final result is in line with the reality of Xi’an.

INTRODUCTION

With the increasing development of economy and society, the disturbance and damage to the ecological environment become more and more serious. Therefore, the ecological problems are becoming more and more prominent, especially the urban ecological problems, which has already attracted widespread attention. In view of this, it is very important to carry on the research about the urban ecological security.

The International Institute for Applied Systems Analysis (IIASA) puts forward the concept of the ecological security, it’s a state expression that is not threatened in terms of human life, health, basic rights, living security, necessary resources, social order and human capacity to adapt to environmental change. In a word, the ecological security is a composite system and composed of natural ecological security, economic ecological security and social ecological security.¹ There are

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many scholars has already carried on the research about the urban ecological security. Li Hui\cite{2}, Guo Min\cite{3}, Zheng Xiaomei\cite{4} and other scholars, establish the PSR model built on the city ecological security index system and obtained the unfavorable factors that influence the urban ecological security. Huang Peng and some other scholars\cite{5} evaluated the ecological security of Longyan city based on the E-E-S synergetic model. Qin Xiaonan\cite{6} constructed coastal ecological security evaluation index system in the basis of the DPSIR model, and used DEMATEL to analyze influencing factors of ecological security system of coastal city. The above studies only make a rough evaluation to urban ecological security, and do not accurately measure the specific situation of ecological security, nor can it predict the future ecological security. In view of these, this paper constructs the socioeconomic-natural L-V symbiosis model based on the symbiotic theory, analyzing the relationship of competition and cooperation between the socioeconomic subsystems and the natural ecological subsystems to judge the specific situation of urban ecological security. Meanwhile, according to the stability condition of the model, predicting the future ecological security status of the city through solving the equilibrium point of the system stability.

**SOCIOECONOMIC-NATURAL L-V SYMBIOSIS MODEL CONSTRUCTION AND ANALYSIS**

**Socioeconomic-Natural L - V Symbiotic Model Construction**

According to the L-V model principle\cite{7,8} and the above analysis, in the ecological composite system, the socioeconomic subsystem and the natural subsystem could inhabit each other by competition, but also promote each other by symbiosis. The socioeconomic-natural symbiosis model can be expressed by the following formula:

\[
\frac{dF(t)}{dt} = r_F F(t) \frac{C - F(t) - (\alpha_{12} - \beta_{12})E(t)}{C} \tag{1}
\]

\[
\frac{dE(t)}{dt} = r_E E(t) \frac{C - E(t) - (\alpha_{21} - \beta_{21})F(t)}{C} \tag{2}
\]

In the formula, \(F(t)\) is the index of the socioeconomic subsystem development level. \(E(t)\) is the ecological level index of the natural environment subsystem. \(C\) is the environmental capacity index of natural resources. \(r(F)\) is the growth rate of socioeconomic development level. \(r(E)\) is the growth rate of natural environment ecological level. \(\alpha_{12}\) is the competition coefficient of natural environment to social economy. \(\alpha_{21}\) is the competition coefficient of social economy to natural environment. \(\beta_{12}\) is the cooperation coefficient of natural environment to social economy. \(\beta_{21}\) is the cooperation coefficient of social economy to natural environment. \(t\) is the time variable.

**Urban Ecological Security Judgment Basis Bases on L-V Model**

The more stable of the urban socioeconomic-natural ecosystem, the more secure of the city's ecology. In order to better determine the city's ecological security situation, we analyze the stability of the social economy and natural L-V
model. The stable conditions of the urban socioeconomic-natural composite system are \( \frac{dE(t)}{dt} = 0 \) and \( \frac{dF(t)}{dt} = 0 \), and then we can get four equilibrium points, that is \( A_1(0,0), A_2(0,C), A_4(C,0) \) and \( A_4(\frac{c-(\alpha_{21}-\beta_{12})c}{1-(\alpha_{21}-\beta_{12})(\alpha_{12}-\beta_{21})}, \frac{c-(\alpha_{12}-\beta_{21})c}{1-(\alpha_{12}-\beta_{21})(\alpha_{21}-\beta_{12})}) \) (In order to simplify the demonstration, we make the \( G_1 \) and \( G_2 \) represent \( 12 \) and \( 21 \) separately). By analyzing the relationship between the two coefficient and equilibrium point, we can obtain the city’s ecological security as follows (during the process, we regard the promotion effect as positive effect and inhibition effect as negative effect):

1. When \( \alpha_{12}-\beta_{12}<0, \alpha_{21}-\beta_{21}<0 \), the two subsystems have positive effect on each other, the two subsystems promote and develop commonly, forming a win-win situation. Here, the ecological system’s equilibrium point is \( A_1 \). ① When \( (\alpha_{12}-\beta_{12})(\alpha_{21}-\beta_{21})<1 \), then \( G_1>0, G_2>0 \), it means that the interaction between the two subsystems make them both increased their possessing natural resources. ② When \( (\alpha_{12}-\beta_{12})(\alpha_{21}-\beta_{21})>1 \), then \( G_1<0, G_2<0 \), they are both less than 0, so it especially means that socioeconomic subsystem and natural subsystem expand \( |G_1| \) and \( |G_2| \) separately on the basis of the original environmental capacity \( C \). It is a mutualistic state; the corresponding urban ecological security belongs to healthy region.

2. When \( \alpha_{12}-\beta_{12}<0 \) and \( \alpha_{21}-\beta_{21}=0 \), the natural subsystem has a greater positive effect on socioeconomic subsystem than the negative, the socioeconomic subsystem’s positive effect to natural subsystem offset the negative effect. So the socioeconomic subsystem gets developed but the natural subsystem has not changed. Here, \( A_4 \) is also the equilibrium point. Due to \( G_1>0, G_2=0 \), the socioeconomic subsystems has expanded their space for natural resources, the natural environment subsystem’s possessing natural resource has no change, therefore forming a state of commensalism (social economy profits, nature changes), the corresponding the urban ecological security belongs to sub-health zone.

3. When \( \alpha_{12}-\beta_{12}<0, \alpha_{12}-\beta_{21}>0 \), the natural subsystem has a greater positive effect on the socioeconomic subsystem, whereas to the natural subsystem, the socioeconomic subsystem’s negative effect dominates, the equilibrium point is \( A_4 \). Moreover, ① If \( 0<\alpha_{21}-\beta_{21}<1 \), then \( G_1>0, 0<G_2<0 \), it means that the socioeconomic subsystem expands the space, while the socioeconomic subsystem contracts. ② If \( \alpha_{21}-\beta_{21}>1 \), then equilibrium point will move to \( A_4(C,0) \), implying that the development of social economy will eventually make the natural subsystem disappear. The urban ecological security belongs to risky region. Conversely, when \( \alpha_{12}-\beta_{12}>0, \alpha_{21}-\beta_{21}<0 \), the ultimate equilibrium point is \( A_4(0,C) \), forming single-hazarded state (single-benefited). The urban ecological security also belongs to the risky zone.

4. When \( \alpha_{12}-\beta_{12}>0 \) and \( \alpha_{21}-\beta_{21}=0 \), the natural subsystem has a greater
negative effect on the socioeconomic subsystem, but the socioeconomic has no
effect on the natural, the initial equilibrium point is \( A_i \). ① If \( 0 < \alpha_{12} - \beta_{12} < 1 \), then
\( 0 < G_1 < c \), \( G_2 = c \), the socioeconomic contracts the space of natural resources whereas
the natural’s unchanged. ② If \( \alpha_{12} - \beta_{12} > 1 \), the equilibrium point will move to the
\( A_i(0, C) \), implying that natural subsystem will lead to the socioeconomic subsystem
perish. So the urban ecological security belongs to high-risk zone. Similarly, when
\( \alpha_{12} - \beta_{12} = 0 \), \( \alpha_{21} - \beta_{21} > 0 \), the urban ecological security belongs to high-risk region.

(5) When \( \alpha_{12} - \beta_{12} > 0 \), \( \alpha_{21} - \beta_{21} > 0 \), it represents that they have negative effect
to each other. To make a further analysis, ① If \( 0 < \alpha_{12} - \beta_{12} < 1 \), \( 0 < \alpha_{21} - \beta_{21} < 1 \),
then \( G_1 < c \), \( G_2 < c \) we can get two subsystems both narrowed the space ② If
\( \alpha_{12} - \beta_{12} > 1 \), \( 0 < \alpha_{21} - \beta_{21} < 1 \) and \( (\alpha_{12} - \beta_{12})(\alpha_{21} - \beta_{21}) < 1 \), then \( G_i < c \), \( G_i > c \), the natural
subsystem expands the space. ③ If \( 0 < \alpha_{12} - \beta_{12} < 1 \), \( \alpha_{21} - \beta_{21} > 1 \) and
\( (\alpha_{12} - \beta_{12})(\alpha_{21} - \beta_{21}) < 1 \), the socioeconomic subsystem expands the space, but the
natural subsystem shrinks. ④ If \( \alpha_{12} - \beta_{12} > 1 \), \( \alpha_{21} - \beta_{21} < 1 \) and \( (\alpha_{12} - \beta_{12})(\alpha_{21} - \beta_{21}) > 1 \),
then \( G_i > c \), \( G_i < c \), the conclusion is that although the inhibition effect of the natural
subsystem to the social economic subsystem is greater, the socioeconomic
subsystem has a larger space for natural resources for some reasons. Vice versa. ⑤ If
\( \alpha_{12} - \beta_{12} > 1 \), \( \alpha_{21} - \beta_{21} > 1 \), the equilibrium point is \( A_i(0, 0) \), implying that two
systems will tend to disappear. The corresponding urban ecological security is a
dangerous region.

(7) When \( \alpha_{12} - \beta_{12} = 0 \), \( \alpha_{21} - \beta_{21} = 0 \), showing that there is no interaction
between the two subsystems, however, which is not in conformity with the reality,
so it is not discussed in this paper.

In summary, the judgment basis of urban ecological security is obtained as
shown in Table I.

<table>
<thead>
<tr>
<th>( \alpha_{12} - \beta_{12} )</th>
<th>( \alpha_{21} - \beta_{21} )</th>
<th>( \alpha_{21} - \beta_{21} )</th>
<th>( \alpha_{21} - \beta_{21} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \alpha_{12} - \beta_{12} &lt; 0 )</td>
<td>health</td>
<td>Sub-health</td>
<td>risk</td>
</tr>
<tr>
<td>( \alpha_{12} - \beta_{12} = 0 )</td>
<td>Sub-health</td>
<td>—</td>
<td>High-risk</td>
</tr>
<tr>
<td>( \alpha_{12} - \beta_{12} &gt; 0 )</td>
<td>risk</td>
<td>High-risk</td>
<td>risk</td>
</tr>
</tbody>
</table>

**SOCIOECONOMIC-NATURAL L-V MODEL COMPETITION AND
COOPERATION COEFFICIENT CALCULATION**

The above-mentioned socioeconomic-natural L-V model is used to judge the
urban ecological security. The competition coefficient \( \alpha_{12} - \beta_{12} \) and cooperation
coefficient \( \alpha_{21} - \beta_{21} \) are the main basis for judging urban ecological security. So
this part is mainly talk about how to calculate the coefficient of competition and
cooperation.
The Calculation Principle of Competition and Cooperation Coefficient

In order to calculate the coefficient of competition and cooperation, we should discretize the formula (1) (2) firstly, make the discrete time variable equals \( K \), and assume that the environmental capacity and the competitive cooperation coefficient is constant in the \( K_{th} \) year, then the equation (1)(2) are changed to:

\[
F(k+1) - F(k) = \frac{F(k) - F(k-1)}{F(k-1)} I(k) \left[ \frac{C(k) - F(k) - [\alpha_{12}(k) - \beta_{12}(k)]E(k)}{C(k)} \right] (3)
\]

\[
E(k+1) - E(k) = \frac{E(k) - E(k-1)}{E(k-1)} \left[ \frac{C(k) - E(k) - [\alpha_{21}(k) - \beta_{21}(k)]F(k)}{C(k)} \right] (4)
\]

In the equation, all the symbols are the values of year \( k \), \( k-1 \), and \( k + 1 \). Their meanings are the same as the formula (1) (2).

Solution: 
\[
\alpha_{12}(k) - \beta_{12}(k) = \frac{\phi_F(k)C(k) - F(k)}{E(k)} (5)
\]

\[
\alpha_{21}(k) - \beta_{21}(k) = \frac{\phi_E(k)C(k) - E(k)}{F(k)} (6)
\]

In the equation,
\[
\phi_F(k) = 1 - \frac{F(k+1) - F(k)}{F(k)} \times \frac{F(k-1)}{F(k) - F(k-1)} = 1 - \frac{r_F(k+1)}{r_F(k)} (7)
\]

\[
\phi_E(k) = 1 - \frac{E(k+1) - E(k)}{E(k)} \times \frac{E(k-1)}{E(k) - E(k-1)} = 1 - \frac{r_E(k+1)}{r_E(k)} (8)
\]

The Calculation of the Basic Index of the Socioeconomic and Natural L-V SYMBIOSIS MODEL

According to above-mentioned, the calculation principles of competition and cooperation coefficient, environmental capacity index \( C \), socioeconomic development level index \( F \) and natural ecological level index \( E \) are the keys of calculating \( \alpha_{12}(k) - \beta_{12}(k) \) and \( \alpha_{21}(k) - \beta_{21}(k) \). Next, we estimate the three basic indexes by using the Index System Method, that is to estimate the basic indexes through the value and weight of the single index. The advantage of the Index System Method is each indicator has a clear ecological or socioeconomic significance, so that it can analyze the development status of basic index directly.

DPSIR MODEL ANALYSIS

Through the relative literature of urban ecological security, it can be known that
there are many kinds of ecological security index system models, such as PSR, DSR, DPSR, PSIRDPSIR and so on \cite{10-14}. Through analyzing the mechanism of ecological security, choosing the DPSIR (Driving force, Pressure, State, Impact, Response) model to construct the ecological safety index system.

The socioeconomic driving force D and socioeconomic pressure P both reflect the socioeconomic demand for natural resources and the level of urban social development. Therefore, this paper combines them to construct the estimation index of socioeconomic development. Resource and environmental state, S, indicates the state of natural resources and environment under the driving and pressure of social economy, and that can directly measure the ecological environment capacity. The human response, R, represents human’s positive response to reduce the damage to natural ecosystems, it can not only reduce the pressure of socioeconomic on environment and natural resources, but also provide conditions for ecological restoration. These two systems both relate to ecological capacity, so they can be used to construct the estimation indexes of ecological capacity. Ecological impact I indicates socioeconomic influence on the natural ecological subsystems under the effect of the resource and environment state, so the factors within the system can be used to build estimation indexes of ecological level.

INDEX SYSTEM ESTABLISHMENT AND WEIGHT DETERMINATION

We adopted the method from Zhao Yuzhe\cite{15} and Shi Baofeng\cite{16}’s literature regarding the ecological port and green industry to build up the index system of social development, environmental capacity and ecological level. Specific steps are as follows:

Firstly, according to DPSIR model structure, select indicators broadly. And then pick the indicators abide by the principles of representativeness, feasibility and observability from above. Next, classifying the indicators by the clustering analysis and continuing selecting the indicators that containing most information using the coefficient of variation. Lastly, testing the indicators’ rationality through the index variance principle.

As to Weight Determination, we adopted Entropy Method because it can avoid the interference of human make the evaluation result is more practical.

BASIC INDEX ESTIMATION

For calculating the three index $C$, $F$, and $E$, we use the following equation:

$$\text{Level Index}=\sum_{j=1}^{n}p_{j}\omega_{j}$$ \hspace{1cm} (9)

In the equation, $p_{j}$ is the $j_{th}$ value after standardizing.

Then using the three indexes to calculate competitive coefficient and cooperation coefficient $\alpha_{ij}(k)-\beta_{ij}(k)$ and $\alpha_{ij}(k)-\beta_{ij}(k)$, judging the ecological security situation of one city.
THE APPLICATION OF URBAN ECOLOGICAL SECURITY MEASURE MODEL


The Calculation of the Basic Index

ESTABLISHMENT OF INDEX SYSTEM AND WEIGHT DETERMINATION

According to the DPSIR model, and follow the relevant methods and steps to establish the index system about C, F and E. Then using the Entropy Method to determine the weight of each indicator. The outcome is shown in Table II.

<table>
<thead>
<tr>
<th>Basic index (Target hierarchy)</th>
<th>Rule hierarchy</th>
<th>Index hierarchy</th>
<th>weight</th>
</tr>
</thead>
<tbody>
<tr>
<td>The index of the level of social and economic development F</td>
<td>Socioeconomic driving force (D)</td>
<td>Engel coefficient of urban residents</td>
<td>0.272</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Per capital GDP</td>
<td>0.123</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Level of hi-tech</td>
<td>0.130</td>
</tr>
<tr>
<td></td>
<td>Socioeconomic pressure (P)</td>
<td>Per capital water resources</td>
<td>0.168</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Energy consumption per unit GDP</td>
<td>0.169</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Natural population growth rate</td>
<td>0.138</td>
</tr>
<tr>
<td></td>
<td>Resources and environment status (S)</td>
<td>Per capital park green space</td>
<td>0.113</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Per capital housing area</td>
<td>0.181</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Sewage treatment rate</td>
<td>0.132</td>
</tr>
<tr>
<td>The index of the environmental capacity C</td>
<td>Human response (R)</td>
<td>The ratio of third industry to GDP</td>
<td>0.289</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Investment level of environmental pollution control</td>
<td>0.185</td>
</tr>
<tr>
<td></td>
<td></td>
<td>The ratio of Research investment to GDP</td>
<td>0.100</td>
</tr>
<tr>
<td>The index of the level of natural ecology E</td>
<td>Ecological influence (I)</td>
<td>Air condition</td>
<td>0.272</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Afforestation area</td>
<td>0.370</td>
</tr>
<tr>
<td></td>
<td></td>
<td>The rate of green space coverage</td>
<td>0.358</td>
</tr>
</tbody>
</table>

CALCULATION OF BASIC INDEX

First, standardize the raw data of each indicator, then obtain the results of the three basic indexes from 2010 to 2014, which is shown in Table III.
TABLE III. 2011-2014 RESULTS OF BASIC INDEX.

<table>
<thead>
<tr>
<th>Basic index</th>
<th>2010</th>
<th>2011</th>
<th>2012</th>
<th>2013</th>
<th>2014</th>
</tr>
</thead>
<tbody>
<tr>
<td>socioeconomic development level F</td>
<td>0.4388</td>
<td>0.6333</td>
<td>0.2384</td>
<td>0.408</td>
<td>0.51</td>
</tr>
<tr>
<td>environmental capacity C</td>
<td>0</td>
<td>0.1516</td>
<td>0.5385</td>
<td>0.8247</td>
<td>0.9157</td>
</tr>
<tr>
<td>natural ecology level E</td>
<td>0.642</td>
<td>0.4176</td>
<td>0.4152</td>
<td>0.4714</td>
<td>0.7628</td>
</tr>
</tbody>
</table>

Measure Competitive and Cooperation Coefficient of the Socioeconomic-Natural L-V Symbiosis Model

As is shown in Table IV, when we put the results of the basic index into the formula (3), we can get the value of the coefficient of competitive and cooperation, \( \alpha_{12}(k) - \beta_{12}(k) \) and \( \alpha_{21}(k) - \beta_{21}(k) \).

TABLE IV. COMPETITIVE COOPERATION COEFFICIENT.

<table>
<thead>
<tr>
<th></th>
<th>( \varphi_1(k) )</th>
<th>( \varphi_2(k) )</th>
<th>( \alpha_{12}(k) - \beta_{12}(k) )</th>
<th>( \alpha_{21}(k) - \beta_{21}(k) )</th>
</tr>
</thead>
<tbody>
<tr>
<td>2011-2012</td>
<td>2.407</td>
<td>0.984</td>
<td>-0.643</td>
<td>-0.424</td>
</tr>
<tr>
<td>2012-2013</td>
<td>2.141</td>
<td>24.552</td>
<td>2.202</td>
<td>53.717</td>
</tr>
<tr>
<td>2013-2014</td>
<td>0.649</td>
<td>-3.567</td>
<td>0.269</td>
<td>-8.365</td>
</tr>
</tbody>
</table>

Result Analysis

According to the above calculation results, it can be seen that from 2011 to 2012, \( \alpha_{12}(k) - \beta_{12}(k) = -0.643 < 0 \), \( \alpha_{21}(k) - \beta_{21}(k) = -0.424 < 0 \), the equilibrium point is \( A_4(0.342, 0.297) \), all of them indicate that the two subsystems promoted and benefited each other, the environmental capacity got expanded. Accordingly the ecological security status of Xi’an belonged to the healthy region.

From 2012 to 2013, \( \alpha_{12}(k) - \beta_{12}(k) = 2.202 > 1 \), \( \alpha_{21}(k) - \beta_{21}(k) = 53.717 > 1 \), the equilibrium point is \( A_1(0, 0) \), which represent that the negative effect of the competition between two subsystems is greater than the positive effect of their mutual cooperation, they two inhibited mutually, and tend to perish. The corresponding state belongs to the competition (mutual harm) state, the ecological security is in a dangerous region.

From 2013 to 2014, \( \alpha_{12}(k) - \beta_{12}(k) = 0.269 > 0 \), \( \alpha_{21}(k) - \beta_{21}(k) = -8.365 < 0 \), the equilibrium point is \( A_5(0, C) \), which represent that the negative effect of the natural environment subsystem to the social economic subsystem is greater than that of positive effect, and the positive of the social economic subsystem to the natural environment subsystem is greater than negative. It belongs to the state of single benefit, namely, the ecological benefit, the social economic damage, and finally the socioeconomic subsystem will perish.

The result of the Xi’an ecological security measure is in accordance with the
actual situation, which shows that the urban ecological security measure model constructed in this paper has important practical significance.

CONCLUSION

(1) This paper based on the ecological security implications, combined with biological symbiosis theory, and established the socioeconomic natural L-V symbiosis model. According to the L-V symbiosis model stable equilibrium point and competitive cooperation coefficient, the city ecological security situation can be divided into five regions, health area, sub-health area, risk area, high-risk area and danger area. In the construction of model, the formula is discretized to calculate the value of the competitive cooperation coefficient and use the index system method to calculate the indexes of environmental capacity C, social and economic development level F and natural ecology level E.

(2) Through using the social economy and natural L-V symbiosis model to measure ecological security situation of Xi'an, we can get the conclusion that the ecological security status of Xi'an from 2011 to 2012 is in a healthy area, the socioeconomic development and the natural development promote each other, which forms a win-win situation. From 2012 to 2013, the status of its ecological security is in a dangerous area and the social economy and the natural environment are mutually inhibit, forming a double deficit situation. From 2013 to 2014, the ecological security situation belongs to high risk area, forming a single-benefited state (ecology benefited, social economy damaged).

(3) The result of the measure of the ecological security of Xi'an is in accordance with the actual situation of Xi'an, which shows that the social economy and natural L-V symbiosis model constructed in this paper has important practical significance in ecological safety measuring.

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