Eco-environment quality assessment: a quantifying method and case study in the Ning Xia arid and semiarid region, China

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Abstract As water resources are limited in the northwest arid and semiarid region in China, the problems of eco-environment quality assessment and protection are becoming very important issues in relation to sustainable development. This paper develops a Pattern Recognition Approach (PRA) to quantify the eco-environmental quality in terms of an index system based on forest, meadow, river and lake, soil water and atmosphere. A case study in Ning Xia, China, is presented as a preliminary application of this method.

Key words eco-quality standard; ecological safety; environmental impact assessment; pattern recognition; methodology; semiarid region; western China; case study; sustainability

INTRODUCTION

As a developing country, China is facing increasing problems in managing its water resources. The new ethic of "sustainable development" not only reinforces but also extends the main principles of water resources management. One of the more important aspects of sustainable water management should be a concern for eco-environmental preservation and protection. Within China this is especially important in the semiarid and arid regions where the ecosystem significantly relies on water availability, which has been greatly reduced in recent decades (Xia, 1999; Chen & Xia, 1999; Xia & Shi, 1998; Jin, 1997).

In the vast region of northwest China where there is a variety of ecological systems, it is difficult to evaluate quantitatively the eco-environmental quality from sample data sets and a conventional classification (Xia, 1996). To study this problem, a Pattern Recognition Approach (PRA) was developed, where the problem of eco-environmental quality assessment can be reduced to a clustering of multi-vector series (i.e. monitoring sample set) relative to reference patterns (i.e. quality standards set). The integrated clustering measurement provides an optimal option for eco-quality evaluation. By practical application of this method in Ning Xia, an arid and semiarid region, it has been shown that this method works and is practical. The results can provide useful information on identification of the main problems and protection measures.
ECO-ENVIRONMENT QUALITY AND ASSESSMENT INDEX SYSTEM

The eco-environmental quality can be viewed as an integrated measurement related to the different ecological states of the area under consideration. In generally, eco-environmental quality can be qualitatively identified from output saturation of the eco-system linked with water issues and sustainable development.

Ning Xia is a region in the northwest arid and semiarid region of China. Because of a water resources shortage, the eco-environmental quality in this region has significantly deteriorated. The main aspects to be addressed are as follows:

*Soil erosion.* In the southern part of Ning Xia, there are quite thick loess layers, rainfall is relatively intense, the topography is hilly, and the vegetation has largely been destroyed by nature and man. The soil loss is very easy to assess. According to statistical data there is a soil erosion problem in 75% of Ning Xia. The most serious soil erosion occurs in the southern loess hills, in which annual soil erosion varies from 5000 to 10,000 t km\(^2\).

*Land desertification.* Due to the climate plus human activities, such as land reclamation and forest logging in the middle and north part of Ning Xia, desertification is gradually causing farmland and grassland loss and 24.3% of the area is now desert.

*Soil salinization.* In arid and semiarid areas, the problem of soil saline-alkalinization can result from over-irrigation. In agricultural irrigation areas in Ning Xia, the soil saline-alkali area approaches 866.7 km\(^2\).

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![An index system for eco-environment evaluation.](image)

**Fig. 1** An index system for eco-environment evaluation.
Vegetation destruction. Vegetation is a very important part of the eco-system. However, the degree of forest cover in Ning Xia is very low due to the arid climate and forest logging. The average forest cover is only 4.85%. It was found that there is a deterioration problem in 97% of grasslands. Moreover, water and air qualities in this region are facing challenges due to pollution. Thus, ecological degradation has become a major threat to the sustainable development of the oases where social and economic activities of the local inhabitants are concentrated.

Such qualitative analysis has not yet been sufficient to provide a quantitative management tool for environmental planning and eco-system protection. Thus, an eco-environmental quality assessment method and index system need to be developed. In general, this issue would be much more difficult than water quality assessment or environmental impact assessment due to limited samples and lack of a uniform eco-quality standard. Case studies will be necessary to develop the available methods and grade standards.

Based on the significant problems mentioned above, the eco-environment quality impact in Ning Xia Region can be considered in terms of five subsystems: forest, meadow, soil, water and air. Each subsystem is composed of a number of factors (Fig. 1). A key step in eco-environment quality evaluation is to identify appropriate factors and form an evaluation index system.

Through a series of environmental monitoring and quality analysis studies in Ning Xia, a set of index systems and relative grades has been developed (Table 1). They provide a very important basis to assess quantitatively the eco-system quality.

A QUANTITATIVE METHOD FOR ECO-ENVIRONMENT QUALITY ASSESSMENT

The ecological environment system in an arid and semi-arid area is a complex hierarchical system (Fig. 1). However, most existing conventional methods, such as the analogy analysis approach, or eco-map or assessment index method, focus on qualitative assessment with limited index variables. To obtain quantitative evaluation of a complex hierarchical system, the pattern recognition approach (PRA) based on distance space analysis is developed in this paper based on the eco-environmental quality grades given in Table 1. This method integrates the advantages of the index approach and fuzzy mathematical assessment. It is shown that this approach can give improved evaluation information through calculation of two measures: the relational degree $r_\theta$ and the inversely-relational degree $\bar{r}_\theta$. Based on the pattern recognition principle and its solution, the final evaluation is objective and avoids subjective selection. Moreover, the principle component approach was also developed to determine weights of integrated evaluation of eco-system quality. The key feature of this method is that weight determination is based on eco-system monitoring information without any subjective selection in advance.

From the technical point of view, the main components of this method are:
(a) sample information matrix, $X_{n \times m}(l)$,
(b) eco-environment quality grade matrix, $S_{m \times n}(l)$ and
(c) the measurement applied to quality evaluation.
Table 1 The index systems and grades for ecological environment quality evaluation in Ning Xia.

<table>
<thead>
<tr>
<th>Evaluation index system</th>
<th>Evaluation index code</th>
<th>Ecological environment quality level:</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>I</td>
</tr>
<tr>
<td>Atmosphere environment quality</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sulphur dioxide (mg m(^{-3}))</td>
<td>SO(_2)</td>
<td>0.01</td>
</tr>
<tr>
<td>Nitrogen oxide (mg m(^{-3}))</td>
<td>NO(_x)</td>
<td>0.01</td>
</tr>
<tr>
<td>Total suspended particles (mg m(^{-3}))</td>
<td>TSP</td>
<td>0.05</td>
</tr>
<tr>
<td>Water environment quality</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Suspended solids (mg l(^{-1}))</td>
<td>SS</td>
<td>30</td>
</tr>
<tr>
<td>Degree of hardness</td>
<td>HD</td>
<td>120</td>
</tr>
<tr>
<td>Dissolved oxygen (mg l(^{-1}))</td>
<td>DO</td>
<td>8</td>
</tr>
<tr>
<td>Chemical oxygen demand (mg l(^{-1}))</td>
<td>COD(_m)</td>
<td>2</td>
</tr>
<tr>
<td></td>
<td>COD(_c)</td>
<td>5</td>
</tr>
<tr>
<td>BOD(_5) (mg l(^{-1}))</td>
<td>BOD(_5)</td>
<td>2</td>
</tr>
<tr>
<td>NH(_3)-N (mg l(^{-1}))</td>
<td>NH(_3)-N</td>
<td>0.4</td>
</tr>
<tr>
<td>Phenol (mg l(^{-1}))</td>
<td>C(_6)H(_5)OH</td>
<td>0.001</td>
</tr>
<tr>
<td>Chromium six valence (mg l(^{-1}))</td>
<td>Cr(^{6+})</td>
<td>0.01</td>
</tr>
<tr>
<td>Phosphorus (mg l(^{-1}))</td>
<td>P</td>
<td>0.02</td>
</tr>
<tr>
<td>Fluoride (mg l(^{-1}))</td>
<td>F</td>
<td>0.6</td>
</tr>
<tr>
<td>Soil environment quality</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Irrigated land</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Land class index</td>
<td>1.00</td>
<td>0.75</td>
</tr>
<tr>
<td>Alkali-saline index</td>
<td>1.00</td>
<td>0.75</td>
</tr>
<tr>
<td>Degree of Groundwater mineralization (g l(^{-1}))</td>
<td>3</td>
<td>5</td>
</tr>
<tr>
<td>Organic matter content (%)</td>
<td>2.5</td>
<td>1.5</td>
</tr>
<tr>
<td>Degree of forest cover (%)</td>
<td>30</td>
<td>20</td>
</tr>
<tr>
<td>Un-irrigated land</td>
<td></td>
<td></td>
</tr>
<tr>
<td>organic matter content (%)</td>
<td>2.5</td>
<td>1.5</td>
</tr>
<tr>
<td>Soil erosive modulus (t km(^{-2}) year(^{-1}))</td>
<td>10000</td>
<td>2500</td>
</tr>
<tr>
<td>Forest quality</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Degree of forest cover (%)</td>
<td>30</td>
<td>20</td>
</tr>
<tr>
<td>Meadow quality</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Deterioration index</td>
<td>1.00</td>
<td>0.75</td>
</tr>
<tr>
<td>Meadow level index</td>
<td>1.00</td>
<td>0.75</td>
</tr>
</tbody>
</table>

Through eco-environmental monitoring, sample information can be obtained for the system under study, such as in Ning Xia. The sample matrix \(X_{m \times n}(I)\) with \(n\) factors, can be defined as:

\[
X_{m \times n}(I) = \begin{bmatrix}
    x_1(1) & x_1(2) & \ldots & x_1(n) \\
    x_2(1) & x_2(2) & \ldots & x_2(n) \\
    \vdots & \vdots & \ddots & \vdots \\
    x_m(1) & x_m(2) & \ldots & x_m(n)
\end{bmatrix}
\]

The eco-environmental quality matrix, \(S_{l \times n}(I)\), with an \(n\) index system and \(l\) different grades, is defined as:

\[
S_{l \times n}(I) = \begin{bmatrix}
    s_1(1) & s_1(2) & \ldots & s_1(n) \\
    s_2(1) & s_2(2) & \ldots & s_2(n) \\
    \vdots & \vdots & \ddots & \vdots \\
    s_l(1) & s_l(2) & \ldots & s_l(n)
\end{bmatrix}
\]
In order to eliminate the effect due to dimensional differences, both the sample information matrix and the eco-environmental quality grade matrix need to be normalized from $X(n 	imes m)$ to $A_{mxn}(I)$, and from $S_{x/n}(I)$ to $B_{1/n}(I)$. This process can be completed according to different types of objective. For instance:

$$
a_i(k) = \begin{cases} 
1, & \text{case(1)}: x_i(k) \leq s_i(k) \\
\frac{s_i(k) - x_i(k)}{s_i(k) - s_i(k)}, & \text{case(2)}: x_i(k) < s_i(k) < s_i(k) \\
0, & \text{case(2)}: x_i(k) \geq s_i(k)
\end{cases} \quad (i = 1, 2, \ldots, m \text{ and } k = 1, 2, \ldots, n) \tag{3}
$$

where $j = 1, 2, \ldots, m$ and $k = 1, 2, \ldots, n$. Case (1) represents such a situation, i.e. the larger the index value, such as BOD in water quality issues, the worse the environmental quality will be. Case (2) indicates the opposite situation such as DO index in water quality assessment, where higher index values relate to better environmental quality.

In the same way, the eco-environmental quality matrix also needs to be normalized given by:

$$
b_i(k) = \frac{s_i(k) - x_i(k)}{s_i(k) - s_i(k)} \quad (i = 1, 2, \ldots, l; k = 1, 2, \ldots, n) \tag{4}
$$

The normalized matrix $A_{mxn}(I)$ and matrix $B_{1/n}(I)$ have the same formulation relative to equations (1) and (2), i.e.

$$
A_{mxn}(I) = \begin{pmatrix}
a_{1}(1) & a_{1}(2) & \cdots & a_{1}(n) \\
a_{2}(1) & a_{2}(2) & \cdots & a_{2}(n) \\
\vdots & \vdots & \ddots & \vdots \\
a_{n}(1) & a_{n}(2) & \cdots & a_{n}(n)
\end{pmatrix} \quad \text{sample } 1
$$

$$
B_{1/n}(I) = \begin{pmatrix}
b_{1}(1) & b_{1}(2) & \cdots & b_{1}(n) \\
b_{2}(1) & b_{2}(2) & \cdots & b_{2}(n) \\
\vdots & \vdots & \ddots & \vdots \\
b_{l}(1) & b_{l}(2) & \cdots & b_{l}(n)
\end{pmatrix} \quad \text{grade } 1 \tag{5}
$$

The main steps in applying the PRA method to eco-quality assessment are as follows:

(a) The $j$th sample vector $\tilde{a}_j = (a_j(1), a_j(2), \ldots, a_j(n))$ taken from matrix $A_{mxn}(I)$ can be defined as a reference pattern, $j = 1, 2, \ldots, m$. Each vector from the quality standard matrix, $B_{1/n}(I)$, i.e. $\tilde{b}_i = (b_i(1), b_i(2), \ldots, b_i(n))$, $i = 1, 2, \ldots, n$, can be regarded as a compared pattern. If subindex $j$ is fixed, and letting subindex $i$ vary from 1 to $l$, the pattern simulation can be identified by a relational function $\xi_{ij}(k)$ ($k = 1, 2, \ldots, n$), where $\xi_{ij}(k)$, developed by Xia (1996), is given by:

$$
\xi_{ij}(k) = \frac{1 - \Delta_{ij}(k)}{1 + \Delta_{ij}(k)} \quad (i = 1, 2, \ldots, l; j = 1, 2, \ldots, m; k = 1, 2, \ldots, n) \tag{6}
$$
where $\Delta_y(k) = |a_j(k) - b_j(k)|$. Evidently, if there is no difference between $a_j(k)$ and $b_j(k)$, then $\Delta_y(k) = 0$. Thus, the relational function describes a clustering distance between $a_j(k)$ and $b_j(k)$. It can be proved that such distance measurement satisfies the basic properties of relational space analysis, such as normality, even-symmetry and close-ability (Xia, 1996).

(b) To integrate total eco-quality assessment, a comprehensive measurement that is also called a relational degree, $r_{ij}$, was developed based on the relational function information, $\{\xi_y(k)\}$, and the index-system weight information, $w(k)$. The formulation of the weighted relational degree, $r_{ij}$, is given by:

$$
 r_{ij} = \sum_{k=1}^{n} w(k) \xi_y(k) \quad (i = 1, 2, ..., l; j = 1, 2, ..., m; k = 1, 2, ..., n)
$$

where $r_{ij} \in [0,1]$, the variable $w(k)$ is a weight index that can be determined objectively by a principle component analysis (PCA) approach. The distinguishing feature of this method is that the weight can be identified directly from eco-monitoring information without any subjective selection in advance (Xia & Shi; 1998).

(c) Calculate every $r_{ij}$ according to steps (a) and (b). The following relational analysis matrix can then be obtained:

$$
 R_{l \times m}(I) = \begin{pmatrix}
 r_{11} & r_{12} & \cdots & r_{1m} \\
 r_{21} & r_{22} & \cdots & r_{2m} \\
 \vdots & \vdots & \ddots & \vdots \\
 r_{l1} & r_{l2} & \cdots & r_{lm}
\end{pmatrix}
$$

The above matrix provides an important tool for quantifying eco-environmental quality. The $i$th sample's eco-quality assessment, for instance, is reduced to determine maximum grade, i.e. $r_{ik^*} = \max(r_{ij})$ where $j = 1, 2, ..., l$. The grade $k^*$ is just the evaluated quality grade corresponding to the $i$th sample. The distribution of the relational degree in all grades can show some of the features for studies of eco-system quality. Of course, the relational degree method usually provides quantitative evaluation with integer grades, such as classes I, II, III, IV, and V.

(d) To obtain quality evaluation with non-integer grading, a coupled pattern recognition approach linked with fuzzy mathematics was further developed. Another parameter called the inverse-relational degree is defined as:

$$
 \bar{r}_{ij} = 1 - r_{ij} = 1 - \sum_{k=1}^{n} w(k) \xi_y(k)
$$

This parameter shows non-relational information. The non-relational measurement in this way can be expressed by the index $d_{ij}$ with a membership degree, $\mu_{ij}$, i.e.

$$
 d_{ij} = \mu_{ij} \bar{r}_{ij} = \mu_{ij} \left[ 1 - \sum_{k=1}^{n} w(k) \xi_y(k) \right]
$$

Thus, pattern recognition in eco-quality assessment has been transformed into the
identification of the optimal membership degree. In the fuzzy approach, the following objective function can directly identify it:

\[
\min \{ F(\mu_{ij}) \} = \min \left\{ \sum_{i=1}^{l} \sum_{j=1}^{m} \left[ \mu_{ij} \left( 1 - \sum_{k=1}^{n} w(k) \xi_{y_k} (k) \right) \right]^2 \right\} 
\]

The optimal solution can be found by letting the partial derivative of the objective function relative to the membership degree, \( \mu_{ij} \), be zero, given by:

\[
\mu_{ij} = \frac{1}{\sum_{k=1}^{n} \left[ 1 - \sum_{k=1}^{n} w(k) \xi_{y_k} (k) \right] \left( 1 - \sum_{k=1}^{n} w(k) \xi_{y_k} (k) \right)} \quad (i = 1, 2, ..., l; j = 1, 2, ..., m; k = 1, 2, ..., n) \quad (12)
\]

Furthermore, the scalar \( GC \) can calculate the eco-quality assessment with non-integer scaling, i.e.

\[
GC = (\mu_{ij} \cdot S = U \cdot S)
\]

where \( S \) is the standard grade vector, \( S = (1, 2, ..., l) \); \( GC \in [1, l] \).

The above process forms the so-called PRA method applied to eco-environmental quality assessment.

**CASE STUDY IN NING XIA, CHINA**

Ning Xia is located in the northwest arid and semiarid region of China (Fig. 2). The total area of Ning Xia is 51,800 km\(^2\). Average annual precipitation is only 305 mm whilst annual evaporation reaches 1800 mm, which accounts for 94% of the total water loss. Ning Xia can be divided into four regions: Shi Zuishan City, Yin Chuan City, Yin Nan District, and Gu Yuan District.

As mentioned in the second section of this paper, the main eco-environmental problems result from soil erosion, land desertification, salinization, vegetation destruction, and water and air pollution. These six aspects can be viewed as subsystems of the total environmental system in Ning Xia.

Based on environmental monitoring data and the eco-quality grades in Table 1, the eco-environmental quality of both the four subregions and the whole of Ning Xia was evaluated in terms of soil erosion, land desertification, salinization, vegetation destruction, and water and air pollution and their integration. A comprehensive evaluation based on all six aspects is given in Table 2 and Fig. 3.

The results show that the regional eco-environmental quality reaches grade 3.5 (III–IV). The best is grade I and the worst is grade V. Thus, regional eco-quality is indeed a worrying issue. In terms of spatial distribution, the eco-quality of Gu Yuan District is the worst. The next worst is Yin Nan District, and so on. The most significant environmental impact aspect in eco-environmental degeneration is forest destruction: the eco-environmental quality for all four subregions being worse than grade IV.
The results of the subsystem evaluation show that forest quality and meadow quality (Table 2 and Fig. 4) degeneration are the dominant reasons for the low environmental quality in the whole region. In Ning Xia, there is only 4.85% forest cover, which is far below the average for China. Moreover, natural meadow covers up to 58% of the land in Ning Xia, but most of this belongs to the middle or middle lower level. Thus, forest resource protection is the most important issue for improving eco-environmental quality in Ning Xia, China.

In addition to individual quality evaluation of the forest and meadow subsystems, the eco-quality assessment of soil erosion was also undertaken. It shows that soil erosion, soil salinity and desertification are the main causes of harmful impacts on the eco-system. These problems usually vary in space and time. Thus, four regions (A1, A2, A3 and A4) with irrigated land and three regions (B1, B2 and B3) of dry land were selected for an evaluation of their soil environment quality. The result shown in Figs 5

Table 2 Results of the ecological environment quality evaluation in Ning Xia.

<table>
<thead>
<tr>
<th>Region</th>
<th>Atmosphere environment (0.155*)</th>
<th>Water environment (0.206*)</th>
<th>Soil environment (0.195*)</th>
<th>Forest quality (0.229*)</th>
<th>Meadow quality (0.215*)</th>
<th>Synthesis quality</th>
</tr>
</thead>
<tbody>
<tr>
<td>Shi Zuishan City</td>
<td>2.9</td>
<td>3.3</td>
<td>3.0</td>
<td>4.7</td>
<td>3.4</td>
<td>3.4</td>
</tr>
<tr>
<td>Yin Chuan City</td>
<td>2.0</td>
<td>3.6</td>
<td>3.0</td>
<td>4.1</td>
<td>3.3</td>
<td>3.0</td>
</tr>
<tr>
<td>Yin Nan District</td>
<td>2.7</td>
<td>4.2</td>
<td>2.7</td>
<td>5.0</td>
<td>3.4</td>
<td>3.6</td>
</tr>
<tr>
<td>Gu Yuan District</td>
<td>3.6</td>
<td>3.5</td>
<td>3.0</td>
<td>4.7</td>
<td>3.4</td>
<td>3.7</td>
</tr>
<tr>
<td>Ning Xia Province</td>
<td>2.8</td>
<td>3.9</td>
<td>3.0</td>
<td>4.7</td>
<td>3.4</td>
<td>3.5</td>
</tr>
</tbody>
</table>

*Weight
and 6 indicate that in the areas of irrigated farming, the impact of land class index to eco-quality is the most notable. In farming areas without irrigation, indexes of the degree of forest cover, organic matter content and soil erosive modulus are the main impact factors.

**CONCLUSIONS**

- In eco-environmental quality assessment, there are three key problems in addition to obtaining the necessary data sets. One is to build an index system that can represent the real ecological system structure and impact factors. Another is to set a reasonable eco-quality standard (grade) that can be used to evaluate quantitatively the eco-environmental quality.
- A set of index systems has been built for Ning Xia. Eco-environmental quality can be represented by habitat quality curves. Field experiments and investigations are means to get the different levels of the standard quality matrix.
- This paper presents a pattern recognition approach applied to eco-environmental quality assessment. An advantage of this method is that it works for the whole region. The Gu Yuan District subregion has the worst eco-quality—the main problems result from the destruction of forest vegetation, soil erosion, land desertification, salinization, and water pollution; the most significant problem
being the destruction of forested areas. The eco-quality of all four subregions is over grade IV, and that of Yin Nan District is already grade V. The next most significant factor is soil loss. Thus, eco-system recovery and protection is one of the most urgent tasks at the present stage.

For improving the eco-environmental quality in the Ning Xia region, a key point is to mitigate forest destruction and soil loss. Water resources management will play an important role in improving eco-system quality. In other words, water resources management needs to consider water demand from the eco-system such as trees and meadows. With the present conflict between economic development and environmental protection, this is indeed a big challenge. If sustainable development is the final objective in this region, eco-system recovery and protection must be considered in the overall resources planning and management.

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