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RESEARCH ARTICLE

Evaluation of the eco-environmental frangibility in west Jilin Province based on the matter-element model

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Abstract The west Jilin Province is a typical area in the ecotone between agriculture and animal husbandry, with a frangible eco-environment. With respect to the three aspects of water resource, natural disasters and land degradation, 10 indices were selected to establish a matter-element model for the assessment of eco-environmental frangibility in the west Jilin Province. The results indicate that during 1985–2000, Qian'an, Fuyu, and Changling had the least frangibility (level I), followed by Da'an and Qianguo (level II), and Taobei, Zhenlai, Taonan, and Tongyu had the highest frangibility (level III). On the whole, the counties in Songyuan city were less frangible than those in Baicheng city. Different counties had different frangibilities to environmental factors, e.g., Da'an and Tongyu were frangible in water resource conditions; Taobei, Zhenlai, Taonan, Tongyu and Qian'an suffered most from natural disasters; while Taobei, Taonan and Qianguo were threatened by severe land degradation.

Keywords matter-element model, west Jilin Province, frangibility, entropy method

1 Introduction

An ecotone is an intermediate transitional zone linking two kinds of environments or two kinds of ecosystems. Being far away from the center, the ecosystem of an ecotone has low stability and is sensitive to external disturbances. Thus, it is characterized by an obvious frangibility and high fluctuation in terms of resource and space competition (Huang and Meng, 1996). The frangible eco-environment of an ecotone has a low carrying capacity for human development and has led to a series of ecological or economic problems which are disadvantageous for both ecological and economic sustainability. China has the third largest territory in the world, with various and complex ecosystems as well as widespread areas of ecotones. Therefore, the study on ecotones is of great theoretical and practical importance for long term sustainable development (Zhao and Zhang, 1998; Sun et al., 2000; Tang and Xue, 2005; Wan et al., 2006). The matter-element model, created by Cai (1996), is a comprehensive analytical method based on the integration of system science, thinking science and mathematics. It can convert complex matter into a visualized model, express the evaluation result with quantitative values, and assess the characteristics and quality of a matter synthetically (Cai, 1996; Cai et al., 1997; Meng et al., 2003). The model has been widely applied to various disciplines (Meng et al., 2003; Nie et al., 2005; Tang et al., 2005). In this paper, we introduce the matter element model to the eco-environmental evaluation of a frangible ecotone in the west Jilin Province, China, and try to use it as a tool for eco-environmental assessment.

2 Materials and methods

2.1 Study area

The west Jilin Province (43°53′–46°18′N, 121°38′–126°17′E), located in the transitional zone between the humid Asian monsoon region and the arid inland area, is a typical agro-pastoral ecotone in northern China, where the ecosystem varies gradually from forest to sub-humid and semi-arid grassland. Affected by the compound interaction between natural climate change and human activities, the west Jilin Province is a vulnerable ecotone with high sensitivity to global environmental changes and external human disturbances (Tang et al., 2005; Huang et al., 2003). There are 10

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counties located in the west Jilin Province, including Taobei, Zhenlai, Taonan, Tongyu and Da'an of Baicheng city, and Ningjiang, Qianguo, Qian'an, Changling, and Fuyu of Songyuan city. With the total annual sunshine being 2800–3000 h, the total annual radiation in this region amounts to 5100–5200 MJ/m^2. The average annual rainfall is 400–500 mm, but the average evaporation is 1600–2000 mm. The average relative humidity of the west Jilin Province is 60%–65%, and the frost-free period may last 140–160 days annually.

The eco-environments are mainly characterized by unfavorable climate conditions and frequent natural disasters; severe land degradation (desertification, salinization, grassland degradation); water scarcity, weak water conservancy facilities and low resistance against natural disasters; irrational industry structures and low productivity (Sheng et al., 2001; Qiu et al., 2003; Qiu, 2004; Wang et al., 2005).

3 Methods

3.1 Matter-element model

If a matter's name N, characteristic C, and its characteristic's value V are known, the three ordinal elements group $R=(N, C, V)$ can be used as a basic element to describe the matter, and the basic element is called a matter element (Cai et al., 1997). The matter N may have many characteristics and if all of them are described by n characteristics, C_1, C_2 … C_n, and the corresponding values are V_1, V_2 … V_n, respectively, $R=(N, C, V)$ is called the n-dimensional matter element, which can be presented as:

$$R=\begin{bmatrix} & C_1 & V_1 \\ N & C_2 & V_2 \\ & \vdots & \vdots \\ & C_n & V_n \end{bmatrix}$$

3.2 Sutra field, section field, and object matter-element

(1) Sutra field (R^j)

If a matter N is composed of m matters, N^1, N^2 … N^m, N^j is matter j ($j=1, 2$ … m), C_i^j is characteristic i of matter j and the value range of characteristic i is V_i^j, then $R^j=\left(N, C_i^j, V_i^j\right)$ is called the sutra field of N. If the value of V_i^j varies from a_i^j to b_i^j, it can be denoted as $V_i^j=\langle a_i^j, b_i^j\rangle$, ($i=1$, 2 … n). The sutra field can be expressed as:

$$R^j=\begin{bmatrix} & C_1^j & V_1^j \\ N^j & C_2^j & V_2^j \\ & \vdots & \vdots \\ & C_n^j & V_n^j \end{bmatrix}=\begin{bmatrix} & C_1^j & \langle a_1^j, b_1^j\rangle \\ N^j & C_2^j & \langle a_2^j, b_2^j\rangle \\ & \vdots & \vdots \\ & C_n^j & \langle a_n^j, b_n^j\rangle \end{bmatrix}$$

(2) Section field (R^p)

Based on the sutra field, we can construct the section field $R^j=\left(N, C_i^p, V_i^p\right)$, of which V_i^p is the value range of characteristic i of N. If the value of V_i^p varies from a_i^p to b_i^p, it can be denoted as $V_i^p=\langle a_i^p, b_i^p\rangle$ ($i=1$, 2 … n) and the section field can be expressed as:

$$R^p=\begin{bmatrix} & C_1^p & V_1^p \\ N^p & C_2^p & V_2^p \\ & \vdots & \vdots \\ & C_n^p & V_n^p \end{bmatrix}=\begin{bmatrix} & C_1^p & \langle a_1^p, b_1^p\rangle \\ N^p & C_2^p & \langle a_2^p, b_2^p\rangle \\ & \vdots & \vdots \\ & C_n^p & \langle a_n^p, b_n^p\rangle \end{bmatrix}.$$

Apparently, $V_i^j \subset V_i^p$.

(3) Object matter element (R^d)

$$R^d=\begin{bmatrix} & C_1^d & V_1^d \\ N & C_2^d & V_2^d \\ & \vdots & \vdots \\ & C_n^d & V_n^d \end{bmatrix}$$

is the object matter element, and V_k^d ($k=1, 2$ … n) is the value of index k.

3.3 Calculation of the relationship function

$$K_j\left(V_k^d\right)=\begin{cases} -\dfrac{\rho\left(V_k^d, V_i^j\right)}{\left|V_i^j\right|}, & V_k^d \in V_i^j \\[2ex] \dfrac{\rho\left(V_k^d, V_i^j\right)}{\rho\left(V_k^d, V_i^p\right)-\rho\left(V_k^d, V_i^j\right)}, & V_k^d \notin V_i^j \end{cases} \quad (1)$$

$$\rho\left(V_k^d, V_i^j\right)=\left|V_k^d-\frac{b_i^j+a_i^j}{2}\right|-\frac{b_i^j-a_i^j}{2}$$

$$\rho\left(V_k^d, V_i^p\right)=\left|V_k^d-\frac{b_i^p+a_i^p}{2}\right|-\frac{b_i^p-a_i^p}{2}$$

The relationship function $K_j\left(V_k^d\right)$ is used to show the relationship degrees of V_k^d to the range $\langle a_i^j, b_i^j\rangle$. The detailed calculation is presented as formula (1), where $\rho\left(V_k^d, V_i^p\right)$ and $\rho\left(V_k^d, V_i^p\right)$ are used to calculate the distance of V_k^d to $\langle a_i^j, b_i^j \rangle$ and $\langle a_i^p, b_i^p \rangle$, respectively.

3.4 Weight coefficient

There are many methods to calculate the weight coefficient, such as by the principal component analysis method (PCA), through analytic hierarchy process (AHP), and the entropy method (Qiao, 2002). In this paper, the entropy weight method is utilized to calculate the weight coefficient of each indicator, which is an objective method distinguishing indicator importance through the information effect value reflected by the related indicators (Zhang, 2004; Zhang and Liang, 2005).

(1) Data standardization

All the data are processed using the following formulas, according to their interactions in the evaluation results.

The positive indicators:

$$f_k = \frac{V_k^d - \min\left(V_k^d\right)}{\max\left(V_k^d\right) - \min\left(V_k^d\right)},$$

and the negative indicators:

$$f_k = 1 - \frac{V_k^d - \min\left(V_k^d\right)}{\max\left(V_k^d\right) - \min\left(V_k^d\right)},$$

where f_k is the standardized form for V_k^d, and $\max\left(V_k^d\right)$ and $\min\left(V_k^d\right)$ are the maximum and minimum of V_k^d, respectively.

(2) Calculation of the entropy value e_k

$$e_k = -\frac{1}{\ln M} \sum_{i=1}^{M} \left(f_k \times \ln f_k\right),$$

where e_k is the entropy value of the objective samples, M is the sample number, and when $f_k = 0$, it is substituted by $f_k = 0.000001$.

(3) Calculation of the weight coefficient ω_k

$$\omega_k = \frac{1 - e_k}{\sum (1 - e_k)}, \tag{2}$$

where ω_k is the weight coefficient of indicator k.

3.5 Calculation of the relationship degrees

$$K_j(N) = \sum_{k=1}^{n} \omega_k K_j\left(V_k^d\right), \tag{3}$$

where $K_j(N)$ is the relationship degree of objective matter N to j. Based on the maximum dependence principle, if the relationship degree value is maximized at $j0$: $K_{j0} = max\{K_j(N)\}$, the objective matter belongs to degree $j0$.

4 A case study—Eco-environmental frangibility assessment of west Jilin Province

4.1 Evaluation of indicators

We chose the administrative districts in the spatial scale of west Jilin Province as the study area, aiming to evaluate their eco-environmental frangibility from the middle of the 1980s to the late 1990s. Ten indicators with close relationships to the eco-environment and reflecting the frangibility differences between the study areas were selected in the construction of the matter-element model: I_1, water scarcity index; I_2, change rate of the dryness index; I_3, change rate of the water area; I_4, frequency of spring drought; I_5, frequency of summer drought; I_6, waterlog frequency; I_7, cold disaster frequency; I_8, degradation rate of grassland; I_9, change of saline area; I_{10}, change of desert area.

$$\text{The water scarcity index} = \frac{\text{Annual evaporation} - \text{Annual average precipitation}}{\text{Annual evaporation}}$$

$$\text{The drought index} = \frac{\text{Annual evaporation}}{\text{Annual average precipitation}}$$

$$\text{Change rate of drought index} = \frac{\text{Average drought index 1990s} - \text{Average drought index 1980s}}{\text{Average drought index 1980s}}$$

We used the summer change rate of the drought index to represent the annual change as only the summer change rate data were available. The land use data were derived from interpretation of the TM remote sensing image of the Landsat Satellite (USA). Since the degraded land may increase in some places but decline in others, the land variation with the most extensive area decline was set as 0, thus all the land variation values were standardized to be positive.

4.2 Independence analysis of the indicators

Independence refers to the characteristic of the variances changing freely with no constraints against each other, which is an opposite concept to the overlap of indicators; an independence analysis should be done to eliminate indicator overlap in the establishment of the indicator system. If the correlation coefficient between two indicators is above 0.9 (including 0.9), the two indicators are defined as overlapped indicators, which should be incorporated (Cao and Wang, 1998). The incorporation method is as follows: first, identify the true correlation and false correlation and then incorporate the indicators with true correlations. For the indicators of the same type (either positive or negative type), the positive correlation coefficients represent true correlation and the negative correlation coefficients represent false correlation; while for the indicators of different types (positive and negative type), the positive correlation coefficients represent false correlation and the negative correlation coefficients represent true correlation. High level indicators and comprehensive indicators have the priority to be preserved (Cao and Wang, 1998). Analyzed with SPSS 13.0, all the indicators met the independence requirement.

4.3 Establishment of the sutra field and section field

Based on the main ecological problems in the west Jilin Province and starting with the three dominant factors (10 indicators) influencing the eco-environment: water resource, natural disasters, and land degradation, the ecological frangibility of west Jilin Province can be divided into three levels: level I, level II, and level III, representing low frangibility, moderate frangibility, and high frangibility, respectively. Then the sutra fields R^1, R^2, and R^3 and the section field R^P were established; the object matter-element is shown in Table 1.

$$R^1=\begin{bmatrix} \mathrm{I} & I_1 & \langle 0.336,0.405\rangle \\ & I_2 & \langle 0.076,0.16\rangle \\ & I_3 & \langle 1.974,2.96\rangle \\ & I_4 & \langle 68.4,75.7\rangle \\ & I_5 & \langle 55.3,64.5\rangle \\ & I_6 & \langle 8.80,12.6\rangle \\ & I_7 & \langle 13.9,16.8\rangle \\ & I_8 & \langle 0.00,1.99\rangle \\ & I_9 & \langle 0.00,23.3\rangle \\ & I_{10} & \langle 0.00,25.8\rangle \end{bmatrix}$$

$$R^2=\begin{bmatrix} \mathrm{II} & I_1 & \langle 0.405,0.443\rangle \\ & I_2 & \langle 0.165,0.224\rangle \\ & I_3 & \langle 0.998,1.974\rangle \\ & I_4 & \langle 75.7,83.00\rangle \\ & I_5 & \langle 64.5,73.9\rangle \\ & I_6 & \langle 12.6,16.3\rangle \\ & I_7 & \langle 16.8,19.7\rangle \\ & I_8 & \langle 1.99,3.98\rangle \\ & I_9 & \langle 23.0,46.6\rangle \\ & I_{10} & \langle 25.8,51.6\rangle \end{bmatrix}$$

$$R^3=\begin{bmatrix} \mathrm{III} & I_1 & \langle 0.443,0.482\rangle \\ & I_2 & \langle 0.224,0.328\rangle \\ & I_3 & \langle 0.00,0.988\rangle \\ & I_4 & \langle 83.0,90.3\rangle \\ & I_5 & \langle 73.9,83.3\rangle \\ & I_6 & \langle 16.3,20.0\rangle \\ & I_7 & \langle 19.7,22.6\rangle \\ & I_8 & \langle 3.98,5.96\rangle \\ & I_9 & \langle 46.6,69.9\rangle \\ & I_{10} & \langle 51.6,77.3\rangle \end{bmatrix}$$

$$R^P=\begin{bmatrix} \mathrm{I-III} & I_1 & \langle 0.336,0.482\rangle \\ & I_2 & \langle 0.076,0.328\rangle \\ & I_3 & \langle 0.00,1.974\rangle \\ & I_4 & \langle 68.4,90.3\rangle \\ & I_5 & \langle 55.3,64.5\rangle \\ & I_6 & \langle 8.80,20.0\rangle \\ & I_7 & \langle 13.9,22.6\rangle \\ & I_8 & \langle 0.00,5.96\rangle \\ & I_9 & \langle 0.00,69.9\rangle \\ & I_{10} & \langle 0.00,77.3\rangle \end{bmatrix}$$

Table 1 Index values of the evaluated factors in west Jilin Province

	water resource (I_1–I_3)			natural disasters frequency(I_4–I_7)				land degradation (I_8–I_{10})		
	I_1	I_2	I_3	I_4	I_5	I_6	I_7	I_8	I_9	I_{10}
Taobei	0.461	0.246	0.59	90.0	67.5	20.0	22.5	5.96	0.000	75.27
Zhenlai	0.461	0.246	0.40	90.3	71.9	12.5	15.6	3.68	69.86	29.14
Taonan	0.432	0.099	1.71	87.1	80.6	9.70	22.6	4.91	62.13	23.46
Da’an	0.481	0.099	0.00	80.6	78.1	9.40	18.8	3.46	45.79	33.32
Tongyu	0.465	0.194	2.96	88.6	83.8	13.9	13.9	4.32	23.55	55.97
Qian’an	0.384	0.328	2.32	84.8	67.6	8.80	14.7	2.67	48.30	52.91
Fuyu	0.366	0.099	1.53	77.4	71.9	9.40	15.4	0.00	26.31	0.000
Changling	0.430	0.076	2.30	68.4	55.3	18.4	15.8	2.46	46.68	77.29
Qianguo	0.383	0.264	1.54	78.4	60.5	15.8	18.3	5.64	40.62	52.51

4.4 Calculation of weight coefficients

The weight coefficients (Table 2) for the correlation functions are calculated according to equation (2).

4.5 Calculation of the relationship degrees

We calculated the correlation functions and relationship degrees according to equations (1) and (3), and obtained comprehensive evaluation results (Tables 3, 4).

4.6 Evaluation results from the matter element model

The results indicate that during 1985–2000, Qian’an, Fuyu, and Changling had the relatively least frangibility (level I) in eco-environment, Da’an and Qianguo followed (level II), and Taobei, Zhenlai, Taonan, and Tongyu had the highest frangibility (level III). With the gradual variation in eco-environments, the counties in Songyuan city (Qian’an, Fuyu, Changling and Qianguo) were less frangible than those in Baicheng city (Taobei, Taonan, Da’an, Zhenlai and Tongyu). Different counties had differential frangibilities to the environmental factors, e.g., Da’an and Tongyu were frangible in water resource conditions, Taobei, Zhenlai, Taonan, Tongyu, and Qian’an suffered most from natural disasters, while Taobei, Taonan, and Qianguo were threatened by severe land degradation. The eco-environmental frangibility is a result of the compound effects of various environmental factors. Generally, the environmental factors of the counties in Baicheng city had higher frangibility (level II or III) and they had a higher eco-environmental frangibility potential than Songyuan city.

Table 2 Coefficients

coefficient	ω_1	ω_2	ω_3	ω_4	ω_5	ω_6	ω_7	ω_8	ω_9	ω_{10}
value	0.130	0.108	0.055	0.176	0. 061	0.132	0.085	0.103	0.060	0.080

Table 3 Comprehensive subordinate degree

area	comprehensive frangibility			water resource			natural disasters frequency			land degradation		
	I	II	III	I	II	III	I	II	III	I	II	III
Taobei	−0.037	−0.061	−0.014	−0.017	−0.008	−0.009	−0.04	−0.038	−0.002	−0.0148	−0.0146	−0.003
Zhenlai	−0.046	−0.034	−0.033	−0.018	−0.008	−0.034	−0.021	−0.024	−0.016	−0.0064	−0.0008	−0.0074
Taonan	−0.034	−0.041	−0.023	−0.004	−0.005	−0.017	−0.011	−0.021	−0.012	−0.007	−0.006	−0.004
Da’an	−0.031	−0.024	−0.045	−0.016	−0.024	−0.008	−0.01	−0.024	−0.028	−0.005	−0.003	−0.009
Tongyu	−0.048	−0.031	−0.024	−0.014	−0.008	−0.005	−0.026	−0.022	−0.008	−0.007	−0.002	−0.01
Qian’an	−0.019	−0.036	−0.029	0	−0.018	−0.014	−0.013	−0.021	−0.003	−0.005	−0.002	−0.011
Fuyu	−0.0004	−0.041	−0.068	0.002	−0.021	−0.024	−0.002	−0.007	−0.034	0	−0.012	−0.01
Changling	−0.005	−0.042	−0.055	−0.005	−0.004	−0.018	−0.017	−0.035	−0.031	−0.012	−0.003	−0.006
Qianguo	−0.014	−0.005	−0.051	0.001	−0.01	−0.018	−0.005	0.011	−0.027	−0.01	−0.006	−0.005

Table 4 Evaluation results of the matter-element model

area	Taobei	Zhenlai	Taonan	Da’an	Tongyu	Qian’an	Fuyu	Changling	Qianguo
comprehensive frangibility	III	III	III	II	III	I	I	I	II
water resource	II	II	I	III	III	I	I	I	I
natural disasters frequency	III	III	III	I	III	III	I	I	I
land degradation	III	II	III	II	II	II	I	II	III

Note: I, II and III refer to the frangibility level of the eco-environment

Songyuan city had a higher resisting ability and was less sensitive to eco-environmental changes than Baicheng.

5 Conclusions

In this paper, the matter-element method was used to evaluate the eco-environment frangibility of west Jilin Province. During the past 15 years, the counties in this region had different sensitivities to environmental factors and showed different levels of eco-environmental frangibility. Therefore, corresponding countermeasures should be taken to ensure the stability and sustainable development of the local ecosystem. For counties with a high frangibility in water conditions, attention should be paid to the maintenance and protection of water resource areas such as wetlands and rivers, which have essential ecological functions. Moreover, the development of water-saving and ecological industries as well as water use efficiency should be strengthened. For counties with severe natural disasters, countermeasures to restore their ecological functions and reconstruct the ecosystem with appropriate structures are in urgent need. Water conservancy engineering and ecological engineering, consistent with the local ecosystem and economic level, such as the ‘Sanbei’ shelter belt, should be constructed to enhance resistance and ecological resilience. For counties with severe land degradation, an integrative appropriate assessment should be implemented for land exploitation. Rational planning of farming and pastoral activities should be made. The treatment and improvement of the sandy land, salt land, and depredated land should be enforced to increase land productivity. Because all the environmental factors of an ecosystem are an integrated unit and the status of an ecosystem is a result of the compound interactions among all the factors, the protection and exploitation of the ecosystem should be based on eco-economic theories and system science methods. All the countermeasures described above are closely correlated with each other, and unilateral emphasis is unsuitable for eco-environmental optimization.

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