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EVOLVEMENT AND CONTROL OF VULNERABLE ECOLOGICAL REGION
—A Case Study in Ongniud Banner and Aohan Banner, Inner Mongolia

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ABSTRACT: The evolvement of a vulnerable ecological region is a dynamic process, which is affected by various factors. During the evolvement process, human activities have a decisive effect. The purpose of studying vulnerable ecological region is to control human economic activities and to develop a negative feedback modulation mechanism. This paper established a model of vulnerable ecological region's evolvement by considering four synthetic variables. These synthetic variables are ecological carrying capacity, ecological resilience, economic development intensity, and economic development velocity. Finally, Ongniud Banner and Aohan Banner in North China were taken as study cases to simulate the evolvement processes of vulnerable ecological regions under different conditions of economic development. The results show that human activities have an important influence on the evolvement trend of vulnerable ecological region.

KEY WORDS: vulnerable ecological region; ecological evolvement; ecological control; simulation; Ongniud Banner; Aohan Banner

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1 INTRODUCTION

Vulnerable ecological regions are complicated systems with certain structures and functions. And the evolvement of vulnerable ecological regions means the changes and trend of state variables that describe vulnerable ecological region, including economic development and environment change, etc. An ecosystem can provide the material basis for the evolvement of a vulnerable ecological region (SMIT and CAI, 1996). When an ecosystem can provide a certain supporting functions, whole vulnerable ecological region can exist and economics is the driving force in the regional evolvement (WESEMAEL *et al.*, 2003). Only human economic activities can stimulate the change of ecosystem and then affect the evolvement direction of an vulnerable ecological region (MESSERLI *et al.*, 2000; CAO and WANG, 1998). Ecological carrying capacity and ecological resilience are synthetic variables, which are used to describe the state of a vulnerable ecological region, and provide the theoretical basis for studying evolvement and control models for vulnerable ecological regions.

2 THEORIES OF SIMULATING VULNERABLE ECOLOGICAL REGION

2.1 Regional Ecological Carrying Capacity

2.1.1 Definition

Regional ecological carrying capacity is the population and economic activities that natural resources (including environmental resources) can sustain under the economic and technological conditions in a certain time and a certain area. It is a measurement of the capability of environmental resources to support human activities.

Regional ecological carrying capacity is objective and adjustable. The objectivity is the basis of studying the quantification of regional ecological carrying capacity, while the adjustability makes it possible that taking some measures can raise the level of regional ecological carrying capacity. In general, the factors that affect

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the value of regional ecological carrying capacity are advances in science and technology, the characteristics and functions of a region, and the pattern of human economic activities in the region as well as the influence of activities outside the region (ROSA *et al.*, 1993, 2000).

2.1.2 Calculation

Here $c_1, c_2, ..., c_n$ is assumed to show restrictive factors of regional economic activities. Each restrictive factor c_i has a threshold value. Under the conditions meeting those threshold values, the maximum of each developing variable d_{ij} can be calculated by:

$$\begin{cases} \sum w_i d_{ij} \rightarrow \max \\ \text{subject to } C_{i\min} \leqslant c_i = f_i(d_{i1}, d_{i2}, ..., d_{im}) \leqslant C_{i\max} \end{cases} \quad (1)$$

where w_i is the weight of the developing variable d_{ij}; d_{ij} is the developing variable that is restricted by c_i; d_i is the ith developing factor of developing variable sets; c_i is the ith restrictive factor of a restrictive variable set; $C_{i\min}$ and $C_{i\max}$ are the limited values of the ith restrictive factor c_i; f_i is the relationship between the ith restrictive factor and all developing factors, and it is calculated by step regression; $\sum w_i d_{ij}$ is the value of ecological carrying capacity.

2.2 Regional Ecological Resilience

2.2.1 Definition

Regional ecological resilience is another important indicator to demonstrate the supporting capability of the environment to economic activities. Regional ecological resilience is the environment's capability to maintain and adjust itself when it is disturbed by outside forces, and it deviates from its initial equilibrium.

Regional ecological resilience has two components: flexible intensity and flexible limit. The former is related to the environmental resources in the region, which includes such variables as land use, climate, soil conditions, water resources, and vegetation types. The latter expresses the adjusting capability in the environmental disturbances. The more complicated the composition of the system, the greater the flexibility limit.

2.2.2 Calculation

There are many factors that affect regional ecological resilience. The main factors include regional climate, regional vegetation, and the complementary capability of each component part in the system (PAIN *et al.*, 1997; DONG, 1996; ROSSI and KUITUNEN, 1996). Regional ecological resilience can be calculated by:

$$El = \lambda \cdot \mu \cdot L_i \quad (2)$$

where El is flexible capability of ecological environment; λ is the adjusting coefficient; μ is flexibility coefficient which demonstrates flexible intensity of ecology environment, $\mu = \frac{H \times V}{a_1 a_2}$ (H is the landscape diversity index, V is the vegetation index, a_1 is the annual variation of regional air temperature, and a_2 is the annual variation in regional precipitation); L_i is the flexibility limit, $L_i = \min\{b_1, b_2, ..., b_m\}$, b_i is the fractal dimension of time series of each restrictive factor in the environment (FANG and ZHANG, 1998).

On the basis of theories of ecological carrying capacity and ecological resilience, the evolvement model of vulnerable ecological region can be established.

3 ESTABLISHMENT OF EVOLVEMENT MODEL OF VULNERABLE ECOLOGICAL REGION

Ecological carrying capacity, ecological resilience, economic development intensity, and economic development velocity are used to demonstrate the state of an vulnerable ecological region (JIANG *et al.*, 1999; GOUGH and HERRING, 1993). Table 1 shows the relationship of these four indicators. According to the change trend of those four synthetic indicators, the evolvement model of a vulnerable ecological region can be studied.

Before establishing the evolvement model of a vulnerable ecological region, some assumptions should be noted:

(1) Ecological carrying capacity y_1 has an potential growth rate r_1 because it is affected by some factors such as improvement in economic development and progress in science and technology. There is also a threshold value $K(t)$ (where t is time variable) for the growth of ecological carrying capacity. If other effect factors are not taken into account, the growth trend of y_1 is described as follows:

$$\frac{dy_1}{dt} = r_1 y_1 \left[1 - \frac{y_1}{K(t)}\right] \quad (3)$$

(2) The change trend of ecological resilience y_2 is similar to the change trend of ecological carrying capacity y_1, that is, there is an potential growth rate r_2 within a certain threshold value.

(3) Economic development is an accelerant. In other words, economic development intensity y_3 also has a potential growth rate r_3 and y_3 will grow as follows:

$$\frac{dy_3}{dt} = r_3 y_3 \quad (4)$$

(4) The change trend of economic development velocity y_4 is similar to that of economic development intensity y_3. That is to say, there is a potential growth

Table 1 Interaction of each state variable in vulnerable ecological region

State variable	Ecological carrying capacity y_1	Ecological resilience y_2	Economic development intensity y_3	Economic development velocity y_4
Ecological carrying capacity y_1	y_1 has an potential growth rate and is restricted by a threshold value	——	y_1 has stimulative function to y_3	——
Ecological resilience y_2	y_2 has stimulative function to y_1	y_2 has an potential growth rate and is restricted by a threshold value	——	y_2 has stimulative function to y_4
Economic development intensity y_3	Smaller value of y_3 can promote the growth of y_1, but when y_3 exceeds an optimum value, it will restrain the growth of y_1	——	y_3 has an potential growth rate and is restricted by a threshold value	Within a certain time, both y_3 and y_4 will produce a "consuming" function on y_1 and y_2; y_3 and y_4 compete with each other, i. e., high value of y_3 will result in low value of y_4
Economic development velocity y_4	——	Smaller value of y_4 can promote the growth of y_2, but when y_4 exceeds an optimum value, it will restrain the growth of y_2	Within a certain time, both y_3 and y_4 will produce a "consuming" function on y_1 and y_2; y_3 and y_4 compete with each other, i. e., high value of y_4 will cause low value of y_3	y_4 has an potential growth rate and is restricted by a threshold value

rate but it is restricted by a certain threshold value.

(5) Both resources variables (y_1 and y_2) stimulate the consuming variables (y_3 and y_4). The bigger y_1 and y_2, the greater the potential growth rates of y_3 and y_4, while the variables y_3 and y_4 have a restraining function on the variables y_1 and y_2. Larger values of y_3 and y_4 mean that the growth rates of y_1 and y_2 are smaller.

(6) Only moderate economic development intensity can promote the improvement of ecological carrying capacity. A certain economic development speed can consume the ecological resilience of a vulnerable ecological region. So, y_4 has a negative function relative to y_2. The negative function can be minimized only when y_4 has a moderate value.

Based on those assumptions, the evolvement models of vulnerable ecological region are established as follows:

$$\begin{cases} \frac{dy_1}{dt}=y_1[r_1(1-\frac{y_1}{K_1(t)})+a_1y_2+a_2(-y_3^2+2y_3-0.95)] \\ \frac{dy_2}{dt}=y_2[r_2(1-\frac{y_2}{K_2(t)})+a_3(-y_4^2+2y_4-0.05)] \\ \frac{dy_3}{dt}=y_3(r_3+a_4y_1-a_5y_4) \\ \frac{dy_4}{dt}=y_4(r_4+a_6y_2-a_7y_3) \end{cases} \quad (5)$$

where, y_1, y_2, y_3, y_4 are state variables of vulnerable ecological regions, r_i (r_1, r_2, r_3, r_4) is the potential growth rate of system's state variable and a_i (i=1, 2, 3, 4, 5, 6, 7) demonstrates the interaction of each state variable in the system.

4 CONTROL MODEL FOR EVOLVEMENT OF VULNERABLE ECOLOGICAL REGION

4.1 Theoretical Basis of Control Model

Based on the evolvement model of a vulnerable ecological region, a control model for moderate economic development was set up. It has been proved that the limit dynamics of a fluctuation system locked to a single fluctuation with a frequency as the mean of the individual frequencies under certain conditions (DENG, 1994), i.e., a coupling system that is made up of the same or similar components. Whether the components that constitute the system are different or not, it is ultimately synchronized to the same frequency. Therefore, if the system $\frac{dX}{dt}=f[x(t)]$, $X=\begin{pmatrix} X_S \\ X_R \end{pmatrix}$ was divided into two parts, the frequency of X_R will affect the frequency of X, where X_S is the state system and X_R is the response system. So we can control the evolvement trend of the whole coupling system by adjusting the frequency of the response system.

4.2 Theoretical Analysis of Control Model

The characters of each equation in control model are determined by its parameters.

(1) When y_3 ranges between 0.78 to 1.23, it has positive contribution to y_1. Economic development intensity being too small or too large would produce a negative effect on the environment. However, y_4 only has negative contribution to y_2. Economic development ve-

locity has a negative effect on ecological resilience only. When y_4 is equivalent to 0.05, this negative effect will be minimal.

(2) Obviously, a system's movement depends on the initial values of the system's state variables. These equations showed that there might be some equilibrium points and a limit cycle in the system. Each equilibrium point has a definite absorbing area (when the equilibrium point is stable) or an exclusive area (when the equilibrium point is unstable). If the initial value is situated in the absorbing area of a certain equilibrium point, it will ultimately move to the equilibrium point.

4.3 Factors Affecting Regional Ecological Evolvement

In order to control regional ecological evolvement more conveniently, factors that affect a regional ecological evolvement should be determined. The principal factors are population, technology, and policy (LU, 1999; NORMAN *et al.*, 2003; FANG, 2000).

(1) Population: Human is the most important and active factor in an ecological region. They are the consumers of ecological systems, and also the producers of an economic system. Both the quantity and quality of population affect ecological status of a region. Population quality affects the style and extent of economic development, and thus affects ecological carrying capacity.

(2) Technology: The system of technology is the medium that joins the ecological system with the economic system. Ecological system is the basis of system's evolvement and economic system is the driving force of system's evolvement. And technology can make an economic system develop in a positive direction.

(3) Policy: Policy affects not only the process of evolvement of ecological region, but also the direction of regional evolvement. When the market is out of order and can not allocate environmental resources effectively, policy will be the key factor that affects regional ecological evolvement.

5 CASE STUDY

The styles of evolvement are different in different vulnerable ecological regions (PRESSEY and TAFFS, 2001; PRESSEY *et al.*, 2002). This paper takes Ongniud Banner and Aohan Banner, both located in Inner Mongolia of China, as study cases (Fig. 1). Ongniud Banner extends between a latitude of 42°26′–43°25′N and a longitude of 117°49′–120°43′E, with an area of 11 882km² and a population of 0.47×10^6 in 1998. It is representative region characterized by hilly terrain and

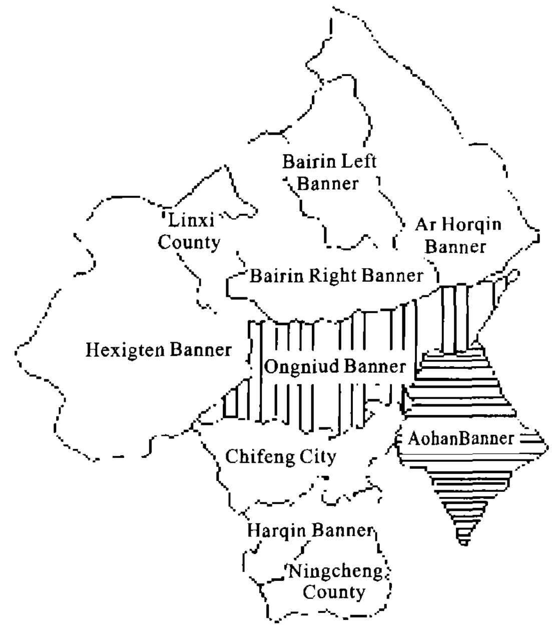

Fig. 1 Location of Ongniud Banner and Aohan Banner

semi-arid climate with a mean annual precipitation of 350–450mm. Aohan Banner extends between a latitude of 41°42′–43°02′N and a longitude of 119°30′–120°53′E, with an area of 8294.14km² and a population of 0.58×10^6 in 1998. It is also a banner characterized by semi-arid climate with a mean annual precipitation of 310–460mm.

Ongniud Banner and Aohan Banner are poor regions, with the GDP per capita of 1415 yuan (RMB) in Ongniud Banner and 2925 yuan in Aohan Banner in 1998. They are greatly lower than those of the average GDP per capita in China (6361 yuan in 1998)(Table 2).

Table 2 GDP per capita in Ongniud and Aohan banners and in China in 1998

	GDP per capita (yuan)	Value-added of primary industry ($\times10^6$ yuan)	Value-added of secondary industry ($\times10^6$ yuan)	Value-added of tertiary industry ($\times10^6$ yuan)
Ongniud Banner	1451	400	145	137
Aohan Banner	2925	970	294	420
China	6361	1459960	3869180	2610430

In China, the areas of semi-arid and sub-humid ecological regions (to which Ongniud Banner and Aohan Banner belong) occupy more area than any other kind of vulnerable ecological region. These two banners have similar natural geographic features. Both suffer from severe soil erosion and irrational industrial structure, caused by overusing or overexploiting environmental resources. But they differ in their level of economic development and access to external markets: Ongniud Banner's level of economic development is lower and its infrastructure and hence access to external markets also lags behind. Based on these features, research has been conducted on the evolvement and control of vulnerable ecological regions.

5.1 Evolvement Model for Ongniud and Aohan

GDP per capita and the modernization level of agricultural and industrial infrastructure were chosen as development variables. The number of limiting variables was determined by calculating the fractal dimension of development variables' time series. The variable that had bigger correlation coefficient with development variables was chosen as the limiting variable. Finally, ecological carrying capacity and ecological resilience were calculated and the results are shown in Table 3.

Based on the theories of ecological carrying capacity and ecological resilience, the evolvement models for the vulnerable ecological regions of Ongniud and Aohan banners are established. The evolvement model of the vulnerable ecological region in Ongniud Banner is as follows:

$$\begin{cases} \frac{dy_1}{dt} = y_1\left[0.5\left(1-\frac{y_1}{K_1(t)}\right)+0.20y_2+0.10(-y_3^2+2y_3-0.95)\right] \\ \frac{dy_2}{dt} = y_2\left[\left(1-\frac{y_2}{K_2(t)}\right)+0.5(-y_4^2+0.1y_4-0.05)\right] \\ \frac{dy_3}{dt} = y_3(0.15+0.03y_1-0.4y_4) \\ \frac{dy_4}{dt} = y_4(0.25+0.25y_2-0.1y_3) \\ (y_1,\ y_2,\ y_3,\ y_4)_0=(1.21,\ 0.052,\ 1,\ 0.05) \end{cases} \tag{6}$$

According to this model, state variables for the vulnerable ecological region in Ongniud Banner have

Table 3 Ecological carrying capacity and ecological resilience in Ongniud Banner and Aohan Banner

		1990	1991	1992	1993	1994	1995	1996	1997	1998
Ecological carrying capacity	Ongniud Banner	1.21	1.17	1.08	1.30	1.40	2.32	1.75	2.60	1.90
	Aohan Banner	1.23	1.20	1.13	3.54	1.73	2.15	4.61	3.92	4.22
Ecological resilience	Ongniud Banner	1.94	0.06	0.73	1.46	0.24	0.53	7.97	0.23	0.40
	Aohan Banner	0.58	1.23	0.30	0.28	1.50	1.97	0.52	0.52	0.22

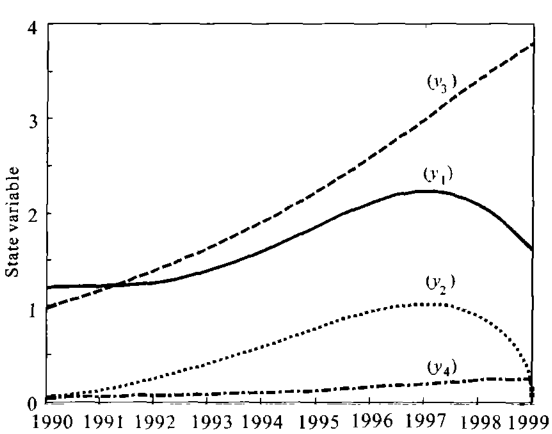

Fig. 2 Evolvement of state variables in Ongniud Banner

been obtained. The results are shown in Fig. 2.

Fig.2 shows that economic development intensity has a fast growth rate while ecological carrying capacity and ecological resilience dropped quickly after a long ascending period under the existing mode of economic development. In addition, being affected by the change of economic development intensity, ecological carrying capacity went up when it dropped to 1.2 in 1991 and then went into a new ascending period and it dropped continuously in 1997 and 1998. The change of ecological resilience has a big fluctuation. In 1998, it changed suddenly and affected the whole evolvement process of the region. Obviously, this model of development was unacceptable to policy makers, and man-made effort must be exerted on the vulnerable ecological region to change this evolvement trend.

Equation (7) is the evolvement model of Aohan Banner. The results are shown in Fig. 3.

$$\begin{cases} \frac{dy_1}{dt} = y_1\left[0.5\left(1-\frac{y_1}{K_1(t)}\right)+0.10y_2+0.02(-y_3^2+2y_3-0.95)\right] \\ \frac{dy_2}{dt} = y_2\left[0.1\left(1-\frac{y_2}{K_2(t)}\right)+0.01(-y_4^2+0.1y_4-0.05)\right] \\ \frac{dy_3}{dt} = y_3(0.05+0.10y_1-0.5y_4) \\ \frac{dy_4}{dt} = y_4(0.10+0.50y_2-0.1y_3) \\ (y_1,\ y_2,\ y_3,\ y_4)_0=(1.232,\ 0.582,\ 0.05,\ 1) \end{cases} \tag{7}$$

Fig. 3 shows that the four state variables of the vulnerable ecological region in Aohan Banner rose to varying degrees under the existing model of economic development. Ecological carrying capacity went up in 1990–1998. And this did not have a negative effect on economic development intensity. Ecological resilience

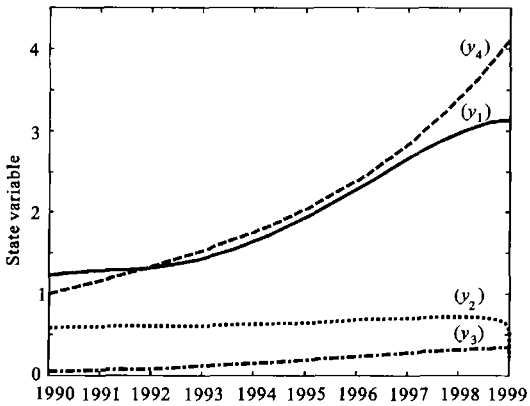

Fig. 3 Evolvement of state variables in Aohan Banner

and economic development intensity both went up continuously in this period. Ecological resilience changed suddenly in the ninth year, which caused uncertainty in the evolvement process. Economic development velocity went rapidly up over the nine years. The range was between 1.0 and 4.2. But in the ninth year, ecological carrying capacity and ecological resilience both fell, directly affected the economic development intensity and velocity in vulnerable ecological region.

5.2 Control Model for Evolvement Process

According to the driving factors of vulnerable features and vulnerability in the vulnerable ecological regions of Ongniud Banner and Aohan Banner, some relevant control measures were put forward and their effects were analyzed. Ongniud Banner is a vulnerable ecological region where economic development level is low and the capacity of linking with the outside is weak. So the relevant measure is to overcome poverty. Aohan Banner is an vulnerable ecological region where main environmental problem was soil erosion caused by the overuse of resources. Correspondingly, the control measure is to raise investment in environmental protection. These control measures can be regarded as response subsystem and they can be quantified. As a result, the state-response coupling model of vulnerable ecological region in Ongniud Banner can be made as Equation (8):

There are six parameters c_1, c_2, c_3, c_4, z_1, and z_2 in this model. Adjusting these parameters demonstrates that the state variables in the model are very sensitive to c_3 and c_4, and it shows that the evolvement trend of Ongniud Banner has a close relationship with its economic development style and the type of investment.

Similarly, adding ecological environment protecting system into the state-response equation as a response subsystem can obtain the coupling model for Aohan Banner(Equation (9)).

It can be found that the rate of increase of the investment amount in environmental protection must be over 80% per year to reverse the declining trend of ecological carrying capacity when adjusting the state-response equation of Aohan Banner. But given the limited resources of the government, this is not acceptable. If the rate of increase of investment was fixed at 5%, and 51% of the investment were used to raise ecological carrying capacity and 49% of the investment were used to raise the regional economic development velocity, it could be found that each state variable could be risen steadily.

$$\begin{cases} \dfrac{dy_1}{dt}=y_1[0.5(1-\dfrac{y_1}{K_1(t)})+0.20y_2+0.10(-y_3^2+2y_3-0.95)+ \\ \qquad c_2z_1] \\ \dfrac{dy_2}{dt}=y_2[(1-\dfrac{y_2}{K_2(t)})+0.5(-y_4^2+0.1y_4-0.05)+c_2z_2] \\ \dfrac{dy_3}{dt}=y_3(0.15+0.03y_1-0.4y_4+c_3(1-c_1)z_1+(1-c_2)c_4z_2) \\ \dfrac{dy_4}{dt}=y_4(0.25+0.25y_2-0.1y_3+(1-c_3)(1-c_1)z_1+ \\ \qquad (1-c_2)(1-c_4)z_2) \\ \dfrac{dz_1}{dt}=b_1 \\ \dfrac{dz_2}{dt}=b_2 \\ (y_1,\ y_2,\ y_3,\ y_4,\ z_1,\ z_2)_0=(1.9, 0.4, 3.5, 0.4, 0, 0) \end{cases} \tag{8}$$

$$\begin{cases} \dfrac{dy_1}{dt}=y_1[0.5(1-\dfrac{y_1}{K_1(t)})+0.10y_2+0.02(-y_3^2+2y_3-0.95)+ \\ \qquad cz] \\ \dfrac{dy_2}{dt}=y_2[0.1(1-\dfrac{y_2}{K_2(t)})+0.01(-y_4^2+0.1y_4-0.05)] \\ \dfrac{dy_3}{dt}=y_3(0.05+0.10y_1-0.5y_4) \\ \dfrac{dy_4}{dt}=y_4[0.10+0.50y_2-0.1y_3+(1-c)z] \\ \dfrac{dz}{dt}=b \\ (y_1,\ y_2,\ y_3,\ y_4,\ z)_0=(4.22, 0.222, 4.316, 0.33, 1) \end{cases} \tag{9}$$

6 CONCLUSIONS

Based on the theories of ecological carrying capacity and ecological resilience, an vulnerable ecological region's evolvement model was established. Those synthetic variables are ecological carrying capacity, ecological resilience, economic development intensity and economic development velocity. It also examined the evolvement processes in a vulnerable ecological region under several hypothetical economic activity styles. The results show that human economic development activity has an important influence on the evolvement trend of vulnerable ecological region. The state of vulnerable ecological region and the effect of human activity on these state variables were described more accurately and quantifiably.

The best control models for economic development in two typical vulnerable ecological regions were analyzed. The results show that the main control measures to make vulnerable ecological region in Ongniud Banner evolve in a benign cycle are to increase investment, overcome poverty and make the investment environment more attractive to raise infrastructure capacity and link with other regions. The general evolvement trend for Aohan Banner is better than that for Ongniud Banner because the trend in economic development intensity for Aohan Banner was more sustainable. Aohan Banner's economic development plan is (on the basis of the existing investment used to administer the environment) to increase investment by 5% each year. One half of this investment is used to increase ecological carrying capacity and the other should be used to increase its economic development velocity. This control model can make each state variable for Aohan Banner rise steadily.

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