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RESEARCH ARTICLE

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Health diagnoses of ecosystems subject to a typical erosion environment in Zhifanggou watershed, north-west China

Abstract Ecosystem health is the object of water and soil conservation and ecological building in loess hilly areas under erosion environment. Using principles of ecosystem health quantitative assessment and diagnosis index selection, 17 factors were considered from three aspects: resource and environmental capacity, social and economic impact, and ecological services. An evaluation index system on ecosystem health was established for a small watershed under erosion conditions. Mean-square deviation was employed to determine the weight of each factor and then step-up multi-layer synthesis with linear weighting function was used to build a two-level hierarchy and collection index health consultation model. The health dynamics of the ecosystem in the small watershed under erosion conditions was analyzed. Results show that the watershed ecosystem is relatively stable and has an increasing annual fluctuation (0.370 in 1985 to 0.573 in 2003) for the health index. This increasing trend indicates an adequately strong ability for sustainable development. At the same time, obstacles and advantages to the watershed ecosystem health were studied by introducing the concepts of obstacle degree and advantage, and path analysis method, considering the real economic optimal level as the uppermost goal. Finally, suggestions on ecological building were provided as a scientific basis for ecosystem rehabilitation in the small watershed.

Keywords ecosystem health, quantitative assessment, small watershed, erosion environment

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1 Introduction

Ecosystem health, which has been a hot topic in ecology since the late 1980s, has focused on the functional amplitude of the system, identification of confusion, load capacity of organizational structure, restoration capacity, expanding capacity, program diagnosis, effective target design, system of health diagnoses, research on coordination, and coupling (Coluell, 1996; Kong et al., 2002). Scholars worldwide have conducted a number of studies on ecosystem health. For example, Schaeffer et al. (1998) studied the tolerance of ecosystem health, and Rapport (1989) expounded on the connotation of health of an ecosystem. Current research has played an important role in natural science (Shen, 1997; Wu et al., 1999; Zeng et al., 1999; Ren et al., 2000). However, these studies are neglected in China, especially the ecosystem health of an erosion environment.

An erosion environment, having a unique erosion landscape and ecosystem, is a compound environmental system defined by both natural and human factors (Tang and He, 1999). The foundation of a healthy ecosystem in a small watershed is an essential unit of the ecosystem of an erosion environment, and supports the ecological and environmental construction of loess hilly areas. The Zhifanggou watershed, located in the loess hilly area north of Shanxi and under a typical erosion environment, has been comprehensively harnessed for over 20 years via three stages: starting recovery, steady development, and present benign circulation, and has progressed into healthy development from a degenerative state (Lu et al., 1997; Liu et al., 2003). However, with the growing awareness of both water and soil conservation and a social economy, there is now a higher demand for the comprehensive control and ecological construction of watersheds worldwide (Walker and Reuter, 1996; Noble and Dirzo, 1997; Liu et al., 1999; Liu et al., 2003). Thus, the analysis on evolving rules of the ecosystem of an erosion environment and its health diagnosis has important theoretical and practical applications to promote such an environment and its sustainable development.

For this paper, we build the hierarchical model of health evaluation based on the work of Liu et al. (2003). Moreover, we introduce indices that reflect the development and improvement of the ecosystem of an erosion environment and human behavior. Applying statistics of postural value about eco-environment restoration, we establish the weight of each factor, which ameliorates calculation methods and eliminates artificial subjective randomness. A quantificational evaluation on the eco-agricultural health of water and soil conservation was provided in the Zhifanggou small watershed in the typical erosion environment, which provided a basis for policy decision-making on system development in the small watershed.

2 Study area

The study site, located in the Zhifanggou watershed, is a typical erosion environment with an area of 8.27 km^2 and is situated in the hinterland of the loess hilly area (36°51′ N, 109°19′ E) in Ansai, Shanxi Province. The climate of the area is warm with a tendency to be semi-arid. Average annual rainfall is 524.5 mm and average annual temperature is 8.8°C. Zonal dark loessial soil was replaced by loess soil developing on the parent-rock due to soil and water loss in the watershed, which is affected by the discontinuous and undulate landform. The area lies in an interim of forest and plains where vegetation was destroyed by human activity. In 1938, the population density in the area was 11.4 person/km^2, coverage of arbors and shrubs was 51.2% and the grain yield was 1,449 kg/hm^2. Between 1938 and 1958, the population density went up to 26.7 persons/km^2, the reclamation index reached 51.5%, the grain yield was reduced to 415.5%, and soil erosion modulus was 15,000 t/km^2. Moreover, the ecosystem was significantly ruined; the forest area was only 0.4% of the watershed. Since 1973, conservation of the soil and water laboratory of Ansai began with comprehensive control on the watershed and the reversion of farmland to forests and grassland. In 2002 the coverage of forest and grass went up to 60%, food yield improved to 4,438.5 kg/hm^2, and the degraded ecosystem recovered. At the same time, annual commissariat and economic earning rose and the ecology improved observably in spite of a continued population increase.

3 Health diagnosis of the small watershed on typical erosion environment

The ecosystem of an erosion environment is a compound system of ecological and economic systems, an open system and a system of relative heterogeneity marked by continuous flows of energy, substance and communication among each subsystem. The health of other subsystems, and even the whole environment, will be affected if one of the subsystems is mangled. At the same time, human activity such as change of land use, irrigation and fertilization of farmland and various hydraulic projects play an important role in the system's health. Research on the health of the ecosystem in an erosion environment must consider vital characteristics connecting each subsystem and human activity. Such a definition recognizes that managers have the ability to carry out rational strategies to maintain ecological safety, production ability and the state of sustainable development. A healthy ecosystem in an erosion environment has at least the following six characteristics (Walker and Reuter, 1996; Lu et al., 1997; Liu et al., 2003):

1) average annual soil loss should be controlled below 1,000 t/($km^2 \cdot$year) and the environment should have the ability to recover when subjected to a natural disturbance;

2) it can safeguard itself from a crisis of the ecosystem;

3) it can maintain itself (can exist without input);

4) it does not damage other ecosystems nearby as it is managed and used;

5) it can provide rational ecological services for nature and humans;

6) it can maintain the health of human communication.

3.1 Index selection and construction of a diagnosis system

The main approaches to a healthy diagnosis of ecosystems are the indicator species and index system. The method of indicator species is popular in land and water ecosystems. Although convenient, it does not consider indices in social economy and human health. Meanwhile, an index system mainly includes indices of social economy and human health and compounds other information to diagnose the health condition of a system. For the erosion environment in Zhifanggou, we adopt the index system based on health, substance circulation and energy flow of the ecosystem. Sieving indices must reach the following five goals: 1) to reflect comprehensively and accurately the health condition of the ecoystem of the erosion environment; 2) to provide representative patterns reflecting present status; 3) to monitor conditions linked to biophysics and human intimidation in the ecosystem and find the relation between natural and human stress and transformation of a healthy ecosystem; 4) to find causes of ecosystem degradation; and 5) to provide a statistical summary and explanatory report about healthy conditions, change and trends of the ecosystem for government, science and human use. Sieving indices must maintain the following principles: 1) entirety; 2) spatial yardstick; 3) category or types of index; 4) conciseness and maneuverability; and 5) standardization.

Based on the above goals and principles, we selected a series of indices reflecting the impact of the present situation and trends of society, economy, resource, environment and human health on the ecosystem in a loess hilly area under an erosion environment, and we construct three levels. The first level is ecosystem health indicators; resource-environment support levels (T_1), social economy state effect (T_2) and eco-comprehensive function (T_3) make up the second level, and the third level covers the resource index (C_1), environment index (C_2), social economy index (C_3), human-culture index (C_4), comprehensive index (C_5) and soil index (C_6), which involves 17 idiographic indices, $x_1, x_2, x_3 \ldots\ldots x_{17}$ (Fig. 1).

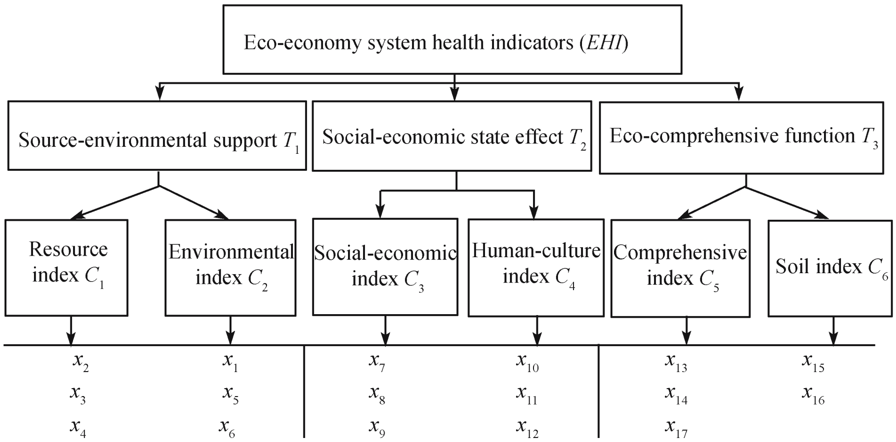

Fig. 1 Hierarchical structure of health diagnosis of an ecosystem in a small watershed in erosion environment

C_1: per capita basic farmland x_2 (hm^2), per capita grassland x_3 (hm^2), amount of livestock on hand x_4;

C_2: forest and grass density x_1 (%), organism content x_5 (g/kg), harness degree x_6 (%);

C_3: output-input ratio of agriculture x_7, per capita net income x_8 (yuan), the rate of contribution of industrial by-line x_9 (%);

C_4: population density x_{10} (a person/km^2), popularization rate of compulsory education x_{11} (%), Engel coefficient x_{12};

C_5: the realization rates of per unit area grain yield productivity x_{13} (Lu et al., 1997) (%), sediment-reducing benefit of comprehensive treatment x_{14} (%), system resilience x_{17} (Lu et al., 1997) (%);

C_6: soil anti-scouribility x_{15} (L·min/g), sediment-reducing benefit of comprehensive treatment x_{16}

3.2 Diagnostic method and model construction

The index weight is vital for the diagnostic method. Generally, the index weight is sorted into subjective and objective endowing methods according to the source of the original data. The subjective endowing method is a relatively mature method but lacks objectivity. Under this approach, experts judge using their experiences, such as the methods of Gulin, Delphi and AHP (analytical hierarchy process). The objective endowing method utilizes statistical calculation according to the source of original data and eliminates the man-made factor. This approach applies techniques such as measure of dispersion, the mean-square deviation decision method, and main components analytical method. We adopted mean-square deviation, which is accurate for ascertaining the weight of indices and constructing a diagnostic model to combine with other statistical measures to comprehensively assess the ecosystem in the small watershed of loess hilly areas under a typical erosion environment.

3.2.1 Definition and calculation of single index

A majority of indices can be acquired by surveying or by field testing, and by observing frequently. A few indices need explanation and are developed using some formula.

1) Engel coefficient (x_{12})

The Engel coefficient is a significant index reflecting poverty and wealth (Wang, 2003). The state of poverty or wealth of living in an erosion environment determines whether the environment is controlled and eco-system is recovered successfully, so this index is representative for the diagnosis of a healthy ecological system. The formula is as follows

Engel coefficient (%) = (payout of food/payout of consumption) × 100%.

Generally, the lower the Engel coefficient, the more well-off are the locals. The Food and Agriculture Organization (FAO) puts forward a standard to differentiate poverty and wealth: over 59%, absolute poverty; between 50%–59%, reluctant living; between 40%–50%, well-to-do level; between 30%–50%, wealthy; below 30%, wealthy enough.

2) Potential realization rates for the grain yield productivity per unit area (x_{13})

The realization rate is a ratio of productivity of land (kg/hm^2) to the potential maximal yield of crop under the local climate (5,745 kg/hm^2) (Wu, 2002). The magnitude of the realization rates can reflect whether local productivity of land is in accord with the actual industry setting. Food security in loess hilly areas plays an important role in the food security in China (Wu, 2002). The realization rate is an integrated productivity index that can reflect the condition of moisture and nutrients of an erosion environment.

3) System anti-converse (x_{17})

System anti-converse (Wu, 2002) is the ability of disaster resistance in the system, and can be expressed as the ratio of agricultural production value in a disaster year to average agricultural production in a watershed.

4) Soil anti-scouribility (x_{15})

Soil anti-scouribility is the resistance ability to breakage from an outside force such as runoff, wind, and rainfall. It plays an important role in the diagnostic system and is associated with soil physiochemistry and biological factors. We measured it by the method of original soil erosion (Hu et al., 2000). The formula is as follows

$$S_0 = (Q \times t) / M \tag{1}$$

where S_0 is soil anti-scouribility (L·(min/g)); Q is total scouring soil (mL); t is scouring time (min); M is scouring dry-soil (g).

5) Soil permeability (x_{16})

Soil permeability is a process wherein water enters the soil and generates soil water. It is an important factor in the transformation of precipitation, surface water, soil water, and ground water (Wu, 2002). It is measured by a large infiltration tube (Wang, 2003). The formula is as follows

$$K_{10} = 10Q_i\,L\,/\,(S\,(0.7+0.03t)\,(H+L)t_i) \qquad (2)$$

where K_{10} is the coefficient of soil permeability; Q_i is the transudatory soil water amount in t_i (mL); S is the area of cross section of the infiltration tube; L is soil thickness (cm); H is water thickness (cm); and t_i is osmotic time (min).

3.2.2 Calculation of indices weight

Fuzzy set theory was adopted to gain the standardization of indices by introducing a subordinate function.

To the benefit type indices

$$y_{ij} = (x_{ij}\,/\,x_{j\max})C \times 10\% \qquad (3)$$

To the cost-oriented indices

$$y_{ij} = (x_{j\min}\,/\,x_{ij}) \times 100\% \qquad (4)$$

where $x_{j\max}$ is the maximum of I_j; $x_{j\min}$ is the minimum of I_j; and C is the constant of scoring ambiguity. Generally, $C>1$, $C=1.1$ in the calculation (ambiguity is lower in the ecosystem of a small watershed).

After the standardization of indexes, the decision-making matrix is

$$Y = (y_{ij})_{nm}$$

Apparently, the larger y_{ij} is the better. The mean-square deviation method (Wang, 1999) was adopted to calculate the coefficient weights w_j, w_k, and w_i of single index (x_j), the second level index (T_i), and the third level index (C_k), respectively (Dai et al., 2005a, 2005b).

3.2.3 Health diagnosis model

Mean-square deviation was employed to determine the weight of each factor, which reflected health level during a certain period, and basically evaluate a harmonious and persistent development trend in the watershed. To study the health condition of a small watershed in a typical erosion environment, we built an index model of a health system. The indices of the health system represented the general level of comprehensive control measures, ecological environment construction and economic development.

1) Second level health indices

According to the character of the index system in the watershed, each index of the secondary level could not be replaced by another. They are indispensable conditions of the resource-environmental support, social-economic state effect and the health of eco-comprehensive function. We thus adopted the linear weighting function method to calculate the secondary health indices (Wang, 1997).

$$I_t = \prod\left[\sum (y_{ij} w_j)^{w_k}\right] \qquad (5)$$

where I_t is the secondary index, T_i is health index, y_{ij} is value of quantitative indices, w_j is the monomial weight of index, and w_k is the weight of the third index.

2) Index of health system

Each index reflects the health level of the erosion environment from different aspects in the secondary index, and the whole level must be evaluated synthetically. Therefore, we adopted a linear weighting function to calculate the index of the health system.

$$I_h = \sum_{i=1}^{3} (I_t w_i) = \sum_{i=1}^{3} \left\{\prod\left[\sum (y_{ij} w_j)\right]^{w_k}\right\} w_i \qquad (6)$$

where I_h is the index of the health system in the loess hilly areas under the eco-economic system; w_i is the weight of the secondary index; the classification meaning of I_i and I_h is in accord with the research by Lu (1997).

The ecosystem in Zhifanggou small watershed was classified on vicious cycle, fragility, relative stability, better and benign cycle. According to the actual change of erosion environment and the development process, the health standard is scientific and credible. We thus introduced this in our research (Table 1).

Table 1 Health criteria of eco-economic system in loess hills area

Health grade	Vicious circulation	Fragility	Relative stability	Better	Benign circulation
Health index	<0.15	0.15–0.35	0.35–0.55	0.55–0.70	>0.70

3.2.4 Diagnoses of barrier and predominance

The objective of diagnoses is not only limited to diagnosing the health condition of the watershed, but also exploring the health development factor about barrier and predominance, which benefits harnessing of the environment and readjusting related policy. First, we calculated the obstacle (L_j) and dominance (A_j) based on literature (Dai et al., 2005b). Second, we used path analysis to ensure the factor about barrier and predominance of the system.

Path analysis was introduced by Sewall Wright in 1921, a geneticist in the USA, to evaluate pluralistic analyses of the relative coefficient in depth (Bhatt, 1973; Ming, 1990). The method is not only able to measure the connection between two variables, but can also reflect significance of the result. Moreover, it can disassemble correlative coefficient as a direct and indirect effect and reflect the relative significance of each fact for the result.

To an inter-related system, there is a linear relation between a dependent variable (y) and n independent variables (x_i) ($i = 1, 2, \ldots, n$). The regression equation is as follows

$$y = b_0 + b_1 x_1 + b_2 x_2 + \cdots + b_n x_n \tag{7}$$

To calculate the path coefficient P_{yx_i}, we used actual observation value and the principle of least squares method. The path coefficient is the coefficient of side-regression of variable standardization and expresses the significance of reason for the result.

The formula (7) can construct a normal matrix equation by means of mathematic commutation

$$\begin{bmatrix} 1 & r_{x_1x_2} & \cdots & r_{x_1x_n} \\ r_{x_2x_1} & 1 & \cdots & r_{x_2x_n} \\ \vdots & \vdots & \ddots & \vdots \\ r_{x_nx_1} & r_{x_nx_2} & \cdots & 1 \end{bmatrix} \begin{bmatrix} P_{yx_1} \\ P_{yx_2} \\ \vdots \\ P_{yx_n} \end{bmatrix} = \begin{bmatrix} r_{x_1y} \\ r_{x_2y} \\ \vdots \\ r_{x_ny} \end{bmatrix} \tag{8}$$

where $r_{x_iy_j}$ is the simple relative relation of x_i and y_j; $r_{x,y}$ is the simple relative modulus of x and y; the path coefficient (P_{yx_i}) can be calculated by formula (8)

$$P_{yx_i} = b_i \frac{\sigma_{x_i}}{\sigma_y}, \quad (i = 1, 2, \cdots, n) \tag{9}$$

where b_i is the side-regresssion coefficient of y to x_i; σ_{x_i}, σ_y are x_i, y respectively; P_{yx_i} is direct path coefficient of x_i to y; $r_{x_iy_j}$ and P_{yx_i} are indirect path coefficients of x_i to y by x_j.

The residual path coefficients of item (P_{ye}) are

$$P_{ye} = \sqrt{1 - (r_{x_1y} P_{yx_1} + r_{x_2y} P_{yx_2} + \cdots + r_{x_ny} P_{yx_n})} \tag{10}$$

The larger P_{ye} representing the less important factor should be considered or a larger error exists.

4 Results and analysis

4.1 Quantification of diagnostic indices and weight determination

On the basis of the index system, we obtained values of each numerical index of the ecosystem in Zhifanggou in the loess hilly areas under an erosion environment by analyzing experimental data, observation and investigation of many years combining the definition of the index. To obtain the weight of each index, we quantified original data with the method above and obtained the value of the quantitative index.

The index values of the watershed system had a wave-like increase over time. In particular, the ecological environment of the watershed improved gradually and took on the trend of benign circulation (Table 2). Each index of the watershed ecosystem had preferable health condition and harmonized with each other commendably. The difference of each index weight was not obvious. For example, the weight of source-environment support was 0.284,3, the weight of social-economic state effect was 0.360,5 and the weight of eco-comprehensive function was 0.355,2 (Table 3).

Source-environment support, social-economic state effect and eco-comprehensive function were of the secondary level index and increased wave-like over time (Fig. 2). Source-environment support rose smoothly, while social-economic state effect and eco-comprehensive function changed rapidly. In particular, the health index of eco-comprehensive function rose rapidly from 0.351 in 1985 to 0.611 in 2003. Generally, the source-environment, social-economic state and eco-comprehensive function of the watershed system improved yearly. Moreover, they followed the trend of benign circulation.

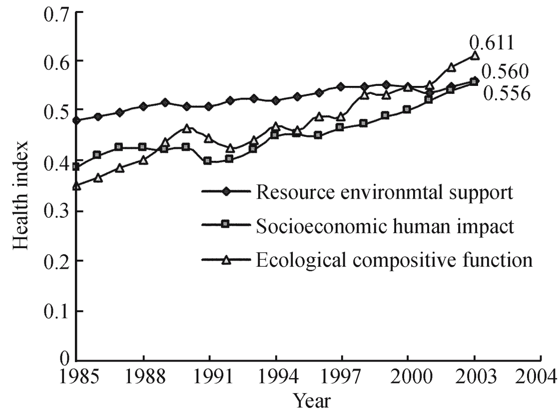

Fig. 2 Variance of resource environmental support, social economy human impact and ecological compositive function health index

4.2 Dynamics diagnoses of health system

We used the values of attribute and index weight from Tables 2 and 3 and formula (5) to calculate and gain dynamic change of the two-level health index of the small watershed ecosystem. Moreover, we used formula (6) to calculate the health index of the ecosystem and draw a dynamic curve (Fig. 3).

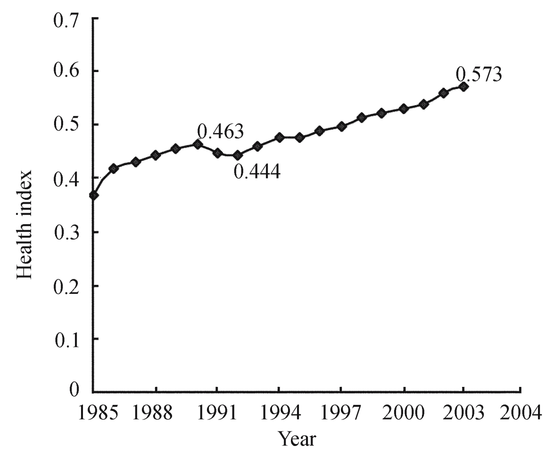

Fig. 3 Temporal variance of integrated health index in Zhifanggou watershed

Table 2 Indicator values for health diagnosis of the ecosystem in the Zhifanggou watershed

Year	Index																
	x_1	x_2	x_3	x_4	x_5	x_6	x_7	x_8	x_9	x_{10}	x_{11}	x_{12}	x_{13}	x_{14}	x_{15}	x_{16}	x_{17}
1985	0.478,7	0.415,5	0.869,5	0.796,6	0.758,7	0.308,2	0.770,2	0.065,2	0.148,2	1	0.461,3	0.630,9	0.155,4	0.070,2	0.137,9	0.704,4	0.750,0
1986	0.567,3	0.432,9	0.832,8	0.768,7	0.758,3	0.374,0	1	0.088,1	0.162,7	0.967,8	0.502,9	0.640,2	0.191,4	0.211,9	0.164,8	0.714,6	0.667,7
1987	0.588,7	0.481,8	0.821,0	0.856,1	0.777,0	0.392,6	0.770,7	0.105,9	0.499,6	0.937,5	0.523,8	0.659,5	0.189,3	0.242,7	0.229,9	0.713,9	0.828,9
1988	0.622,2	0.591,6	0.832,0	0.838,2	0.802,4	0.476,0	0.818,4	0.138,0	0.447,6	0.914,6	0.544,8	0.690,7	0.230,8	0.437,9	0.231,7	0.723,1	0.771,5
1989	0.637,8	0.605,9	0.817,1	1	0.808,6	0.495,0	0.586,0	0.180,7	0.487,2	0.892,7	0.565,9	0.701,7	0.266,2	0.613,5	0.512,2	0.732,3	0.709,8
1990	0.658,2	0.660,0	0.766,2	0.661,2	0.816,2	0.547,0	0.467,7	0.223,3	0.586,0	0.882,9	0.608,2	0.690,7	0.448,6	0.614,9	0.569,0	0.731,8	0.902,7
1991	0.663,0	0.710,2	0.663,5	0.575,2	0.870,9	0.549,7	0.326,2	0.155,4	0.455,1	0.810,1	0.672,2	0.724,7	0.335,8	0.581,3	0.614,2	0.747,7	0.700,4
1992	0.727,2	0.736,2	0.756,0	0.613,7	0.903,5	0.643,9	0.230,1	0.239,6	0.439,8	0.769,7	0.726,1	0.749,3	0.194,9	0.623,3	0.624,9	0.751,2	0.477,6
1993	0.750,3	0.783,7	0.725,6	0.602,5	0.893,1	0.688,6	0.418,6	0.305,8	0.436,2	0.747,9	0.780,2	0.775,5	0.423,8	0.643,0	0.629,8	0.754,3	0.359,2
1994	0.716,3	0.791,1	0.707,7	0.540,6	0.903,2	0.709,7	0.384,2	0.577,9	0.426,0	0.734,5	0.823,7	0.803,5	0.528,3	0.685,4	0.637,0	0.759,5	0.678,8
1995	0.736,9	0.842,6	0.731,9	0.630,5	0.903,7	0.740,7	0.612,3	0.594,9	0.283,9	0.739,3	0.812,8	0.818,3	0.420,6	0.674,1	0.642,6	0.769,4	0.713,5
1996	0.784,5	0.852,5	0.714,2	0.776,5	0.897,0	0.742,1	0.552,9	0.518,4	0.351,2	0.743,4	0.856,5	0.803,5	0.613,4	0.725,2	0.641,5	0.773,7	0.968,6
1997	0.779,7	0.886,4	0.727,9	0.936,4	0.940,1	0.774,7	0.427,4	0.499,3	0.690,8	0.743,4	0.878,4	0.833,5	0.359,1	0.985,3	0.668,7	0.783,9	0.987,5
1998	0.789,4	0.909,9	0.716,2	0.714,8	0.942,5	0.917,9	0.384,9	0.702,3	0.593,1	0.740,4	0.900,5	0.882,8	1	0.778,0	0.938,9	0.945,6	0.900,3
1999	0.793,1	0.909,9	0.735,1	0.739,8	1	0.950,8	0.304,9	0.786,6	0.779,9	0.740,4	0.922,5	0.937,9	0.719,8	0.785,2	0.962,3	0.965,7	0.959,6
2000	0.862,0	1	1	0.380,9	0.977,8	0.983,8	0.429,7	0.590,2	1	0.843,1	0.977,8	0.978,5	0.789,1	0.838,3	0.969,6	0.985,9	0.962,3
2001	0.900,4	0.984,2	0.773,4	0.279,5	0.980,0	0.983,9	0.380,0	0.749,8	0.912,5	0.829,8	0.977,8	0.957,8	0.808,4	0.854,4	0.979,3	0.997,4	0.966,9
2002	0.960,0	0.982,0	0.631,6	0.540,2	0.987,0	0.989,8	0.403,8	0.814,2	0.930,8	0.827,9	0.988,9	1	0.844,7	0.970,7	0.986,9	0.988,1	0.976,5
2003	1	0.954,0	0.680,0	0.448,4	0.989,1	1	0.467,8	1	0.988,8	0.804,3	1	1	0.843,2	1	1	1	1

Table 3 Indicator weights for health diagnoses of the ecosystem in the Zhifanggou watershed

Hierarchical structure			Indicator	Weight
			x_2	0.059,2
	Source-environment T_1 0.284,3	Resource index C_1 0.144,3	x_3	0.026,6
			x_4	0.058,5
			x_1	0.042,1
		Environment index C_2 0.140,0	x_5	0.025,7
			x_6	0.072,1
			x_7	0.063,1
Health indicator *CHI*	Social economy T_2 0.360,5	Social economy index C_3 0.236,6	x_8	0.091,7
			x_9	0.081,8
			x_{10}	0.027,0
		Human-culture index C_4 0.123,8	x_{11}	0.057,8
			x_{12}	0.039,2
			x_{13}	0.089,9
	Ecology function T_3 0.355,2	Comprehensive index C_5 0.228,2	x_{14}	0.081,2
			x_{17}	0.057,0
			x_{15}	0.090,7
		Soil index C_6 0.127,1	x_{16}	0.036,3

The health index followed an ascending fluctuating trend, rising from 0.370 in 1985 to 0.536 in 2001 after a relatively steady state. It entered a rapid state after 2002 and reached 0.573 in 2003. Moreover, the trend was developing to the highest grade of health phase, which was a benign circulation (Fig. 3). Since 1973, water and soil conservation laboratory of Anshai began to control the small watershed, with support from the sixth and seventh five-year plans of Shanxi Province Technologies Research and Development Programme. Thus, the ecological system in the erosion environment was recovered and rebuilt by carrying out a series of measures, putting rainfall interception in place, setting up soil and water loss prevention at the center, and taking land utilization rationally as a prerequisite. Moreover, the system took recovering and rebuilding of vegetation and basic farmland, and developing the eco-forest and aquaculture as four dominant measures of eco-agricultural development of soil and water conservation. Apparently, the method and measures were scientific and rationally generalized for a loess hilly site under an erosion environment.

4.3 Diagnoses of obstacle and predominance

4.3.1 Obstacle diagnoses

We must diagnose the obstacle of the system to improve health conditions of a typical erosion environment. According to the above methods, we counted every single index by applying formula (9) and calculated obstacle (L_i) and health index (I_h) with SAS (science analysis software) software (Table 4). Numbers with * sign were direct path coefficients, while the others were indirect path coefficients. The path coefficient of residual items of health index (I_h) was 0.056,2.

The following obstacle factors have good correlations with health index (I_h), including forest and grass density (L_1), per capita net income (L_8), the rate of contribution of industrial by-line (L_9), and the realization rates for the per unit area grain yield productivity (L_{13}) and system resilience (L_{17}). Their summations of path coefficients were 0.097,7, 0.107,4, 0.060,6, 0.410,4 and 0.064,3, respectively. Their direct path coefficients of health index (I_h) were 0.336,8, 0.663,5, 0.033, 0.468,2 and 1.015,3. Forest grass density (x_1) affected the health of the impediment system indirectly with per capita net income x_8 (0.354,2), popularization rate of compulsory education x_{11} (0.237,3), sediment-reducing benefit of comprehensive treatment x_{14} (0.283,6) and soil permeability x_{16} (0.334,1). Per capita net income (x_8) affected the health of the impediment system indirectly with forest grass density x_1 (0.179,8), amount of livestock on hand x_5 (0.106,0), agriculture output-input ratio x_7 (0.180,6), popularization rate of compulsory education x_{11} (0.193,8) and soil permeability x_{16} (0.297,6). The direct path coefficient of contribution of industrial by-line was only 0.330, but affected forest and grass density x_1 (0.168,7), amount of livestock on hand x_5 (0.117,6), output-input ratio of agriculture x_7 (0.217,0), popularization rate of compulsory education x_{11} (0.208,4), Engel coefficient x_{12} (0.123,5), sediment-reducing benefit of comprehensive treatment x_{14} (0.166,3), and soil permeability x_{16} (0.297,6) so that the summations of path coefficients were augmented. The realization rates for the per unit area grain yield productivity x_{13} affected the health of the impediment system indirectly with soil permeability x_{16} (0.370,8). System resilience affected the health of the impediment system indirectly with agriculture output-input ratio x_7 (0.167,0), popularization rate of compulsory education x_{11} (0.135,7), and soil permeability x_{16} (0.370,8). Therefore, forest grass density, per capita net income, rate of contribution of industrial by-line, the realization rates for the per unit area grain yield productivity, and system resilience were obstacle factors of the watershed ecosystem in an erosion environment.

Table 4 Path coefficients between the limiting degree of diagnosis and health index of system in Zhifanggou watershed

Independent variable	L_1	L_2	L_3	L_4	L_5	L_6	L_7	L_8	L_9	L_{10}	L_{11}	L_{12}	L_{13}	L_{14}	L_{15}	L_{16}	L_{17}	Summation
L_1	0.336,8*	0.050,8	–0.677,9	–0.655,2	0.082,1	–0.605,9	0.181,0	0.354,2	0.016,5	–0.284,4	0.237,3	0.107,8	–0.122,2	0.283,6	–0.036,5	0.334,1	0.006,8	0.097,7
L_2	0.077,0	0.222,1*	–0.446,4	–0.718,4	0.236,0	–1.388,9	0.300,3	0.025,1	0.011,4	–0.495,6	0.433,5	0.131,4	0.087,0	0.232,3	–0.093,3	0.557,3	0.017,8	0.000,0
L_3	–0.224,2	–0.097,4	1.018,5*	0.740,8	–0.174,0	1.129,5	–0.328,9	–0.483,3	–0.010,5	0.584,7	–0.335,5	–0.131,0	–0.065,7	–0.305,5	0.080,5	–0.597,5	–0.035,7	0.000,1
L_4	–0.211,3	–0.152,8	0.722,4	1.044,3*	–0.199,4	1.424,2	–0.349,1	–0.287,0	–0.022,7	0.533,2	–0.410,7	–0.166,8	–0.091,1	–0.219,5	0.098,0	–0.872,2	–0.035,7	0.000,0
L_5	0.094,7	0.179,7	–0.607,4	–0.713,8	0.291,7*	–1.434,5	0.333,5	0.241,1	0.013,3	–0.559,7	0.423,6	0.149,2	–0.000,7	0.224,6	–0.099,1	0.680,5	0.017,3	0.000,1
L_6	0.126,6	0.191,4	–0.713,6	–0.922,6	0.259,6	–1.612,0*	0.376,0	0.249,6	0.016,0	–0.621,7	0.455,8	0.165,8	0.131,1	0.220,3	–0.110,9	0.855,8	0.029,3	0.000,0
L_7	–0.153,8	–0.168,2	0.845,0	0.919,8	–0.245,4	1.529,0	–0.396,4*	–0.302,3	–0.018,1	0.648,9	–0.430,8	–0.161,5	–0.105,8	–0.277,1	0.111,0	–0.827,8	–0.039,8	0.000,0
L_8	0.179,8	0.008,4	–0.741,9	–0.451,7	0.106,0	–0.606,5	0.180,6	0.663,5*	–0.001,0	–0.418,0	0.193,8	0.073,0	–0.003,2	0.166,1	–0.038,9	0.297,6	0.011,3	0.107,4
L_9	0.168,7	0.076,9	–0.323,2	–0.719,1	0.117,6	–0.779,7	0.217,0	–0.020,4	0.033,0*	–0.208,9	0.208,4	0.123,5	–0.121,9	0.166,3	–0.054,7	0.643,3	0.035,0	0.060,6
L_{10}	–0.138,5	–0.159,1	0.860,8	0.804,9	–0.236,0	1.448,8	–0.371,8	–0.400,9	–0.010,0	0.691,8*	–0.426,5	–0.141,4	–0.105,3	–0.291,2	0.101,2	–0.665,6	–0.035,2	0.000,0
L_{11}	0.165,4	0.199,2	–0.707,1	–0.887,5	0.255,7	–1.520,3	0.353,4	0.266,1	0.014,2	–0.610,5	0.483,3*	0.160,2	0.060,8	0.276,8	–0.099,2	0.687,9	0.026,5	0.000,0
L_{12}	0.198,2	0.159,3	–0.728,2	–0.950,7	0.237,6	–1.459,1	0.349,4	0.264,4	0.022,2	–0.534,1	0.422,6	0.183,2*	0.025,8	0.225,0	–0.096,5	0.866,9	0.031,3	0.000,1
L_{13}	–0.087,9	0.041,3	–0.142,8	–0.203,2	–0.000,4	–0.451,6	0.089,6	–0.004,5	–0.008,6	–0.155,6	0.062,8	0.010,1	0.468,2*	–0.143,2	–0.042,9	0.370,8	–0.002,6	0.410,4
L_{14}	0.219,1	0.118,4	–0.713,7	–0.525,8	0.150,3	–0.814,5	0.252,0	0.252,7	0.012,6	–0.462,2	0.306,8	0.094,6	–0.153,8	0.435,9*	–0.056,2	0.173,2	0.021,3	0.001,1
L_{15}	0.104,4	0.176,1	–0.696,6	–0.869,6	0.245,6	–1.518,3	0.373,9	0.219,1	0.015,3	–0.594,8	0.407,4	0.150,1	0.170,6	0.208,0	–0.117,7*	0.840,1	0.021,9	0.000,0
L_{16}	0.110,8	0.121,9	–0.599,4	–0.897,2	0.195,5	–1.358,8	0.323,2	0.194,5	0.020,9	–0.453,5	0.327,4	0.156,4	0.171,0	0.074,4	–0.097,4	1.015,3*	0.035,1	0.002,1
L_{17}	0.024,2	0.041,9	–0.385,2	–0.394,8	0.053,5	–0.500,5	0.167,0	0.079,7	0.012,3	–0.257,8	0.135,7	0.060,8	–0.012,8	0.098,4	–0.027,3	0.377,9	0.094,4*	0.064,3

* Path coefficients

Table 5 Path coefficients between the advantage degree of diagnosis and health index of system in Zhifanggou watershed

Independent variable	A_1	A_2	A_3	A_4	A_5	A_6	A_7	A_8	A_9	A_{10}	A_{11}	A_{12}	A_{13}	A_{14}	A_{15}	A_{16}	A_{17}	Summation
A_1	0.226,4*	–0.039,0	–0.102,2	0.055,5	–1.033,7	–0.046,8	0.147,7	–0.198,1	–0.084,1	–0.290,6	0.012,4	0.672,6	–0.147,3	–0.151,9	–0.093,0	0.294,1	0.037,6	0.000,3
A_2	0.050,3	–0.175,6*	0.035,0	–0.027,0	–0.058,0	0.076,2	–0.124,2	0.037,6	–0.025,5	0.131,5	0.023,0	–0.015,4	–0.003,9	0.245,4	0.092,4	–0.107,7	–0.183,7	0.904,0
A_3	0.156,2	0.041,5	–0.148,2*	0.082,0	–1.128,8	–0.096,2	0.229,0	–0.246,7	–0.098,5	–0.400,3	–0.000,1	0.756,2	–0.150,0	–0.344,0	–0.156,0	0.391,5	0.190,0	0.000,0
A_4	0.131,1	0.049,5	–0.126,8	0.095,9*	–1.010,2	–0.103,2	0.214,1	–0.230,8	–0.103,0	–0.356,4	–0.003,9	0.625,1	–0.154,3	–0.265,5	–0.153,1	0.321,4	0.196,7	0.000,0
A_5	0.189,9	–0.008,3	–0.135,7	0.078,6	–1.232,3*	–0.077,6	0.193,9	–0.237,3	–0.118,9	–0.376,1	0.008,3	0.798,7	–0.159,1	–0.279,5	–0.129,9	0.381,3	0.136,3	0.000,0
A_6	–0.085,6	–0.108,1	0.115,2	–0.079,9	0.772,6	0.123,8*	–0.217,6	0.215,6	0.052,3	0.349,3	0.014,1	–0.491,9	0.116,0	0.307,0	0.157,4	–0.296,3	–0.259,1	0.001,2
A_7	0.128,8	0.084,0	–0.130,7	0.079,0	–0.920,2	–0.103,7	0.259,7*	–0.203,6	–0.111,5	–0.371,9	–0.005,4	0.640,8	–0.124,3	–0.360,4	–0.177,7	0.346,9	0.213,9	0.000,2
A_8	–0.161,1	–0.023,7	0.131,2	–0.079,5	1.050,0	0.095,9	–0.189,8	0.278,5*	0.050,2	0.367,7	0.002,7	–0.649,8	0.149,5	0.241,8	0.128,8	–0.344,6	–0.171,8	0.000,0
A_9	–0.091,7	0.021,6	0.070,3	–0.047,6	0.705,2	0.031,2	–0.139,4	0.067,3	0.207,7*	0.191,6	–0.012,1	–0.466,7	0.053,5	0.189,8	0.081,8	–0.200,1	–0.065,5	0.007,0
A_{10}	0.160,0	0.056,2	–0.144,3	0.083,1	–1.127,6	–0.105,2	0.235,0	–0.249,1	–0.096,8	–0.411,1*	–0.002,2	0.753,3	–0.147,7	–0.354,1	–0.160,4	0.399,0	0.206,8	0.000,0
A_{11}	0.096,0	–0.138,2	0.000,6	–0.012,6	–0.348,3	0.059,6	–0.047,6	0.025,3	–0.086,0	0.030,6	0.029,2*	0.233,9	–0.024,8	0.071,7	0.040,2	0.018,5	–0.139,3	0.432,7
A_{12}	0.185,6	0.003,3	–0.136,6	0.073,0	–1.199,7	–0.074,2	0.202,9	–0.220,6	–0.118,2	–0.377,4	0.008,3	0.820,4*	–0.151,2	–0.317,4	–0.134,7	0.394,2	0.132,8	0.000,0
A_{13}	–0.173,5	0.003,5	0.115,6	–0.077,0	1.019,9	0.074,7	–0.168,0	0.216,6	0.057,8	0.315,8	–0.003,8	–0.645,3	0.192,2*	0.161,3	0.121,5	–0.289,5	–0.131,1	0.000,1
A_{14}	–0.078,8	–0.098,7	0.116,8	–0.058,3	0.789,1	0.087,1	–0.214,4	0.154,3	0.090,3	0.333,5	0.004,8	–0.596,5	0.071,1	0.436,5*	0.147,7	–0.351,6	–0.213,3	0.004,7
A_{15}	–0.114,2	–0.088,0	0.125,4	–0.079,6	0.868,2	0.105,7	–0.250,4	0.194,5	0.092,2	0.357,8	0.006,4	–0.599,5	0.126,7	0.349,7	0.184,3*	–0.323,3	–0.234,8	0.000,5
A_{16}	0.160,6	0.045,6	–0.139,9	0.074,3	–1.133,2	–0.088,5	0.217,3	–0.231,4	–0.100,2	–0.395,6	0.001,3	0.779,9	–0.134,2	–0.370,1	–0.143,7	0.414,6*	0.173,8	0.000,0
A_{17}	0.028,6	0.108,5	–0.094,7	0.063,4	–0.565,0	–0.107,9	0.186,8	–0.160,9	–0.045,7	–0.286,0	–0.013,7	0.366,5	–0.084,8	–0.313,1	–0.145,6	0.242,4	0.297,3*	0.001,4

* Path coefficient, the path coefficient of the rest of I_h is 0.037,2

4.3.2 Predominance diagnoses

We counted each single index with formula (10) and calculated predominance with SAS to analyze the path coefficients (Table 5). The results indicated that the predominance of per capita basic farmland (x_2) and popularization rate of compulsory education (x_{11}) have a good relation with health index (I_h). The summations of path coefficients were 0.904,0 and 0.432,7, while direct path coefficients of I_h were –0.175,6 and 0.029,2. Apparently, direct effects were not apparent. Per capita basic farmland was negatively affected by the index, although the effect was indirect by control x_6 (0.076,2), population density x_{10} (0.131,5), sediment-reducing benefit of comprehensive treatment x_{14} (0.245,4), and the realization rates for the per unit area grain yield productivity x_{15} (0.092,4). This led to an increase of the summations of path coefficients and promoting system health. The popularization rate of compulsory education also weakly affected the index and affected indirectly by control x_6 (0.059,6), Engel coefficient x_{12} (0.023,4), and sediment-reducing benefit of comprehensive treatment x_{14} (0.245,4) to also promote system health. The path coefficient of control x_6 was big (0.123,8), its direct action apparent and its indirect action on other factors also obvious. That is, per capita basic farmland, popularization rate of compulsory education and control were dominant conditions of the healthy ecosystem of the watershed that should be maintained and developed continuously.

4.4 Countermeasures and advice on system health in a typical erosion environment

Landform-physiognomy and drought of the loess hilly area under erosion environment showed how the ecological environment of the area was sensitive and fragile, making it easily disturbed and damaged. By exerting predominance, eliminating obstacles, adjusting measures to local conditions, and combining health system (meliorated source-environment, apparent social-economic state effect and constantly enhanced eco-comprehensive function) with the diagnoses of obstacle and predominance (predominance was apparent and obstacle was outstanding), we put forward the following countermeasures and advice:

1) we should strengthen the conversion of cropland to forest and grassland, enlarge the area of forests and grass, speed up recovery and rebuilding of the ecology, improve conditions of the ecological environment, and enhance system anti-converse effects;

2) we should guarantee quantity of per capita basic farmland, increase investment (especially science), advance the realization rates for the per unit area grain yield productivity and guarantee corn-security;

3) we should carry out livestock breeding and support the processing industry, transform primary products efficiently, develop industrial by-line and improve standard of living.

Ecological renovation of an erosion environment is an important measure that can accelerate system health. Therefore, we should develop such environmental renovation to realize steady development of system health.

5 Conclusions

The health diagnosis of an ecological system in an erosion environment is a new research field with limited studies. Applying characteristics of an ecosystem given the environment, we construct and set up an index system and appraisal model based on the health theory of ecology systems supported by a source-environment, and taking the social-economic state effect and eco-comprehensive function as major clues. Furthermore, we research the health of an ecosystem of the watershed dynamically. The results show that health indices have strong capacity for sustainable development and follow a wave-like increase over time, from 0.370 in 1985 to 0.573 in 2003.

At the same time, to attain optimal reality conditions for the eco-economic system, we introduced obstacle and predominance and diagnosed obstacle and predominance by applying path analysis. The result indicated that forest and grass density, per capita net income, the rate of contribution of industrial by-line, the realization rates for the per unit area grain yield productivity and system resilience were impediments to ecosystem health in the watershed. Although the factors improved, their velocities were slow and continued to block the health and sustainable development of the system. While per capita basic farmland, popularization rate of compulsory education and control were the dominant conditions of the system, augmenting these factors can promote healthy development of the ecosystem. Long-term practice over the years prove that results from the method were in accord with reality, establishing the method as an efficient and rational way that can be easily managed.

The health condition of the system is relatively steady and has prodigious potential. The health level of the system increased wave-like over time. Moreover, the obstacle and predominance of the system were apparent. The developmental significance of the system is that an ecological environment was constructed and human living conditions and levels were improved after we purposely introduced the following countermeasures: 1) we should strengthen the conversion of cropland to forest and grassland, enlarge their area and enhance system resilience; 2) we should guarantee the quantity of per capita basic farmland, increase investment (especially technology) and guarantee corn-security; 3) we should transform the primary products efficiently, develop industrial by-line and improve standard of living to realize steady development of the ecosystem health.

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