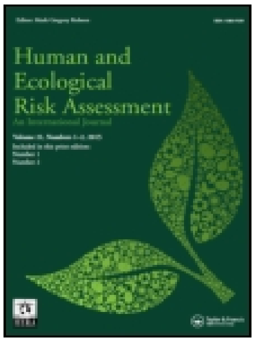

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A Quantitative Health Evaluation of an Eco-Economy in the Semi-Arid Loess Plateau of China

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ABSTRACT

Understanding the factors that affect the health of a semi-arid region's eco-economy is necessary for its sustainable development. The health evaluation, or diagnoses, of an eco-economy at the small watershed scale requires the integrated analysis of ecological, economic, and social factors, yet few studies have achieved this. The health of an eco-economy comprises three components: vigor, organization, and resilience. We use an analytic hierarchy process to develop a health evaluation index system that evaluates the health of an eco-economy system. We then use this diagnostic method to explore the factors affecting the health status of a semi-arid loess watershed in China in 2007 and 2009. The results show that between 2007 and 2009 the health status of the eco-economy improved from the "better" stage to the "benign circle" stage. The primary productivity of grassland, land productivity, rural per capita net income, number of livestock per household, input–output ratio, commodity rate of farm produce, and labor productivity were the main factors influencing the health of this eco-economy. Furthermore, this study shows that the eco-economy depends on material input from regions outside the watershed.

Key Words: health evaluation, health diagnoses, eco-economic system, watershed scale, Loess Plateau.

INTRODUCTION

The semi-arid region of the Chinese Loess Plateau covers an area of 400,000 km^2. This area plays an important role in the ecological conservation and economic development of northwest China. The soil erosion rate in this region is 5000–10,000 t·km^{-2}a^{-1}, one of the highest rates in the world. Furthermore, the long history of human activities combined with more recent climate change have led to increasingly serious vegetation degradation and have damaged the biodiversity and productivity

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of the ecosystem (Jiang *et al.* 2003; He *et al.* 2006; Chen *et al.* 2013). These changes deeply influence and restrict ecological services, and can affect regional socioeconomic development and the ecological environment (Liu *et al.* 2008). In 1999, with the aim of decreasing soil erosion and restoring the local environment, the Chinese government initiated one of its national environment programs, the Grain-for-Green program in this region (Xu *et al.* 2006; Liu *et al.* 2008). A series of changes in land use, vegetation, industrial structure, and the source of income for farmers have occurred since that time (Cao *et al.* 2009; Fu *et al.* 2010). Many studies have focused on this program's effect on the restoration of vegetation and the control of soil erosion in this region (Gong *et al.* 2004; Chen *et al.* 2007; Deng *et al.* 2012). However, the issues of economic structure, farmers' participation and cooperation, and the sustainable development of the eco-economy at the watershed scale have received limited attention (Cao *et al.* 2009). In fact, the Grain-for-Green program has changed the socioeconomic structure of the region and the living standards of farmers (Hu *et al.* 2006; Cao *et al.* 2009). Thus, the issues of how the Grain-for-Green program has affected social and economic structures, and how to combine environmental restoration with social and economic development are still problems that need to be solved.

Ecosystem health is the desired endpoint of environmental management (Rapport *et al.* 1998; Costanza and Mageau 1999). To meet the mandate to effectively manage the environment, a clear definition of and method for assessing ecosystem health is required (Costanza and Mageau 1999). However, evaluations of ecosystem health vary significantly depending on the scales of analysis chosen (Ren *et al.* 2000). Combining the comprehensive definition of ecosystem health given in Costanza and Mageau (1999) and an interdisciplinary definition based on the socioeconomic aspects of ecosystem health (Rapport *et al.* 1998; Rapport 2007), we defined a healthy eco-economy at a watershed scale that has the ability to maintain its structure (organization), function (vigor), and the mutual coupling relationships (organization) between each subsystem, to adjust and recover from external threatens (resilience), and to ensure its stability and sustainability. These three components of vigor, organization, and resilience can be used to assess a system's performance and health (Haskell *et al.* 1992; Rapport *et al.*1998; Zeng *et al.* 1999; Chaves and Alipaz 2007; Horlings and Marsden 2014). According to this ecological–economic definition, the study of an eco-economy involves transboundary, interdisciplinary, and multi-party issues drawn from ecology, economic, and sociology (Pavlikakis and Tsihrintzis 2000; Rapport and Maffi 2011; Rapport and Hildén 2013). Therefore, when we select indices for quantifying the health of eco-economy at a watershed, we must consider ecological, economic and social perspectives.

Several studies in the last decade have examined the relationship between ecological restoration and socioeconomic development in the semi-arid areas of China since the implementation of the Grain-for-Green program. They found that in the Loess Plateau, income is positively correlated with awareness of environmental protection. Cao *et al.* (2009) found that this program did not result in a significant increase in farmers' incomes, and that local farmers were not enthusiastic about the program. Furthermore, Wang *et al.* (2011a) found that this program had a positive influence on farmers' income. However, the main income source of farmers was not related to the Grain-for-Green program but the result of labor export. The development of alternative land uses and public participation in these changes has also influenced the management of watershed ecosystems (Chen *et al.* 2013). Factors such as land use, soil quality, farmers' environmental awareness, and household economic structure significantly influence the eco-economy at the watershed scale (Shi and Shao 2000). These factors are important for the scientific and quantitative evaluation of the health of small eco-economies, and have important implications for the revegetation and sustainable development of a watershed.

Most studies have focused on the relationship between ecological indices and the ecosystem (Kong *et al.* 2002; Huang *et al.* 2005; An *et al.* 2009; Bai *et al.* 2008). Although a few studies have considered a watershed's ecology, economy, and society when evaluating its health status, only a limited number of economic and social indices were used in these studies (Xie *et al.* 2005; Long *et al.* 2006), despite the evidence that the market economy and social changes have affected the health status of the eco-economy in the Loess Plateau. Thus, in this study, indices representing economic and social factors were used to develop a health evaluation index system.

In this study, an index system for the health evaluation of eco-economies was developed using an analytic hierarchy process (AHP). Once developed, the system was used to evaluate the health status of an eco-economy in a semi-arid watershed on the Loess Plateau and to determine what factors affected its health status. The aims of this study were to: (1) evaluate the health status of an eco-economy at a watershed scale; (2) identify the main factors affecting the health of an eco-economy; and (3) make suggestions for the sustainable development of local ecosystems and economies in semi-arid loess regions.

STUDY AREA

The Longtan catchment (35°45′ N, 104°30′ E), our study area, is located in Dingxi, Gansu Province of China. The watershed is part of a typical semi-arid loess hilly area and has a highly fragmented landscape with an elevation ranging from 1840 to 2260 m. The mean annual temperature is 6.8°C and the mean annual rainfall is 386 mm. Most of the rainfall occurs in the form of thunderstorms from July to September. Soil types in the study area are mainly loess soil, which has low fertility and is vulnerable to soil erosion. The soils have a loose structure and low organic matter content. The predominant land use types in the catchment are rain-fed farmland, natural grassland, pasture grassland, shrubland, forestland, and fallow farmland. In 2009, the 16.1 km^2 area had 401 households with 1545 residents, giving a population density of 74 persons per km^2. The agricultural acreage is 657.1 hm^2, and the area of cultivated land per capita is 0.41 hm^2.

METHODS

Establishing the Health Evaluation Index System

A rational target index system is the core requirement for evaluating the health of an eco-economy (Zhang *et al.* 2011; Peng *et al.* 2007). Combining ecological, economic, and social perspectives, we developed a health evaluation index for

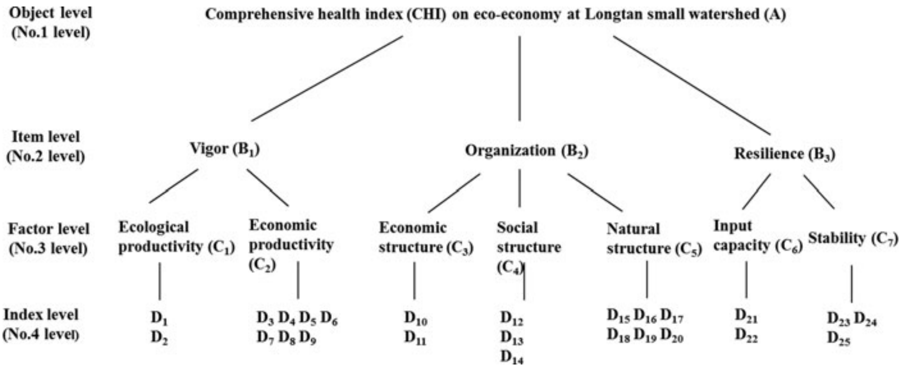

Figure 1. The heath evaluation hierarchical structure of eco-economy at a watershed.

an eco-economy using the AHP; the process was built on the vigor-organization-resilience framework. The system contained four levels: object, item, factor, and index (Figure 1).

Vigor, organization, and resilience are the three components of ecosystem health, therefore, quantifying vigor, organization, and resilience is the first step in assessing ecosystem health (Haskell *et al.* 1992; Rapport *et al.* 1998; Costanza and Mageau 1999). The vigor is defined as the functional ability of a watershed eco-economy, and is generally measured by the system's primary productivity in its ecological sub-system or by the means of production (the production of life materials) in its economic system. Therefore, appropriate indices for its measurement are those that reflect the activity of the ecological and economic subsystems. For this study, the primary productivity of grassland (D_1), number of livestock per household (D_2), labor productivity (D_4), land productivity (D_5), and the commodity rate of farm produce (D_6) were selected as suitable indices. Two indices that reflect how well a system functions, gross output value of agriculture (D_3) and rural per capita net income (D_7) were also selected. The government implementation of the new rural construction projects and a series of poverty alleviation plans have improved rural human habitat and production and living facilities. Thus, we also used indices of road area per capita (D_8) and housing area per capita (D_9) to measure the ability of the system.

The organization is evaluated according to both the stability of each subsystem structure and the mutual connectivity of the components. To measure the stability of economic subsystem we used an index of the number of labor export per household (D_{11}). The stability of the society subsystem was measured with the following indices: Engel coefficient (D_{12}), educational level (D_{13}), and environmental awareness (D_{14}). Land as the basic means of production and land use structure also influence the stability of a system. The two indices used to capture these features are woodland and grassland area per capita (D_{16}) and rain-fed cropland per capita (D_{17}). The input–output ratio (D_{10}) is an index of the relationship between the ecological and economic systems. Due to the soil and water conservation measures implemented in this region, the following indices can be used to measure the connections between the ecological and social systems: percentage of natural grassland in watershed (D_{15}), vegetation coverage (D_{18}), soil erosion modulus (D_{19}), and percentage of land with soil erosion controlling measures (D_{20}).

The resilience refers to the input capacity and stability that a watershed eco-economy needs to maintain its structure and function in the face of inputs from external events such as natural disasters, human activities, the market economy, and social changes. Two indices, fertilizer input (D_{21}) and growth rates of production facility (D_{22}), are selected to measure these input capacities. After a certain threshold is reached, a health system can no longer absorb various stresses (Costanza and Mageau 1999); the indices of soil organic matter content (D_{23}) and soil desiccation degree (D_{24}) were selected to determine the presence of a shortage of water and soil with low organic matter and fertility, as indicators that this threshold had been reached. As the breeding industry is now one part of the sustainable development program in the region (Wang *et al.* 2011b), the captivity animal rate (D_{25}) was also used as a threshold to measure the stability of the system.

Methods for Evaluating the Health of an Eco-Economy

Data collection

The measured values of each index were collected using the methods shown in Table 1. The social and economic data were collected using a household-level questionnaire. The household surveys were conducted from September to November 2007 and again from September to November 2009. The survey followed the principle of combining a general questionnaire with a key-points investigation. First, to determine the basic situation, a semi-structural interview was conducted with 15 local farmers who were community leaders. These farmers were asked to discuss the current issues and difficulties in ecological management, resource utilization, socioeconomic development, and so on. The data from these interviews were used to design a standardized questionnaire, which asked about personal characteristics, household consumption, farming, land use, participation in the ecological restoration program, perceived changes in socioeconomic conditions, and attitudes toward the Grain-for-Green program. Twenty-two typical farmers participated in face-to-face interviews in their household based on the standardized questionnaire. With assistance from village leaders, a further 197 questionnaires were randomly distributed to local farmers, and 141 questionnaires were returned. In the data sorting process, 10 questionnaires were eliminated, leaving 131 valid questionnaires. Combined with the data from the interviews with the typical farmers, there were 153 valid questionnaires from the 401 residential units in the watershed. The values of the economic and social indices were calculated using the appropriate formulas. Finally, the mean (Mean), median (M_e), and mode (M_o) values were calculated for each index.

Evaluation steps

Estimating the relative importance of each index. The relative importance of each index was evaluated by applying the AHP method to create a judgment matrix $A_{m\times n}$

Table 1. The data collection of measured values of each index.

Indices	Data collection
Number of livestock per household (D_2)/number	Obtained by face-to-face interviews with local farmers and questionnaire used to interview farmers during the survey
Number of labour export per household (D_{11})/person	
Educational level (D_{13})	
Environmental awareness (D_{14})	
Fertilizer input (D_{21})/t•hm^{-2}	
Labour productivity (D_4)/ \$•work day^{-1}	Calculated based on face-to-face interviews with local farmers, questionnaire, market investigation, and government statistics
Land productivity (D_5)/\$•(km^2•a)$^{-1}$	
Commodity rate of farm produce (D_6)/%	
Input–output ratio (D_{10})/%	
Engel coefficient (D_{12})/%	
Growth rates of production facility (D_{22})/%	
Gross output value of agriculture (D_3)/\$	Obtained by investigation typical farmers and government statistics
Rural per capita net income (D_7)/\$	
Road area per capita (D_8)/m^2	
Housing area per capita (D_9)/m^2	
Captivity animal rate (D_{25})/%	
Percentage of natural grassland in watershed (D_{15})/%	Obtained by field investigation and computer interpretation
Vegetation coverage (D_{18})/%	
Percentage of land with soil erosion controlling measures (D_{20})/%	
Woodland and grassland area per capita (D_{16})/hm^2	Calculated on field and social investigation
Rain-fed cropland per capita (D_{17})/hm^2	
Primary productivity on grassland (D_1)/kg•hm^{-2}	Obtained by weighting the hay of alfalfa on unit area
Soil erosion modulus (D_{19}) /t•(km^2•a)$^{-1}$	Obtained by routine monitoring from Dingxi Institute of Soil and Water Conservation
Soil organic matter (D_{23})/%	Obtained by the chromic acid titration method
Soil desiccation degree (D_{24})/%	Calculated by soil desiccation degree = [(soil field capacity-soil water storage)/soil field capacity] × 100

or $(a_{ij})_{\mathrm{m}\times\mathrm{n}}$ such that

$$A = \begin{bmatrix} a_{11} & a_{12} & \dots & a_{1j} \\ a_{21} & a_{22} & \dots & a_{2j} \\ \vdots & \vdots & \vdots & \vdots \\ a_{i1} & a_{i2} & \dots & a_{ij} \end{bmatrix}$$

where a_{ij} is the value of the relative importance of a_i to a_j ($i = 1, 2, \ldots ,; j = 1, 2, \ldots ,$).

The AHP method uses a 9-point scale to evaluate the relative importance of each index (Saaty 2000). Each evaluator uses his or her expert judgment to assess the relative importance and ranking of the assessment indicators, and to identify 11 judgment matrices for layer 1, layer 2, layer 3, and layer 4. It is recommended that to use the AHP method, there should be between three to seven experts (Huang *et al.* 2013). However, as an eco-economy involves three subsystems, we selected nine evaluators who were familiar with the semi-arid Loess Plateau, to form the experts group. Two of the experts were researchers engaged in agroforestry ecosystem rehabilitation and the reestablishment of watersheds in the Loess Plateau. Two were senior engineers with extensive experience in watershed management, who had been involved in many environmental quality evaluation programs. One expert was a professor who studied sustainable integrated watershed ecosystem management from the perspective of landscape ecology. Two representatives from a technical institute had extensive experience in water and soil conservation in the semi-arid loess hilly region. One researcher was an expert on vegetation restoration in the semi-arid loess hilly region, and one researcher was an expert in afforestation in arid areas. These nine evaluators had different experience, knowledge, and understanding of the indicator characteristics and, hence, together were qualified to assign pairwise comparison judgments for the proposed AHP model. To reduce the biases of the evaluators in assessing the pairwise comparisons, the arithmetic average value of the assessment indicators given by each expert was taken as the measured value.

Identifying the weight coefficient and consistency check.

(1) Single index weight calculation. The value of the single index weight W_i for each layer was calculated using the following formula:

$$W_i = \sqrt[n]{\prod a_{ij}}, \tag{1}$$

where W_i is the value of each single index in each layer and n is the index number of each layer.

(2) Normalization of the single index weight. The normalized single index weight $\overline{W_i}$was calculated using the following formula:

$$\overline{W}_i = W_i / \sum W_i, \tag{2}$$

where i is the number of the item (3) and factor (2, 3).

W_{ij} is the normalization weight on the corresponding items or factors, and was calculated using the following formula:

$$W_{ij} = W_{i'} / \sum W_{i'j'}, \tag{3}$$

where i' is the number of the factor or index (1, 2, … … , 7) and j' is the number under a different factor or index (2, 3, 6, 7).

(3) Calculating the combination weights on each level. The combination weight was calculated using the following formula:

$$\text{Combination weight} = \overline{W_i} \times W_{ij}, \tag{4}$$

Table 2. Variety of *RI* following the n of the size of matrix.

The order of matrix (n)	1	2	3	4	5	6	7	8	9
The mean random index of consistency (*RI*)	0	0	0.58	0.90	1.12	1.24	1.32	1.41	1.45

where i is the number of the item or factor $(1, 2, \ldots \ldots, 7)$ and j is the number of the index under the factor level $(1, 2, \ldots \ldots, 25)$.

(4) Consistency check (CR). A consistency check was used to judge the consistency of the experts' evaluations (Cao *et al.* 1996). The *CR* was calculated using the following formula:

$$CR = \frac{CI}{RI}, \tag{5}$$

where CI is the degree to which the judgment matrix deviates,

$$CI = \frac{\lambda_{\max} - n}{n - 1}, \tag{6}$$

where $\lambda_{\max}$ is the maximum value of the judgment matrix, and

$$\lambda_{\max} = \sum \frac{(A\overline{W})_i}{n\overline{W}_i}, \tag{7}$$

where RI is the mean random index of consistency. Table 2 shows the mean random index of the consistency values (Cao *et al.* 1996).

If $CR \leq 0.1$, the judgment matrix has good consistency; if $CR > 0.1$, the judgment matrix needs to be modified until good consistency is established.

Dimensionless indices. It is necessary to make the indices dimensionless, as each index uses a different unit. First, two concepts, standard value and optimal value, must be clarified. The standard value is a level of achievement, specifically a level that is acceptable for a specific time and particular range. The optimal value is the best level or state that an index can achieve in a certain period. In this study, the standard value was represented by the optimal value. Then, the 25 indices were divided into two groups: positive indicators and negative indicators. Indices in the positive indicator group were positively correlated with the health of the eco-economy. Indices in the negative indicator group were negatively correlated with the health of the eco-economy. The input–output ratio, Engel coefficient, percentage of natural grassland, degree of soil desiccation, and soil erosion modulus were negative indicators, and the others were positive indicators. Finally, the indices were made dimensionless using the membership function of a fuzzy assemblage. The dimension of the positive indicators was calculated using the following formula:

$$X_{ij} = C_{ij}/S_j,\ X_{ij} \subset [0, 1]. \tag{8}$$

The dimension of the negative indicators was calculated using the following formula:

$$X_{ij} = S_j/C_{ij},\ X_{ij} \subset [0, 1], \tag{9}$$

where X_{ij} is the value of a non-dimensionalized variable, C_{ij} is the measured value, and S_j is the standard value of this index.

In this study, the standard values for the social and economic factors were obtained from the medium or long-term development plan reports of the local government and through expert consultation; the standard values for the ecological factors were extracted from the results of specific relevant studies.

Comprehensive health index for an eco-economy. The comprehensive health index was calculated using the following formula:

$$A = \sum_{i}^{j} X_{ij} \times \left(\overline{W_i} \times W_{ij}\right), \tag{10}$$

where A is the comprehensive index at the object, item, and factor level.

Determining a healthy grade. The standard for evaluating the health status of an eco-economy was established by Liu *et al.* (2003), and this method has been shown to be suitable for the Loess Plateau. In this evaluation scale, an eco-economy is considered to be in the vicious circle stage when comprehensive health index (CHI) is smaller than 0.15, in the fragility stage when the CHI is 0.15–0.35, in the relative stability stage when the CHI is 0.35–0.55, in the better status when the CHI is 0.55–0.70, and in the benign circle stage when the CHI is larger than 0.70.

The effect of the limiting degree value on the diagnosis of health indicators. The limiting degree (O_j) was calculated using the following formula:

$$O_j = P_j R_j \Big/ \sum_{j=1}^{n} P_j R_j \bullet 100\%, \tag{11}$$

where R_j is the degree to which a single factor influences the total object. R_j was calculated using the following formula:

$$R_j = W_i \cdot W_j, \tag{12}$$

where W_j is the weight of the j^{th} single index, W_i is the i^{th} item or factor level weight that j^{th} belongs to, i is the number of item/factor (1, 2, … … , 7), and j is the number of the index in factor level (1, 2, … … , 25).

The P_j reflects the gap between the investigated/measured value and the standard value. The P_j was calculated using the following formula:

$$P_j = 1 - x_j, \tag{13}$$

where x_j is the dimensionless value of each single index.

The advantage degree (A_j) was calculated using the following formula:

$$A_j = \left(x_j R_j \Big/ \sum_{j=1}^{n} x_j R_j \right) \times 100. \tag{14}$$

Table 3. The values from the consistency test.

Judgment matrices	*CR*	Judgment	Whether consistency or not (Yes or No)
Item level indicator (A)	0.007 93	≤0.1	Yes
Vigor level (B_1)	0.000 00	≤0.1	Yes
Organization level (B_2)	0.046 23	≤0.1	Yes
Resilience level (B_3)	0.000 00	≤0.1	Yes
Ecological productivity level (C_1)	0.000 00	≤0.1	Yes
Economic productivity level (C_2)	0.087 68	≤0.1	Yes
Economic structure level (C_3)	0.000 00	≤0.1	Yes
Social structure level (C_4)	0.046 23	≤0.1	Yes
Natural structure level (C_5)	0.000 00	≤0.1	Yes
Input capacity level (C_6)	0.000 00	≤0.1	Yes
Stability level (C_7)	0.046 23	≤0.1	Yes

RESULTS

The results of the consistency test are shown in Table 3; all of the values are ≤0.1. These results indicated that the judgment matrices had good consistency.

The normalization weights on the object level were ranked as follows: $B_1(0.540) > B_2(0.297) > B_3(0.163)$. The effect of vigor ($B_1$) on the health status of the system was more than 50%, and the effect of resilience (B_3) on the system was limited to 16.3%. These results showed that it is necessary to strengthen the resilience (B_3) of our eco-economy.

At the item level, the factor (C_i) normalization weights (W_i) were divided into three groups representing the three factor levels. In the first group, ecological productivity (C_1) and economic productivity (C_2) had the same effect on vigor (B_1). In the second group, the effects of economic structure (C_3, 0.493) and natural structure (C_5, 0.311) on the eco-economy were more important than the effect of social structure (C_4, 0.196). These results showed that good natural conditions and the enthusiasm of local farmers for operating an eco-industry system had positive effects on the organization (B_2) of the system. In the third group, input capacity (C_6, 0.667) played an important role in the system's resilience (B_3) than stability (C_7, 0.333). This result indicated that the eco-economy of the study area still largely relied on outside input, and the effect of outside forces was stronger than the system's ability to self-rehabilitate.

The combination weights at the item level were ranked as followings: $C_1(0.270) = C_2(0.270) > C_3(0.147) > C_6(0.109) > C_5(0.092) > C_4(0.058) > C_7(0.054)$. This result showed that ecological productivity (C_1) had the same amount of influence on the system's health as economic productivity (C_2). The combined effects of these two factors account for more than 50% of the change. Although the influence of resilience (B_3) was relatively low, the combination weight of input capacity (C_6), which is an aspect of resilience (B_3), had a greater influence on the eco-economy than the social (C_5) or natural structures (C_4). The combination weight of stability (C_7), which is also a feature of resilience (B_3), had the lowest value. Obviously, the eco-economy of the study area deeply depends on input from outside the system, and its resilience is low.

The top five combination weights at the factor level were ranked as follows: $D_1 (0.225) > D_{10} (0.098) > D_{21} (0.091) > D_5 (0.076) > D_4 (0.068)$. Three of these indices (D_1, D_5, and D_4) were related to the vigor level, and D_{10} was related to the organization level. This result showed that vigor played an important role in the eco-economy. Furthermore, it was obvious that the input conditions and utilization efficiency of the production materials, including land and labor, played important roles in the eco-economy. The last three combination weights were percentage of sparse natural grassland (0.008) < environmental awareness (0.009) = percentage of land with soil erosion controlling measures (0.009).

The indices used to evaluate the health of the different levels of the eco-economy in 2007 and 2009 are given in Table 4. The CHI was 0.600 in 2007 and 0.738 in 2009. The health of the eco-economy improved from "better" stage in 2007 to the "benign circle" stage in 2009. The relative importance of the three main components of the eco-economy was vigor > organization > resilience. Resilience increased more than the other two categories (from 0.11 in 2007 to 0.15 in 2009), but had a relatively small effect on the eco-economic system. The evaluation index for vigor increased 22.5% between 2007 and 2009, going from 0.29 in 2007 to 0.36 in 2009. The evaluation index of organization was 0.20 in 2007 and 0.23 in 2009, increasing 14.48%.

Factors limiting the health status of our eco-economy are listed in Table 5. These results showed that the primary productivity of grassland was a significant restriction on the health of the system in both 2007 and 2009. The land productivity, rural per capita net income, number of livestock per household, and input–output ratio also restricted the health of the eco-economy in 2007 and 2009 (Table 5).

DISCUSSION

Key Factors Influencing the Health of the Eco-Economy

It is difficult to evaluate the health of an eco-economy system at the watershed scale as it is affected by ecological, economic, and social factors. In fact, dozens of factors can influence the ecosystem, economy, and social system of a watershed (Liu *et al.* 2014). For example, Liu *et al.* (2003) found that land use structure and the percentage of land that used soil erosion controlling measures both had significant effect on ecosystems in the Loess Plateau. Their study was also the first to use the soil properties indices (soil anti-scourability and soil organic matter content) as part of a comprehensive health index. Dai *et al.* (2005) found that the input–output ratio and rain-fed cropland per capita affect economic systems at a watershed scale. Furthermore, land use (afforestation and sustainable land use) was found to have a positive relationship with local social systems in arid and semi-arid regions (Jiao *et al.* 2012; Chen *et al.* 2013). These studies demonstrated that land use, soil properties, and the input and output of agricultural production were important factors in the eco-economy of China's Loess Plateau (Shi and Shao 2000; Liu *et al.* 2014). This present study used an index system to evaluate the heath of a semi-arid eco-economy. The system used indices to measure the factors that affect the system's health such land use, energy input and output of farm produce, soil organic matter content, soil

Table 4. The results of heath evaluation in an eco-economic system.

Evaluation index on object level			Evaluation index on item level			Evaluation index on factor level		
Object	Year 2007	Year 2009	Item indicator	Year 2007	Year 2009	Factor indicator	Year 2007	Year 2009
CHI (A)	0.60	0.74	Vigor (B_1)	0.29	0.36	Ecological productivity (C_1)	0.19	0.23
						Economic productivity (C_2)	0.10	0.12
			Organization (B_2)	0.20	0.23	Economic structure (C_3)	0.11	0.12
						Social structure (C_4)	0.03	0.04
						Natural structure (C_5)	0.06	0.06
			Resilience (B_3)	0.11	0.15	Input capacity (C_6)	0.07	0.10
						Stability (C_7)	0.05	0.05

Table 5. Factors limiting the health status of eco-economy in 2007 and 2009.

Order		1	2	3	4	5	6	7	8
2007	LI	O_1	O_5	O_2	O_7	O_{21}	O_{10}	19 indices	
	O_j (%)	28.1	15.46	8.81	7.52	5.65	5.34	≤5.00	
2009	LI	O_1	O_5	O_7	O_2	O_{10}	O_6	O_4	18 indices
	O_j (%)	23.14	13.5	12.32	8.36	8.12	5.03	5.02	≤5.00

erosion modulus, soil desiccation degree, primary productivity on grassland, and number of livestock per household.

The soil organic matter content was less than 0.8%, and was one of the important limiting factors for agricultural production (Lu *et al.* 1994). As the soil organic matter can directly reflect productivity, this index was used in evaluating the system. Serious soil erosion is a known environmental problem in the Loess Plateau; it is usually related to low land productivity and a fragile ecosystem (Wei *et al.* 2007). For this reason, the soil erosion modulus was selected as a key index for measuring the health of eco-economy.

Soil water is the key limiting factor for vegetation restoration and ecological reconstruction in a loess region (Yang *et al.* 2014). Low available soil water will inevitably affect sustainable vegetation restoration (Yang *et al.* 2012). The degree of soil desiccation can reflect available soil water content, especially for the human-introduced ecosystem of the Loess Plateau. Thus, the index of soil desiccation was selected to measure the deterioration of the health of the eco-economy system.

The Loess Plateau is a highly distressed region where intensive crop production has been undermined by high soil erosion rates that threaten the long-term livelihood of its inhabitants (Hou *et al.* 2014). With the Grain-for-Green program, the planting structure was changed from grain-production oriented plantations to characteristics-production oriented plantations, and the land use structure has changed correspondingly (Chen *et al.* 2013). Due to the increasing yield of pastures grass in this region, the breeding industry has expanded. For this reason, the two indices of primary productivity of grassland and the number of livestock per household were selected as important indices for measuring the health of the eco-economy.

Advantage Degree and Limiting Indices Influencing the Health of the Eco-Economy

Previous studies have conducted health evaluations and have diagnosed the eco-economy of a watershed in the loess hilly areas of the Loess Plateau. Liu *et al.* (2005) found that over almost 20 years of soil conservation practices from 1985 to 1999 in the Zhifanggou watershed, the health of the eco-economy underwent an initial restoration, then stable improvement, and finally entered the circulation phase. Dai *et al.* (2005) found that under different rehabilitation practices the health of a watershed ecosystem can develop sustainably. These studies all suggested that the health of these regions was on the mend. This study found a similar pattern; however, the limiting indices and health indicators varied across regions and scales.

Then advantage degree is a composite index that reflects positive changes in the health of an eco-economy. The results from this study indicated that woodland

and grassland area per capita and percentage of land with soil erosion controlling measures had clear positive effects on the system's health. Due to the Grain-for-Green program, the area of pasture grassland has increased significantly (Zhang and Liu 2007). Thus, the development of a "pasture grassland-animal husbandry-increasing income" eco-economy has become a major production system in the semi-arid Loess Plateau. At the same time, due to efforts of soil and water conservation and other ecological restoration projects since 1950s, the percentage of land subject to soil erosion controlling measures has become a positive factor in the health of this small watershed.

Evaluating the limiting degree index and the health indicators of small eco-economies is for the first step in developing more effective and scientific management systems for these areas (Ma *et al.* 2006). The limiting degree index is an index of the factors that have a negative effect on the health of an eco-economy. Soil and water loss have seriously depleted land resources and degraded the ecological and economic systems of the Loess Plateau. This directly affects local agricultural and industrial productivity (Shi and Shao 2000). In this study, the following five health indicators were found to limit the health development of the eco-economy in the Loess Plateau: primary productivity of grassland, land productivity, rural per capita net income, number of livestock per household, and input–output ratio. The commodity rate of farm produce and labor productivity became additional limiting factors limiting the health of the eco-economy in 2009. For a long time it has been thought that the comprehensive management plan for a small-watershed only needs to consider natural resources and does not have to be concerned with regional social and economic conditions (Shi and Shao 2000; Chen *et al.* 2013; Baumgart-Getz *et al.* 2012). Most local farmers also only consider small-scale agriculture, pasture, and animal husbandry production. However, the market economy influences farmers' production pattern, and thus influences the health status of eco-economic systems (Shi and Shao 2000; Horlings and Marsden, 2014; Liu *et al.* 2014). This study showed that the ecological and economic productivities were both increased by the adjustments of planting structures and animal husbandry, which led to a new problem. The farm products were transformed into commodities, and thus the commodity rates of farm produce became a new limiting factor in 2009. Thus, when attention is paid to increasing labor productivity, it is also necessary to increase the commodity rate of farm produce, and the agricultural production structure must be co-ordinated with the market economy.

Improving the Health of Eco-Economies at the Watershed Scale

Based on the above discussion, we have several recommendation for maintaining the health and sustainable development of eco-economic systems at the watershed scale.

(1) Use scientific management to make the use of water resources more efficient. The "limiting degree" diagnosis indicated that the primary productivity of grassland and land productivity were the main limiting factors. Low productivity in these areas led to reduction in rural per capita net income and in the input–output ratio, which limited the healthy development of the eco-economy in the Loess Plateau. All of these limitations were the result of the shortage of precipitation in these regions. For this reason, it is necessary to use water resources effectively. First, we recommend the use of engineering and biological measures to retain rainfall. Xu *et al.* (2012) argued that a check dam is the most appropriate conservation practice for controlling soil and water loss on the Loess Plateau. Such a system meliorates the effects of the runoff and ground water, making the land more fertile, and greatly improves the environment. Chen and Cai (2006) also found that a combination of biological and engineering measures can control hillslope/gully erosion and reduce both runoff volume and the amount of sediment yield in the semi-arid regions of the Loess Plateau. Such engineering and biological measures can transform surface runoff into soil water and thus increase agriculture production.

Second, the plantation structure should be changed to use rainfall efficiently. In the semi-arid areas of the Loess Plateau, there is little rainfall in April, May, and June; precipitation is concentrated in July, August, and September. The rainfall in these three months often accounts for 60–70% of the total annual precipitation (Shi and Shao 2000). The rainy season does not coincide with the growing season of the traditional aestival annual crops (wheat, dolichos lablab, broom corn millet, *etc.*) in this region. Therefore, to efficiently utilize rainfall, it is necessary to encourage local farmers to replace traditional aestival annual crops with autumnal crops.

Third, agricultural technology should be used to efficiently use precipitation and soil water. Liu *et al.* (2009) found that plastic film mulch and tillage can effectively collect rainfall and prevent soil water evaporation, thus improving crop yields. Huang *et al.* (2010) carried out experiments to explore the high water use efficiency of maize planting in furrows that alternate mulched narrow and wide ridges systems. The techniques of whole plastic-film mulching on double ridges and planting in catchment furrows are now widely used in the semi-arid Loess Plateau.

(2) Optimize land use management. This study indicated that the combination weight of land productivity plays an important role in the health of eco-economy of the semi-arid Loess Plateau. Therefore, it is important to optimize land use management in this region. Scientific land use management techniques, such as optimizing land use structure, soil and water conservation measures, tillage activities, and a lower density of introduced vegetation planting should be applied.

(3) Increase investment in agricultural technology. Although the health of the eco-economy of the semi-arid Loess Plateau was classified as being in the benign circle phrase in 2009, the system still largely depends on material input from outside the watershed. Increasing investment in science and technology will ensure the best use of this material input. For this reason, the following measures should be taken: introduce new crops, introduce high efficiency farmland management and cultivation techniques, extend the technique of formula fertilization by soil testing, and extend dry farming techniques.

(4) Enhance environmental protection and ecological conservation awareness. Encouraging local farmers to participate in land use planning and vegetation restoration is recommended. Converting slope cropland to pasture grassland or orchards leaves more time for local farmers to engage in off-farm work; for example, animal breeding and labor export (Chen *et al.* 2013; Liu *et al.* 2014; Osman 2014). Furthermore, the local government can encourage farmers to participate in integrated ecosystem management. Previous studies found that financial aid from the Grain-for-Green program was a high proportion of household income in this region (Wang *et al.*

2011b), and that this program had increased farmers' environmental awareness. The program's ecological compensation may thus play a positive role in environment conservation (Zheng *et al.* 2013). Financial benefits linked to different environment conservation or poverty alleviation projects encourage farmers to participate in environment conservation.

CONCLUSIONS

As social issues and the market economy influence the eco-economic system of a watershed, it is necessary to consider ecological, economic, and social factors when designing watershed ecosystem management plants. A comprehensive health evaluation of an eco-economic system is the basis for watershed management and environment restoration, particularly in areas with fragile ecosystems. This study developed a system for evaluating the health of eco-economic systems at a watershed scale. Specifically, it evaluated the health of a typical semi-arid watershed in the Loess Plateau. The results showed that the health of the eco-economy of the study area had improved from a "better" status in 2007 to a "benign circle" status in 2009. The primary productivity of grassland, land productivity, rural per capita net income, number of livestock per household, input–output ratio, commodity rate of farm produce, and labor productivity were the main factors limiting the health of the studied eco-economy. Measures to improve the efficiency of water resource use, to optimize land use management, to increase investments in agricultural technology, and to enhance environmental protection and ecological conservation awareness would improve the eco-economy in the semi-arid Loess Plateau of China.

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