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ORIGINAL ARTICLE

Ecosystem management based on ecosystem services and human activities: a case study in the Yanhe watershed

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Abstract With activities that alter the structure and function of the habitat, humans have a direct impact on ecosystems and ecosystem services, i.e., the conditions and processes that sustain human life. In this study, 35 townships in the Yanhe watershed in the Loess Plateau of China were selected. The net primary production (NPP), carbon sequestration and oxygen production (CSOP), water conservation, and soil conservation were the ecosystem services selected and valuated. Human activity was quantified by an integrated human activity index (HAI) based on population density, farmland ratio, and the influence of road networks and residential areas. The NPP, CSOP, and water conservation showed a conspicuous spatial pattern fanning outward from the southwest, while the soil conservation showed an obscure spatial pattern distinguished primarily by the peripheral area surrounding the urbanized areas. Total ecosystem services in the Yanhe watershed demonstrated a decreasing pattern from south to north, and the HAI was in proportion to administrative and economic development. Based on the selected ecosystem services and HAI, we mapped the townships of the Yanhe watershed by cluster analysis, and provided sustainable ecosystem management suggestions, tailored to the social-ecological map.

Keywords Ecosystem services · Human activity · Spatial trend · Ecological conservation policy · Yanhe watershed

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Introduction

Ecosystem services are conditions and processes through which natural ecosystems, and the species that make them up, sustain and fulfill human life (Daily 1997). The Millennium Ecosystem Assessment (MA) (2005a) popularized the term 'ecosystem service' and categorized it into four types: provisioning, regulating, cultural, and supporting. Significantly shaped and altered by human activities, especially after the industrial revolution (Foley et al. 2005; Haberl et al. 2007; MA 2005b), ecosystems have exhibited dramatic changes in structure and function, such as biogeochemical flows (Vitousek et al. 1997). Ecosystem services and human activities are sensitive to each other, reflected by the closed, chain-like loop of demand–action–pressure–states–response (MA 2005b). Humans affect ecosystem services in three primary ways: by modifying the land habitat, altering the ecosystem structure, or changing the biogeochemical cycle. These changes can have a negative or positive effect on ecosystem services.

The anthropogenic factors of ecosystem services can be broadly categorized into direct and indirect drivers. The direct drivers include land use changes, overexploitation, and pollution, which unequivocally influence ecosystem services by altering their intrinsic processes. The indirect drivers include population, economic activity, social, political, and cultural factors, and technological change, which operate more diffusely by altering one or more direct drivers (MA 2005b). Trading 'natural' ecosystems with agricultural and industrial production has been the most principal and explicit anthropogenic change in ecosystems and biogeochemical cycles (MA 2005b).

Ecosystem services and human activity assessment is essential to ensure sustainable ecosystem stewardship and effective natural resources allocation (Chapin et al. 2010; Euliss et al. 2010). However, ecosystem service valuations are, in most cases, confined on researchers' desks and haven't yet aroused due attention from the public. The neglect of ecosystem service in decision-making cause a high risk of ecological degradation and infringement on the social and ecological sustainability (Jordan et al. 2010). Researchers attempted to valuate ecosystem services at different spatiotemporal scales (Balick and Mendelsohn 1992; Costanza et al. 1997; McNeely 2003; Peters et al. 1989; Zhang et al. 2010), within which monetary valuation was broadly adopted due to: (1) easy acceptance and integration of economic performance, such as GDP; and (2) the power in assessing management options, costs, and constraints in the context of ecological benefits (the United States Environmental Protection Agency, EPA 2008).

Human activity is an overarching and difficult term to be quantified (Danz et al. 2007; Stein et al. 2002), demonstrated by the risk of human bias in indicator selection and the challenges in quantifying some human factors, such as policy and culture. Researchers have unidimensionally assessed human activities through valuating human population density (Wang et al. 2001; Zheng et al. 1993), agriculture (Elhatip et al. 2003), coal mining (Lee and Bukaveckas 2002), and sheep farming (Frenot et al. 2001) as surrogates for human activity. As human roles in ecosystems depend on much more than their biological density and population characteristics (Machlis et al. 1994), it seems prudent to establish an integrated human activity index for assessing human activity intensity. Researchers have endeavored to create a consistent framework for assessing human activity (Falcone et al. 2010). The United Nations Development Programme (UNDP 1990) advocated a human development index (HDI) in 1990. Based on the HDI framework, researchers designed multidimensional human activity indices that include human population, farmland ratio, natural endowment, economic development, urbanization, policy, etc. (Li et al. 2004; Wen 1998; Zhang and Wang 2004). Literature on the quantitative, multidimensional assessment of human activities is very scarce, in both the fields of ecology and economics.

To effectively integrate ecosystem services into conservation programs, an ecological management policy should be enacted with the full consideration of spatial heterogeneity, especially when we want to identify 'hotspots' of ecosystem services and human activity (Naidoo et al. 2008; Raymond et al. 2009). Researchers have made various efforts to map ecosystem service values based on a 'sense of place' principle, in order to inform environmental management (Alessa et al. 2008; Kliskey 1994; McIntyre et al. 2008; Tyrväinen et al. 2007). One of the key challenges in ecological mapping lies in balancing the mismatched scale between ecosystem services and human activity, as most data related to human activity is based on administrative divisions, which is incompatible to the traditional ecological zone.

The Yanhe watershed in the northern region of the Loess Plateau in China is a typical gully area, incised by water flow and soil erosion due to severe human disturbances (Fu 1989; Fu and Gulinck 1994). In 1999, an ambitious ecological conservation project, the 'Grain for Green' (GfG) project, was launched to curb the deteriorating ecological situation. Since the inception of the GfG project, the land use pattern of the Yanhe watershed underwent a great change, demonstrated by increased forest and grassland, while slope farmland shrank tremendously (Zhou et al. 2009). Soil erosion and water loss were curbed (Feng et al. 2010; Xu and Cao 2001; Zheng 2006) and ecosystem services were greatly improved (Li et al. 2010; Zhang and Wei 2008). Simultaneously, human livelihood also varied immensely, characterized by the conspicuous decreasing of ratios for farm labor and the primary industry in GDP (Lai and Zhu 2009). This drastic variation in the spatial pattern of the social and ecological characteristics makes the Yanhe watershed an ideal place for studying ecosystem services, human activities, and their resultant management.

In this research, we used the Yanhe watershed as a study area, and: (1) valuated ecosystem services and assessed human activities; (2) provided a social-ecological map, based on the ecosystem services and human activities; and (3) advanced suggestion for ecosystem management, tailored to the social-ecological map.

Materials and methods

Study area

The Yanhe watershed (36°21′–37°19′N, 108°38′–110°29′E) is located in the central part of the Loess Plateau (Fig. 1), in the middle reaches of the Yellow River. It has a warm temperate continental monsoon climate (Table 1), and the mean annual precipitation is 495 mm, of which more than 65% fall from July to September. The annual average temperature varies from 8.8 to 10.2°C. The Yanhe watershed is mantled by thick loess, a fine and silt soil prone to erosion. The mean annual runoff in the Yanhe watershed is 2.89×10^8 m^3, with

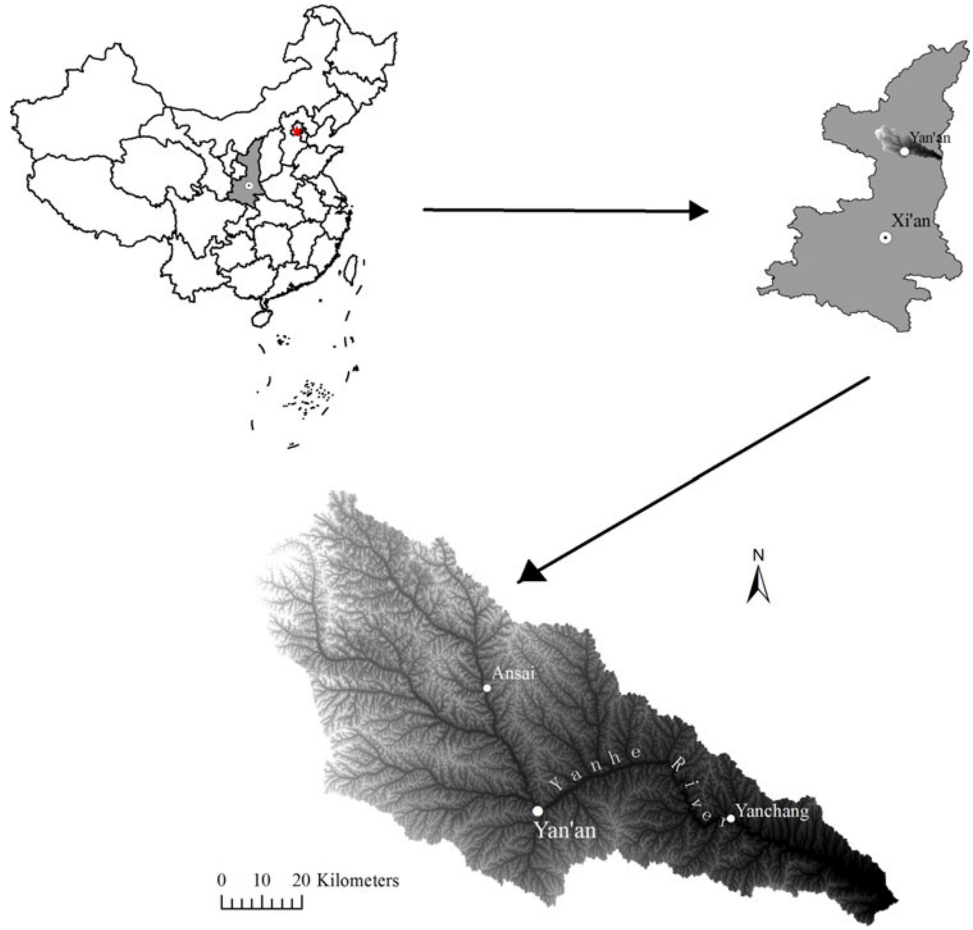


Fig. 1 Location of the study area

Table 1 Basic information of the Yanhe watershed

Area (km^2)	Land use types (km^2)			Population		GDP (billion RMB¥)[a]		
	Farm lands	Forest	Grassland	Nonagricultural	Agricultural	Primary	Secondary	Tertiary
7,869	979	899	2,900	88,985	412,475	0.12	1.56	0.3

The data is from the Yan'an Statistic Bureau and a land use map of the Yanhe watershed of 2006 from the Institute of Remote Sensing Application, Chinese Academy of Science

[a] The leading industries of the Yanhe watershed is energy production (oil, natural gas, coal et al.), agriculture, and tourism

runoff modulus and sediment transportation modulus of 36,425 m^3/km^2 a and 7.80 $\times$ 10^4 t/km^2 a, respectively. As a rugged region with 90% of the terrain in forms of gullies and ridges, the Yanhe watershed loses around 4,540 tons/km^2 of soil each year, causing enormous sedimentation and increasing flood risks in areas downstream of the Yellow River system (Stolte et al. 2003). The watershed involves 44 townships within four counties, of which nine townships were merely partially in the watershed, and, thus, eliminated from the study.

Selection of indicators

Selecting suitable indicators for quantifying ecosystem services on a local or regional scale is a vexed challenge, as the variety of major ecosystem services differ across various ecosystems. Adding too many indicators may confuse the public and decision-makers, while too little will unsubstantiate the results. In addition, from a system analysis viewpoint, largely unexplored correlations between indicators reduce the marginal information of a new indicator (Ronchi et al. 2002). Ecosystem services should be selected to best reflect the ecological problems facing the study area (Wallace 2007); the Yanhe watershed was plagued by numerous austere ecological problems of dry climate, spatially and temporally uneven precipitation, vegetation degradation, and erosion-prone loess soil. In order to account for these local constraints, especially serious soil erosion and vegetation degradation (Fu et al. 2005), we selected the following as indicators for ecosystem services: net primary production (NPP), carbon sequestration and oxygen production (CSOP), water conservation, and soil conservation. Correlations often exist in ecosystem services indicators (Fu et al. 2011; Wallace 2007): NPP and CSOP are closely related based on a common ecological process, photosynthesis, while water and soil conservation are connected by common vegetation configuration patterns.

Selecting appropriate indicators is also critical for assessing the impact of human activities on ecosystem services. Population is a common and necessary index for human activity, as the ever-increasing population leads to an expanding demand for farm produce and natural resources. More than 82% of the populace in the Yanhe watershed is traditionally agricultural, although the GfG project made significant progress in converting farmland to forest and grassland (Table 1). Accelerated urbanization and the implementation of rural development projects have improved the quality and availability of housing in both urban and rural areas. In addition, the transportation system, e.g., highway, railway, and aviation facilities, also developed very quickly (Xu 2010). Hence, we selected human population, farmland ratio, residential settlement, and road network, and formulated them into a comprehensive index, the human activity index (HAI), to assess human activity in the Yanhe watershed.

Complex interrelations exist between the HAI and the ecosystem services indicators that we selected in the Yanhe watershed. Previously, farmers would reclaim vast areas of land full of original vegetation for agricultural production, which disturbed the intact soil and exacerbated water and soil erosion (Zhou et al. 2009). In this regard, the farmland ratio exhibits the profound influence on soil and water conservation, NPP, and CSOP. Urban expansion and road construction, demonstrated by the residential settlement and road network, influence soil and water loss directly by altering the ground surface (Sun et al. 2001) or by driving an industrial readjustment from farm to nonfarm productions (Jacquin et al. 2008), reflected by the variation of farmland ratios.

The scale dependence of ecosystem services requires extensive attention (Limburg et al. 2002, Turner et al. 2000), which possibly incurs either tradeoffs or synergies (Fu et al. 2011; Rodríguez et al. 2006; Swallow et al. 2009). The valuation of ecosystem services is largely affected by the assessment scale and methods. In our study, the NPP and CSOP are calculated from large-scale remote sensing data; the water conservation method is more suitable for the field scale; and the land use and land cover change for soil conservation is more suitable on a slope level. To offset the scale mismatch, we calculated the sum for each individual ecosystem service and normalized them by the territory area of each township.

Data sources

The calculation of the NPP and CSOP was based on normalized differential vegetation index (NDVI) data, extracted from Landsat thematic mapper (TM) images. Water conservation was calculated from vegetation coverage and annual precipitation. Soil conservation was assessed by the revised universal soil loss equation (RUSLE) model, using data from soil types, annual precipitation, vegetation coverage, slope angle, and slope length. Vegetation coverage was obtained from a Landsat 5 TM of 2007 land cover map with 30-m thematic resolution, which included construction areas, farmlands, natural forests, sandy and gobi deserts, shrubbery, grassland, rivers, reservoirs, etc. The annual precipitation of 2007 was obtained from Yan'an Meteorological Bureau. A soil type map was obtained from the Institute of Soil Science, Chinese Academy of Sciences, with a scale of 1:100,000. The slope angle/length was obtained from a 1:50,000 digital elevation map (DEM) with a spatial resolution of 25 m of the Yanhe watershed from the National Fundamental Geographic Information System (NFGIS) of China.

The Yanhe watershed encompasses a total of 44 townships, the basic level of administrative division in China, but nine are only partially in the watershed (Lou et al. 2010). To secure the calculation accuracy, these nine townships were omitted, and the remaining 35 townships were used as the bases unit for analysis. Each township population, as of 2007, was obtained from statistical data (Ansai Statistic Bureau, ASB 2008; Baota Statistic Bureau, BSB 2008; Yanchang Statistic Bureau, YSB 2008; Zhidan Statistic Bureau, ZSB 2008). The data from the townships' administrative boundaries, road networks, and residential sites, as of 2007, were acquired from a 1:400,000 administrative map of Yan'an city from the Yan'an Civil Affairs Bureau (2007) and then used to create a vector map with ArcMap. The 2007 data for township population, annual precipitation, vegetation coverage, parameters for soil type, and farmland ratio were digitized by adding fields to the attribution table of the township vector maps (Yan'an Civil Affairs Bureau 2007). These vector maps were then converted into raster datasets for map calculations with a spatial resolution of 25 m.

Quantification and valuation of ecosystem services and the HAI

Net primary production (NPP)

Living green plants absorb solar radiation in the photosynthetically active radiation (PAR) spectra for photosynthesis and reflect near-infrared radiation, which causes leaves to overheat and damage the tissue. The NDVI can indicate the growth status, health condition, and photosynthesis intensity of living green vegetation, and had an integral part in the calculation of the NPP. The NDVI was calculated as follows (Tucker 1979):

$$\mathrm{NDVI} = \frac{(\mathrm{NIR} - \mathrm{RED})}{(\mathrm{NIR} + \mathrm{RED})} \quad (1)$$

where RED and NIR stand for the spectral reflectance acquired in the red and near-infrared spectra, respectively.

Zheng and Zhou (2000) established a model to simulate the NPP of forest vegetation by comparing the forecasted versus observed forest NPP data. We calibrated their model with data from the Yanhe watershed (Jiao et al. 2008) and established the following NPP model:

$$\mathrm{NPP} = -0.2131 - 22.355 \times \ln(1 - \mathrm{NDVI}) \quad (2)$$

We tested this model with data from 2007 Landsat 4–5 TM images and the "Report of forest resources planning and design survey in Yan'an City, Shaanxi Province, China" by the Northwest Institute of Forest Inventory (NIFI 2006). The results showed that the two-tailed test correlation is significant at the 0.05 level, with a Pearson correlation of 0.625.

In our study, five cloud-free Landsat 4–5 TM images in each month from May to September of 2007 were downloaded from the U.S. Geological Survey (USGS) website (http://glovis.usgs.gov). The NDVI was calculated based on these five TM images with the raster calculator module in ArcGis. The NPP was further calculated from the mean value of the NDVI.

The economic value of the NPP was calculated by converting the NPP into standard coal through its energy equivalent. The energy equivalent of coal was then multiplied by the price of standard coal in 1995, as the price of coal after 1996 fluctuated erratically due to the energy policy adjustments. The equation for the economic value of the NPP is (Li et al. 2006):

$$V = \frac{AQ_1}{BQ_2} \times P_c \quad (3)$$

where V stands for the economic value of plant organic matter; A stands for the dry weight of organic matter, i.e., the volume of the NPP obtained from Eq. 2; B stands for the quality coefficient of coal (equal to 1 for standard coal); P_c stands for the 1995 market price of standard coal, 479 RMB¥/t; Q_1 is the quantity of heat per dry weight of organic matter, equal to 6.7 kJ g^{-1}; and Q_2 is the quantity of heat of standard coal, equal to 10 kJ g^{-1}.

Carbon sequestration and oxygen production (CSOP)

Plants sequester carbon and release oxygen through photosynthesis. According to the photosynthesis equation: $6CO_2 + 6H_2O \rightarrow 6O_2 + C_6H_{12}O_6$, the ratio of organic matter produced by photosynthesis, carbon sequestered by photosynthesis, and oxygen released by photosynthesis is 1:1.47:1.07. Using this ratio, the amounts of sequestered carbon and released oxygen were calculated from NPP data.

The economic value of carbon sequestration was calculated from the cost of reforestation. In this study, we adopted a reforestation cost of 260.9 RMB¥/t of carbon (Li et al. 2006). The value of oxygen production was calculated from the average cost of oxygen production from reforestation (352.93 RMB¥/t O_2) and industrial methods (400 RMB¥/t O_2) (Li et al. 2006), for a value of 376.47 RMB¥/t O_2.

Water conservation

Water conservation is performed by vegetation through processes of rainfall interception, evapotranspiration, sorption, and storage (Li et al. 2006). Generally, water conservation can be obtained by the summation of canopy retention, litter absorption, and soil storage. The equations are given as follows:

$$Q_t = Q_c + Q_l + Q_s \quad (4a)$$

$$Q_c = \varepsilon \times P_y \times A \quad (4b)$$

$$Q_l = L \times A \quad (4c)$$

$$Q_s = P \times A \quad (4d)$$

where Q_t is the total amount of water conserved; Q_c is the water intercepted by the vegetation canopy; Q_l is the water absorption by litter; Q_s is the water stored by the soil under the vegetation; ε is the interception ratio of the canopy; P_y is the annual precipitation; A is the area of each vegetation type; L is water retention ratio by litter per unit area of vegetation; and P is the maximum storage capacity of the soil under the vegetation. Here, the values of ε, L, and P of different vegetation types were taken from the results of Jiao et al. (2002).

The economic value of water conservation was calculated from the shadow price of reservoir-building in China, i.e., 0.67 RMB¥/m^3 (Ren and Zhang 2003).

Soil conservation

The soil conservation was calculated by the RUSLE empirical model, as follows:

$$A = R \times K \times L \times S \times C \times P \quad (5)$$

where A is the estimated average soil loss; R is the rainfall erosivity factor; K is the soil erodibility factor; L is the slope length factor; S is the slope steepness factor; C is the vegetation management factor; and P is the conservation practices factor.

If both C and P are assigned the value of 1, i.e., there is no surface soil coverage or land management practices, then the calculated soil erosion is the potential soil erosion (A_p):

$$A_p = R \times K \times L \times S \quad (6)$$

The amount of soil conservation can be estimated by the difference between potential soil erosion and actual soil erosion. The new formula is as follows:

$$A_c = A_p - A_r = R \times K \times L \times S \times (1 - C \times P) \quad (7)$$

where A_c is the amount of soil conserved; A_p is the potential soil erosion; and A_r is the actual soil erosion.

The rainfall erosivity factor (R) was calculated using the Wischmeier empirical formula (Wischmeier and Smith 1978): $R = \sum 1.735 \times 10^{(1.5 \times \lg \frac{P_i^2}{P} - 0.8188)}$, where P_i is the monthly rainfall (mm) and P is the annual rainfall (mm).

S and L constitute the topography factor, which were calculated as follows (Zhou and Liu 2006):

$$S = \left(\frac{\sin\theta}{0.0896}\right)^{0.6} \quad (8a)$$

$$L = \left(\frac{\lambda}{22.13}\right)^{m} \quad (8b)$$

where θ is the percentage slope grade and λ is the horizontal length of the slope. Both θ and λ were extracted from the DEM of the Yanhe watershed. m is the coefficient for the length of slope, which was assigned the following values (Wischmeier and Smith 1978):

$$m = 0.5 \quad \theta \geq 9 \quad (9a)$$

$$m = 0.4 \quad 9 > \theta \geq 3 \quad (9b)$$

$$m = 0.3 \quad 3 > \theta \geq 1 \quad (9c)$$

$$m = 0.2 \quad 1 > \theta \quad (9d)$$

In large spatial scales, the differences in conversation practices, such as terracing or contour tillage, cannot be determined from the land use map, so we calculated it using the Wiener equation: $P = 0.2 + 0.3 \times \theta$ (Lufafa et al. 2003), where θ is the percentage grade. The vegetation management factor C is relevant to the vegetation type, the intensity of rainfall, the coarseness of the land surface, the rotation method, and the soil water content. The soil erodibility (K) is determined by soil type. The values of C and K were taken from Fu et al. (2005).

In this paper, the economic benefit of soil conservation was calculated from its role in conserving soil fertility, reducing land abandonment, and reducing sediment accumulation. Soil loss causes fertility loss, including N, P, K, and organic matter. The soil fertility conservation value was calculated by the market price, i.e., determining the contents of N, P, K, and organic matter by the amount of soil conserved, and multiplying by the prices of N, P, K, and organic matter.

The economic benefit of land abandonment reduction caused by soil erosion was calculated by the opportunity cost. In economic terms, an opportunity cost refers to the foregone benefits of alternative actions (or inactions) (Goh 2000). For ecosystem services, the opportunity cost refers to the value forgone in order to protect, enhance, or create a particular environmental asset (Adams et al. 2010), e.g., retaining forestry at the expense of agricultural production. In this research, the necessary index for the opportunity cost included the average GDP per unit area (Shaanxi Provincial Statistical Bureau 2007) and the average thickness of the surface soil; 0.6 m in the Yanhe watershed (Li and Ren 2006).

The economic benefit of reducing sediment accumulation was calculated from the water storage cost, i.e., the shadow price of building reservoirs.

All of the equations for the economic estimation of soil conservation are as follows:

$$V_t = V_1 + V_2 + V_3 \quad (10a)$$

$$V_1 = \sum P_s C_i P_i \quad (10b)$$

$$V_2 = \left(\frac{P_s}{D\rho}\right) \times B \quad (10c)$$

$$V_3 = \left(\frac{P_s}{\rho}\right) \times C \times 24\% \quad (10d)$$

where V_t is the total economic value of soil conservation; V_1 is the economic value of fertility conservation; V_2 is the economic value of land abandonment reduction; V_3 is the economic value of sediment accumulation reduction; P_s is the soil retention volume; C_i is the content of N, P, K, and organic matter in the soil; P_i is the price of N, P, K, and organic matter; D is the mean thickness of soil; ρ is the bulk density of soil; B is the GDP value per unit area; and C is the shadow price of building reservoirs. In China, the average sediment delivery ratio of soil loss into the reservoir is 24% (Ren and Zhang 2003), which was also taken into account.

The human activity intensity (HAI)

The HAI was calculated by integrating human population, farmland ratio, road networks, and residential land information, the weights of which were assigned by the analytic hierarchy process (AHP). Based on mathematics and psychology, the AHP was developed by Saaty in the 1970s to deal with complex decision-making (Saaty 1977, 1980, 1990). The AHP builds a hierarchy, or ranking, of decision elements, and then compares each possible pair in each cluster, as a matrix. A weighted value is assigned for each element within the cluster, and a consistency ratio is also provided for checking the consistency of the data. Based on expert consultation and reference to relevant documents (Hu et al. 2007), we used the AHP method to assign weighted values to the four indices as follows: human population 0.3, farmland 0.3, road network 0.2, and residential land 0.2. These assigned values were inserted into the HAI calculation as follows:

$$\mathrm{HAI} = P \times 0.3 + C \times 0.3 + R \times 0.2 + S \times 0.2 \qquad (11)$$

where P, C, R, and S stand for population, farmland ratio, road influence, and residential influence, respectively. The values were standardized using standard deviation.

Tailored to local conditions and referring to the State Basic Geographical Data Coding System, the residential land (Table 2) and road network (Table 3) were assigned influence values (Hu et al. 2007). The influence values were then spatialized by the interpolation of the inverse distance weight (IDW) and path distance (PD) using ArcGIS software.

Ecosystem services and HAI specialization, and townships clustering

Supported by ArcGIS, the parameters for the NPP, CSOP, soil conservation, water conservation, and HAI were converted into a raster dataset. The layers of the raster dataset were then calculated with their respective equations to obtain a raster dataset layer for each individual ecosystem service and HAI using the ArcGIS raster calculator module. Finally, the mean values for each township-based individual ecosystem service and HAI were obtained by allocating ecosystem services and HAI to the township vector map by the ArcGIS zonal statistics module.

We clustered the townships by the hierarchical cluster analysis of SPSS 11.5 software based on each individual ecosystem service and HAI index by application of the Euclidean distance.

Table 2 Influence of residential land (after Hu et al. 2007)

Residential rank	Influence[a]
City	25,000
County	20,000
Township	10,000–15,000
Village	5,000

[a] The value is dimensionless

Table 3 Influence of road network (after Hu et al. 2007)

Road rank	Influence[a]
High-grade expressway	12,000
National trunk highway	10,000
Railway	10,000
Provincial trunk highway	8,000
County and township road	5,000
Cart road	3,000
Earth road	2,000

[a] The value is dimensionless

Results

Spatial pattern of ecosystem services

The economic values of the NPP and CSOP varied tremendously, with higher values in the south and lower in the northwest (Fig. 2). The water conservation demonstrated a similar trend, with values highest in the southern midsection of the watershed, with decreasing values fanning outward (Fig. 2). The spatial patterns of the NPP, CSOP, and water conservation are closely related to the corresponding vegetation coverage, i.e., the southern area has greater forest coverage, and, thus, higher economic values, while the northwestern area, dominated by land for farming, has lower economic values. Soil conservation values exhibit the exception: a more complex spatial pattern distinguished primarily by the peripheral area surrounding the urbanized areas (Fig. 2). This unique pattern is possibly due to the complicated soil erosion mechanism, reflected, to some extent, by the RUSLE equation. The total value of ecosystem services demonstrated a spatial trend that increased essentially from south to north (Fig. 3), with the highest value, 13,869 RMB¥/ha, in the southern township of Liulin, and the lowest value, 4,966 RMB¥/ha, in the northwestern township of Liandaowan.

Spatial pattern of the HAI

The HAI demonstrated a spatial trend whose concentration was highest in the center of the watershed, and decreased outward towards the rural areas, which directly reflects the administrative hierarchy and economic development (Fig. 4). The highest HAI was 0.429 in the urban township of Qiaogou, and the lowest HAI was 0.058 in the countryside township of Zhangqu. This result demonstrates the advantages that urban areas and county seats have in obtaining resources and investments for infrastructure, which creates many job opportunities and attracts an influx of people from other areas.

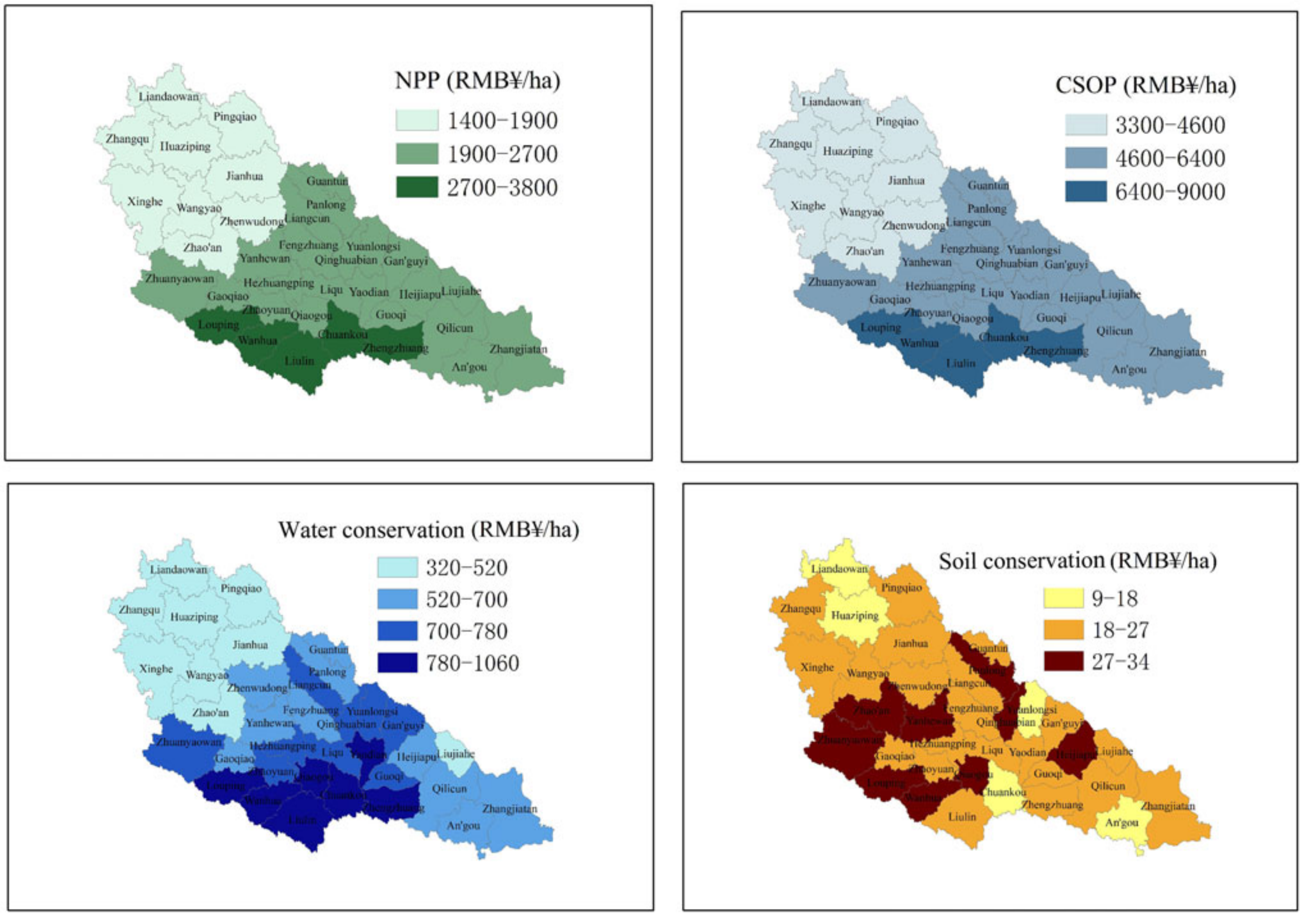


Fig. 2 Values of the NPP, CSOP, water conservation, and soil conservation in the Yanhe watershed (RMB¥/ha). NPP stands for the net primary production and CSOP stands for the carbon sequestration and oxygen production

Cluster analysis of townships by individual ecosystem services and the HAI

Based on ecosystem services and the HAI, the townships of the Yanhe watershed were clustered into five groups with distance coefficients of between 5.8 and 7.0 (Figs. 5, 6).

Group 1, the *suburban area*, includes the Fengzhuang, Gaoqiao, Heijiapu, Panlong, Yanhewan, Zhao'an, Zhuanyaowan, Liangcun, Gan'guyi, Guoqi, Zhaoyuan, Yuanlongsi, Qilicun, and Zhangjiatan townships. Covering 40.7% of the total area of the watershed and mainly surrounding the urban city of Yan'an, this area was characterized with moderate ecosystem services and HAI values (Table 4). Rapid economic development provided sufficient funds for these townships to conduct ecological rehabilitation. The ecological conditions of these townships have positive future improvement potential.

Group 2, the *urban area*, includes the Qinghuabian, Qiaogou, Yaodian, Liqu, Hezhuangping, and Zhenwudong townships. Covering the urban area, this group is the most anthropogenically disturbed area, with high HAI values. In order to improve the human habitat, the Yan'an city government has implemented a series of ecological improvement projects, such as the "Urban Area Beautifying Project", "Harnessing Program of Three Mountains and Two Rivers", and "Mountain Phoenix Afforestation Project". Vegetation coverage has recovered gradually.

Group 3, the *agricultural area*, includes the Liandaowan, Huaziping, Pingqiao, Zhangqu, Wangyao, Xinghe, Jianhua, Liujiahe, and Guantun townships. Located in the northwestern part of the watershed, this area has low ecosystem services and HAI values. The land use pattern of this area is characterized by larger farmland ratios (17 vs. 14% for the entire watershed) and smaller permanent vegetation ratios (81 vs. 84% for the entire watershed). Within the vegetation pattern, trees and shrubs account for a very small ratio, which hinders water and soil conservation.

Group 4, the *degraded ecological shelterbelt*, includes only one township, An'gou. Compared to other townships, An'gou is characterized by a very low HAI index (0.073 vs. 0.155 for the watershed as a whole), yet, has a relatively high ecosystem service value (9,722 vs. 7,892 RMB¥/ha for the watershed as a whole). As an underdeveloped

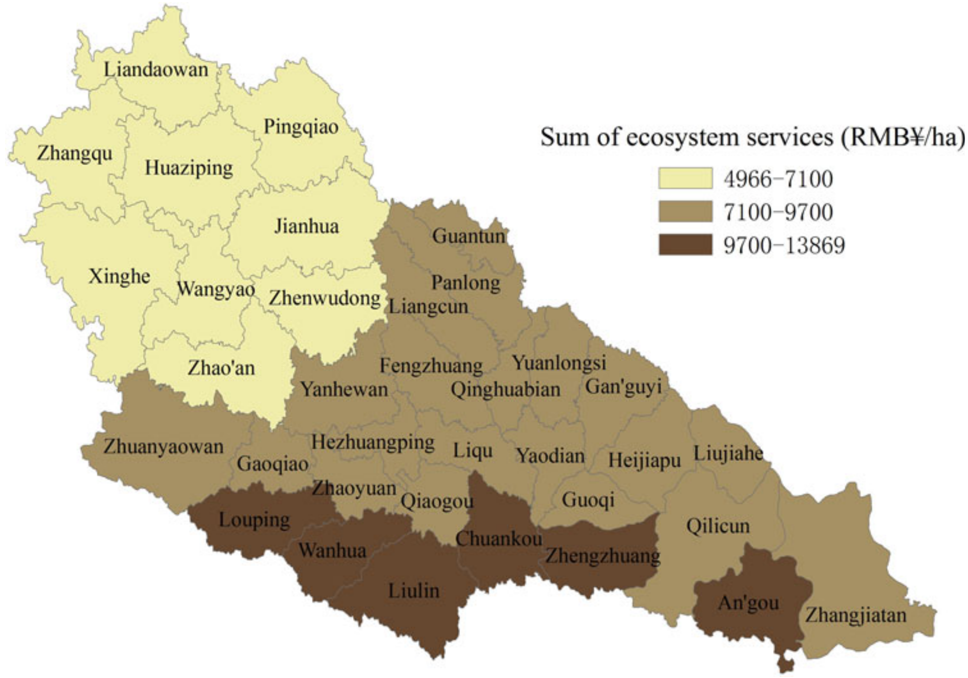


Fig. 3 Total ecosystem service value in the Yanhe watershed (RMB¥/ha)

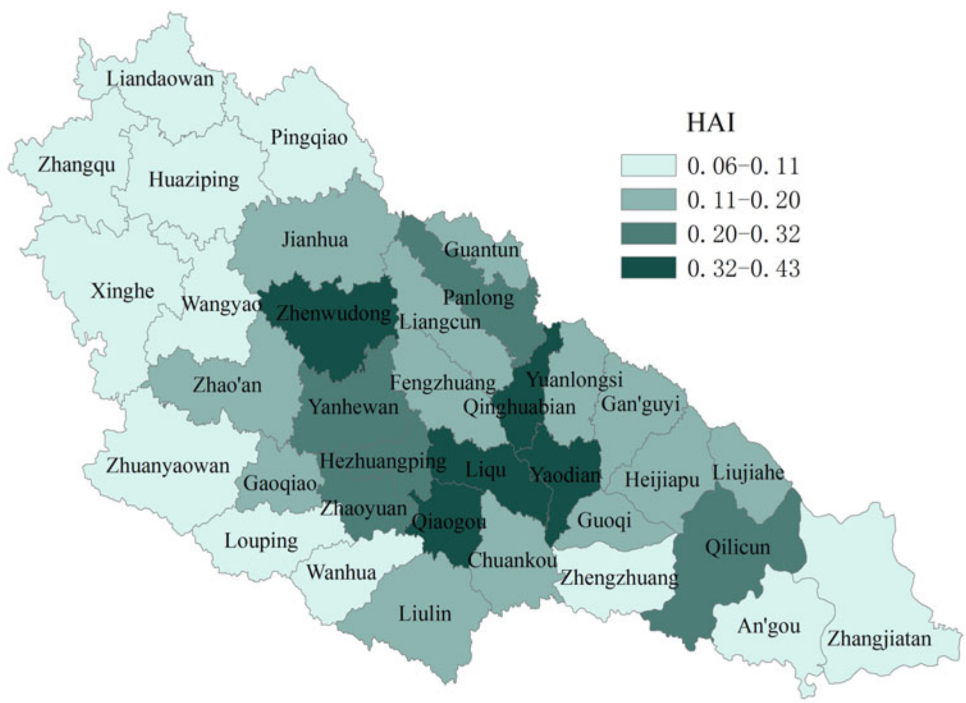
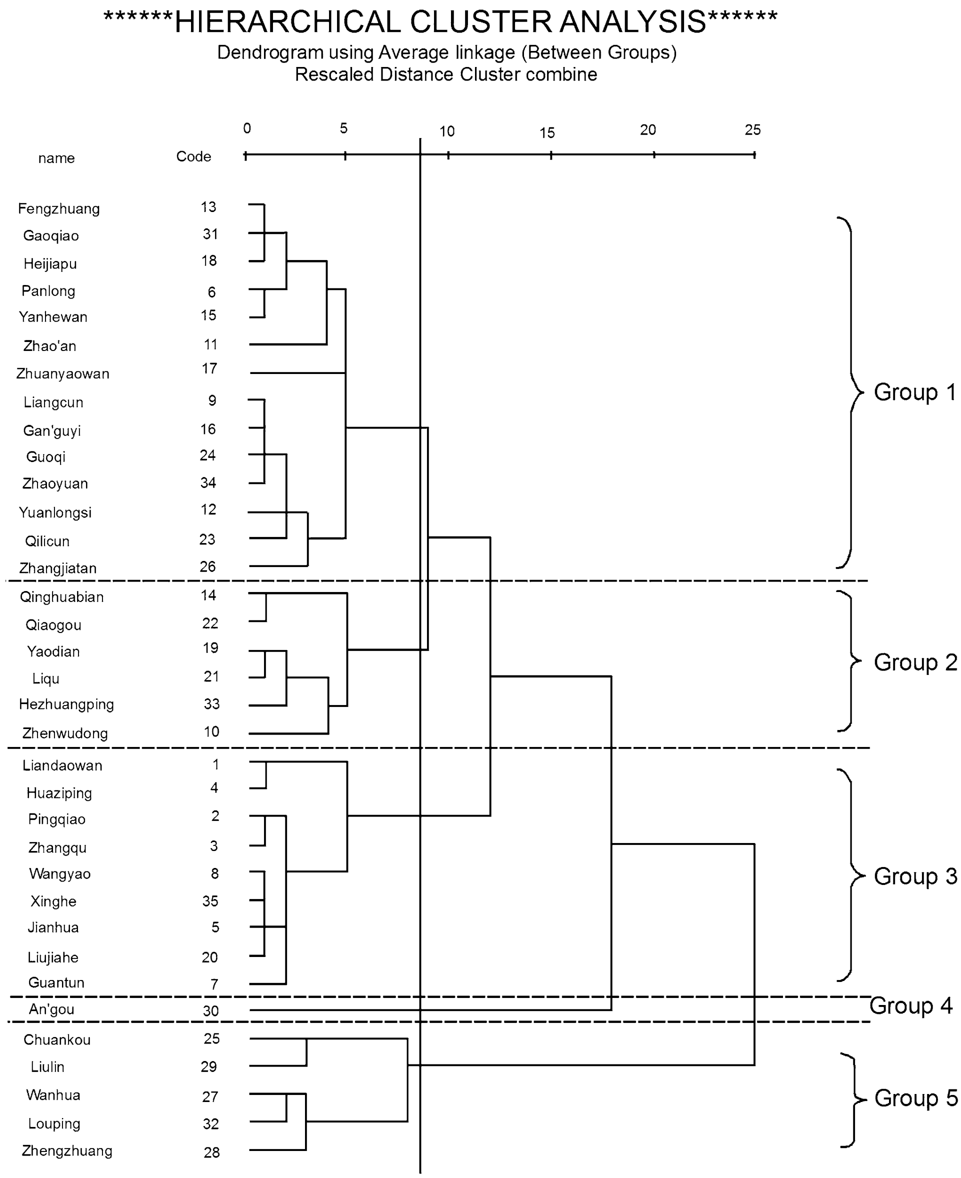


Fig. 4 The human activity index (HAI) in the Yanhe watershed

township, An'gou is confronted with a series of disadvantages, such as inaccessibility, poor land quality, and lack of development opportunities. To alter the ever-deteriorating ecological situation and decrease the ecological pressure, large numbers of people were encouraged to migrate to other areas. An'gou has somewhat favorable vegetation coverage, with the tree and shrubs ratio overwhelming that of cultivated lands, which provides a relatively higher water resource conservation value.

Group 5, the *ecological shelterbelt*, includes the Chuankou, Liulin, Wanhua, Louping, and Zhengzhuang townships. Because large populations immigrated to the city, the HAI of this area is very low. Historically boasting thick forests, this area has the highest ecosystem service

Fig. 5 Clustering dendrogram of townships in the Yanhe watershed



value (12,630.62 vs. 8,178.36 RMB¥/ha for the entire watershed). As an ecological shelterbelt for Yan'an, the local government has invested ample funding to protect the ecological conditions in this area, e.g., forest and park construction.

Discussions

Socioecological mapping based on ecosystem services and human activities

Quantified ecosystem services and human activities present only a general scenario of the study area; it is still constrained by some presumptuous assumptions which, to some extent, infringe its reliability. For example, the economic value of carbon sequestration deducted from the reforestation cost was somewhat arbitrary, as time intervals are different and the permanence of forests are varied. Besides, this study only included four ecosystem services, which definitely cannot fully reflect the ecological panorama of the study area. As for human activity, we failed to include the pivotal industry of oil exploration into the HAI due to low data availability. Notwithstanding the above caveats, our results have a wide array of policy implications, as they provide the necessary, albeit raw, information of human-dominated ecosystems management.

Spatial heterogeneity is the major characteristic of ecosystems. Both the structure and function of the ecosystem and the pattern and intensity of human exploitation varied between localities. An ecological map should be enacted with full, prudent consideration of spatial

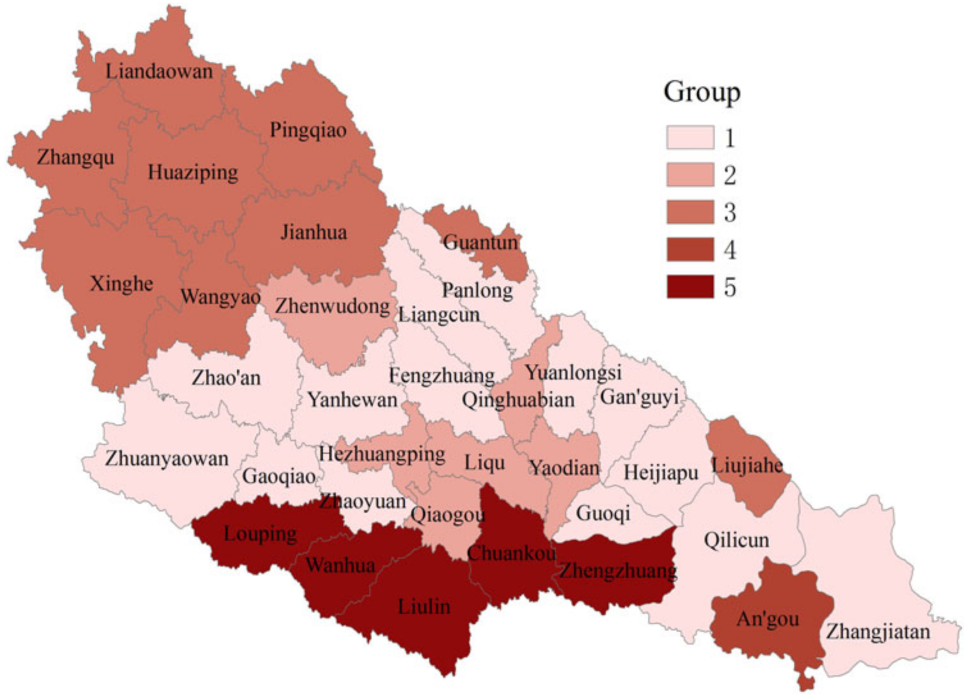


Fig. 6 Spatial pattern of clustering of townships in the Yanhe watershed

Table 4 Ecosystem service value and human activity index (HAI) of the different groups of townships

Clusters	Ecosystem service value (RMB¥/ha)					HAI[a]
	Total value (RMB¥/ha)	NPP (RMB¥/ha)	CSOP (RMB¥/ha)	Soil conservation (RMB¥/ha)	Water conservation (RMB¥/ha)	
Group 1	8,384.35	2,258.18	5,459.64	25.70	640.82	0.158
Group 2	8,080.64	2,149.00	5,195.66	26.18	708.80	0.379
Group 3	5,889.03	1,592.47	3,850.15	20.41	426.00	0.101
Group 4	9,721.64	2,636.73	6,374.86	9.17	699.87	0.073
Group 5	12,631.59	3,406.14	8,235.10	24.61	964.73	0.120
Total area	7,892.37	2,125.25	5,138.24	23.17	605.66	0.155

NPP net primary production, *CSOP* carbon sequestration and oxygen production, *HAI* human activity index

[a] The value is dimensionless

heterogeneity (Naidoo et al. 2008; Raymond et al. 2009), which can effectively guide ecosystem planning due to its strong spatially explicit characteristics. Ecological mapping also has the potential to reflect the thresholds of ecosystem restoration, anticipate the ecosystem's evolving trends, and optimize the configuration of natural resources (Beauchesne et al. 1996). For a long time, biogeographic factors were considered to be the sole basis for ecological mapping, e.g., White (1983) took phytogeographic factors as the basis for mapping the Afrotropic ecozone. Thackway and Cresswell (1995) created an Australian ecological map by using biogeographic regionalization. The Chinese Vegetation Map Compilation Committee (CVMCC1979) and the Changchun Institute of Geography, Chinese Academy of Science (1990) developed an ecological map of China based on the biogeographic eco-regions.

Ecosystem services support and regulate the ecological processes that underpin life on Earth, while also providing diverse, 'tangible' goods which are directly or indirectly involved in the social, ecological, economical, and socio-cultural sectors (MA 2005a). The ecosystem services in this study varied in rhythm with socioeconomic development, and could reflect a comprehensive ecological and environmental evolution. With the increasing awareness of ecosystem services, an ecosystem service-based ecological map increasingly serves as a guide for ecological management and ecosystem conservation. Naidoo et al. (2008) mapped ecosystem services and compared it to the global-targeting area of biodiversity conservation, and concluded that 'win–win' areas (regions where both ecosystem services and biodiversity are important) can be usefully identified both among eco-regions and at finer scales. Based on in-depth interviews with 56 decision-makers and community representatives, Raymond et al. (2009) mapped values of natural capital assets and ecosystem services in the southern Australian Murray-Darling Basin region and stressed their significance in environmental management and planning. Egoh et al. (2008) mapped five ecosystem services in South Africa (surface water supply, water flow regulation, soil accumulation, soil retention, and carbon storage), assessed their relationship and spatial congruence to primary production, and concluded that: (1) most of the land surface is important for supplying at least one service; (2) there are low levels of congruence between the service ranges and even lower levels between hotspots for different ecosystem services; and (3) primary production appears to show some surrogate potential for ecosystem services distribution.

Due to the influence of 'Ecological Determinism' (Paine 1984), the traditional ecological mapping scheme excessively stressed physical conditions, yet, neglected human factors, which lead to uneven development. Dynamic interlinks exist between society and ecosystem services (Liu et al. 2007; MA 2005a). Social-economic development threatens ecosystem services provisions due to the mismatches between short-term individual needs and long-term societal well-being (Cumming et al. 2006; Saunders and Briggs 2002). The conflict between supply and demand over environmental resources cannot be resolved by socioeconomic systems, per se, featured by self-organization and feedback (Pirot et al. 2001). External anthropogenic forces are needed in order to guide these systems into a sustainable rail, which also holds true for social ecological mapping. Only, until then can socioecological mapping identify the key processes, advance the socioecological system to be resilient towards disturbances or shocks (Alessa et al. 2008), and enable humans to anticipate, learn, and plan for the future (Holling 2001). Alessa et al. (2008) observed the human-related aspects involved in socioecological mapping, including life support, economic, scientific, cultural, recreation, aesthetic, natural history, spiritual, and intrinsic etc. In our research, we formulated a comprehensive HAI based on population, farmland ratio, residential settlements, and road networks and integrated it into the socioecological mapping process, seeking to provide an applicable means for ecological management.

Implication of socioecological mapping on sustainable ecosystem management

The IUCN Commission for Ecosystem Management (IUCN-CEM) defined ecosystem management as a "process integrating ecological, social-economic, and institutional factors into a comprehensive analysis and action in order to sustain and enhance the quality of the ecosystem to meet current and future needs" (Pirot et al. 2001). The core objective of ecosystem management is the sustainable, efficient, and equitable use of natural resources. The main task of sustainability science is to bridge the natural and social sciences in order to seek creative solutions to the challenges facing a coupling socioecological system (Jerneck et al. 2011; Savage 2006; Zhang et al. 2009); therefore, the ecosystem management scheme with the full integration of both ecosystem services and human activities help to make sustainable, sensitive, and effective ecological policies. Based on selected ecosystem services and HAI indicators, the townships of the Yanhe watershed were clustered and mapped into five groups, i.e., *suburban area* (relatively high HAI and moderate ecosystem services), *urban area* (high HAI and moderate ecosystem services), *agricultural area* (low HAI and low ecosystem services), *degraded ecological shelterbelt* (very low HAI and relatively high ecosystem services), and *ecological shelterbelt* (medium HAI and high ecosystem services). Suggestions on sustainable development were delivered based on the socioecological map as follows:

Group 1 (*suburban area*) is most productive both in agriculture and industry. The farming system should be enhanced by increasing high value-added sideline productions, such as animal husbandry and cash crops. Intensified farming should be extended into the farmland by applying improved technologies (such as advanced irrigation techniques, agricultural mechanization, and high-yield varieties). Conservation farming practices, such as straw mulching and reduced or eliminated tillage, should be encouraged, as they can reduce soil and water losses (Su et al. 2007). In addition, multicrop rotation could be advanced, as it can increase the duration of vegetation cover (Zhang et al. 2000). This area includes the lower reaches of the Yan River, so check-dams are an advisable engineering measure for curbing soil losses into the Yellow river (Xu et al. 2002).

Group 2 (*urban area*) consists of the urban area in Yan'an district. As the economic and political center, this area should be given full use of secondary and tertiary industries to create job opportunities and absorb the influx of population from ecologically vulnerable areas. Forests, parks, and an urban river system should be established. Tourism could be developed, as various historic relics are scattered throughout this area.

Group 3 (*remote farming area*), located in the upper region of the Yan River, is the most ecologically degraded area. The mountains in this area need to be closed completely in order to allow ecological recuperation. Farmland on slopes over 25° and yield less than 750 kg/ha of grain should be converted to trees or grassland (State Council of the People's Republic of China 1998). Farmers should be subsidized for their loss of farmland due to the implementation of the GfG project. Within the GfG project area, the protective forests should overwhelm the commercial forests. The low ecological capacity of this area necessitates resettlement of the vast population to other areas.

Groups 4 and 5 (*ecological shelterbelt*) have well-established vegetation coverage areas and play a significant role in safeguarding the whole Yanhe watershed. As an ecological shelterbelt, this area should be nourished. Farming should be prohibited and large populations be resettled. The revenue resulting from any subsequent boom in eco-tourism in this area due to the advantageous vegetation coverage should be used for ecological restoration.

Conclusion

Ecosystem services of net primary production (NPP), carbon sequestration and oxygen production (CSOP), and water conservation showed similar gradient spatial tendencies, high in the south and low in the northwest. The complicated mechanisms determined that the soil conservation is somewhat obscure, with a pattern roughly concentrated in the peripheral area surrounding the urbanized areas. The total value of ecosystem services exhibited a south to north decreasing spatial pattern. The human activity index (HAI) is roughly proportional to the administrative and the economic developments, which showed a spatial pattern with the highest values concentrated in the center of the watershed surrounding the urban area and decreasing outward.

Based on the selected ecosystem services and HAI, the townships of the Yanhe watershed were mapped into five groups, i.e., *suburban area*, *urban area*, *remote farming area*, *degraded ecological shelterbelt*, and *ecological shelterbelt*. Suggestions for ecological management were provided, tailored to the socioecological maps of each area.

Even though our study merely provided a static 'snapshot' of the dynamic influences of ecosystem services and human activities, it can be referred to as a useful case study for human and nature research, e.g., exploration of land use driving mechanisms. In addition, it also sheds some light on the cultural landscape and sustainability science in the Yanhe watershed. Humans and nature continue to synchronically evolve, so time-series data are required in order to explore the long-term variances in ecosystem services, human activities, and their corresponding interactions, e.g., driving, and feedback mechanisms. Improving this data, as well as the upgrades of valuation methods and theories from which they are derived, guides our progressive research into the future.

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