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Integrated Assessment and Restoration Pathways for Holistic Ecosystem Health in Anxi County, China

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Abstract: Different types of ecosystems form a complex community of life. Hence, ecosystem protection and restoration should not focus solely on a single ecosystem. Ecosystem health assessments should consider the integrity and systematicity of interrelated ecosystems to inform rational environmental planning and management. In this study, the key characteristic indicators of major ecosystems (mountain, water, forest, and cropland) and ecosystem service capacity indicators in Anxi County, China, were selected to construct an integrated assessment system of ecosystem health that led to integrated ecosystem restoration pathways that addressed the county's ecological problems. The results revealed that ecosystem health was higher in the western and lower in the eastern parts of the county. Throughout the county, "medium" and "poor" ecosystem health levels predominated, revealing that overall ecosystem sustainability was weak. Ecosystem restoration programmes should be tailored to each health level. Where there was "excellent" and "good" ecosystem health ratings, those healthy ecosystem functions should be strengthened and maintained. In the "medium" health areas, the control and prevention of ecological problems should be strengthened. "Poor" health areas require immediate integrated ecological restoration projects that ensure the connectivity and coordination of restoration tasks in fragile ecosystems. This then will enhance holistic ecosystem stability and sustainability.

Keywords: ecosystem health; ecosystem community; ecological conservation and restoration; ecosystem services

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1. Introduction

Ecosystems provide a substantial material base for human survival, and maintaining healthy ecosystems ensures the sustainability of human development [1]. There is no doubt that the industrialisation and urbanisation of human societies have developed rapidly by relying on natural resources and energy from ecosystems. However, the ecosystems have been stressed during this process and many have been altered and damaged by extensive human activities [2], thus exacerbating many ecological problems such as global warming, natural disasters, energy resource shortages, atmospheric pollution, and biodiversity reduction [3,4]. Due to massive human disturbances, Earth's ecosystem structure and function have changed dramatically, thus leading to a destabilisation of ecosystem functioning [5]. At the same time, when disturbances exceed an ecosystem's capacity for self-repair, that ecosystem can provide only lower-quality services, so social and economic benefits decline and the sustainable development of human well-being is limited [6–8]. Therefore, a key ecosystem research task is to better understand ecosystem health and use that information to provide a strong scientific basis for environmental planning and management [9,10].

Healthy ecosystems maintain their integrity and stability while also providing ecological services to humans [11]. Ecosystem health research focuses on identifying ecological problems in specific ecosystem processes and ecological patterns, and on providing the basis for research methods that assess the degree of health or damage. This then provides a scientific basis for rational environment management, which also aids the sustainable development of ecology and human beings [12–14]. Ecosystem health has been explained from different perspectives (e.g., ecological and sociological). From an ecological perspective, ecosystem health is considered as a state of equilibrium achieved through the interactions among various biological populations within the ecosystem and their environment. From a sociological perspective, ecosystem health is viewed as a balance achieved when the ecosystem meets human well-being, and natural resources are utilized and protected in a reasonable manner. This perspective focuses more on the interrelationships between human society and the ecosystem. However, because different researchers may adopt distinct focuses and methodologies to define and assess ecosystem health, consequently, ecosystem health has yet to be defined in a coherent and clear manner [15–17].

The widely accepted concept of ecosystem health proposed by Costanza [1] pointed out that a healthy ecosystem can provide ecosystem services (ES) that support human society. The concept includes a "vigor-organisation-resilience" framework that combines ecosystem structure, function, and ESs to identify and analyse ecosystem health. In recent years, most ecosystem health studies have based their evaluation indicator systems on this framework [18–22]. To understand the functions and conditions of ecosystems, and to assess and address the vulnerability or degradation of ecosystems through effective, scientific methods, researchers have meticulously studied various types of ecosystems (e.g., marine ecosystems [23,24], river ecosystems [25,26], forest ecosystems [27,28], agroecosystems [29], wetland ecosystems [30,31], and desert ecosystems [32]). These studies have yielded important results that have provided strong scientific bases for ecosystem restoration. At the same time, in addition to basic research on ecosystem health, many countries, such as China, have instituted many ecological restoration projects [33]. To harmonise human society with the natural environment, restoration measures that promote the smooth operation of ecosystems help maintain and enhance the ability of those ecosystems to cope with environmental changes and human disturbances (e.g., vegetation restoration [34], desertification management [35], sandstorm management [36], water management [37], and soil and water conservation [38]). These ecological engineering projects have achieved significant positive results and have greatly improved ecological environments.

However, ecological conservation and restoration projects tend to focus on a single ecological element, and that severs the integrity of ecosystems and ignores the linkages in ecological processes. We must remember that the ecosystem is a large and complex community of life that interacts on multiple levels with the physical environment, and the subsystems within it are universally linked and interact with each other. One of the more common ecological problems in China is that population pressures and over-exploited resources have caused an expansion of arable land in mountainous areas, and that has led to problems such as degraded vegetation cover and reduced soil quality. These problems then exacerbate soil erosion problems, and multiple interactions among those problems creates a vicious cycle [39]. Additionally, while the stabilisation of a major ecosystem function can regulate the dynamic balance of a region's combined ecosystems, the degradation of a major ecosystem function can trigger a decline in the ES capacity of other ecosystems [40]. Therefore, how do we effectively explore overall ecosystem health and its integrated conservation and restoration? Obviously, the level of such holistic ecosystem health must be determined by constructing an integrated assessment model, and that is a key task in the process of exploring this issue.

Researchers have used various methods to conduct ecosystem assessment studies at different scales (e.g., fuzzy mathematical methods [41], grey system models [42], artificial neural network models [43], and the composite index method [1]). However, from any perspective, research on integrated diagnosis and assessment of ecosystem health is particularly scarce [44]. In addition, considering ecosystem restoration pathways from a holistic perspective, sorting out ecological problems that exist in different ecosystems may be an effective way to promote the preservation or restoration of ecosystem health and create a beneficent cycle.

Based on the interconnectedness of ecosystem types, the main objective of this study is to construct an integrated assessment system that combines key characteristic indicators of the major ecosystem types and of the ES capacity indicators. The final assessment results can reflect the integrated ecosystem health and provide services for the integrated ecological restoration in Anxi County. The study area used to test the assessment system was Anxi County, Fujian Province, China. Finally, we developed integrated ecosystem restoration pathways based on the county's ecological issues. The implementation of restoration pathways can be guided by the integrated assessment results to develop integrated restoration plans for different regions. This study provides a scientific basis for ecosystem health regulation and ecological restoration in municipalities in Anxi County.

2. Study Area

2.1. Anxi County Conditions

Anxi County (24°50′–25°26′ N, 117°35′–118°17′ E) is in the southeastern Fujian Province in China and has an area of 3057.28 km^2 (Figure 1). It is in the central and southern subtropical maritime monsoon climate zone and has abundant sunshine (1850 h per year), sufficient rainfall (1500–2000 mm), and an average annual temperature of 16.0–21.0 °C. Its geomorphological types are complicated and diverse, and the terrain differs greatly between the east and west parts of the county. Also, a dense network of rivers and abundant water resources include the Jinjiang River basin water system in the eastern part of the county and the Jiulongjiang River basin in the western part. Together, they account for 64.8% and 35.2% of the county's river basin area, respectively. The southern part of the county is subtropical rainforest and the middle is subtropical evergreen broad-leaved forest.

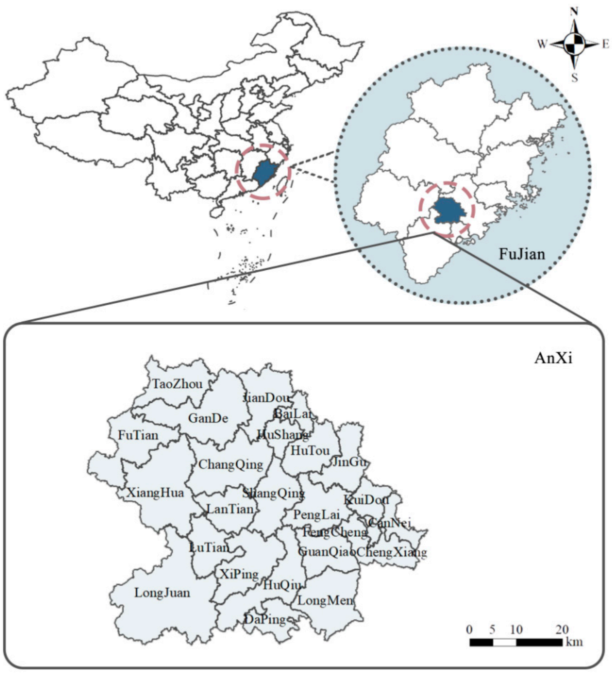

Figure 1. The location of Anxi County in Fujian Province, China. Smaller subdivisions within the county are townships.

2.2. Ecosystem Issues

Anxi County's rapid social and economic development has placed it among the top 100 counties in China in terms of comprehensive strength. However, many ecological problems have emerged due to the impact of urban development and construction. In recent years, the local government has intensified the protection of the ecological environment and developed a series of relevant policies to vigorously support the implementation of ecosystem conservation and restoration work. To determine Anxi County's current ecological problems, we examined field research and pertinent information provided by the Anxi Natural Resources Administration.

Anxi County is composed of mountain, water, forest, and cropland ecosystems. The main problems in the mountain ecosystem are exposed hill pits, destroyed mountain surfaces and vegetation, a high incidence of geological disasters from mining, and an accumulation of loose surface sediments. The water ecosystem suffers from accumulated pollutants in the rivers, inadequate sewage disposal facilities, reduced water system connectivity, and untreated sewage discharge. Meanwhile, the forest ecosystem suffers fragmentation, a monocultural stand structure, disastrous pest outbreaks, and a reduction in natural forests. Finally, the main cropland ecosystem problems are low soil fertility, an irrational fertilisation structure, a low rate of cropland reclamation, and contaminated soil.

The interactions among these ecological problems have intensified water and soil losses and created fragile shelterbelt forests, severe water pollution loads, and degraded cropland. Ultimately, the results of those interactions further contribute to a reduced ES capacity and overall ecosystem instability (Figure 2).

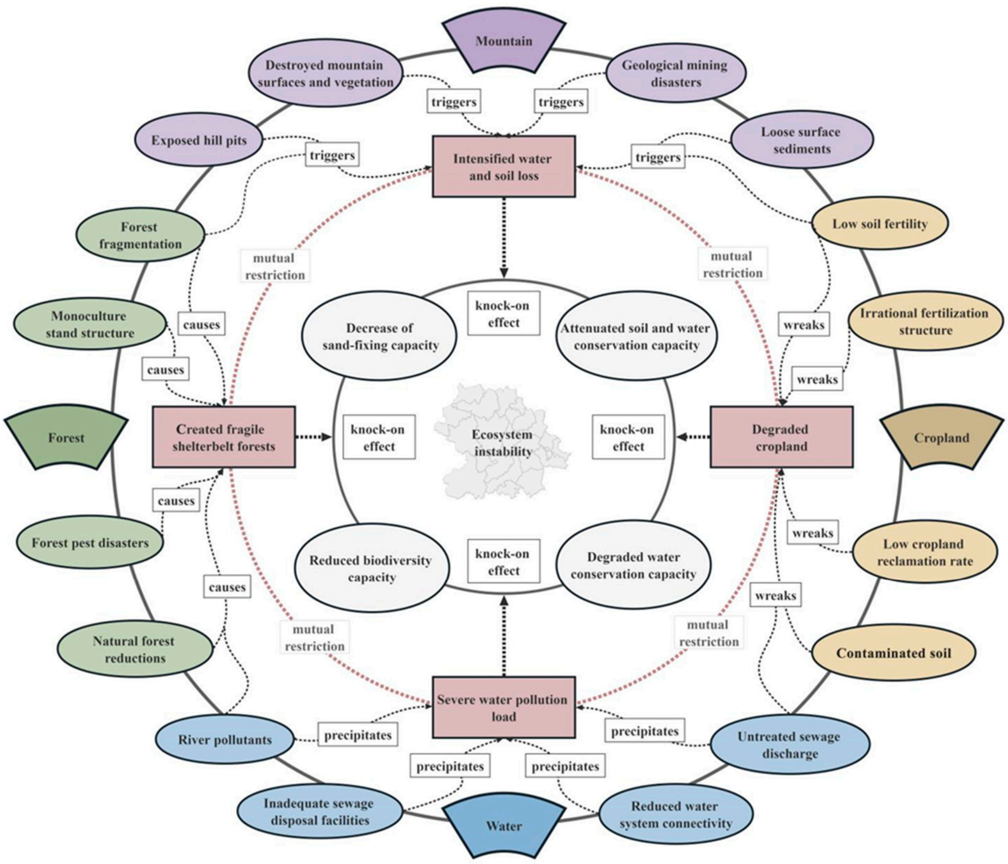

Figure 2. The relationships between the various ecological issues in Anxi County. Ecological issues in mountain, forest, water and cropland ecosystems (outer ring). These problems interact to create broader problems (next inner ring), which then contribute to reduced ecosystem service capacity and overall ecosystem instability (innermost ring).

3. Methodologies

3.1. Indicator System for Assessing Ecosystem Health

3.1.1. Establishing the Indicator System

To comprehensively assess ecosystem health, an evaluation indicator system must first be established. The indicators must be easily quantified and understood, as well as indicative of the topic being evaluated. From our study area, we have consulted a wealth of local planning documents and incorporated the insights of relevant experts. Finally, we selected key characteristic indicators of the major ecosystems and of the ES capacity to construct a comprehensive ecosystem health assessment system based on scientificity, comprehensiveness, and operability (Figure 3).

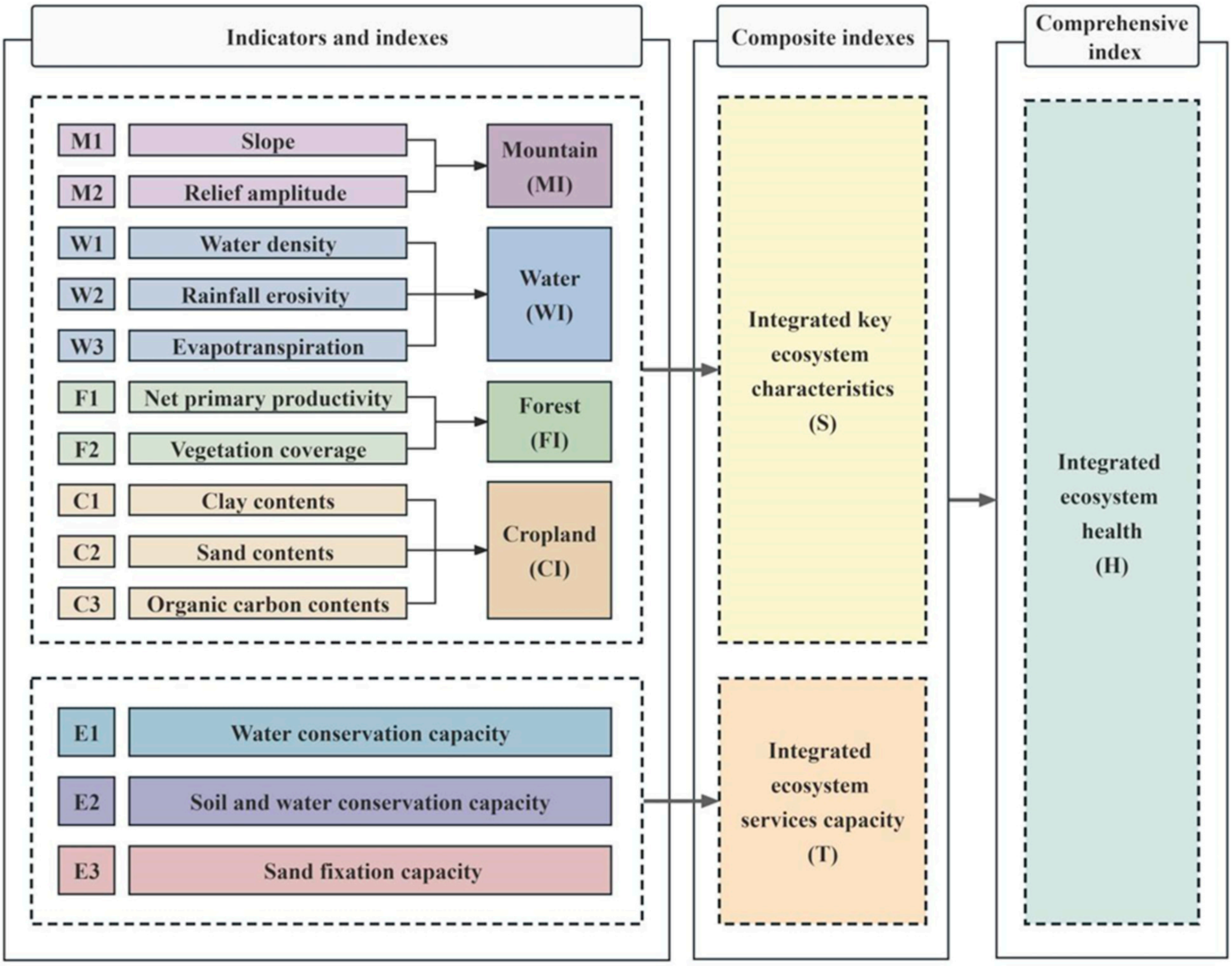

Figure 3. Comprehensive evaluation indicator system for ecosystem health in Anxi County. The indicators and indexes included the characteristic indicators for each of the four ecosystem types and their resulting composite indexes (top box) and the ecosystem service capacity indicators (bottom box). The composite indexes and comprehensive index show the progression of combining the indexes and indicators into a final assessment of the overall ecosystem health for the entire county.

Selection of the Key Characteristic Indicators for the Four Ecosystems

The study area is predominantly mountainous with many abandoned mines, and geological disasters such as landslides and collapses occur often. Therefore, we selected slope (M1) and relief amplitude (M2) as the two key characteristic indicators for the mountain ecosystem (Figure 3). Because M1 and M2 reflect the geomorphological pattern and the steepness of the land surface, they best judge both the terrain complexity and the risk levels of natural disasters.

The study area has abundant water resources, but the water ecosystem's greatest problem is that the gradual disconnection between water systems is leading to limited ecological function. Therefore, the indicators selected for the water ecosystem were water density (W1), rainfall erosivity (W2), and evapotranspiration (W3). We selected W1 to reflect the overall distribution of water bodies, which enabled us to determine whether the region can maintain water cycle stability, as well as provide a strong water supply. Because the abundant rainfall and strong convective weather in the study area can cause heavy rainfall and flash floods, W2 was selected to reflect the potential impact of soil erosion caused by rainfall, and that then helps us judge whether the area is susceptible to rainfall erosion that could then cause serious soil erosion and natural disasters. The long and hot summers in parts of this area can cause rapid water evaporation from soil and vegetation. Therefore, W3 was selected to reflect the total amount of water vapour released by vegetation and the surface to the atmosphere, and that helped determine whether the soil can consistently provide enough water for vegetative growth.

The study area has abundant forest resources, but due to human activities, the natural forests are gradually giving way to planted, monoculture forests, thus resulting in low forest quality. Therefore, for the forest ecosystem, we selected net primary productivity (F1) and vegetation coverage (F2) as indicators. First, F1 was selected to reflect the energy remaining for other organisms in the ecosystem after the vegetation itself was consumed. This helps judge whether the ecosystem can then provide what those organisms need to survive and reproduce. Second, F2 indicates the level of forest resources and greening, which can then be used to judge the extent of vegetation resources coverage and the potential of those resources to help maintain ecosystem stability.

The study area is affected by both natural and anthropogenic factors such as steep terrain, frequent heavy rainfall, and irrational farming practices, and those factors have led to poor soil quality, as well as to a disaster-prone situation. Therefore, the indicators selected for the cropland ecosystem were soil quality indicators: clay (C1), sand (C2), and organic carbon (C3) contents. First, C1 reflects the soil water-retention property, and can be used to judge the soil's ability to retain water and nutrients. Next, C2 reflects the soil's water retention and wind erosion resistance properties and indicates the soil's susceptibility to nutrient loss and drought, as well as its ability to resist wind erosion. Finally, C3 reflects soil fertility and thus shows whether the soil can support crop growth and soil microorganisms.

Selection of the Ecosystem Service Capacity Indicators

The indicators selected for ES capacity were water conservation capacity (E1), soil and water conservation capacity (E2), and sand fixation capacity (E3) (Figure 3). Among these three indicators, E1 reflects the ecosystem's ability to intercept, infiltrate, store, and purify precipitation through its structure and interactivity with water. Thus, it was used to determine the ecosystem's ability to regulate the water cycle and the supply of water resources. Next, E2 reflects the ecosystem's ability, through the absorption and infiltration of rainfall combined with soil stabilisation by plant roots, to reduce soil fertility loss and to mitigate river silting. Thus, it was used to determine the ecosystem's ability to mitigate flooding, maintain the water table and water supply, prevent soil erosion, and improve soil quality. Finally, E3 reflects the ecosystem's ability to reduce soil bareness and weaken wind strength and sand carrying capacity by fixing soil and improving soil structure. Thus, it was used to determine the ecosystem's ability to resist soil erosion and wind-sand hazards. These ES capacity indicators were used to determine the study area's four ecosystems' abilities to maintain ecological function and security.

3.1.2. Data Sources

Data for this study were gathered as follows.

(1) Landsat-8 remote sensing image and Digital Elevation Model (DEM) data were acquired from the Geospatial Data Cloud Platform (https://www.gscloud.cn/ (accessed on 19 August 2022)). The remote sensing image data were collected in September 2019 with a resolution of 30 m. We used ENVI 5.3 (NV5 Geospatial, Hollywood, FL, USA) to pre-process the remote sensing image using cropping, fusion, radiometric calibration, and atmospheric correction. In addition, the 30 m resolution DEM data were used to extract land slope and relief amplitude in ArcGIS 10.5.
(2) Data on precipitation, evapotranspiration, wind speed, and net primary productivity with 500 m resolution for the years 2011–2020 were obtained from the National Earth System Science Data Centre, China (http://www.geodata.cn/ (accessed on 23 August 2022)).
(3) Soil data (clay, sand, and organic carbon contents) with 500 m resolution were obtained from the World Soil Database (https://www.fao.org/soils-portal/data-hub/ (accessed on 29 August 2022)).
(4) The Anxi Natural Resources Administration (http://www.fjax.gov.cn/ (accessed on 25 July 2022)) provided information that was used to determine the ecosystems' main problems, as well as data on water density.

Additonally, the indicators were resampled as raster data with a resolution of 250 m in ArcGIS 10.5. This choice was made in accordance with the detailed guidelines in China's "Guidelines for the Delineation of Ecological Conservation Redline" (https://www.mee.gov.cn/ (accessed on 12 September 2022)).

3.1.3. Indicator Calculations

The base data for the 13 indicators selected for this study were pre-processed and then spatially analysed in ArcGIS 10.5 (https://www.esri.com/ (accessed on 10 October 2022)). However, rainfall erosivity, vegetation coverage, and the ES capacity indicators required additional calculations as follows.

Vegetation Coverage and Rainfall Erosivity Calculations

We first calculated the normalized difference vegetation index ($NDVI$) extracted from the pre-processed Landsat-8 remotely sensed images and used that to calculate vegetation cover ($F2$) [45]:

$$NDVI = (Band4 - Band3)/(Band4 + Band3) \tag{1}$$

$$F2 = (NDVI - NDVI_{soil})/\left(NDVI_{veg} - NDVI_{soil}\right), \tag{2}$$

where $Band3$ is the infrared band, $Band4$ is the near-infrared band, $NDVI_{veg}$ is the information contributed by a fully vegetated surface, and $NDVI_{soil}$ is the information contributed by an unvegetated surface.

We used the formula in the "Guidelines for Measurement and Estimation of Soil Erosion in Production and Construction Projects" of China (http://www.swcc.org.cn/ (accessed on 12 September 2022)) to calculate rainfall erosivity (W2) based on 10 years of rainfall data for the study area. The formula is

$$R = 0.067P_d^{1.627}, \tag{3}$$

where P_d is the average rainfall over the years.

Ecosystem Service Capacity Indicator Calculations

The ES capacity indicators ($E1$, $E2$, and $E3$) were calculated according to the functional ecosystem importance assessment methods in the "Guidelines for the Delineation of Ecological Conservation Redline" in China (https://www.mee.gov.cn/ (accessed on 12 September 2022)). First, we calculated

$$E1 = NPP_{mean} \cdot F_{sic} \cdot F_{pre} \cdot (1 - F_{slo}), \quad (4)$$

where NPP_{mean} is the average multi-year net primary productivity of vegetation, F_{sic} is the soil percolation factor, F_{pre} is the multi-year average precipitation factor, and F_{slo} is the slope factor.

Before calculating $E2$, we first calculated the pre-amended soil erodibility factor (K_{EPIC}), and used it to calculate the amended soil erodibility factor (K):

$$K1 = 0.2 + 0.3exp[-0.0256m_{sand}(1 - m_{silt}/100)] \quad (5)$$

$$K2 = \left[m_{silt}/\left(m_{clay} + m_{silt}\right)\right]^{0.3} \quad (6)$$

$$K3 = 1 - 0.25orgC/[orgC + exp(3.72 - 2.95orgC)] \quad (7)$$

$$K4 = 1 - 0.7(1 - m_{sand}/100)/\{(1 - m_{sand}/100) + exp[-5.51 + 22.9(1 - m_{sand}/100)]\} \quad (8)$$

$$K_{EPIC} = K1 \cdot K2 \cdot K3 \cdot K4 \quad (9)$$

$$K = (-0.01383 + 0.51575K_{EPIC}) \cdot 0.1317, \quad (10)$$

where, m_{sand}, m_{clay}, m_{silt}, and $orgC$ are the sand, clay, silt, and organic carbon content of the soil, respectively.

Then,

$$E2 = NPP_{mean} \cdot (1 - K) \cdot (1 - F_{slo}). \quad (11)$$

Before calculating $E3$, we first calculated the multi-year average climatic erosive force (F_q) and the surface roughness factor (D) as follows:

$$F_q = \frac{1}{100}\sum_{l=1}^{12} u^3\left(\frac{ETP_i - P_i}{ETP_i}\right) \cdot d \quad (12)$$

$$D = 1/cos(\theta), \quad (13)$$

where ETP_i is the monthly potential evapotranspiration, P_i is the monthly precipitation, d is the number of days in the month, and θ is the slope. Next,

$$E3 = NPP_{mean} \cdot K \cdot F_q \cdot D \quad (14)$$

3.2. Construction of a Comprehensive Index of Ecosystem Health

3.2.1. Entropy Weight Method

The entropy weight method is usually used to determine indicator weights in studies related to ecosystem health assessment [46,47]. This method objectively assigns weights that are used to judge the degree of dispersion of the indicator values, thus eliminating interference from subjective factors and avoiding the problem of overlapping information between multiple indicators. This then renders objective and reliable evaluation results [48]. In this study, this method was employed to calculate the weights of 10 characteristic indicators (M1, M2, W1, W2, W3, F1, F2, C1, C2, and C3) for the four ecosystem types in the study area.

Data Standardisation

Because of the large differences among the indicators' dimensions and quantities, their orders of magnitude must be eliminated to make the data easily and directly comparable. In the entropy weight method, indicators are classified as positive or negative. Specifically, a higher value of a positive indicator corresponds to a higher value of the comprehensive assessment, whereas a higher value of a negative indicator corresponds to a lower value of the comprehensive assessment. Therefore, they necessitate distinct calculation methods. The positive and negative indicators were standardised as follows, respectively:

$$X_{ij} = \frac{x_{ij} - Min(x_{ij})}{Max(x_{ij}) - Min(x_{ij})} \tag{15}$$

$$X_{ij} = \frac{Max(x_{ij}) - x_{ij}}{Max(x_{ij}) - Min(x_{ij})}, \tag{16}$$

where X_{ij} is the standardised indicator value, x_{ij} is the original indicator value, and $Min(x_{ij})$ and $Max(x_{ij})$ are the minimum and maximum indicator values, respectively.

Indicator Entropy Calculation

The indicator entropy calculation began with calculating F_{ij}, the integrated standardised value of the indicator, which was then used to calculate J_j, the entropy of the jth indicator:

$$F_{ij} = \frac{X_{ij}}{\sum_{i=1}^{n} X_{ij}} \tag{17}$$

$$J_j = -\frac{1}{\ln n}\sum_{j=1}^{n} F_{ij} \ln F_{ij}, \tag{18}$$

where n is the number of evaluation indicators. If F_{ij} = 0, then F_{ij} lnF_{ij} = 0.

Determination of Indicator Weights

Indicator weights were determined with

$$W_j = \frac{1 - J_j}{m - \sum_{j=1}^{m} J_j}, \tag{19}$$

where W_j is the weight of the jth indicator and m is the number of evaluation indicators.

3.2.2. Composite Index Determinations

The composite index method is used to determine the comprehensive level of a certain aspect in a complex system. It can transform indicators of different scales into a unified form [49]. We used this method to construct a composite index of each ecosystem's characteristic indicators and ES capacities (Figure 3).

First, using the entropy weight method (see Section 3.2.1), we determined the weights of each of the 10 characteristic indicators for the four ecosystems. Then, those weights were used to calculate the composite indexes of the key features of the mountain (*MI*), water (*WI*), forest (*FI*), and cropland (*CI*) ecosystems as follows:

$$MI = \sum_{j=1}^{m} W_j \cdot mi_j \tag{20}$$

$$WI = \sum_{j=1}^{m} W_j \cdot wi_j \tag{21}$$

$$FI = \sum_{j=1}^{m} W_j \cdot fi_j \tag{22}$$

$$CI = \sum_{j=1}^{m} W_j \cdot ci_j, \tag{23}$$

where mi_j, wi_j, fi_j, and ci_j are the standardised values of the jth indicator of the mountain, water, forest, and cropland ecosystems, respectively.

Next, we considered each indicator to be equally important because the four ecosystems together form a single living community. Therefore, to integrate the key ecosystem characteristics' composite indexes (S) and ES capacities (T), each composite index or ES capacity indicator was given equal weight, as follows:

$$S = \frac{1}{4} \cdot MI + \frac{1}{4} \cdot WI + \frac{1}{4} \cdot FI + \frac{1}{4} \cdot CI \tag{24}$$

$$T = \frac{1}{3} \cdot E1 + \frac{1}{3} \cdot E2 + \frac{1}{3} \cdot E3. \tag{25}$$

3.2.3. Integrated Ecosystem Health Assessment

While ESs may importantly inform the sustainability of ecosystems [50], ecosystem health valuation usually focuses on the ecosystem itself and ESs are often overlooked [51]. Healthy ecosystems not only maintain their stable structure, but also have the capacity to provide sustainable ESs to humans [44]. Therefore, linkages between ecosystems and ESs must be established [52,53]. While various ES research methods are gradually gaining attention, researchers are also adopting the relevant ES indicators as an important part of the indicator system [54]. Meanwhile, some researchers have developed a "vigor-organisation-resilience" framework that incorporates ES factors to more comprehensively assess ecosystem health [18]. Here, we assessed integrated ecosystem health based on integrated key ecosystem characteristics and integrated ES capacity as $H = ST$, where H is the composite index of overall ecosystem health (Figure 3).

Finally, in ArcGIS 10.5, we classified each of the 13 indicators, and subsequently each of the integrated assessment indicators, into four grades based on the Jenks natural breaks classification method. This method is a statistical technique for dividing a continuous variable into categorical classes based on the inherent structure of the data. It involves identifying natural breaks, or inflection points in the data distribution, which serve as partition points to create classes that are relatively equal in size and represent distinct regions of the variable's range [55].

4. Results

4.1. Spatial Distributions of the Key Characteristic Indicators of the Four Ecosystems

4.1.1. Mountain Ecosystem

The study area's topography has much variation. In the central part, specifically Changqing, and the eastern part, which includes Hutou, Cannei, Fengcheng, Guanqiao, and Longmen, both slope (M1) and relief amplitude (M2) were comparatively low (Figure 4). However, the northwestern area, which includes Taozhou, Futian, and Gande, has considerably higher slope and greater relief amplitude, thus disasters, such as landslides and avalanches, occur frequently in those mountainous areas. Therefore, those areas have higher disaster risks and M1 and M2 are negative indicators. Also, the weights for M1 and M2 were 47.725% and 52.275%, respectively.

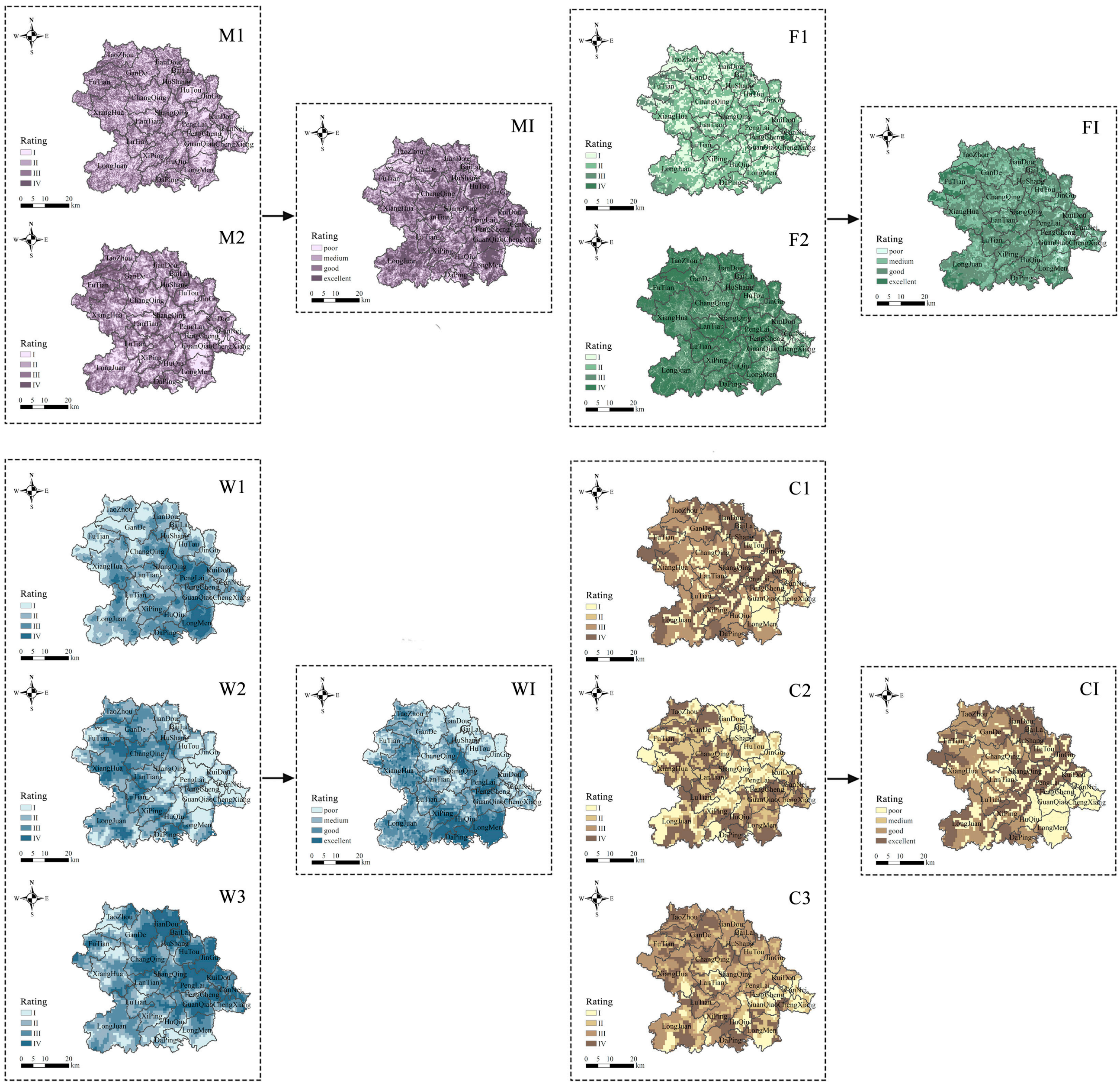

Figure 4. The spatial distributions of key characteristics of the four ecosystem types (purple, mountain; blue, water; green, forest; yellow, cropland) in Anxi County. Each ecosystem type's characteristic indicator spatial distribution maps are shown to the left of their composite index spatial distribution map. Higher grade numbers indicate higher values for each indicator. The composite characteristics maps rate the spatial distributions of each ecosystem's quality as poor, medium, good, or excellent. See Figure 3 for ecosystem type and indicator definitions.

In general, the mountain ecosystem is rated highly, but its composite index has no obvious spatial distribution pattern (Figure 4). Specifically, the central and eastern areas of the county (e.g., Changqing, Hutou, Guanqiao, and Longmen) have more "excellent" ratings than the other areas do. That part of the county has a gentle topography, so the frequency of natural disasters is relatively low. Areas rated "poor" are scattered throughout the study area, but there is a large area in Futian, Gande, and Taozhou. This type of area has a higher risk of safety hazards in the event of geological disasters such as landslides and mudslides.

4.1.2. Water Ecosystem

While W1 and W3 have similar spatial distribution characteristics, their higher grades were in Penglai, Guanqiao, Longmen, and Daping in the eastern part of the county (Figure 4). The grades were lower, especially for W1, in the northwest. Meanwhile, W2 had high grades in only small areas in Xianghua, Xiping, and Daping.

Because areas with high water density can provide more water ESs, W1 is a positive indicator. However, areas with high rainfall erosivity are prone to soil erosion, which causes potentially serious soil disturbance. Also, regions with high evapotranspiration can experience reduced local soil moisture that adversely impacts vegetation growth. Therefore, W2 and W3 are negative indicators. The entropy weighting method assigned W1, W2, and W3 weights of 39.369%, 14.424%, and 46.207%, respectively.

In general, the composite index for this ecosystem (WI) showed a general spatial distribution trend of higher ratings in the south and lower in the north. Specifically, the south is dominated by "excellent" and "good" ratings, and Huqiu, Daping, and Longmen have large "excellent" areas. Those townships' common characteristics are high water density, low rainfall erosivity, and low evapotranspiration. Poorly rated areas were in the central part (e.g., Gande and Changqing) and eastern edge of the county. This area is characterised by high evapotranspiration and low water density, which tends to reduce soil moisture content and accelerate groundwater depletion.

4.1.3. Forest Ecosystem

Anxi County has much vegetation cover (F2), with only small areas with little cover in Hutou, Fengcheng, Cannei, and Guanqiao in the east (Figure 4). Conversely, the county's overall net primary productivity (F1) was low, with a small number of high-value areas mainly in Fengcheng, Cannei, and Guanqiao. Areas with high net primary productivity have ample available energy for ecosystem members to use, and that contributes to the members' survival and reproduction. Also, areas with much vegetation cover are relatively rich in ESs. Therefore, both F1 and F2 are positive indicators and their weights were 57.309% and 42.691%, respectively.

In general, the forest composite index spatial distribution was moderate. Specifically, though, large areas in the west, including Gender, Futian, and Longjuan, had "excellent" ratings. This area is characterised by much vegetation coverage and net primary productivity that can provide high quality ESs to organisms. However, the eastern area, including Hutou, Guanqiao, Longmen, and a small part of Chengxiang were rated "poor". Although the net primary productivity of this area is high, the vegetation coverage is relatively low due to the large, urban population.

4.1.4. Cropland Ecosystem

Because soil with a low sand content (C2) had a high clay content (C1), and vice versa, the clay and sand spatial distributions trended oppositely, especially in the eastern part of the county (Figure 4). Meanwhile, soil organic carbon contents (C3) were generally high, with low value areas randomly distributed in the central and southern parts of the county.

Because soils with higher clay contents have stronger water-holding and fertility-holding properties than soils with less clay, areas with high-clay soils are less susceptible to drought. Also, high-organic-carbon-content soil promotes the growth and reproduction of soil microorganisms and provides more nutrients for crop growth. Thus, C1 and C3 are positive indicators. However, soil temperature fluctuates greatly in areas with high-sand-content soil. Such soil possesses weak water retention and fertility; thus, it is susceptible to drought. Therefore, C2 is a negative indicator. The weights for C1, C2, and C3 were 67.771%, 14.784%, and 17.445%, respectively.

In general, the spatial distribution of the cropland ecosystem composite index shows a "good-excellent-poor" distribution trend from west to east. The northeastern part of the county has large "excellent" areas, including Jiandou, Bailai, Hushang, Shangqing, Jingu, and Penglai, which are characterised by soils with high clay and organic carbon contents and low sand contents. In contrast, the southeastern area (e.g., Longmen, Guanqiao, Chengxiang, Fengcheng, and Cannei) has large areas rated "poor", and they have soils with low clay and organic carbon contents and high sand contents. The fertility of the soil in that region is low and vulnerable to drought.

4.1.5. The Spatial Distribution of Integrated Key Ecosystem Characteristics

In general, we found no distinct pattern in the spatial distribution of the integrated key ecosystem characteristics (Figure 5). Anxi County had large areas rated "medium", while the "excellent" rating applied to a small area, mainly in the centre of the county (e.g., Shangqing and Penglai) and in small parts of Longjuan, Lutian, Huqiu, and Longmen in the south. Also, areas with "poor" ratings were scattered throughout the county. Overall, most of the county was rated "poor" and "medium", thus indicating that the county's ecosystems possess a low ability to regenerate after sustaining damage.

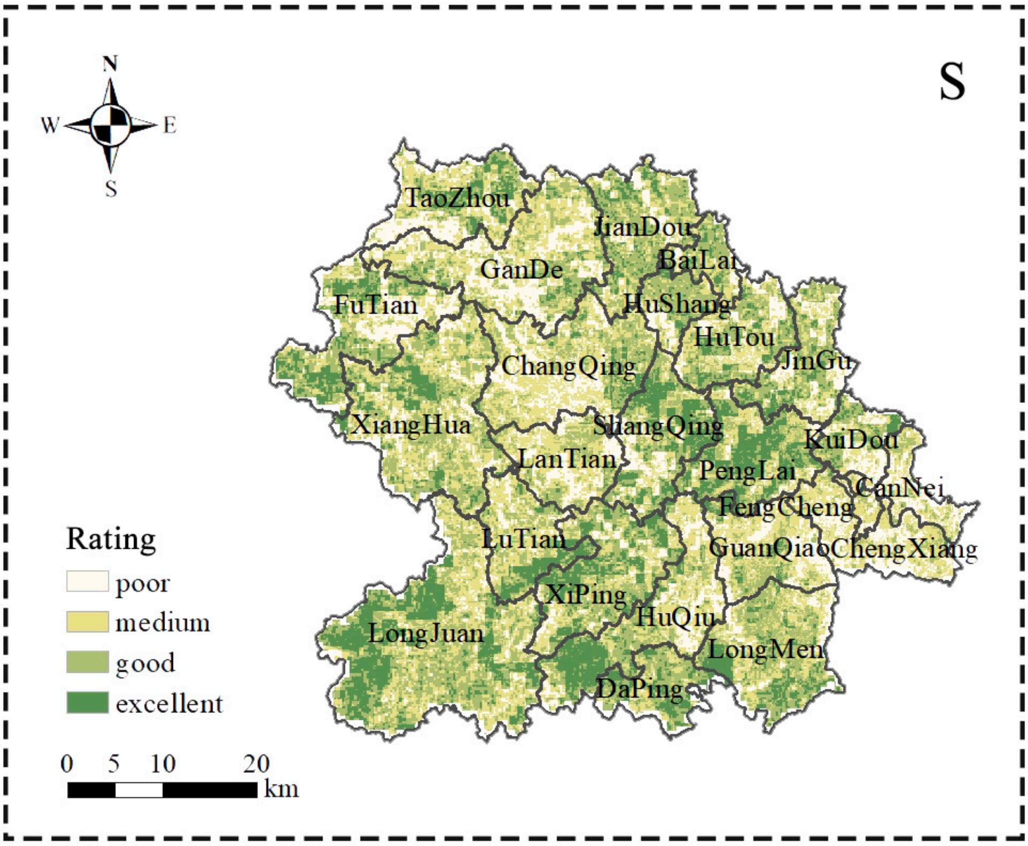

Figure 5. The spatial distribution of the integrated key ecosystem characteristics composite index (S in Figure 3) for Anxi County, China.

4.2. The Spatial Distributions of Ecosystem Service Capacity Indicators

4.2.1. Water Conservation Capacity

In general, E1′s spatial distribution trended higher in the west and lower in the east, but there was a small area rated "excellent" in Lantian (Figure 6). The areas with "good" and "medium" ratings were mainly distributed in the west, while the areas with "poor" ratings were mainly in the east. Overall, the county's ecosystems only weakly regulate regional water circulation and thus fall short at preventing floods and maintaining the quality of water sources, especially in the east.

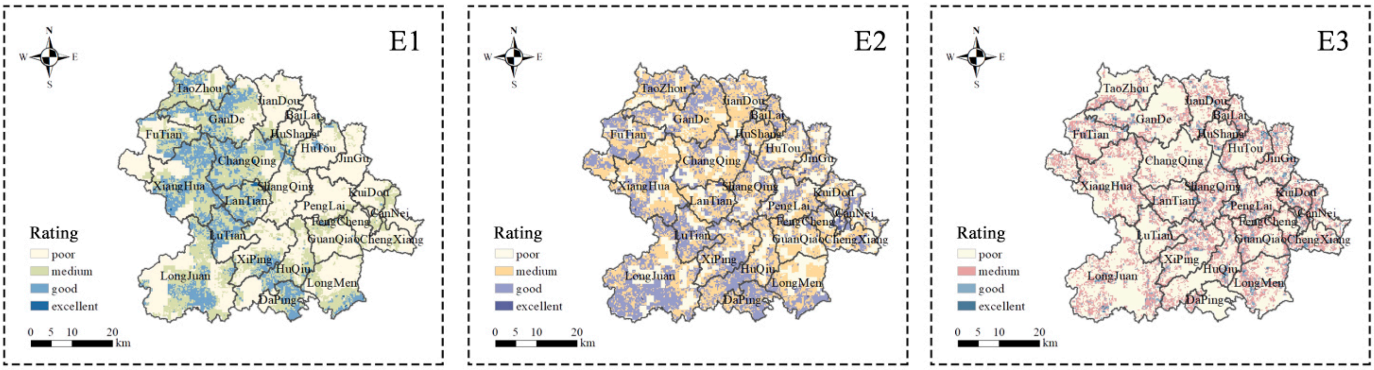

Figure 6. The spatial distributions of ecosystem service capacity indicators for Anxi County, China. (**E1**), water conservation capacity; (**E2**), soil and water conservation capacity; and (**E3**), sand fixation capacity.

4.2.2. Soil and Water Conservation Capacity

In general, E2′s spatial distribution followed no distinct pattern, and "excellent" ratings were rare (Figure 6). However, areas with "good" and "medium" ratings occupied most of the county and areas rated "poor" were scattered throughout. These results show that the ES capacity to reduce soil erosion and resist flooding is unremarkable, despite the few "poor" areas.

4.2.3. Sand Fixation Capacity

The spatial distribution of E3 trended lower in the west and higher in the east, with few areas rated "excellent" (Figure 6). The distribution of "good" ratings was also small, while "medium" areas were more densely distributed in the eastern part of the county. However, the "poor" rating applied to most of the eastern area. These results show that the county ecosystems lack sufficient ecological services to stabilise wind–sand disturbances, prevent dry–hot wind hazards, and reduce soil erosion caused by wind.

4.2.4. The Spatial Distribution of the Integrated Ecosystem Services Capacity Index

The importance of water conservation capacity, soil water retention capacity, and anti-wind and sand-fixing capacity differ, but they can all be used to judge the sustainability of an ecosystem, both singly and as an integrated whole. Based on its spatial distribution, the integrated ES capacity in the study area was basically weak (Figure 7). While there were no areas with "excellent" ES capacity ratings in the county, areas with "good" ratings were located mainly in the west, and "medium" and "poor" rated areas were found throughout the county.

4.3. The Spatial Distribution of the Integrated Ecosystem Health Comprehensive Index

In general, the spatial distribution of the integrated ecosystem health index showed better health in the west and worse in the east (Figure 8), but the county's overall ecosystem health was weak. Specifically, there were very few areas with "excellent" health, but there were some limited "good" health areas in the western part of the county, as well as in Xiping, Huqiu, and Daping in the south. However, "medium" and "poor" health areas were spread throughout the county, and those lowest ratings dominated the east, except for small "medium" health areas in Fengcheng and Longmen.

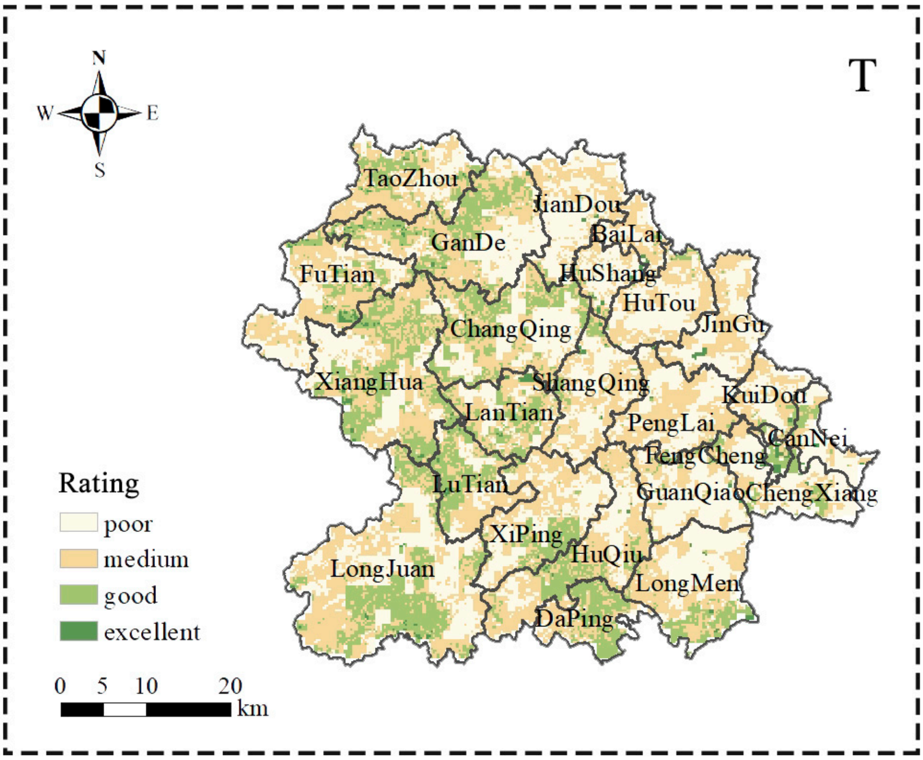

Figure 7. The spatial distribution of the integrated ecosystem services capacity index (T in Figure 3) for Anxi County, China.

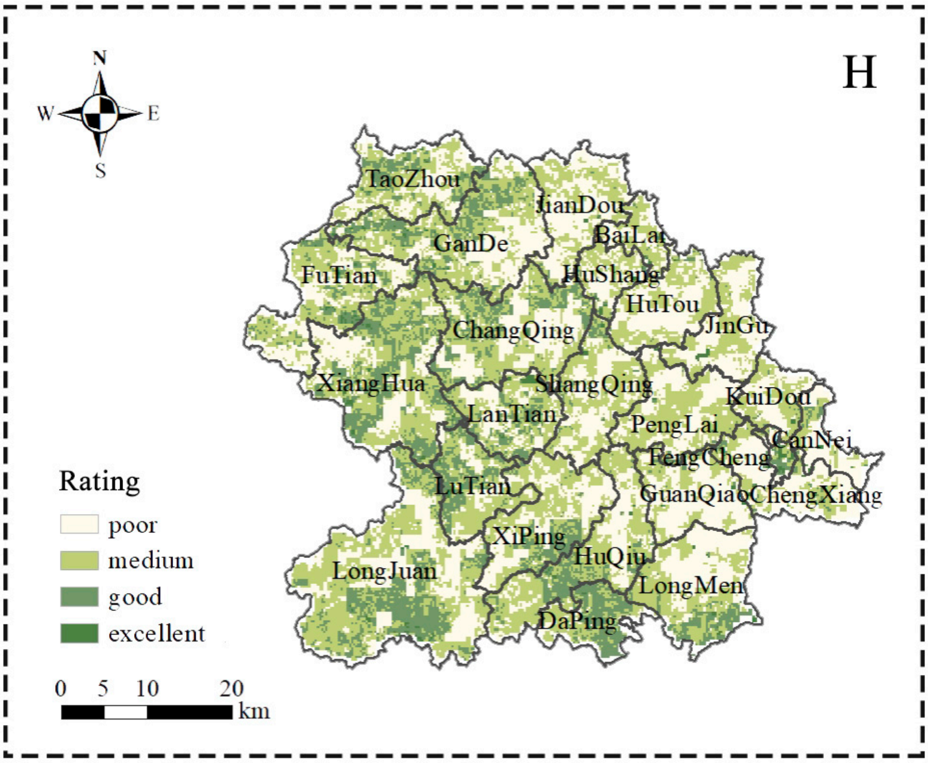

Figure 8. The spatial distribution of the integrated ecosystem health comprehensive index (H in Figure 3) in Anxi County, China.

5. Discussion

5.1. Traditional Forms of Ecosystem Restoration Are Facing Transformation

Previously, protecting and restoring ecosystems focused on safeguarding individual ecological elements and addressing environmental pollution [56]. This approach enables a clearer understanding of the ecological status and operational processes of individual ecosystems, and current ecological restoration objectives typically include most of the key ecological elements in the ecosystem [57]. However, this cannot ascertain the comprehensive situation of the ecosystem. If ecological restoration persists in such a manner over an extended period, it can lead to neglected inter-ecosystem connections, which then disrupts that interconnectedness and causes destabilisation [58]. Simultaneously, such practices may heighten the exposure of ecosystems to unpredictable disaster risks and undermine their capacities for recovery and renewal [59].

Unlike most preceding studies, our study focuses on constructing an integrated assessment system for ecosystem health, which is founded on the core concept that all ecosystem types form a complex community of life. The integrated assessment framework is designed to provide guidance for our integrated restoration pathways, addressing an array of specific ecological issues. This demonstrates a distinct deviation from conventional studies that emphasize single ecosystems, and it underscores the importance of inter-ecosystem interactions and integrated restoration in maintaining ecological health and resilience. A distinctive feature of this assessment system is its ability to encompass not only the integrated key characteristic of each major ecosystem within the study area but also the integrated ecosystem service capacity.

Given the current situation, traditional forms of ecosystem restoration are facing transformation. We must establish a systematic and comprehensive restoration and governance model for interconnected ecosystems, as well as a new model of integrated ecosystem restoration. The new model should focus on the interactions between ecological elements and on the implementation of a subsequent holistic optimisation and adaptation of ecosystem structure and function. Ultimately, uncertain ecological crises are resisted, and maybe even prevented, and the integrated ecosystems as a whole are stabilised and made sustainable.

5.2. Integrated Pathways for Ecosystem Restoration

Based on specific ecological problems, we propose an integrated conservation and restoration approach for the ecosystem in Anxi County, China. Subsequently, guidance is provided for the implementation of restoration pathways based on diverse comprehensive assessment levels of ecosystem health.

Firstly, our aim was to effectively maintain and improve ecosystem functions and ecological service capacities by following integrated pathways for ecosystem restoration (Figure 9).

Based on the local planning documents provided by the Anxi Natural Resources Administration and our comprehensive analysis of the primary ecological issues, we have proposed specific restoration pathways for a range of ecological problems in each ecosystem. In our example, we used the four ecosystems of Anxi County, China. Specific restoration measures for the mountain ecosystem include steps to restore mine landscapes, prevent and control geological disasters, comprehensively treat disused mines, remove loose residue, maintain repaired mountains, and change slopes to bench terraces. For the water ecosystem, water source areas should be protected; "sponge cities", ecological riverbanks, and an ecological water network should be constructed; watersheds should be comprehensively treated; and sewage treatment systems should be improved. Measures for the forest ecosystem should include enclosing hillsides for natural afforestation, managing forest resources, improving forest stands, stabilising forest community structure, protecting animal habitats, and constructing nature reserves. The cropland ecosystem measures should include constructing an agricultural forest network, transforming and improving agricultural practices to create quality farmland with improved soil moisture and fertility, controlling agricultural pollution, and developing efficient water-saving agriculture.

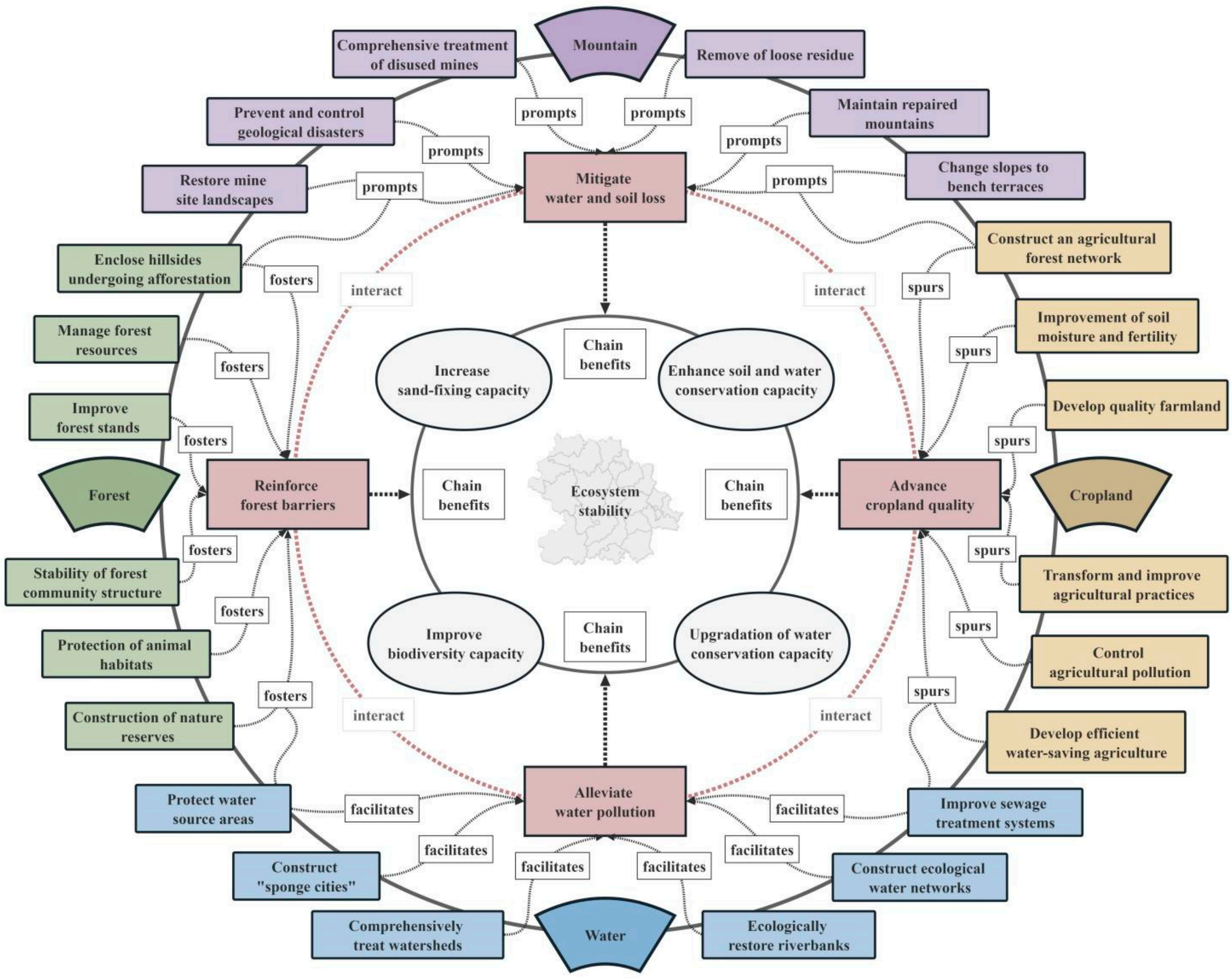

Figure 9. Integrated pathways for the mountain, forest, water, and cropland (outer ring) ecosystem restoration in Anxi County, China. Those solutions for each ecosystem's problems interact positively to alleviate broader problems (central ring), which then contribute to improved ecosystem service capacity and overall ecosystem stability (innermost ring).

Next, appropriate protection or restoration programmes should be developed to match the different levels of integrated ecosystem health found throughout the county. Areas with "excellent" and "good" integrated ecosystem health ratings must have their existing ecosystems protected and their overall ecological services maintained. To accomplish this, areas with natural forests and water sources must be closed to any disturbances so that new ecological damage caused by artificial modifications is avoided [60–63]. At the same time, those areas may be given vegetation buffer zones or isolation zones, and regular surveys and wildlife monitoring should be carried out [64]. In addition, harmful organisms should be eliminated or controlled to maintain good ecological functions and biodiversity [65,66]. Also, the environments surrounding restored mountains should be comprehensively protected by clarifying the scope of their protection and monitoring systems, and by formulating natural disaster prevention and control measures [67,68]. Then, to a certain extent, safety hazards may be prevented. In areas with "medium" integrated ecosystem health ratings, low-impact restoration measures should be instituted, and ecological problem prevention and control should be strengthened. If mining practices that protect the environment were adopted, serious damage to the mining regions' ecological environments could be lessened [69]. At the same time, mine waste should be properly disposed of and production sites kept in order during the mining process [70]. Next, the riverbanks in areas rated "medium" should be softened and transformed by building ecological berms and ecological corridors [71,72]. This would both improve the ecological protection capacity and create good habitats for aquatic organisms. The areas with "poor" integrated ecosystem health ratings need integrated ecological restoration projects that address their serious ecological problems. Restoration work should focus on the holistic and systemic nature of ecosystems, and on linking and integrating the different restoration tasks in each project. In areas with important water systems and water source protection sites, sources of water pollution should be reduced and silt removed from water bodies and connecting water systems, while restoration tasks should include protecting slopes and constructing conservation forests peripheral to the water sources [73–75]. Thus, ecological problems may be solved while the surrounding areas' water storage and drainage capacities, as well as the overall ecological function of the ecosystem, are improved. Because frequent geo-disasters like landslides and ground collapses occur in the mountainous regions, it is essential that geological disaster management techniques be used to repair damaged mountains [76,77]. It is also crucial to guarantee the mountains' capacity to tolerate disasters and maintain ecological sustainability [78]. Moreover, many mountainous areas that have been converted to tea plantations experience severe soil erosion, which compounds ecological problems. Therefore, the ecosystem restoration in "poor" health mountain areas should prioritise constructing protective forests and enhancing soil quality while undertaking continuous disaster prevention and monitoring activities [79].

The primary objective of restoring and maintaining ecosystem stability and health in Anxi County is to jointly mitigate water and soil loss, reinforce forested ecological barriers, alleviate the water pollution load, and advance cropland quality by systematically protecting and restoring all ecosystems. By accomplishing this, soil water-retention capacity would be enhanced, water conservation capacity upgraded, anti-wind and sand-fixing capacity increased, and biodiversity capacity improved. In the end, the ecological service functions generate positive feedback on one another and the integrated ecosystems achieve stability and sustainability.

5.3. Limitations and Future Research

Ecosystem health is a complex concept that includes not only its own state, but also depends on the capacity of ESs to support human survival. This study has constructed a comprehensive ecosystem health assessment system that combines key ecosystem characteristics and ES capacity, as well as integrated ecosystem restoration pathways for the study area. However, to make the results of the study more objective, we focused only on the natural characteristics of the ecosystem, although there is also a complex relationship between ecosystems and socio-economic systems. Common human activities that constantly affect ecosystem structure and function also precipitate changes. Therefore, further research should comprehensively explore the ecosystem health evaluation framework from a multidimensional perspective that is based on indicators with different attributes. At the same time, the applicability of ecological restoration methods for local natural conditions and integrated management approaches must be established. This would ensure the integrity of individual ecosystem elements and contribute to sustainable integrated ecosystem health. Furthermore, the primary issue to be addressed is the assessment of the integrated health level of ecosystem in this study. The selection of indicators focuses on the internal status of an ecosystem. However, developing more detailed restoration plans for different types of restoration projects requires new assessments. This encompasses the selection of indicators that can reflect the diverse ecological issues within each ecosystem, as well as the assessment of the effectiveness of the integrated ecosystem health index in this study. This is also an aspect that deserves continued in-depth exploration in our future study.

6. Conclusions

Based on the perspective that the ecosystem is a community of life, this study used key characteristic ecosystem and ES capacity indicators to construct an integrated assessment system that examined the health of the ecosystems in the study area: Anxi County, China. Then, we identified the ecological problems that exist in each of the area's four ecosystems and used them to propose integrated pathways for restoring those ecosystems. Ultimately, the integrated index assessment results can guide the development of ecological restoration models tailored to different regions. The integrated assessment of the ecosystems' key characteristics revealed that most areas in the county had an overall weak self-recovery potential. The integrated assessment of ES capacity also showed that most of the county's areas had a generally weak overall ES capacity. According to the integrated ecosystem health assessment, the overall ratings trend was higher in the west and lower in the east, but as a whole, the county's ecosystem health was weak. Therefore, conservation and restoration programmes based on comprehensive assessments should be implemented in different areas. In the areas with better integrated ecosystem health, the overriding need is to protect the ecosystems and maintain their overall ESs. In moderately healthy areas, low-impact restoration measures should be enacted, as well as a strengthening of the prevention and control of ecological problems. In the areas with the worst ecosystem health, integrated ecological restoration projects are needed to address serious ecological problems. Also, the restoration process should consider the realistic ecological challenges of the diverse ecosystems in the area and ensure the connectivity and coordination of each restoration task. This approach benefits the maintenance of ecosystem stability and an enhanced sustainability of ES.

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