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RESEARCH ARTICLE

A new framework for assessing ecosystem health with consideration of the sustainable supply of ecosystem services

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Abstract
Context The establishment of an ecosystem health assessment framework from a human–environment view is vital to landscape sustainability. Although several studies have improved the assessment framework by integrating ecosystem services (ESs) supply or demand, consideration of the sustainable supply of ESs is lacking.
Objectives The objective of this paper is to improve the current methodological framework by integrating ecological integrity and the sustainable supply of ESs to establish an ecosystem health assessment framework.
Methods An improved assessment framework, including four indicators, vigor, organization, resilience, and ecosystem services supply rate, was established from the perspective of human–environment systems. Then, the performance of the improved assessment framework was demonstrated in a case study in China from 2000 to 2020.
Results From 2000 to 2020, the overall spatial pattern of ecosystem health values in China was high in the southern and southeastern coastal regions, and low health values were mostly located in the western region, parts of Inner Mongolia, and metropolitan areas, with a descending trend from southeast to northwest. The imbalance between the potential and actual supply of ESs greatly contributed to the deterioration of regional ecosystem health. During the study period, the regional ecosystem in China was found to be in a more unhealthy state than in traditional Vigor-Organization-Resilience-Ecosystem services (VORES) evaluation.
Conclusions The improved assessment framework that incorporates the ecological integrity and sustainable supply of ESs provides a new perspective for understanding the complex inherent characteristics of ecosystems and the regional human-nature connectedness in coupled human–environment systems. Our results could serve as a scientific reference for

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practical landscape governance in a changing world to achieve landscape sustainability.

Keywords Landscape sustainability · Ecosystem health · Ecosystem health assessment framework · Ecosystem services · China

Introduction

Landscape sustainability science (LSS) focuses on the dynamic relationship between ecosystem services (ESs) and human well-being (Wu 2013). Natural ecosystems provide humans with a variety of essential products and services (Das et al. 2021; Leviston et al. 2018; Summers et al. 2012). Thus, the maintenance of healthy ecosystems (e.g., a forest, lake, or pastoral landscape) is vital to meet human needs and achieve the ultimate goal of landscape sustainability (Hermoso and Clavero 2013; Rapport and Maffi 2011). However, in the past few decades, due to continuous urbanization and the intensification of human activities, natural ecosystems have been subject to unprecedented load pressure and various ecological problems, such as soil erosion, biodiversity loss, habitat fragmentation, and even ecosystem degradation (Defries et al. 2004; Paruelo et al. 2001). Considering the adverse effects of environmental issues on human survival and the sustainable development of human society, it is necessary to monitor and evaluate the current status of ecosystems for scientific land use planning and ecological policy-making (Mallick et al. 2021; Rapport and Hildén 2013).

Ecosystem health refers to the capacity of an ecosystem to maintain its original state and structure and to meet the demands of human society after disturbances (Comberti et al. 2015; Costanza 1992; Costanza and Mageau 1999; Lackey 2001; Rapport 1989). When there has been a detrimental effect of rapid socioeconomic development on natural ecosystems, ecosystem health is considered the objective and basis of environmental management and the most direct reflection of regional ecosystem quality (Li et al. 2021a; Pan et al. 2020).

In recent years, ecosystem health assessment has gained increased attention as one of the most effective methods to assess the health status of ecosystems and thereby guide the utilization of natural resources, conservation and restoration of ecological environments, and landscape sustainability (Costanza et al. 1997; Cui et al. 2019; Lackey 2001; Liu et al. 2023, 2022; Bao et al. 2022). In a systematic review, the widely used evaluation frameworks could be classified into three categories: (1) the Vigor-Organization-Resilience-Ecosystem services (VORES) framework mainly focuses on measuring the integrity and quality of the actual ecosystem itself (Shu et al. 2021; Wang et al. 2022) and ignores the impact of human activities on ecosystems (Chen 2022; Pan et al. 2021); (2) the Pressure-State-Response (PSR) and its extension models, such as the Driving-Pressure-State-Impact-Response (DPSIR) model, emphasize the linkages between the environment and human society, largely considering ecosystem pressure, state, and response (He et al. 2019); however, they fail to measure the ecological integrity and nature of ecosystems (Shen et al. 2021); and (3) the Natural-Social-Economic subsystems model highlights the integrity of ecosystems from the perspective of complex subsystem composition (Wang et al. 2022) but does not truly reflect the essential connotation of regional ecosystem health (Pan et al. 2021) and the interaction between human demand and ecosystems (Liu et al. 2022). In summary, the above evaluation frameworks typically assess ecosystem health through the internal attributes of the ecosystem itself or external anthropogenic disturbances, whereas there are only a few studies on the interconnections between the natural ecosystem and human activities (He et al. 2019; Peng et al. 2017; Su et al. 2010; Wang et al. 2020).

There is an inextricable linkage between human systems and ecosystems (Ostrom 2009; Srinivasan et al. 2013). A healthy ecosystem is capable of providing the human community with essential ecosystem services (ESs), such as food, fiber, and clean air (Costanza 2012; Wang et al. 2020). Moreover, due to severe disturbances caused by rapid urbanization and industrialization, ecosystems have been transformed into a highly artificial natural-social-economic complex ecosystems (MacDonald et al. 2019a, b). Therefore, to strengthen the interactions between natural ecosystems and human activities in the context of coupled human and ecological systems, some scholars have proposed an improved evaluation framework based on ESs, such as ES supply (Cui et al. 2019; Li et al. 2021a; He et al. 2019; Pan et al. 2020; Peng et al. 2015; Wang et al. 2020; Wu et al. 2021) or ES demand (Liu et al. 2022; Luo et al. 2018; Pan et al.

2021). There is a close link between potential ES supply and the natural ecosystem, whereas ES demand is dependent on the socioeconomic system (Pan et al. 2021). However, ES demand represents the amount of ecosystem goods and services required or desired by human society, which can vary regardless of the ability and function of ecosystems (Baró et al. 2016; Burkhard et al. 2012; Schirpke et al. 2019a; Schröter et al. 2014; Villamagna et al. 2013). Thus, the actual ES supply should also be considered to capture human activities. In this study, the potential capacity of goods and services that an ecosystem can provide to human well-being is considered the potential ES supply, while the actual level of production or use is considered to be the actual ES supply (Burkhard et al. 2012, Villamagna et al. 2013). From a human-nature coupled view, ecosystem evolution is a dynamic process, and an ecosystem with a continuous provision of ESs means that the relationships between the potential and actual ES supply must be balanced and sustainable. Based on the above considerations, the sustainable supply of ESs, which reflects the relationships between the potential and actual ES supply, should be considered an important indicator in the ecosystem health assessment framework (Liyun et al. 2018; Paetzold et al. 2010).

This paper aims to improve the current methodological framework by constructing an ecosystem assessment framework from a coupled human-ecosystem perspective. The main purposes of our research are as follows: (1) to establish an improved evaluation framework based on ecological integrity and the sustainable supply of ESs; (2) to evaluate the trend and dynamic evolution of ecosystem health in China from 2000 to 2020; and (3) to analyze the advantages of the improved evaluation framework and propose sustainable policy recommendation strategies. Our assessment framework is expected to enrich and extend the current ecosystem health evaluation frameworks and provide policy references for landscape sustainability and ecological civilization construction in China.

Methods

Study area

China (3°51′–53°33′N, 73°33′–135°05′E) is located in eastern Asia and covers an area of approximately 9.6 million km^2 (Fig. 1) (Wu et al. 2021). The terrain in China is high in the west and low in the east, forming three ladder-like distributions in space from

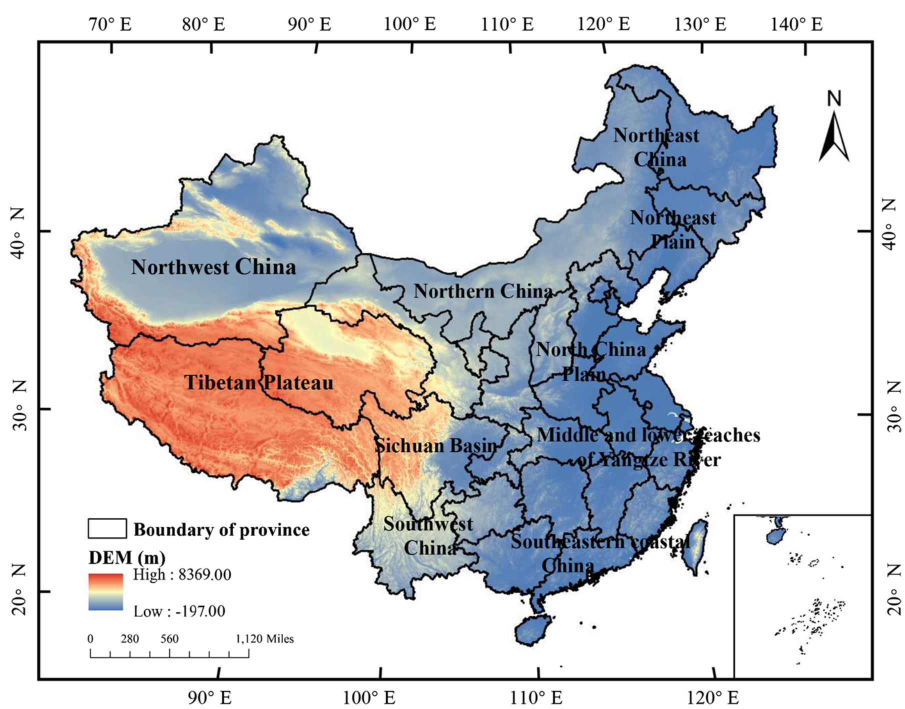

Fig. 1 Locations of study area

− 197 to 8369 m (He et al. 2019). Multiple climate zones are found in China, including the subtropical monsoon, temperate monsoon, tropical monsoon, temperate continental climate, and alpine climate zones (He et al. 2019). The land use types in China are cropland, forestland, grassland, waterbody, built-up land and barren land. The two main land use types are grassland and barren land, accounting for 29.21% and 22.01% of the total area, respectively, in 2020.

Since the Reform and Opening-up Policy began in the late 1970s, China has been undergoing rapid economic development and industrialization (Liao et al. 2020). From 1978 to 2021, the proportion of the urban population increased from 17.92 to 63.89%, and the area of urban construction land increased from 6720 to 61,300 km^2 (http://www.stats.gov.cn/). Such accelerating urban construction and industrial development have also led to profound land use change and serious ecosystem deterioration in China, such as air pollution, water shortages, biodiversity loss, and ecosystem destruction (Zhang et al. 2021; Li et al. 2023). Therefore, there is an urgent need for a systematic assessment of ecosystem health to support the formulation of sustainable management policies and ecological civilization construction in China.

Framework of improved ecosystem health assessment

In this study, an improved ecosystem health assessment framework was established from two dimensions, ecological integrity and sustainable supply of ESs, to ensure that human and natural systems are coupled. It is well known that humans are an integral part of ecological integrity, and the achievement of human well-being largely depends on the provision of ESs (Pan et al. 2021; Li et al. 2016). Therefore, in this improved framework, we introduced a new indicator: the ecosystem services supply rate (ESSR), which can more objectively measure the impacts of human activities on the environment than the potential supply capability of ESs in the traditional framework. That is, this improved framework is composed of four indicators: vigor, organization, resilience, and ecosystem services supply rate, and it is called the "Vigor-Organization-Resilience-Supply rate" model (VORESSR) (Fig. 2). The indicator system of the VORESSR model is shown in Table 1. Several datasets were employed to conduct this study. Table 2 provides a brief description of the datasets.

A healthy regional ecosystem is active, capable of maintaining its organization, self-adjustment,

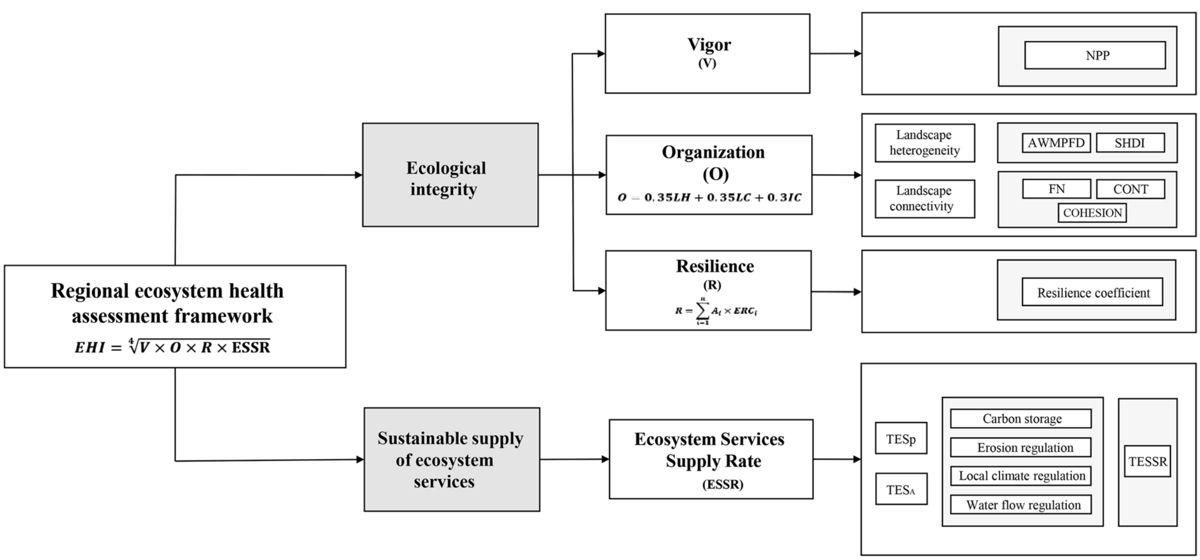

Fig. 2 The improved ecosystem health assessment framework based on ecological integrity and sustainable supply of ecosystem services. (AWMPFD: Area-Weighted Mean Patch Fractal Dimension; SHDI: Shannon's Diversity Index; FN: Landscape Fragmentation Index; CONT: Landscape Contagion Index; COHESION: Patch Cohesion Index; ESSR: Ecosystem Services Supply Rate; TES_P: The total potential ESs supply; TES_A: The total actual ESs supply; *TESSR*: The total ESs supply rate)

Table 1 The indicator system of ecosystem health assessment in China

Indices Item	Indicators	Dimension	Description	Methods
Vigor (V)	NPP		Net Primary Productivity	Carnegie-Ames-Stanford Approach (CASA) model (Li et al. 2021b)
Organization (O)		Landscape heterogeneity (LH)	Area-weighted mean patch fractal dimension index (AWMPFD)	FRAGSTATS (Cui et al. 2019; Xiao et al. 2020)
			Shannon's diversity index (SHDI)	FRAGSTATS (Wang et al. 2020; He et al. 2019)
		Landscape connectivity (LC)	Landscape fragmentation index (FN)	FRAGSTATS (Li et al. 2021a, 2021b)
			Landscape contagion index (CONT)	FRAGSTATS (Mallick et al. 2021; Kang et al. 2018)
			Patch cohesion index (COHESION)	FRAGSTATS (Wu et al. 2021; Shu et al. 2021)
Resilience (R)	Resilience coefficient			The area-weighted ecosystem resilience coefficients (Peng et al. 2017; Wu et al. 2021)
Ecosystem Services Supply Rate (ESSR)	Carbon storage	Potential supply	CO^2 sequestration	Carbon storage module of InVEST model (Schirpke et al. 2019a, b)
		Actual supply	CO^2 sequestration	Carbon storage module of InVEST model (Schirpke et al. 2019a, b)
	Erosion regulation	Potential supply	Vegetation cover	Normalized Difference Vegetation Index (Burkhard et al. 2014)
		Actual supply	Amount of soil retained or sediment captured	Revised Universal Soil Loss Equation (RUSLE) model of InVEST model (Burkhard et al. 2014)
	Local climate regulation	Potential supply	Evapotranspiration	Annual evapotranspiration (Burkhard et al. 2014)
		Actual supply	Evapotranspiration deviation from surrounding areas	Absolute deviation of annual evapotranspiration (Burkhard et al. 2014)
	Water flow regulation	Potential supply	Water storage capacity	Water yield module of InVEST model (Burkhard et al. 2014)
		Actual supply	Available water content	Plant available water content (Burkhard et al. 2014)

and recovery under external disturbance, and is capable of providing ESs to meet the reasonable demands of humans; that is, it is stable and sustainable (Costanza 2012; Rapport 1989; Paetzold et al. 2010). Therefore, the ecosystem health index (EHI) can be quantified as follows (Costanza 2012):

$$EHI = \sqrt[4]{V \times O \times R \times \mathrm{ESSR}} \quad (1)$$

where EHI refers to the regional ecosystem health index, and V, O, R, and ESSR denote ecosystem vigor, organization, resilience and ecosystem services

Table 2 Several datasets used in the study

Data	Data description	Data source
Soil data	Soil type Soil moisture Soil depth Soil organic carbon Soil particle composition	Harmonized World Soil Database 1.1 (HWSD) (http://www.fao.org/soils-portal/soil-survey/soil-maps-and-databases/)
Meteorological data	Temperature Precipitation Solar radiation Evapotranspiration	Chinese National Meteorological Science Data Service Center (http://data.cma.cn/)
NDVI	Normalized difference vegetation index	Resource and Environment Science and Date Center, Chinese Academy of Sciences (http://www.resdc.cn/)
DEM	Digital elevation model	Geospatial Data Could Platform (http://www.gsclooud.cn)
Land use/cover data	Cropland Forestland Grassland Water-body Construction land Bare land	Resource and Environment Science and Date Center, Chinese Academy of Sciences (http://www.resdc.cn/)

supply rate, respectively. The detailed calculation methods of each indicator are described as follows.

Ecological integrity

Vigor

Vigor refers to the activity, metabolism or primary productivity of regional ecosystems (Summers et al. 2012; Mallick et al. 2021; Rapport et al. 1998). Referring to previous studies, NDVI and NPP (net primary productivity) have been widely applied in regional ecosystem health assessments to measure ecosystem vigor (Pan et al. 2020, 2021; Costanza 2012; Kang et al. 2018; Nemani et al. 2003). In this study, NPP was chosen because it is a valid indicator for measuring ecosystem primary productivity (Costanza and Mageau 1999; Costanza 2012; Kang et al. 2018). NPP was estimated by using the Carnegie-Ames-Stanford Approach (CASA) (Gou et al. 2022; Li et al. 2021b).

Organization

Organization means the structural stability of ecosystems (Wang et al. 2020; Wu et al. 2021) and describes the diversity and quantity of interactions among the components of landscapes (Costanza 2012; Das et al. 2021). It is recognized that spatial patterns are fundamental and important factors contributing to the management of ecosystem processes (Peterson 2002). In this study, ecosystem organization was assessed in terms of landscape heterogeneity (LH) and landscape connectivity (LC) (Mallick et al. 2021; Pan et al. 2020; Shu et al. 2021; Howell et al. 2018). In detail, Shannon`s diversity index (SHDI) and the area-weighted mean patch fractal dimension index (AWMPFD) were selected to indicate landscape heterogeneity (LH) (He et al. 2019; Li et al. 2021b; Peng et al. 2015). Landscape connectivity (LC) was mainly measured from two aspects: the landscape fragmentation index (FN) and landscape contagion index (CONT) were used to measure the overall landscape connectivity, and the landscape fragmentation index (FN) and patch cohesion index (COHESION) were applied to measure the connectivity of important ecological ecosystems (IC), such as forestland, grassland and waterbodies (Li et al. 2021a, 2021b; He et al. 2019; Wang et al. 2020). All landscape pattern indexes were calculated by using FRAGSTATAS 4.2.

Furthermore, referring to previous studies (Li et al. 2021a, 2021b; He et al. 2019; Pan et al. 2020; Wang et al. 2020), the weights assigned to LH, LC, and IC were 0.35, 0.35, and 0.3, respectively. The detailed formula is expressed as follows:

$$
\begin{aligned}
O &= 0.35LH + 0.35LC + 0.3IC \\
&= (0.25SHDI + 0.10AWMPFD) + (0.25FN_1 + 0.10CONT) \\
&\quad + (0.07FN_2 + 0.03COHESION_1 + 0.07FN_3 \\
&\quad + 0.03COHESION_2 + 0.07FN_4 + 0.03COHESION_3)
\end{aligned}
\tag{2}
$$

where O is the regional ecosystem organization; LH, LC, and IC refer to landscape heterogeneity, landscape connectivity, and landscape connectivity index of important ecological ecosystems (forestland, grassland, and waterbody), respectively; SHDI is Shannon`s diversity index; AWMPFD is area-weighted mean patch fractal dimension; FN_1 and CONT are the landscape fragmentation index and landscape contagion index, respectively; FN_2, FN_3 and FN_4 are the fragmentation index of forestland, grassland, and waterbody, respectively; and $COHESION_1$, $COHESION_2$, and $COHESION_3$ denote the patch cohesion index of forestland, grassland, and waterbody, respectively.

Resilience

Resilience can be explained as the capacity of an ecosystem to maintain its original structure and functions under stress (Costanza 2012; Cui et al. 2019; Wu et al. 2021). Because of the important role of land use in the concept of ecosystem resilience (Colding 2007; Foster et al. 2003), ecosystem resilience is measured based on the area-weighted ecosystem resilience coefficients (ERC) for each land use type (Wang et al. 2020; Cui et al. 2019; He et al. 2019; Peng et al. 2015). Specifically, ERC was determined based on expert knowledge and previous studies (He et al. 2019; Li et al. 2021b; Kang et al. 2018; Mallick et al. 2021; Peng et al. 2017; Wang et al. 2020; Wu et al. 2021) (Table 2). The specific calculation formula is as follows (Mallick et al. 2021):

$$R = \sum_{i=1}^{n} A_i \times ERC_i \tag{3}$$

where R stands for regional ecosystem resilience; n represents the number of land use types; A_i represents the area ratio of land use type I; and ERC_i is the ecosystem resilience coefficient of land use type i.

Sustainable supply of ecosystem services

The sustainable supply of ESs can link the ecosystem benefit to human society, indicating the relationships between the potential and actual ES supply. According to the data availability, feasibility of data harmonization, and modeling methods, four important ESs were selected, including carbon sequestration, erosion regulation, local climate regulation, and water flow regulation (Burkhard et al. 2014; Schirpke et al. 2019b; Sharp et al. 2016). The specific potential and actual supply indicators for the four ESs are listed in Table 3. To calculate the total ES supply rate, the potential and actual supply of each ES was standardized to a value from 0 to 1 using range standardization because of the different formulas and units.

Then, the total potential and actual ES supply are calculated as follows:

$$TES_P = \sum_{j=1}^{m} ES_{pj} \tag{4}$$

where TES_P is the total potential ES supply; m represents the number of ES types (m = 4); and ES_{pj} is the standardized potential supply of ES type j.

$$TES_A = \sum_{j=1}^{m} ES_{Aj} \tag{5}$$

where TES_A is the total actual ES supply; m represents the number of ES types (m = 4); and ES_{Aj} is the standardized actual supply of ES type j.

Finally, the total ES supply rate (TESSR) can be expressed as:

Table 3 Ecosystem resilience coefficient (ERC) and ecosystem service coefficient (ESC) of each land use type in China

Ecosystem type	Cropland	Forestland	Grassland	Waterbody	Built-up land	Barren land
ERC	0.50	0.90	0.70	0.80	0.20	0.10
ESC	0.50	1.00	0.80	0.85	0.33	0.013

$$TESSR = \frac{TES_A}{TES_P} \quad (6)$$

where TESSR is the total ES supply rate and TES_A and TES_P represent the total actual and potential ES supply, respectively. A TESSR value larger than 1 means that the actual ES supply is greater than the potential ES supply, representing an unsustainable supply of ESs; a TESSR value less than 1 means that the actual ES supply is lower than the potential ES supply, indicating a sustainable supply of ESs; and a TESSR value of 1 means a balance between the actual and potential ES supply.

Identification of the EHI types

The identification and classification of the ecosystem health index can provide a reference to comprehensively understand the actual situation of regional ecosystems in China. To eliminate the positive or negative effects of different numerical dimensions and magnitudes on the evaluation indicators, the original data need to be standardized before calculations (Li et al. 2021a). In this study, the five elements (i.e., EHI, V, O, R and ESSR) were normalized to the range of 0–1 according to the following equations:

$$\text{Positive indicator}: \ Y_j = (X_j - X_{j\,min})/(X_{j\,max} - X_{j\,min}) \quad (7)$$

$$\text{Nagetive indicator}: \ Y_j = (X_{j\,max} - X_j)/(X_{j\,max} - X_{j\,min}) \quad (8)$$

where Y_j is the standardized value of indicator X_j; X_j is the initial value of indicator j; and $X_{j\,max}$ and $X_{j\,min}$ are the maximum and minimum values of indicator j, respectively.

In addition, to generate comparable study results, the ecosystem health index was categorized into five levels as follows: poor (0–0.1), relatively poor (0.1–0.3), moderate (0.3–0.5), relatively good (0.5–0.7), and good (0.7–1) (Das et al. 2021; Mallick et al. 2021; Pan et al. 2021; Xiao et al. 2020; Shu et al. 2021).

Results

Spatial patterns of ecosystem health indicators

Vigor

As shown in Fig. 3a, from 2000 to 2020, ecosystem vigor in China presented an increasing trend from northwest to southeast. This finding was in agreement with (He et al. 2019). Because of the dense vegetation covering the southern and southeastern parts of the study area, vigor values were higher in those areas, while lower values were observed in the northwestern and southwestern regions due to high altitude, complex natural conditions, and low vegetation coverage (Kang et al. 2018; Xie et al. 2021). A significant spatial variation in ecosystem vigor was detected in Southwest China, with an upward trend from 2010 to 2020, as a result of the implementation of a series of ecological conservation projects (i.e., Natural Forest Protection Project and The Grain for Green Program) (Li et al. 2021b).

Organization

From 2000 to 2020, the level of organization was lower in the western part of the study area and higher in the central and eastern regions (Fig. 3b), primarily due to large-scale urban expansion and infrastructure construction (i.e., road network and public housing) that increased landscape diversity and fragmentation (Kang et al. 2018; Tao et al. 2018). For spatial variation, from 2000 to 2020, the areas with marked growth in ecosystem organization mainly occurred in western China at high altitudes, including Tibet and Qinghai, due to slow socioeconomic development and the low intensity of human activities (Fang et al. 2013).

Resilience

Figure 3c demonstrated that higher values of ecosystem resilience were primarily distributed in forestland, such as southern and southeast China, but lower values were found in areas with construction land, cropland, and unused land, such as the Northeast Plain, North China Plain, Sichuan Basin, and the northwestern part of China (Xie et al. 2021). Our

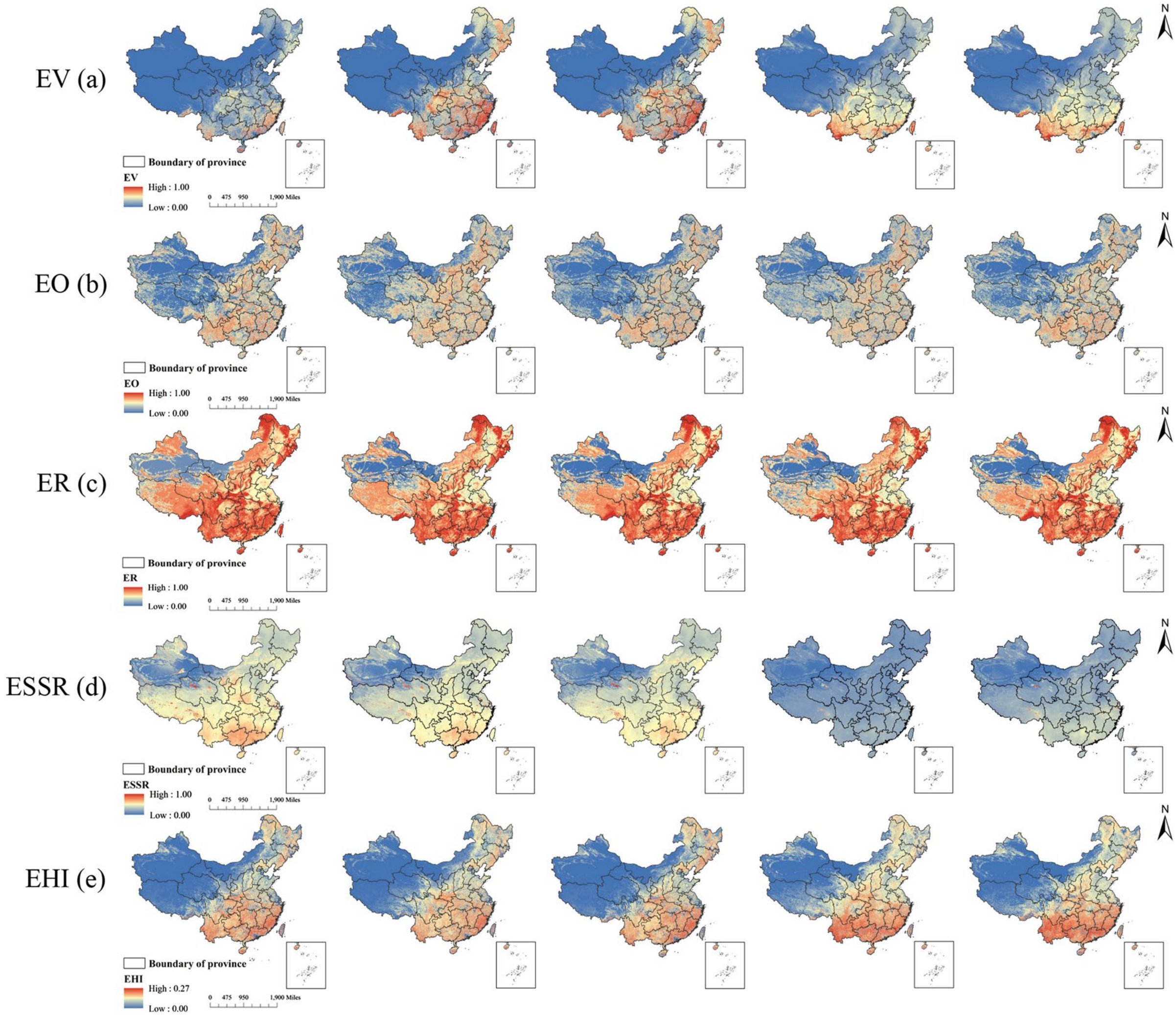

Fig. 3 Spatial pattern of ecosystem health indicators from 2000 to 2020. Notes: **a**: ecosystem vigor (EV), **b** ecosystem organization (EO), **c**: ecosystem resilience (ER), ecosystem services supply rate (ESSR) and ecosystem health index (EHI)

conclusions were basically consistent with Pan et al. (2021) and He et al. (2019), in which densely vegetated areas had a higher ecosystem resilience capacity, while constructed land and cultivated areas displayed a lower ecosystem resilience capacity. From 2000 to 2020, most regions showed no significant changes in ecosystem resilience. However, from 2010 to 2020, the ecosystem resilience values in the Tibetan Plateau, Sichuan Basin, North China Plain, and Northeast Plain regions displayed downward trends. The main reason for this is rapid urban sprawl, which has resulted in a shortage of ecological land and a decline in the ability of natural ecosystems to resist external interferences (Li et al. 2021b; Xie et al. 2021).

Ecosystem services supply rate

During the period from 2000 to 2020, the ecosystem services supply rate (ESSR) in China showed an upward trend from north to south (Fig. 3d), which is somewhat similar to the spatial patterns of ecosystem resilience. Because of high urbanization, industrial development, and population density, regions with high ESSR were primarily located in the southwestern and southeastern coastal areas, whereas low values were mainly scattered in northern parts due to a lower population density and ES consumption (Pan et al. 2021). In terms of spatial variation, regions with distinct decreases in the ESSR were mainly concentrated in southern China, including Guangxi Province and Guangdong Province, primarily because the increase in ecological land has improved the regional potential supply of ESs.

Spatial patterns of the ecosystem health index

Based on the results of four ecosystem health indicators in China, the ecosystem health index (EHI) was calculated in China from 2000 to 2020 (Fig. 3e). During 2000–2020, the EHI in China showed distinct spatial differentiation, with a descending trend from southeast to northwest. The areas of high EHI values were primarily concentrated in the southern and southeastern coastal regions of the study area with favorable natural conditions and high vegetation coverage, which was consistent with Kang et al. (2018) and Xie et al. (2021), and low levels were mostly located in the western region, parts of Inner Mongolia, and metropolitan areas with high urbanization and industrialization. Previous studies have also proven that regional differences in the EHI in China are largely influenced by land use intensity (He et al. 2019). Regarding spatial variation, from 2010 to 2020, the areas with marked growth in the EHI mainly occurred in West China. These findings showed that the overall health level of the study area significantly improved, which may be related to the implementation of the Grain for Green Project and main function zone planning (Li et al. 2021a).

Comparison of traditional and improved evaluation frameworks

The final evaluation results of VORESSR were analyzed in comparison with the traditional (VORES) evaluation method to further assess the rationality of our improved evaluation framework. Referring to previous research (Mallick et al. 2021; Wu et al. 2021) of traditional (VORES) frameworks, we used the improved value coefficient of China`s terrestrial ecosystem services as proposed by Xie et al. (2015) to obtain the ecosystem services value (ESV). The following equation is as follows:

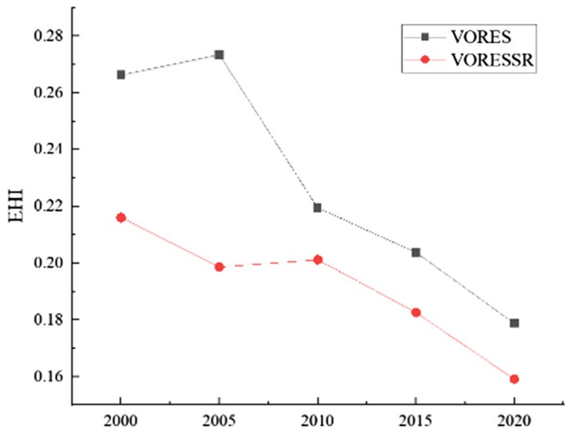

Fig. 4 The ecosystem health index (EHI) of VORESSR and VORES and frameworks from 2000 to 2020

$$ESV = \sum_{i=1}^{n} A_i \times P_i$$

where A_i denotes the area of LULC type i, n denotes the number of LULC types, and P_i denotes the values per unit area of LULC type i. The final obtained ESV is shown in Table 2.

In terms of temporal change trend, both traditional (VORES) and improved (VORESSP) frameworks showed an overall decreasing trend of EHI from 2000 to 2020, a slight recovery, and then a continued deterioration (Fig. 4). The results indicated that the overall health level of the study area experienced a fluctuating increase throughout the study period. Furthermore, the change rates from 2000 to 2020 differed greatly between them.

Figure 5 implied the changes in the proportions of areas with different EHI levels under the two evaluation results from 2000 to 2020. For example, from 2000 to 2020, the "poor" ecosystem levels occupied the largest proportion under the two evaluation results, revealing that the study area was primarily dominated by high levels of human disturbance. During the study period, the VORES evaluation method showed that areas with "relatively poor" health accounted for over 15% of the total area, while the VORESSR method indicated that these areas covered more than 15% from 2000 to 2010, while from 2015 to 2020, the coverage rate increased from 34 to 42%. Moreover, according to the two evaluation frameworks (Fig. 6), the proportion of high EHI levels (i.e.,

Fig. 5 Proportions of areas with different ecosystem health levels under two evaluation results

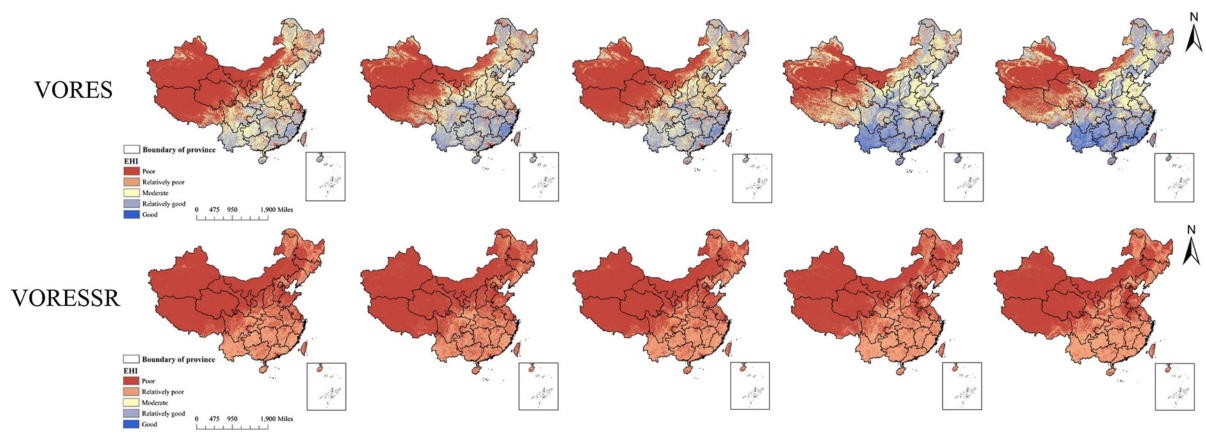

Fig. 6 Comparing the results of ecosystem health index under two evaluation results

relatively good and good levels) declined significantly from 2000 to 2020, implying that the area of high health level was remarkably smaller in the improved evaluation results.

Comparing the results of the two assessment frameworks revealed that the spatial distribution of poverty health levels was broadly consistent (Fig. 6), mainly concentrated in Northwest China and the Inner Mongolia Plateau, while the health levels in the Northeast China Plain, the Yunnan-Guizhou Plateau, the Sichuan Basin, and the middle and lower reaches of the Yangtze River showed distinct differences. Moreover, from 2015 to 2020, areas categorized as having "relatively good" or "good" health were mainly distributed in eastern, central and southern China based on the traditional evaluation results, whereas they were categorized as having "relatively poor" or "moderate" health according to the improved evaluation results. In summary, these findings emphasize that during the study period, the regions with low health levels were significantly larger than those calculated in the traditional VORES evaluation, suggesting that the regional ecosystem in China was in a more unhealthy state.

Discussion

Analysis of the ecosystem health levels in China

Our findings showed that the unsustainable or near-unsustainable ES regions were mainly in the southern and southeastern coastal regions. For example, due to the implementation of the Yangtze River Economic Belt Development Strategy, the Yangtze River Economic Belt has become a densely populated area and important development zone in China (Pan et al. 2021). Undoubtedly, frequent human activities, such as population agglomeration and rapid economic development, have resulted in sharp growth in the consumption of ESs and destroyed the balance between the potential and actual ES supply (Li et al. 2021a), thereby increasing ecological pressure and reducing the level of EHI (Shi et al. 2019). Similar studies have also found that socioeconomic factors (i.e., land use intensity, population density, and urbanization rate) are the primary contributors to changes in EHI in the Yangtze River Economic Belt and the southeastern coastal areas (He et al. 2019). Thus, the ecosystem health assessment results based on the improved framework were consistent with the actual ecosystem situation in the study area.

Comparison of traditional and improved evaluation frameworks

On the basis of previous studies, in this study, an improved ecosystem health assessment method based on ecosystem integrity and sustainability of ES supply was proposed from a human-nature system coupled perspective. In addition, a comparison analysis of the results generated by the traditional (VORES) and improved (VORESSR) frameworks was performed to further assess the rationality of our improved evaluation framework.

In terms of the temporal change trend, as shown in Fig. 4, there was a general downward trend in the EHI from 2000 to 2020 for both the traditional and improved frameworks. Moreover, a significant difference was found from 2000 to 2005, when the EHI of the improved framework showed a decreasing trend, while the EHI of the traditional framework increased over this study period. The possible reason for this phenomenon may be related to the differences in the performance of the ESV and ESSR from 2000 to 2005 (Fig. S1). During this period, China launched and implemented a series of large-scale ecological policies, such as the Grain for Green Project (GGP), the Natural Forest Conservation Program (NFCP), and the "Greening China Action" plan, which contributed significantly to the conservation of ecological land and enhanced environmental recovery (Xiaolin et al. 2016; Yuan et al. 2014; Viña et al. 2016). As a result, those ecological lands with specific high ecosystem service coefficients, such as forests and grasslands, increased over the time period, and in turn, the ESV increased (Fig. S2). The decline in the ESSR, on the other hand, may be related to the fact that during this period, the population size continued to increase, leading to an increase in human consumption.

In terms of spatial distribution characteristics, the EHI values were lower in most regions of China, especially in the central, southern, and southeastern coastal regions, and the regions with low health values were significantly larger than those calculated in the traditional VORES evaluation. According to our research findings, using the ESSR instead of the ESV resulted in lower EHI values for some areas with high ES coefficients, especially in forest areas. This may be due to the different methods of calculating ESV and ESSR. ESV is used to monetize different types of ESs and account for natural resource assets from an economic perspective to formulate ecological protection policies and optimize land use structures (Manea et al. 2019). This means that existing ESV-based ecosystem health assessments cannot reflect the differences in biophysical values of different ESs within the same land use category and therefore cannot fully capture the contribution of ecosystems to human welfare (Peng et al. 2015).

The above results indicated that by applying the improved framework, the traditional evaluation results can be modified according to the enhanced description of the impacts of human activities on the environment and the ecosystem benefit on the human system. In this regard, this approach can contribute to a deeper understanding of the complex inherent characteristics and health essence of ecosystems and the regional human-nature connectedness in coupled human–environment systems (Wu 2021).

Advantages of the improved framework

Since entering the Anthropocene, serious disturbance caused by human activities, such as population size, economic structure, and road network density, has led to the conversion of ecological land to constructed land and the gradual transformation of natural ecosystems into highly artificial coupled human–environment systems (MacDonald et al. 2019a, b), which emphasizes the integrity between human and ecological systems (Liu et al. 2022). However, it has become increasingly evident that with the increased intensity and breadth of human activities, the conflict between the limited potential capacity of regional ecosystems to benefit humans and the growing human needs for natural resources continues to intensify. When human consumption exceeds the potential provision capability of an ecosystem, changes in the structure and function of regional ecosystems may arise, which in turn cause a series of ecological environmental problems, such as soil erosion and biodiversity loss, and pose adverse effects on regional ecosystem health (Shi et al. 2019). Essentially, these problems result from the significant imbalance between the ES potential supply and actual supply. Therefore, by combining the sustainable supply of ESs with ecosystem health as an integral system, the VORESSR evaluation framework can provide insight into the impact of increased human activities on regional ecosystem health and serves as a transmitter of interactions between humans and natural ecosystems. It also validated the scientific significance of our improved VORESSR framework for regional ecosystem health assessments.

In recent years, given the popularity of a variety of methods for measuring ESs, researchers have taken ES as an indicator and combined ES supply or demand with vigor, organization, and resilience in regional ecosystem health assessments; however, few studies have considered the sustainability of ESs, which may lead to some biased results. We believe that the VORESSR evaluation framework that incorporates the ecological integrity and sustainable supply of ESs could provide a reference for other fields to discuss localized landscape sustainability.

Policy implications

Based on the ultimate goal of landscape sustainability, a healthy ecosystem should consistently provide long-term ESs for maintaining and improving human well-being (Wu 2013). Therefore, when addressing issues related to coupled human–environment systems in a changing world, it is crucial to consider the LSS framework. In this work, based on the core components of LSS, relevant planning and regulatory recommendations are provided to local governments to improve the capacity of ecosystems to consistently provide long-term ESs and facilitate sustainable development in China.

In terms of ESs, our findings suggest that strong imbalances between the potential and actual ES supply exacerbate the decline in EHI values. In this way, policy makers can develop targeted measures to mitigate the conflict between the ES potential supply and actual consumption and guarantee the sustainable supply of ESs. For example, for the decision makers of the Yangtze River Economic Belt, priority should be given to constructing green infrastructure (e.g., interconnected green spaces) and optimizing landscape patterns to improve potential ES supply (Xiao et al. 2020) and promote the health of natural ecosystems (Xiao et al. 2020; Jia et al. 2020). In terms of human well-being, densely populated regions should convert human resources into environmental advantages to pursue sustainable product and service production (Wu et al. 2021). For instance, the North China Plain and the Yangtze River Delta region could take full advantage of their natural geography and population concentration to engage more local actors in shaping current and future landscape sustainability through participatory and adaptive landscape governance (Wu 2021). Aiming for a sustainable landscape, it is time to slow the economic growth rate, optimize the composition and configuration of urban and rural landscape patterns to improve ecosystem structure, functions and biodiversity, and simultaneously limit urban development by controlling the speed and size of urban expansion (Peng et al. 2015). These results can also provide guidance for other areas to carry out ecological environmental protection and management.

Limitations

There are, of course, some uncertainties and limitations in this work as well. First, we analyzed only four major ES types, which cannot represent the variety of goods and services that regional ecosystems provide for local human well-being; therefore, we will explore more ES types, such as food production, water yield, and outdoor recreation, in our future studies. Second, this work used the indicator method to quantify the potential and actual ES supply, and the method will need to be revised in the future in light of field survey data and experimental results. Finally, the proposed framework is limited in its application to a wide range of spatial scales, as it uses only raster as a spatial statistical unit, and future research should address these limitations from a multiscale perspective (e.g., county, city, and province).

Conclusions

Healthy ecosystems are considered to be the basis and ultimate goal of landscape sustainability. ES is an important indicator in the ecosystem health evaluation framework to strengthen the relationships between the natural ecosystem and human activities. Previous ES-based studies have failed to consider the ability and function of natural ecosystems when identifying the impacts of human activities. This study attempted to establish an improved framework for assessing regional ecosystem health based on ecological integrity and the sustainable supply of ESs from the perspective of coupled human and ecological systems and to evaluate the trend and dynamic evolution of ecosystem health in China from 2000 to 2020. The results of the case study demonstrated the validity of this approach and indicated a mismatch between potential and actual ES supply, resulting in overall poor ecosystem health. We found that understanding the sustainable supply of ESs can provide insight into the impact of increased human activities on regional ecosystem health. This approach can contribute to reflecting the complex inherent characteristics and health essence of ecosystems and enriching our current knowledge of the regional human-nature connectedness in coupled human–environment systems. In a changing world, these findings have significant implications for promoting the practical application of ES theory in landscape governance and providing scientific references for other fields to achieve sustainable development.

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Declarations

Conflict of interest The authors declare that they have no conflicts of interest.

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