Pol. J. Environ. Stud. Vol. XX, No. X (XXXX), 1-14
DOI: *10.15244/pjoes/190023* ONLINE PUBLICATION DATE:

Original Research

Exploring the Human-Land Nexus in China's Xin'an River Basin: Remote Sensing Analysis of Ecosystem Services Variability and Synergy

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Received: 11 April 2024
Accepted: 12 June 2024

Abstract

This study scrutinized the Xin'an River Basin from 2017 to 2022, employing refined methodologies such as updated ecosystem service value tables, welfare assessment systems encompassing material, health, and public well-being metrics, human-environment coupling models, and advanced remote sensing technologies for land use patterns and satellite data analysis. Key findings revealed that: (1) The valuation of ecosystem services exhibited periods of equilibrium followed by slight declines, with a spatial distribution pattern described as 'rising at the periphery, diminishing at the core', culminating in a modest overall depreciation. (2) Human settlement welfare demonstrated a distinct geographical trend of 'enhancement in the southeast, reduction in the northwest', highlighting exceptional welfare in Jiande City, Shexian, and Chun'an County. (3) Over the observation period, the dynamic interplay between ecosystem services and human settlement welfare fluctuated, reaching its zenith in 2018 and its nadir in 2020. This interaction displayed a spatial gradient of 'excellent in the southeast, subpar in the central regions, and favorable in the northwest', indicating an overall moderate level of integration. The results underscore a mutual adjustment and a clear convergence towards minimal functional discord between the two systems.

Keywords: ecological system services, human settlement well-being, human-land system coupling, coupling harmonization degree, Xin'an River Basin, Land Satellite Remote Sensing

Introduction

The disorderly development of production space under industrialization and urbanization has suppressed the development of social and ecological space, ultimately leading to competing spaces and dysfunctional human-land relationships. These issues pose significant challenges to global sustainable development and the synergistic governance of human settlements [1]. Ecological system services are central to the study of human-land system integration and serve as a crucial connector between the natural environment and human settlement well-being. Progress in remote sensing technologies, including data from Landsat and Sentinel satellites, has significantly

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improved explorations into the significance of ecosystem services and their bearing on human development. These technologies enable us to assess the multi-dimensional impacts of various ecosystems on human society and their spatio-temporal dynamic interrelations. Emphasizing watershed ecological system concerns, the Chinese government has implemented various watershed ecological system compensation rules and policies, along with pilot projects in multiple water systems. Remote sensing and satellite data are increasingly used to monitor watershed health and inform policy decisions aimed at enhancing green development in watersheds through market-driven and varied watershed ecological system compensation techniques. However, the restoration of watershed ecological system services is a prolonged, challenging, and intricate process. The practice and theoretical development of China's watershed ecological system services remain in an initial phase of investigation without establishing a structured and precise governance framework [2]. Remote sensing and satellite data analysis can provide valuable information to support the development of such a framework. Conducting studies on the synchronized evolution of human-land across various watersheds is crucial for building an ecological society where humans and nature live in harmony. Through remote sensing, land use planning, and satellite data analysis, we are equipped with potent instruments to unravel the multifaceted links between human endeavors and environmental systems, thus enabling more sagacious decision-making toward our planet's enduring sustainability.

In the context of ecosystem services [3], which encompass provisioning, regulation, cultural, and support services, remote sensing technology, land use planning, and satellite data analysis play an integral role in understanding the complex interplay between these services and human well-being. Human settlement well-being, a multidisciplinary concept that integrates concerns from anthropology, economics, psychology, and sociology [4], can be significantly enhanced by the consumption of ecosystem services [5]. Costanza defines these services as benefits derived from ecological systems, which include the utility and value that humans obtain from them [6]. Ecosystem service research primarily seeks to improve human welfare by focusing on the human experience, ultimately striving to cultivate a harmonious interplay between ecosystem services, the welfare of human settlements, and their administration. At this juncture, the roles of remote sensing, land utilization planning, and satellite information become crucial. These findings offer a crucial understanding of the evolution and condition of ecosystem services across various times and locations, aiding in the creation of tactics that maximize the mutual benefits of both natural ecosystems and human social frameworks [7]. A comprehensive understanding of this relationship is necessary to implement effective management strategies that balance human development with environmental preservation.

Nonetheless, the interplay is complex and takes place across multiple layers. While the majority of research remains confined to theoretical models and basic linear correlations, there is a scarcity of studies exploring the full extent of their interconnection. In response to this gap, our study establishes a comprehensive impact framework for human-environment coupled systems. Employing data from remote sensing sources like Landsat and Sentinel satellites, our approach utilizes a coordinated degree model to explore the interplay in various watersheds. The results aim to inform policy decisions and contribute to managing ecological environments while building harmonious human habitats in the Xin'an River Basin.

Literature Review

Drawing on the work of Daily and Costanza, Chinese scholars began to introduce theories and research methods on ecosystem service functions in the 1980s [8, 9]. Xie Gaodi et al. [10] Amalgamated the findings of over 200 Chinese ecologists, grounded in the theoretical groundwork and valuation framework suggested by Costanza and colleagues. And developed the "Chinese Ecological System Service Value Equivalent Factor Table", aligning with China's unique circumstances, significantly influencing studies on appraising ecological system services in China [11]. The potency and frailties of ecological systems dictate the degree and efficiency of ecosystem services, with a multifaceted interaction between these services and human well-being, influenced by the nonlinear alterations in ecological systems [12]. An in-depth analysis of the complex relationship is vital for the progression of ecosystem management, the creation of human habitats, aligning the protection of ecosystem services with socio-economic expansion, and nurturing a balanced, happy human society. The trend in recent years has seen a transition from theoretical concepts and analysis to adopting more quantitative and systematic research methods. There's an accentuated interest in the assessment of ecosystem service values, the examination of their spatial and temporal relationships, and the recognition of spatial trade-offs. Furthermore, there is a push towards embedding these valuations within decision-making and management processes to foster social development [13-16]. On this basis, research should also consider the broader impacts of different types of ecosystem services on various aspects of human well-being and conduct multi-scale studies across different regions.

The Xin'an River Basin in China, a transboundary watershed that spans multiple provinces, presents a unique case study for implementing cross-provincial ecological compensation mechanisms. These mechanisms integrate natural, economic, and social factors to address historical conflicts between environmental protection and socio-economic development, such as water pollution, biodiversity loss, and soil degradation experienced in both upstream and downstream regions since the 1990s [17]. The difficulties encountered by the basin highlight the necessity for an all-encompassing strategy in managing ecosystems, one that harmonizes the needs of economic and social progress with the principles of environmental sustainability. Research into how ecosystem services affect human welfare in the Xin'an River Basin serves as a prime example of provincial ecological management and is vital for enhancing the basin's ecological environmental governance framework and capabilities.

With ongoing studies delving into the complex interplay, the integration of remote sensing, land utilization, and satellite information is crucial. Such technologies are instrumental in pinpointing key conservation and restoration zones, directing land use strategies to enhance ecosystem service provision, and tracking the success of ecological compensation schemes over time. Furthermore, they aid in evaluating the compromises among various land utilizations and their effects on local community welfare, guaranteeing that the basin's ecological function corresponds with its economic and social growth objectives. To sum up, the study updated the scale of equivalent ecological system service values, focusing on agricultural output and land utilization across nine county-level areas in the study area between 2017 and 2022. It involved assessing the worth of ecological system services and their impact on human settlement well-being in the Xin'an River Basin and examining the interplay between these elements. This was done to lay the groundwork for uncovering how ecological system service values influence human settlement well-being in the Xin'an River Basin over time and space.

Study Area and Research Methodology

Xin'an River Basin

Situated in the southeast of Anhui Province and Zhejiang Province, the Xin'an River Basin spans approximately 17,600 square kilometers. It is positioned between east longitude 117°38'-119°32' and north latitude 29° 10'-30° 19' (Fig. 1). Situated in the northern subtropical monsoon zone, the Xin'an River Basin experiences an average yearly temperature. The temperature ranges from 15-17ºC. The area is mainly hilly and mountainous, with a beautiful natural environment that remains lush throughout all four seasons. Xin'an River is the mother river of Huizhou merchants, which is famous for its wonderful combination of China's unique Huizhou culture with natural scenery and ancient villages. The natural environment on both sides of the river basin is excellent, presenting a three-dimensional ecological pattern of "high mountain forests, mid-mountain teas, low mountain fruits, and fish in the water", which, together with the ancient villages and dwellings that cover them, constitute an ideal map of the human gathering place. The rapid amalgamation of the Yangtze River Delta and the merging of urban and rural areas have recently led to issues such as illogical planning and disjointed human-land interactions in this region. This situation has led to numerous detrimental effects on the region's social well-being and ecological surroundings. Consequently, this study delves into and examines the quality of the local human environment, grounded in factual reality.

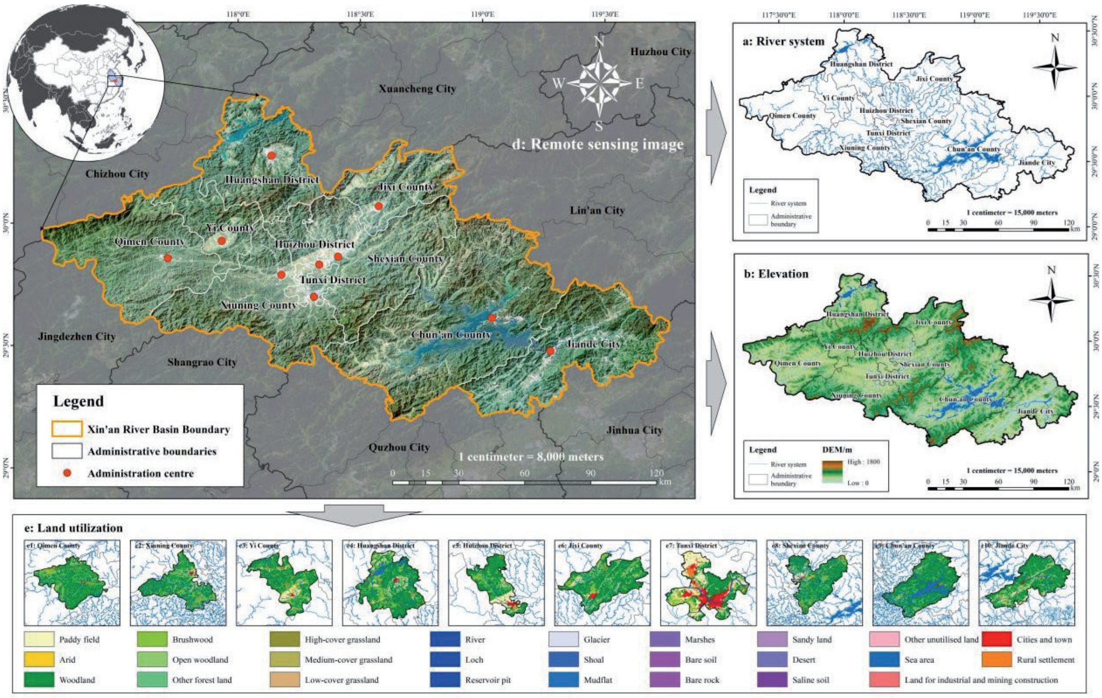

Fig. 1. Geographic scope and location of the Xin'an River Basin.

Research Methodology

Evaluating Ecosystem Services through the Lens of Land Use Categories

Upon refinement of the ecosystem service equivalence coefficients table, informed by the research of predecessors [10, 18], clarity was brought to the valuation of diverse ecosystem categories through land-use remote sensing data. The study utilized land use data, interpreted from Sentinel-2A Landsat imagery with a spatial resolution of 30 meters (Fig. 1). This refined approach has yielded a more equitable and extensive framework for the evaluation of ecosystem services within the Xin'an River Basin. The methodology for calculating the ecosystem service value, which outlines the computation of these values, is presented as follows:

$$f(E) = \sum_{i=1}^{n} S_i Q_i \quad (1)$$

In this context, "f(E)" symbolizes the ecological system's service worth; "S_i" denotes the land use type's area; and "Q_i" denotes the value coefficient associated with ecosystem services, which signifies the ecological service value per unit area attributed to the ith category of land use.

The land use classifications within the study area were segmented into six distinct ecological system types and four ecological service categories, as informed by the "Equivalent value of ecological system services per unit area of ecological systems in China [17]" (Table 1). Given that over a decade has passed since its inception, the initially calculated ecological system service value equivalent factor of 884.9/hm^2 has become inapplicable due to inflation and various other reasons. This study, aiming to ascertain the value factor of ecological system services aligned with the Xin'an River Basin's development and land use traits, considers 2022 as the foundational year. The method determines the net earnings from food production in each farmland ecological system area, equating the ecological system's service value to a single standard factor. Predominantly, the value of grain output in agricultural ecological systems is determined by the trio of primary grain commodities - rice, wheat, and corn - in Anhui and Zhejiang Provinces as of 2022. The formula for calculation is outlined below.

$$P_i = \frac{(V_r F_r + V_w F_w + V_c F_c) G_i}{7} \quad (2)$$

In the context of this framework, "G_i" represents the ith equivalent factor for ecological service value within these systems. The variables "V_r, V_w", and "V_c" are used to represent the proportions of the total cultivated area dedicated to rice, wheat, and maize in the year 2022, respectively. Meanwhile, "F_r, F_w", and "Fc" signify the average net incomes per unit area for rice, wheat, and maize in 2022, respectively. Based on the data obtained, the estimated equivalent factor for ecosystem service value was approximately 2,774.460 yuan per hectare squared, with a conversion coefficient of 3.135. The calculation of this figure led to the creation of a table showing the equivalent value of ecological services per ecological system area (Table 1).

Assessment of the Degree of Well-Being in Human Settlements

Drawing from the implications of well-being in the Millennium Ecological System Assessment Report and similar research [20], this document develops an all-encompassing indicator framework for human settlement well-being in the research area, encompassing material, health, and public well-being, while considering data accessibility (Table 2). It should be noted that (1) the human settlement well-being measured in this paper focuses only on objective well-being, mainly considering that subjective well-being is mostly internalized in objective well-being, and accordingly the spiritual and cultural space is also based on the material space, and there is no need to distinguish between the differences of different population subjects in the coupling study of services and well-being for the time being; (2) To reduce inaccuracies in data, the comprehensive indicator system's significance is established through a blend of subjective and objective weighting techniques. To reduce inaccuracies in data, the comprehensive indicator system's weights are calculated using both subjective and objective weighting techniques, with the mean value derived from the subjective hierarchical analysis approach and the objective entropy value method serving as the ultimate weights. Then, the happiness index of the living environment of each district and county is calculated by the method of combining the good and bad solution distance method and comprehensive weight [21]. The specific calculation steps are as follows:

Data normalization: Through the data normalization process, the original data of each indicator is scaled to the interval of [0, 1] in order to eliminate the influence of different units of measurement and simplify the calculation process. Using the extreme difference method for data normalization, there are the forward indicator formula (3) and the reverse indicator formula (4).

$$x_{ijt} = \frac{o_{ijt} - \min(o_{ijt})}{\max(o_{ijt}) - \min(o_{ijt})}, \ (o_{ijt} \text{is a positive indicator}) \quad (3)$$

$$x_{ijt} = \frac{\max(o_{ijt}) - o_{ijt}}{\max(o_{ijt}) - \min(o_{ijt})}, \ (o_{ijt} \text{is an inverse indicator}) \quad (4)$$

Where "o" is the raw indicator value, "x" is the normalized indicator value, "t" denotes the year, "I" denotes the region, and "j" denotes the specific indicator.

Comprehensive Evaluation Value: The assessment of human settlement well-being is conducted using the

Table 1. Equivalent value of ecosystem services per unit area of terrestrial ecosystems and value of ecological services (yuan/ hm^2) in China [19].

Ecological system services		Forest		Grassland		Farmland		Wetland		Water body		Desert	
C1:Regulatory service	X1:Gas regulation	3.5	1387.230	0.8	317.081	0.5	198.176	1.8	713.433	0	0.000	0	0.000
	X2:Climate regulation	2.7	1070.149	0.9	356.716	0.89	352.753	17.1	6777.610	0.46	182.322	0	0.000
	X3:Water conservation	3.2	1268.325	0.8	317.081	0.6	237.811	15.5	6143.448	20.38	8077.643	0.03	11.891
	X4:Waste treatment	1.31	519.220	1.31	519.220	1.64	650.016	18.18	7205.670	18.18	7205.670	0.01	3.964
C2:Support service	X5:Soil formation and conservation	3.9	1545.771	1.95	772.885	1.46	578.673	1.71	677.761	0.01	3.964	0.02	7.927
	X6:Biodiversity conservation	3.26	1292.106	1.09	432.023	0.71	281.410	2.5	990.879	2.49	986.915	0.34	134.760
C3:Supply service	X7:Food production	0.1	39.635	0.3	118.905	1	396.351	0.3	118.905	0.1	39.635	0.01	3.964
	X8:Raw materials	2.6	1030.514	0.05	19.818	0.1	39.635	0.07	27.745	0.01	3.964	0	0.000
C4:Cultural service	X9:Entertainment culture	1.28	507.330	0.04	15.854	0.01	3.964	5.55	2199.751	4.34	1720.165	0.01	3.964

technique of distance to optimization. The method of measuring the distance of merit solutions assesses the value of a set of objects by calculating the Euclidean distance between the evaluation indices and the most and least vectors for each indicator. Unrestricted by the distribution of data and the size of the sample, it is capable of precisely calculating the all-encompassing evaluation index for each subject utilizing insights provided by numerous influencing factors. The precise formula for calculation is detailed in Equations (5)-(9).

$$P_{ijt} = \frac{o_{ijt}}{\sum_{i=1}^{n} o_{ijt}}, \quad P_{ijt} \in [0,1] \tag{5}$$

$$e_j = \frac{-1}{\ln n}\sum_{i=1}^{n} P_{ijt}\ln(P_{ijt}), \quad e_j \in [0,1] \tag{6}$$

$$g_j = 1 - e_j \tag{7}$$

$$W_j = \frac{1}{2}\left[\frac{g_j}{\sum_{j=1}^{m} g_j} + \frac{\left(\prod_{i=1}^{n} a_{ij}\right)^{\frac{1}{n}}}{\sum_{j=1}^{n}\left(\prod_{i=1}^{n} a_{ij}\right)^{\frac{1}{n}}}\right] \tag{8}$$

$$f(H) = \frac{\sqrt{\sum_{j=1}^{m} W_j\left(x_{ij}^{min} - x_{ij}\right)^2}}{\sqrt{\sum_{j=1}^{m} W_j\left(x_{ij}^{max} - x_{ij}\right)^2} + \sqrt{\sum_{j=1}^{m} W_j\left(x_{ij}^{min} - x_{ij}\right)^2}} \tag{9}$$

Where "P" denotes the magnitude of the indicator's effect on the evaluated object; "a_{ij}" is the judgment matrix scale, which denotes the weighting of the importance of the factor to the object. "e" is the entropy value; "g" is the entropy redundancy, which denotes the magnitude of the variability of the individual indicators; and "W" denotes the composite weighting. "f(H)" is the degree of well-being in human settlements.

Coupled Coordination Degree Models

The model of coupling coordination degree is employed to assess the extent of synchronized development in various areas [22]. The coupling degree denotes the dynamic interplay among multiple systems that interact and impact one another, leading to synchronized development, indicative of the extent of interdependence and reciprocal limitations among these systems. Coordination level denotes the extent of harmless coupling within a coupled interaction, indicative of whether the coordination is effective or not. The ultimate degree of coupling coordination for each component is ascertained by combining the D value of this degree with the standard classification of coordination levels. C is designated as the measure of interconnection between system pairs, T signifies the harmony index, and the D value, which is ascertained through a mathematical formula in the context

Table 2. Comprehensive Indicator System for human settlement well-being in the Xin'an River Basin.

Target layer	Dimensionality layer	Indicator layer	Interpretation of indicators	Causality	Weights		
					Entropy weight	AHP weight	Combined weight
H:Degree of well-being in human settlements	D1:Material well-being	Y1:Disposable income per capita (yuan)	Wage income + Net business income + Net property income + Net transfer income	+	0.082	0.058	0.070
		Y2:GDP per capita (yuan)	Gross regional product/Total population	+	0.055	0.094	0.075
		Y3:Balance of household deposits (Ten thousand yuan)	Balance of urban residents' savings deposits + Balance of farmers' personal savings deposits	+	0.083	0.064	0.073
		Y4:Engel's coefficient (%)	Food expenditure/Total household expenditure	–	0.035	0.098	0.100
		Y5:Per capita living space (m^2)	Total living space/Total population		0.083	0.103	0.069
	D2:Healthy well-being	Y6:Number of urban and rural residents enrolled in basic medical insurance (Quorum)	Number of urban basic medical insurance Participants + Number of rural basic medical insurance participants	+	0.075	0.052	0.067
		Y7:Beds in health-care facilities (Amount)	Total number of beds in medical and health institutions	+	0.081	0.066	0.070
		Y8:Number of health technicians (Quorum)	Total number of health technicians	+	0.037	0.073	0.077
		Y9:Population mortality rate (‰)	Deaths/total population	+	0.116	0.093	0.065
	D3:Public well-being	Y10:General public budget expenditure (Ten thousand yuan)	Salary and Well-being expenditures + Commodity expenditures + Service expenditures	+	0.139	0.051	0.083
		Y11:Number of urban and rural residents enrolled in social pension insurance (Quorum)	Number of urban residents enrolled in old-age pension insurance + Number of rural urban residents enrolled in old-age pension insurance	+	0.072	0.049	0.094
		Y12:Number of persons covered by the subsistence minimum (Quorum)	Total number of persons receiving minimum subsistence allowance	–	0.102	0.125	0.082
		Y13:Number of full-time teachers (Quorum)	Total number of persons with teaching qualifications specializing in teaching	+	0.040	0.075	0.074

of the coupling degree model, dictates the level of coupled coordination.

$$C = \left[\frac{\prod_{i=1}^{n} U_i}{\left(\frac{1}{n} \sum_{i=1}^{n} U_i \right)^n} \right]^{\frac{1}{n}} = \frac{\sqrt[2]{U_E U_H}}{(U_E + U_H)^2} \tag{7}$$

$$T = \sum_{i=1}^{n} \omega_i U_i = \omega_E U_E + \omega_H U_H \tag{8}$$

$$D = \sqrt{C \times T} \tag{9}$$

In this context, "n" represents the count of subsystems, "U_i" denotes the all-encompassing evaluation index for the ith system, and "U_E" and "U_H" are the standardized values of f(E) and f(H), respectively, distributed within a range of [0,1]. The symbol "ω" is used to denote the mass of the ith subsystem. The sum of ω_E and ω_H equals 1, which respectively denote the significance of ecological system services and the impact on the well-being of human habitats. The Xin'an River Basin, playing a crucial role in China's initial inter-provincial ecological compensation scheme for the Yangtze River Delta's integration, is swiftly evolving. The region's primary challenges lie in fostering cooperative economic and environmental management, as well as enhancing urban-rural integration and growth. Consequently, the harmonious progression of ecological system services and the impact on human settlement well-being are crucial for the basin's sustainable growth, which is just as vital for the development of the Xin'an River Basin, where $\omega_E = \omega_H = 1/2$.

As the C value, indicative of the coupling level, escalates, there is a concomitant augmentation in the influence of ecological system services on the well-being of human settlements; conversely, a higher T value (coordination level) amplifies the collaborative growth between ecological system services and human settlement well-being [23].

By defining "μ" as the degree of relative development, one can determine the variance in development levels between ecological system services and human settlement well-being using a specific equation (13).

$$\mu = {U_E}/{U_H} \tag{9}$$

Within this context, a range of $0<\mu\leq0.6$ indicates a delay in ecological system service development compared to human settlement well-being; a range of $0.6<\mu\leq1.2$ suggests a balance between the two systems, and a range of $1.2<\mu$ implies a lag in human settlement well-being development relative to ecological system services. Reflecting on pertinent studies, the interplay and synchronization of ecological system services with human settlement well-being were segmented into three distinct groups and ten tiers, merging the extent of coupling coordination with the comparative level of development, aiming to visually discern the methodical developmental traits of the interconnection between the two.

Data Sources

This research employs land use data obtained from the CNLUCC, which is distinguished by a Kappa coefficient above 0.8, an integrated test accuracy of over 95%, and an overall positive interpretation result. The comprehensive indicator system utilized to assess human settlement well-being predominantly gathers data from the statistical yearbooks representing various localities across Anhui and Zhejiang provinces. Specifically, this investigation includes data from multiple district and county statistical yearbooks, alongside reports detailing the economic and social development of each area. Given the practicality of gathering data and the study's emphasis, this document employs a five-year span from 2016 to 2020 for assessment. In cases of incomplete data, calculations are performed using the method of average growth rate and interpolation. Owing to the accessibility of data and the scope of this research. The research employs a six-year assessment timeframe spanning from 2017 to 2022. To address certain data gaps, the methods of average growth rate and interpolation were employed.

Statistical Analysis

The Geographical and Chronological Features of Ecological System Services

Value Analysis of Integrated Ecological System Services

From 2017 to 2022, the value of ecological system services was approximately split into two stages: a period of equilibrium and a minor decrease. The figure fell from f (E) 168.214×10^8 yuan in 2017 to 144.427×10^8 yuan in 2022, marking a 14.14% reduction. Included in these is the period from 2017 to 2020, where f(E) fell from 168.214×10^8 yuan to 168.030×10^8 yuan, marking a 0.11% reduction, while the value of ecological system services stayed relatively constant over these four years (Table 3). This suggests a consistent level of ecological system services from 2017 to 2022. Between 2020 and 2022, there was a minor downturn, as f(E) fell from 168.030 × 10^8 yuan to 144.427 × 10^8 yuan, marking a 4.05% reduction, and the worth of ecological system services approximately diminished over these three years (Table 3). This suggests a minor decline in the ecological system services between 2020 and 2022.

Viewed spatially, the levels of ecological system services typically exhibit a pattern of being "elevated near and diminished centrally." Areas of significant ecological system service value predominantly span tributaries, mountainous regions, and extensive

Table 3. Evaluating the worth of ecological system services during 2017-2022.

Ecological system services/Years	2017	2018	2019	2020	2021	2022
Regulatory services	86.802	86.870	86.855	86.706	74.952	74.888
Support services	51.886	51.944	51.936	51.831	44.794	44.766
Supply service	19.542	19.560	19.555	19.521	16.872	16.162
Cultural service	9.984	9.999	9.998	9.972	8.618	8.610
Integrated ecosystem services	168.214	168.373	168.345	168.030	145.236	144.427

non-urban zones, encompassing Qimen County's southern section, Xiuning County's southern area, and Shexian County's western sector, among others. The area with the second-highest f(E) primarily lies in the intermediary zone between human habitation and the natural ecological setting, predominantly in the vicinity of the Xin'an River and the picturesque natural landscape, with agricultural land and aquatic bodies being the predominant land uses. Regions with minimal value for ecological system services predominantly exist in heavily populated zones near the Xin'an River and within Huangshan City's urban areas, such as Tunxi and Huizhou districts, which align closely with the forest cover distribution trends.

This document illustrates yearly variations in ecological system service value through interannual discrepancies, with higher figures signifying an increase in ecological system value from the prior year and lower figures denoting a decrease from the previous year (Fig. 2). The diagram illustrates that from 2017 to 2018, the f(E) in each region generally increased, while from 2018 to 2022, there was a general decrease in each region's ecological system service value. In 2017, with the exception of Qimen County, Jixi County, and Jiande City, which experienced a decline in ecological system service values, dropping by 3.143 yuan/ hm^2, 2.315 yuan/ hm^2, and 7.401 yuan/ hm^2 respectively, other regions witnessed a rise in ecological system service values, averaging an increase of 11.439 yuan/ hm^2. However, in 2018, Jiande City's ecological system service value fell by 2.019 yuan/ hm^2, while all other areas displayed an increase, averaging 19.324 yuan/ hm^2. By 2019, Huizhou District, Shexian County, and Chun'an County were on the rise, with decreases of 6.993 yuan/ hm^2, 1.665 yuan/ hm^2, and 0.449 yuan/ hm^2, respectively, but in other regions, there was a consistent decline in ecological system service values, averaging 2.909 yuan/ hm^2. The year 2020 saw a decline in the worth of ecological system services across the entire research region, averaging a reduction of 15.392 yuan/ hm^2. Jiande City experienced the gravest reduction, recording a decline of 20.612 yuan/ hm^2. The year 2021 witnessed a decline in the worth of ecological system services across the entire research region, averaging a reduction of 5.298 yuan/ hm^2. 5.298 yuan/ hm^2. The most significant drop is observed in Qimen County, falling by 13.567 yuan/ hm^2. In 2022, with the exception of Xuining County, which experienced an increase in ecological system service value by 6.369 yuan/ hm^2, the overall ecological system service value in other regions is declining, averaging a reduction of 7.852 yuan/ hm^2. In summary, the overall value of ecological system services of the Xin'an River

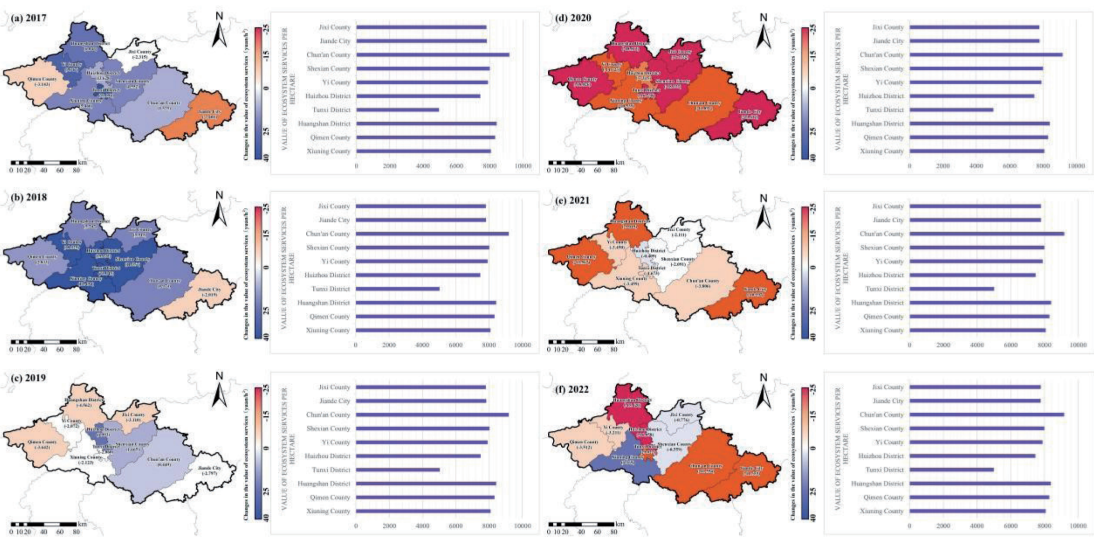

Fig. 2. Variations over time and space in the value of ecological system services, along with quantitative shifts during 2017-2022.

slightly increased from 2017 to 2018, and after 2018, the value of ecological system services generally maintained a decline.

Evaluation of the Worth of Every Ecological System Service

Over the six-year period, the value of regulating services decreased from 86.802×10^8 yuan in 2017 to 74.888×10^8 yuan in 2022, or 13.73 percent; the value of support services decreased from 51.886×10^8 yuan in 2017 to 44.766×10^8 yuan in 2022, or 13.72 percent; the value of supply services decreased from 19.542×10^8 yuan to 16.162×10^8 yuan in 2022, a decrease of 17.29%; and the value of cultural services decreased from 9.984×10^8 yuan in 2017 to 8.610×10^8 yuan in 2022, a decrease of 13.76%. From 2017 to 2022, the regulating, supporting, supplying, and cultural services all show two stages of a steady-state period and a slight decline period (Table 3). Among them, the 2017-2020 period is a steady-state period, in which the value of regulating services decreases from 86.802 × 10^8 yuan to 86.706 × 10^8 yuan, with a decrease of 0.11%; the value of supporting services decreases from 51.886 × 10^8 yuan to 51.831 × 10^8 yuan, with a decrease of 0.11%; and the value of supplying services decreases from 19.542 × 10^8 yuan to 19.521 × 10^8 yuan, a went down of 0.11%; and the value of cultural services went down from 9.984×10^8 yuan to 9.972×10^8 yuan, a decrease of 0.12%. The data indicates a steady state of regulatory, support, supply, and cultural services from 2017 to 2020. Between 2020 and 2022, there has been a minor decline, with the regulatory service's value dropping from 86.706×10^8 yuan to 74.888×10^8 yuan, marking a 3.63% reduction; the supporting service's value falls from 51.831×10^8 yuan to 44.766×10^8 yuan, a 13.63% fall; the supply services' value fell from 19.521×10^8 yuan to 16.162×10^8 yuan, a 17.20% fall; and the cultural services' value fell from 9.972×10^8 yuan to 8.610×10^8 yuan, a 13.66% fall. The data indicates a decline in regulatory, supportive, supplying, and cultural services from 2020 to 2022.

Regarding geographical spread, the regulatory and cultural services from 2017 to 2022 will exhibit a pattern of "levanted in the southeast and diminished in the northwest" (Fig. 3), predominantly in the high-value areas of Qiandao Lake and Taiping Lake. Areas of lesser value predominantly reside in the heavily populated zones of districts and counties, represented by the Tunxi and Huizhou districts at the heart of Huangshan City. Over a span of six years, there's been a minor decline in both regulatory and cultural services, with the extent of supportive and supplying services exhibiting a spatial pattern of being "elevated in the vicinity and diminished in the center" during 2017-2022 (Fig. 3), predominantly situated in tributaries, hilly areas, and extensive non-metropolitan zones, notably encompassing Qimen District and Huizhou District in Huangshan City's heart. Areas of significant value predominantly span tributaries, mountainous regions, and extensive non-urban zones, encompassing Qimen County's southern section, Xiuning County's southern area, and Shexian County's western sector. Areas of secondary importance predominantly lie in the intermediary zone separating human habitation zones from the natural ecological system, especially near the river's picturesque natural surroundings, where land predominantly consists of farmland and aquatic environments. Conversely, areas of lesser value are predominantly found in the heavily populated regions near the river and within the urban

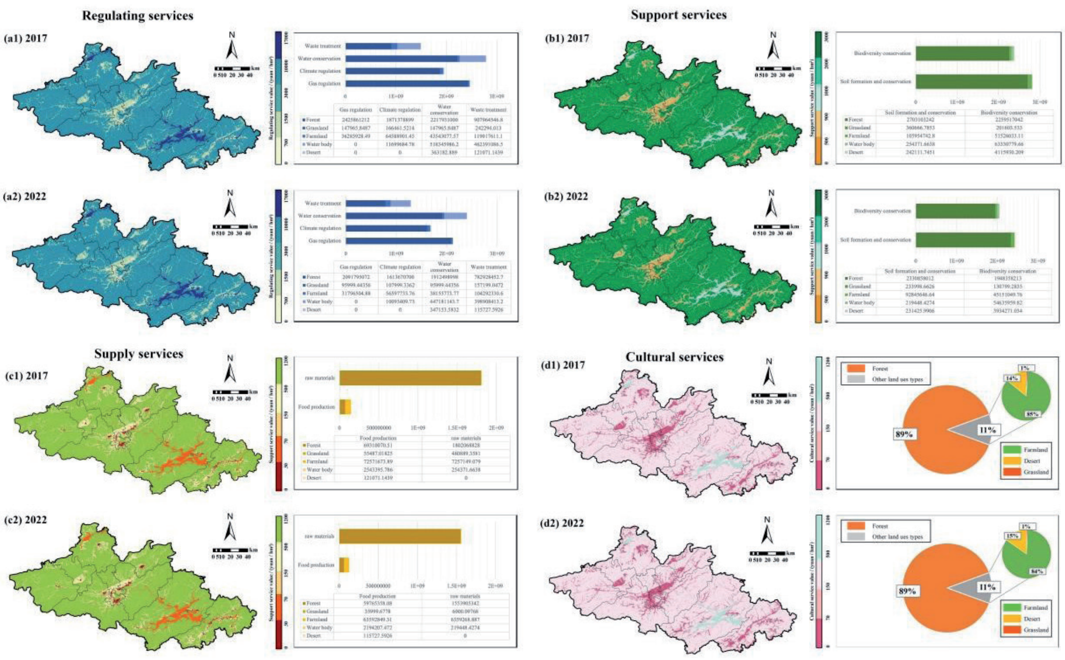

Fig. 3. The geographical and chronological allocation of regulatory, support, supply, and cultural services during 2017-2022.

zones of Huangshan City, encompassing the Tunxi and Huizhou districts.

The Spatial and Chronological Aspects of the Well-Being of Human Settlements

The comprehensive human settlement well-being from 2017 to 2022 is divided into three periods: decline, fluctuation, and slow uplift. The overall decline from 0.572 in 2017 to 0.458 in 2022 is 19.93%. Among them, 2017-2018 is a period of decline, with human settlement well-being slightly decreasing from 0.572 to 0.503, a decrease of 12.06%; 2018-2020 is a period of fluctuation, with human settlement well-being swiftly rising from 0.503 in 2018 to 0.745 in 2019, an increase of 48.11%, and then dropping sharply to 0.414 in 2020, a decrease of 44.43%; 2020-2022 is a period of slow uplift, with human settlement well-being rising slightly from 0.414 to 0.458, an increase of 10.63%.

The human settlement well-being was categorized into five distinct levels using the natural breakpoint method: high level area (f(H) ∈ [0.70-1.00]), higher level area (f(H) ∈ [0.60-0.70]), medium level area (f(H) ∈ [0.50-0.60]), lower level area (f(H) ∈ [0.35-0.50]), low level area (f(H) ∈ [0.25- 0.35]), low level area (f(H) ∈[0.25-0.25]) and very low level area (f(H) ∈ [0.00-0.25]). The state of human health between 2017 and 2022 exhibited a distribution trend of "elevated in the southeast and diminished in the northwest." Among them, the human settlement well-being levels of Shexian and Chun'an counties have been above 0.5, fluctuating between the medium and high-level zones, while Jiande city has been in the high-level zone all year round, with its human settlement well-being level higher than 0.6; this indicates that Jiande city, Shexian County, and Chun'an county have the highest human settlement well-being levels, with Jiande city being the most optimal one. Yixian County's human settlement well-being level has been between 0.35-0.50 in the lower level zone; Qimen County, Huangshan District, Tunxi District, Huizhou District, and Xiuning County are in the low level and lower level zones, and the human settlement well-being level of the five regions fluctuates roughly between 0.25-0.50; Jixi County's human settlement well-being level has been in the low level zone between 0.35-0.20, and in 2021 it will be the very low level zone. The degree of well-being in human settlements in Jixi County is at the trough of 0.244, indicating that the degree of well-being in human settlements in the seven regions of Yixian, Qimen, Huangshan, Tunxi, Huizhou, Xiuning, and Jixi counties has always been at a low level, and Jixi County, in particular, has the worst level.

From the perspective of spatial clustering characteristics, the spatial relationship of f(H) from 2017 to 2019 exhibits a pattern of 'hot expansion and cold contraction' (Fig. 4). Put differently, regions with high well-being in human settlements are inclined to experience an uplift in their well-being levels, irrespective of the degree of agglomeration – high or low—while the areas identified as cold spots tend to diminish. The primary hot spot region is situated in the northeastern section of Zhejiang Province, while Chun'an County, Jiande City, and Shexian County are positioned within the southwestern part of Anhui. Notably, the cold spot area shifted from Huining County to Qimen County and Jixi County over this period. Further, from 2019 to 2022, the cold spot area expanded to include Huining County and Huangshan District, and Jixi County underwent a slight shift towards becoming a cold spot.

The Interplay between Ecological System Services and the Well-Being of Human Settlements Over Time and space.

Characterization of Changes in the Degree of Coupling Coordination

The average figures for the combined impact of ecological system services and human settlement

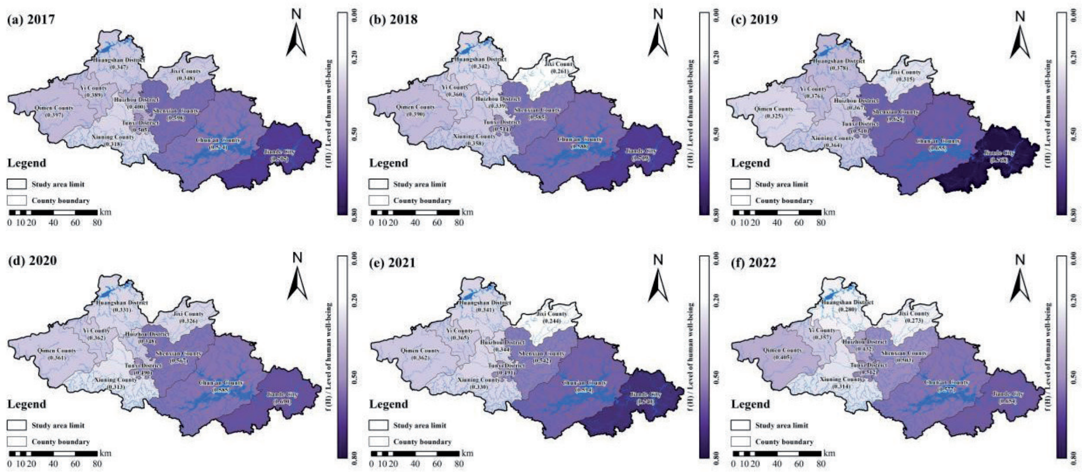

Fig. 4. Spatial and temporal distribution of human settlement well-being levels during 2017-2022.

well-being between 2017 and 2022 were 0.504, 0.537, 0.490, 0.481, 0.529, and 0.519. The interplay in the research area exhibited fluctuating wave movements. Throughout various periods in 2020, the integration and synchronization in the research area remained minimal, with the general status classified as endangered and dysfunctional decline. Among them, Xiuning County in Anhui Province was in the moderate dysfunctional decline category, with a relative development degree of μ equal to 1.300. This suggests that the region experienced minimal intensive land utilization, with both systems either underdeveloped or excessively developed, lagging behind each other in enhancing human settlement well-being. In 2018, the watershed experienced the most intense interaction, ranking minimally in the development sector. Among them, Chun'an County in Zhejiang Province is in the category of high-quality coordinated development, with a relative development degree of μ 1.701. This indicates that the two types of systems in the region promote each other and coexist, but the development of human settlement well-being in the area is lagging behind.

In terms of regional differences, the coupled coordination of ecological system services and the degree of well-being in human settlements is higher in Zhejiang Province than in Anhui Province, which is similar to the dynamic change characteristics of the human settlement well-being level index. Situated at the heart of China within the Yangtze River Delta, Anhui Province boasts a more intricate geo-environment compared to Zhejiang Province. The Xin'an River Basin in Anhui Province features a central and elevated base, characterized by hilly and mountainous landscapes. The geographical layout and spatial separation of these areas obstruct economic links with cities like Hangzhou and Hefei, complicating the coordination of advancements in human settlement well-being and higher boundaries. However, following the third phase of the cross-provincial Basin ecological compensation mechanism trial, there has been a marginal improvement in the value of ecological system services, resulting in a slight increase in the overall impact of ecological system services and human settlement well-being in 2022 compared to 2018. In contrast, Zhejiang Province enjoys stronger connectivity between land, river, and sea, situated close to Hangzhou, the provincial capital, in the east, and offering downstream river access to the sea. This enhances the adaptability of human habitats and facilitates regional development.

Spatial Pattern of Coupling Harmonization Degree

From 2017 to 2022, there was a gradual change in the spatial grouping of ecological system services and human settlement well-being impacts, moving from a state of more synchronized improvement, less synchronized change, and more ineffective recession to one of more synchronized improvement, less synchronized change, and less ineffective recession. Regarding spatial arrangement, the comprehensive pattern of coordinated ecological system services and human settlement well-being impacts from 2017 to 2022 shows "superb in the southeast, subpar in the center, and favorable in the northwest" (Fig. 5), and the area of low coupled coordination degree in the center includes the densely populated areas such as Huangshan City (Tunxi, Huizhou, and Huangshan), Jixi County, Xiuning County, Yixian County, and Qimen County, where urban and agricultural functions dominate due to the constraints of location. Xiuning County, Yixian County, Qimen County, and other densely populated areas, where urban and agricultural functions dominate due to locational conditions. This situation intensifies the effect of local spatial polarization, leading to a scenario where ecological system services and human settlement well-being are mutually exclusive; in the median coupling coordination area in the northwest, the terrain is hilly, the ecological system is highly concentrated and continuous, the socio-economic development is dominated by traditional agriculture, and the ecological environment is under greater pressure, with "two highs and one low" features of high agricultural and ecological functions, and low urban functions; in the southeast, the ecological function is dominated by towns and agriculture, and the ecological function is dominated by cities and towns. In the southeastern part of the area with high coupling coordination, driven by the Hangzhou Common Wealth Demonstration Zone and the coordinated and integrated development mechanism, there is a small gap between urban and rural areas in neighboring units, with good livelihoods and excellent human-land relations. The degree of well-being in human settlements and ecological system services has evolved symbiotically, fostering improved spatial synergies that bolster the system's harmonious equilibrium.

Regarding coupling and coordination, approximately 50.29% of areas in the study area fall into the coordinated enhancement category, around 29.76% into the coordinated transition category, and close to 19.95% are categorized as dysfunctional decline. Regarding internal development, approximately 54.50% of areas in the study area exhibit a harmonious progression of ecological system services and their impact on human settlement well-being, around 37.17% show a lag in human settlement well-being compared to ecological system services, and close to 8.34% fall behind in ecological system services relative to human settlement well-being. To summarize, the interplay is generally mild and moderate, exhibiting a rough correlation. There was a notable trend of minimal dysfunctional assimilation in the ecological system service-human settlement well-being interaction, with the coupling coordination stage's distribution aligning closely with the degree of well-being in human settlements' spatial pattern. This suggests that the spatial nature of the coupling relationship was primarily influenced by the strictness of the human settlement's well-being level,

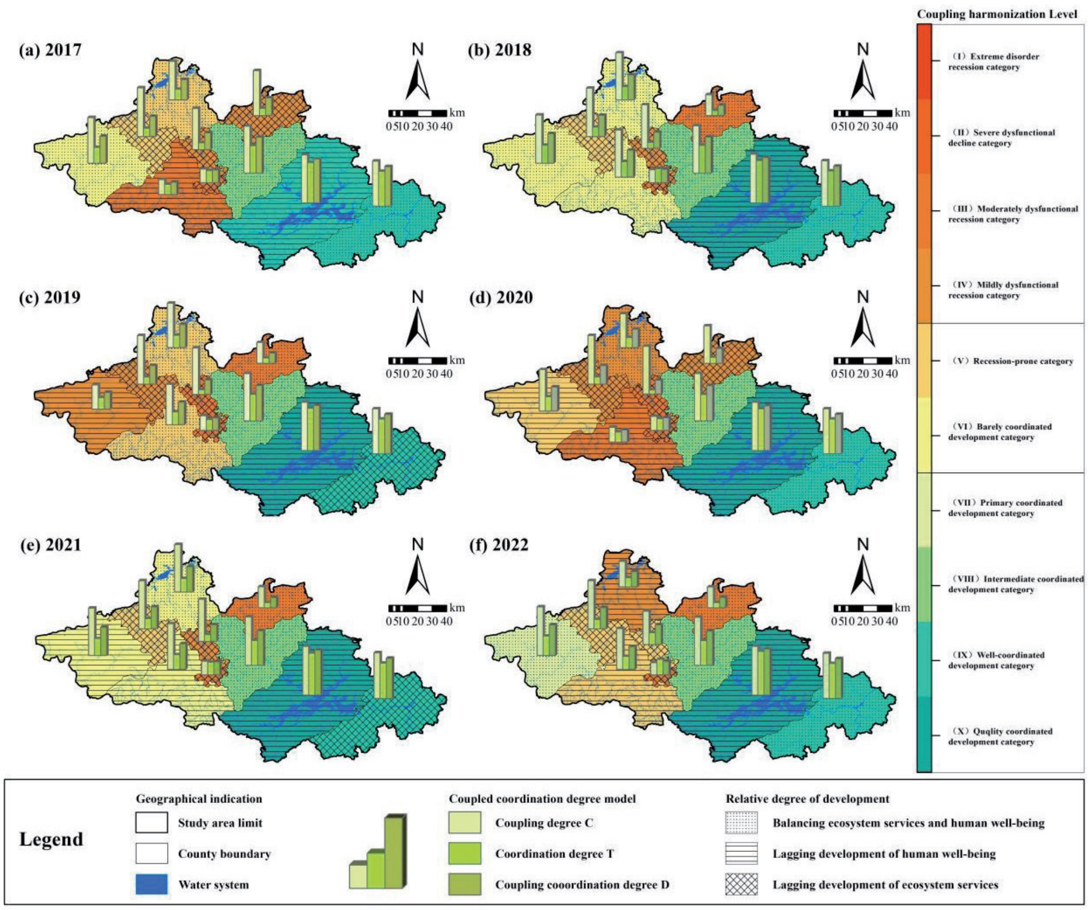

Fig. 5. Spatial and temporal distribution of coupled coordination of ecological system services and human settlement well-being during 2017-2022.

whereas ecological system services served as adaptable facilitators or restrictors.

Discussion

The impact of ecological system services on human settlement well-being has been a subject of global research for an extended period. This research delves into the interlinked dynamics between ecological system services and their impact on human settlement well-being within an inter-provincial area, viewed from a meso-level angle. This area merges urban and rural settings, embracing natural ecological systems as well as human-social systems. Unlike earlier research, the study zone of this paper is distinguished by its unique geospatial components, particularly through the integration of remote sensing land use and satellite image data. This innovative approach lays the groundwork for upcoming studies on the intricate interconnection between humans and land in various provinces, urban-rural regions, and systems throughout China, providing valuable spatial and temporal insights into the complex interplay between ecological processes, land use patterns, and human activities.

This research amalgamates both subjective and objective methods of empowerment, along with the integration of coordination levels and various methodological models, to methodically and visually examine the evolution of ecological system services and the interplay between humans and land, considering the ecological impact of changes in land use, the significance of ecological system services, and human settlement well-being. Remote sensing technology plays a pivotal role in this investigation, allowing for the monitoring and mapping of land cover changes, vegetation health, water quality, and other critical ecological parameters. The application of land use data, derived from satellite imagery and ground surveys, enables the identification of distinct land use types, their spatial distribution, and their shifts over time, which directly influence the provision of ecosystem services and human well-being.

An analysis was conducted on the pros and cons of varying levels of ecological system services and their impact on human settlement well-being across diverse areas, utilizing satellite-based data and advanced image processing techniques to assess the spatial patterns and temporal trends of these effects. Significant disparities exist in the levels of well-being and environmental conditions among individuals residing in economically underdeveloped regions compared to those in more developed areas. Studies and examinations of the interaction between humans and land in both city and countryside settings, supported by high-resolution satellite imagery and sophisticated remote sensing analyses, can offer invaluable insights for local governments to enhance the well-being and environment of the community. Additionally, the report sheds light on various ongoing environmental and societal issues in the research area, as revealed by the integrated analysis of remote sensing, land use, and satellite data.

The results of the study offer valuable perspectives and backing for ecological administration across provincial boundaries and the blending of urban and rural sectors, highlighting the critical role of employing sophisticated technological instruments to guide decision-making processes. Ultimately, utilizing GIS spatial visualization technologies, an analysis comparing the impact of ecological system services on human settlement well-being across different areas was conducted to delve deeper into the spatial and temporal patterns of these effects. The research area's human-land coordinated development was segmented into various regional categories, derived from the distribution samples and informed by the wealth of remotely sensed, land use, and satellite image data, thereby aiding policymakers and researchers in enhancing local human-land coordinated development. This comprehensive, data-driven approach serves as a scientific guide for upcoming governance and ecological compensation strategies in urban-rural integration areas, ensuring that decisions are grounded in accurate, up-to-date information on the state of the environment and its relationship with human settlements.

While acknowledging the significant contributions of this research, it is important to recognize the numerous issues and limitations present in the study. Many of the assessment indicators are not currently included in this study's comprehensive human settlement well-being indicator system for the Xin'an River Basin, partly due to the complexities involved in integrating and harmonizing remote sensing, land use, and satellite image data across diverse regions. There are some differences in the development and collection of indicators, both in terms of statistical indicators and statistical units across regions. This means that in some regions, the indicators in question either do not have relevant data or the data are unauthorized and unavailable, etc. An assessment indicator can only be included in the evaluation system if it is ensured that data are available for any indicator in any region. During this process, the evaluation indicators were repeatedly reviewed, and some of them were eventually deleted due to data unavailability or inconsistency. As a result, the final appraisal indicator system of this study, while leveraging the power of remote sensing, land use, and satellite imagery, may not provide a fully comprehensive and accurate overview and description of local ecological system services related to human settlement well-being. The primary limitation of this research lies in the challenges associated with data availability, consistency, and integration across diverse geographical contexts, which can affect the representativeness and robustness of the findings. In spite of its constraints, the research marks notable progress in applying advanced remote sensing and land use information to enhance our understanding and management of the intricate linkage between ecosystem services and the quality of human habitats within and across different provinces.

Conclusions

The research mainly reveals four points. Initially, the value of ecological system services between 2017 and 2022 is approximately divided into two stages: a period of equilibrium and a minor decrease. The total value of its ecological system services dropped from 168.214×10^8 yuan in 2017 to 144.427×10^8 yuan in 2022. Ecological system service levels typically exhibit a distribution trend of being "elevated near and diminished centrally." Regulatory and cultural service levels typically exhibit a geographical pattern of being "elevated in the southeast and reduced in the northwest". Typically, support and supply services manifest a spatial configuration marked by elevated levels on the periphery and reduced levels centrally.

Additionally, the extensive state between 2017 and 2022 was segmented into three phases of: deterioration, variation, and gradual improvement. Human settlement well-being's aggregate measure fell from 0.572 in 2017 to 0.458 in 2022, marking a reduction of 19.93%. The geographical spread of human settlement well-being is characterized as "elevated in the southeast and diminished in the northwest". Jiande City, Shexian County, and Chun'an County stand out for their superior human settlement well-being standards, particularly Jiande City. The Xin'an River Basin's areas of Yixian, Qimen, Huangshan, Tunxi, Huizhou, Xiuning, and Jixi counties exhibit the lowest rates of human settlement well-being, with Jixi County ranking as the poorest. Between 2017 and 2019, there was a noticeable pattern of "hot expansion and cold contraction" in human settlement well-being, with the cold spot region likely to grow from 2019 to 2022.

Over time, the interplay exhibited fluctuating wave patterns from 2017 to 2022. In 2020, the lowest level of coordinated coupling was observed, and the overall rank fell into the borderline dysfunctional decline category. The coupled coordination level was the highest in 2018, and the overall classification was barely coordinated development class. Among them, Chun'an County falls under the category of high-quality coordinated development, yet the advancement of human settlement well-being in this region is lagging behind. In terms of regional differences, the coupled coordination level of ecological system service-human settlement well-being in the Zhejiang province domain is higher than that in the Anhui province domain, which approximates the dynamic change characteristics of the human settlement well-being level index. From 2017 to 2022, there was a noticeable shift in the spatial arrangement of ecological system service-human settlement well-being, moving from a more synchronized uplift, less synchronized transition, and more impaired decline to a more unified uplift, less synchronized transition, and less impaired decline. The overall pattern of these effects from 2017 to 2022 revealed a distribution of "superior in the southeast, subpar in the middle, and favorable in the northwest". The interplay between ecological system services and human settlement well-being is generally mild and moderate, exhibiting a correlation akin to abrasion. The general trend of linking ecological system services with human settlement well-being indicates a notable trend of minimal dysfunctional assimilation, with the spatial nature of this coupling primarily influenced by the inflexibility of human settlement well-being and the adaptability of ecological system services.

Conflict of Interest

The authors declare no conflict of interest.

References

1. BEETON R.J., LYNCH A.J.J. Most of nature: A framework to resolve the twin dilemmas of the decline of nature and rural communities. Environmental Science & Policy, **23** (12), 45, **2012**.
2. TAN L., YANG G. Market-oriented Watershed Payment for Ecosystem Services: Progress and Future Perspectives. Scientia Geographica Sinica, **42** (7), 1218, **2022**.
3. Proceedings of the 3rd 2017 International Conference on Sustainable Development (ICSD 2017). Available online: http://creativecommons.org/licenses/by-nc/4.0/ (accessed on 11 March 2024).
4. WU J. Landscape sustainability science: ecosystem services and human well-being in changing landscapes. Landscape ecology, **28** (4), 999, **2013**.
5. WANG D., ZHENG H. Ecosystem services supply and consumption and their relationships with human well-being. Chinese Journal of Applied Ecology, **24** (6), 1747, **2013**.
6. COSTANZA R., D'ARGE R. The value of the world's ecosystem services and natural capital. Nature, **387** (6630), 253, **1997**.
7. ZHENG H., LI Y. Progress and perspectives of ecosystem services management. Acta Ecologica Sinica, **33** (3), 702, **2013**.
8. YING L., KONG L. The research progress and prospect of ecological security and its assessing approaches. Acta Ecologica Sinica, **42** (5), 1679, **2022**.
9. WANG D., LI Y. Ecosystem services' spatial characteristics and their relationships with residents' well-being in Miyun Reservoir watershed. Acta Ecologica Sinica, **34** (1), 70, **2014**.
10. XIE G., YAN L. Expert knowledgebased valuation method of ecosystem services in China. Journal of Natural Resources, **23** (5), 911, **2008**.
11. ZHOU L., SU X. Simulation of the coupling relationships between ecosystem services and human well-being in Chongqing. China Environmental Science, **43** (5), 2560, **2023**.
12. LIU J., DIETZ T. Complexity of coupled human and natural systems. Science, **317** (5844), 1513, **2007**.
13. HUANG G., JIANG Y. Advances in human well-being research: a sustainability science perspective. Acta Ecologica Sinica, **36** (23), 7519, **2016**.
14. NELSON E.J., KAREIVA P. Climate change's impact on key ecosystem services and the human well-being they support in the US. Frontiers in Ecology and the Environment, **11** (9), 483, **2013**.
15. TAN X., WU G. Progress in time use research in the framework of well-being. Economic Perspectives, **55** (7), 151, **2014**.
16. WANG B., TANG H. Human Well-Being and Its Applications and Prospects in Ecology. Journal of Ecology and Rural Environment, **32** (5), 697, **2016**.
17. REN Y., LONG Y. Impact of Watershed Eco-compensation Policy on Water Pollution Intensity in the Compensated Area: A Case Study of the Xin'an River Basin. Economic Geography, **43** (11), 181, **2023**.
18. COSTANZA R., DE GROOT R. The value of the world# s ecosystem services and natural capital. Ecological economics, **25** (1), 3, **1998**.
19. XIE G., LU C. Ecological assets valuation of the Tibetan Plateau. Journal of Natural Resources, **18** (2), 189, **2003**.
20. YANG H., DIETZ T. Changes in human well-being and rural livelihoods under natural disasters. Ecological Economics, **151** (9), 184, **2018**.
21. ORTEGA M.M., RUBIERA M.F., PÉREZ G.B. Ranking residential locations based on neighborhood sustainability and family profile. International Journal of Sustainable Development & World Ecology, **28** (1), 49, **2021**.
22. ZHANG Q., KONG Q., ZHANG M. New-type urbanization and ecological well-being performance: A coupling coordination analysis in the middle reaches of the Yangtze River urban agglomerations, China. Ecological Indicators, **159** (2), 111678, **2024**.
23. WANG M., SU M.M., GAN C. A coordination analysis on tourism development and resident well-being in the Yangtze River Delta Urban Agglomeration, China. Journal of Cleaner Production, **421** (10), 138361, **2023**.