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ASSESSING LANDSCAPE SUSTAINABILITY BY COUPLING ECOSYSTEM SERVICE SUPPLY-DEMAND AND ES-SDG LINKAGES: A CASE STUDY OF YIXING CITY IN THE TAIHU LAKE BASIN

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Abstract: Understanding the coupling relationship between ecosystem service (ES) supply-demand matching and Sustainable Development Goals (SDGs) is crucial for achieving landscape sustainability in rapidly urbanizing regions. This study focuses on Yixing City, a typical urbanizing area within the Taihu Lake Basin, and constructs a "Landscape Sustainability Assessment Framework Coupling ES Supply-Demand and ES-SDG Linkages". Using the InVEST model and socioeconomic data, we quantified the supply-demand levels of five key ESs, evaluated SDG attainment across Yixing's townships based on ES-SDG linkages, and comprehensively characterized their landscape sustainability (LS). Key findings include: (1) Significant spatial variability in ES supply-demand balances across townships, with carbon sequestration showing the most pronounced imbalance; (2) SDG 8 (Economic Growth) consistently outperformed other SDGs, while SDG 7 (Clean Energy), SDG 9 (Industry, Innovation, and Infrastructure), and SDG 11 (Sustainable Cities) exhibited lower attainment levels; (3) Among the 18 townships, 12 displayed improving trends in landscape sustainability. Xinzhuang achieved the highest sustainability, whereas Yicheng and Qiting ranked lowest; (4) Targeted strategies—such as ecological restoration tailored to local ES deficits, enhancing critical ES supplies, and prioritizing key SDGs—are needed to improve regional landscape sustainability.
Keywords: Ecosystem service supply and demand; ES-SDG linkages; Landscape sustainability; Taihu lake basin

1 INTRODUCTION

Landscape sustainability science emphasizes harmonizing human well-being and ecological conservation by optimizing the supply-demand relationships of ecosystem services (ES) [1]. Rapid urbanization worldwide has caused severe mismatches between ES supply and demand, posing significant challenges to achieving the United Nations Sustainable Development Goals (SDGs) [2]. The Taihu Lake Basin, a highly urbanized region in eastern China, faces challenges such as water scarcity, water pollution, and shrinking ecological space [3]. Yixing City, located in the upper reaches of Taihu Lake, serves dual roles as an ecological barrier and an economically developed area, experiencing conflicting pressures. Its ES supply-demand dynamics critically influence the basin's ecological security [4].

Matching ES supply and demand is central to sustainable landscape management [5]. For instance, carbon sequestration services are directly linked to SDG 13 (Climate Action), while water purification services support SDG 6 (Clean Water and Sanitation). However, ES supply is typically determined by natural systems, whereas demand is driven by socioeconomic factors, and their spatial mismatches may trigger ecological risks [6]. Although many studies have quantified ES supply [7], few have systematically integrated demand-side analysis, resulting in an incomplete understanding of landscape sustainability. Moreover, existing research often focuses on single-ES assessments, lacking comprehensive analyses that couple supply-demand dynamics with SDG linkages [8]. Additionally, current ES-SDG studies predominantly adopt static linkage frameworks, failing to account for regional heterogeneity [9]. There is an urgent need for spatially explicit methods that can identify priority areas for landscape interventions based on ES mismatches and their impacts on SDGs.

To address these gaps, this study proposes a "Landscape Sustainability Assessment Framework Coupling ES Supply-Demand and ES-SDG Linkages", using Yixing City as a case study. The objectives are: (1) to quantify the spatiotemporal patterns of supply and demand for five key ES (e.g., carbon sequestration, water yield) using the InVEST model and socioeconomic data; (2) to assess regional SDG attainment and integrated landscape sustainability using a modified version of the ES-SDG linkage framework proposed by Wood et al.; (3) to propose landscape optimization strategies for enhancing sustainability. Our study contributes to the field in three ways: (1) We develop a novel assessment framework that captures the dynamic interplay between ecological capacity and human development needs. (2) The study provides spatially explicit guidance for landscape planning while addressing multiple sustainability goals. (3) It offers a replicable methodology for rapidly urbanizing regions facing ecosystem degradation challenges. Furthermore, this research supports decision-making for ecological management in the Taihu Lake Basin and advances the regional application of ES-SDG linkage studies.

2 MATERIALS AND METHODS

2.1 A landscape Sustainability Assessment Framework based on the ES-SDG Linkages

After reviewing the linkages between ecosystem services and SDGs, this study selected five key ecosystem services for the study area: Carbon sequestration (SC) , Food production (FP), Nature-based recreation (NbR), Water provision (WP), and Water purification (Wpu). The supply-demand levels and supply-demand ratios of these five services were calculated separately. Based on the ES-SDG linkages, the attainment levels of 15 Sustainable Development Goals were then quantified. Finally, the integrated level of these 15 SDGs was used to characterize the regional landscape sustainability (LS) (Figure 1).

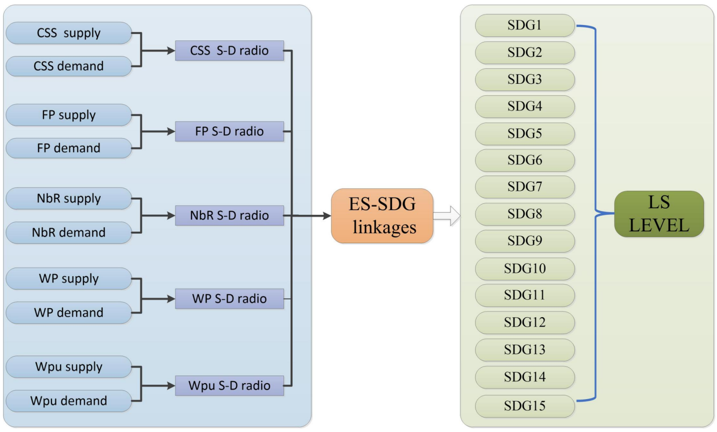

Figure 1 A Landscape Sustainability Assessment Framework based on the ES-SDG Linkages

2.2 Study Area and Data Source

This study selected Yixing City, a typical area in the Taihu Lake Basin, as the research region (Figure 2). Located on the western shore of Taihu Lake, Yixing serves as an important ecological barrier and water conservation area for the basin, with its water system directly influencing the environmental safety of Taihu Lake [10]. In recent years, rapid economic development in the Taihu Lake Basin has intensified land use changes and exacerbated ecological pressures, presenting new challenges to regional ecosystem service supply-demand relationships and landscape sustainability. Considering Yixing's socio-ecological conditions and ecological functional importance, this study selected five key ecosystem services to analyze regional landscape sustainability: carbon sequestration, food production, recreation, water yield, and water purification.

The data used in this study primarily include five categories: (1) Land use and population distribution data were obtained from the Resource and Environment Science and Data Center, Chinese Academy of Sciences (http://www.resdc.cn); (2) DEM and soil data were acquired from the Geospatial Data Cloud (www.gscloud.cn) and Harmonized World Soil Database (HWSD), respectively; (3) Precipitation and evapotranspiration data came from the China Meteorological Data Service Center's "Annual Dataset of Chinese Surface Climate Data" (http://data.cma.cn/); (4) Per capita carbon emission data were sourced from the China Emission Accounts and Datasets; (5) Per capita water consumption, per capita food consumption, and population data were obtained from the Jiangsu Statistical Yearbook.

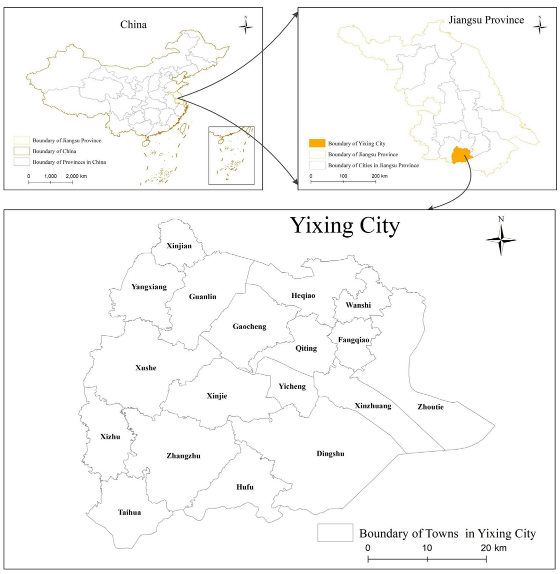

Figure 2 Study Area

2.3 Landscape Sustainability Assessment

2.3.1 Carbon sequestration service

(1) supply

$$S_{cs} = 1.63 \times NPP \tag{1}$$

S_{cs} represents the carbon sequestration service supply per grid, and NPP represents the net primary productivity of vegetation per grid. The carbon sequestration service supply at grid scale was summarized to obtain the carbon sequestration service supply in each study area.

(2) demand

$$D_{cs} = C_{PER} \times POP \tag{2}$$

Demand for carbon sequestration services is represented by actual carbon emissions. According to the product of the per capita carbon Emission of each city and the population of the assessment unit, the per capita carbon emission data of districts and counties were obtained from the China Emission Accounts and Datasets. C_{PER} represents per capita carbon emissions， POP represents the current resident population of the assessed area.

2.3.2 Food provision

(1) supply

Per unit area method and GAEZ (Global Agro-Ecological Zones) model were used to spatial assign the grain yields grain production statistical data [11, 12].

(2) demand

$$D_{fp} = D_{average} \times POP \tag{3}$$

The demand for food production services is calculated based on the per capita grain consumption in Jiangsu Province (2000,2010,2020).

2.3.3 Nature-based recreation

(1) supply

$$A_i = \frac{S_i}{P_i} \tag{4}$$

$$NR_{Si} = \left(\sum_{k=1}^{k} A_i\right) \times POP_i \tag{5}$$

Nature-based recreation service refers to the total area of ecological land such as forestland, grassland, water body and wetland that can provide leisure and recreation services. 5 km is set as the accessible radius of ecological land for people to enjoy. It is assumed that the ecological land within a grid can provide leisure and recreation services for all people within the accessible radius, and the residents within the grid can enjoy all the ecological land within the accessible radius [13, 14] . S_i is the ecological land area in grid I, is the total population within the reachable radius corresponding to grid i, A_i is the per capita usable area of ecological land in grid i, represents the supply of leisure and recreation services in grid i, j represents all grids within the corresponding buffer radius of grid i， POP_i indicates the total number of people in the i grid.

(2) demand

$$D_{NR} = B_{per} \times POP \tag{6}$$

The demand for Nature-based recreation service can be calculated by the product of per capita green space demand and population. D_{GR} represents the total demand for green space entertainment and leisure services of residents in the evaluation area， B_{per} represents the per capita green space demand area of residents, POP represents the number of populations in the area. According to [14] ， B_{per} was set to 60m^2.

2.3.4 Water provision

(1) supply

$$WY_{xj} = \left(1 - \frac{AET_{xj}}{P_{xj}}\right) \times P_x \tag{7}$$

Based on the water production module of the InVEST model, the water production of a grid cell is the difference between rainfall and actual evaporation based on the principle of water balance. The water yield of each study area is obtained by summarizing the calculation results of grid scale water yield.

(2) demand

$$WY_D = D_{per} \times POP \tag{8}$$

The demand for water supply services is determined based on the product of per capita comprehensive water consumption (including agricultural water, industrial water and domestic water) and the current resident population of the assessed area. The data of per capita comprehensive water consumption is derived from the Water Resources Bulletin of Jiangsu Province. WY_D represents the regional water supply service demand, D_{per} represents the comprehensive water consumption per capita of the assessment area in the current year， POP represents the permanent population of the assessment area in the current year.

2.3.5 Water purification

(1) supply

$$S_{WP} = efficiency_n \tag{9}$$

The potential supply of water purification services refers to the maximum retention efficiency of each LULC class in the landscape.

(2) demand

$$D_{PW} = \begin{cases} 0, if\ AVL_{load} \le Exp_{allow} \\ \frac{AVL_{load} - Exp_{allow}}{AVL_{load}} \times 100\%, if\ AVL_{load} > Exp_{allow} \end{cases} \tag{10}$$

$$Exp_{allow} = \sum Y_x \times \rho \tag{11}$$

Water purification service demand(WP_D) is the amount of nitrogen that should be retained and intercepted before entering the water body in order to maintain surface water quality standards.。 Referring to the water quality standard. The is measured by comparing the total nitrogen load (AVL_{load}) with its allowable nitrogen output .$\sum Y_x$ represents the total regional water production, ρ value is set to 1 g/m^3, in line with China's national water quality standards.

2.3.6 Level of ecosystem service supply and demand

To account for significant variations in supply-demand ratios across different ecosystem services and ensure equitable consideration of their supply-demand levels, we classified the ecosystem service supply-demand ratio results into six categories (Table 1). Levels 1-4 were divided using equal intervals, while Level 5 (80%-120%) indicates a relatively balanced supply-demand state for the specific ecosystem service. Level 6 (>120%) represents cases where the ecosystem service supply substantially exceeds local demand.

Table 1 Classification of the Ratio between Supply and Demand of Various Ecosystem Services

LEVEL	1	2	3	4	5	6
S-D radio	＜20%	20%-40%	40%-60%	60%-80%	80%-120%	＞120%

2.3.7 Landscape sustainability assessment based on ES-SDG linkages

① First, based on the assessed supply-demand values of various ecosystem services and the ES-SDG linkages, we calculated the attainment levels of individual SDG targets (Figure 3). Different ecosystem services contribute to distinct SDG targets with varying degrees of relevance. Drawing upon studies [8, 15, 16] and considering the five selected ecosystem services in this research, we established the strength of connections between ecosystem services and SDG targets to quantify each SDG's contribution to landscape sustainability.

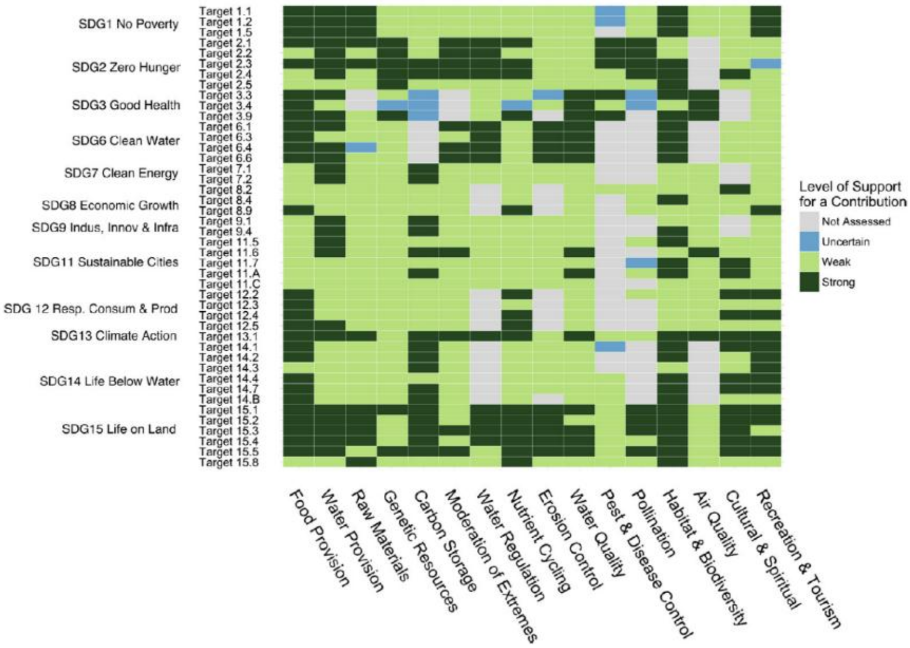

Figure 3 ES-SDG Linkages[8]

② Subsequently, the regional landscape sustainability level was characterized by averaging the attainment levels of all SDG targets. The formula is as follows:

$$LS_{average} = \sum_{i=1}^{n} Level_{SDG_i} / n \tag{12}$$

$LS_{average}$ represents the composite landscape sustainability level, $Level_{SDG_i}$ denotes the attainment level of SDGi*i* , *n* indicates the number of SDGs assessed (here, 15).

3 RESEARCH RESULTS

3.1 Temporal and Spatial Dynamics of Ecosystem Service Supply and Demand

3.1.1 Spatio-temporal dynamics of carbon sequestration service supply and demand

Temporally (Table 2), from 2000 to 2020, the overall carbon sequestration service supply in Yixing City fell far short of local demand, showing a significant decline in the supply-demand ratio from 27.24% to 9.13%. Specifically, carbon storage supply initially decreased slightly before rebounding, while demand for carbon sequestration surged dramatically, leading to a marked deterioration in the supply-demand balance.

Spatially (Figure 4), townships in northeastern Yixing generally exhibited lower carbon sequestration supply-demand levels compared to those in the southwest. All townships experienced substantial declines in carbon sequestration service balance: western and northwestern townships dropped from Level 2 to Level 1, three eastern townships declined from Level 3 to Level 1, while Taihua and Hufu decreased from Level 4 to Level 2. Notably, Qiting, Yicheng, and Dingshu maintained persistently low Level 1 balances throughout the study period.

3.1.2 Spatio-temporal dynamics of Food provision supply and demand

Temporal analysis (Table 2) reveals that from 2000 to 2020, Yixing City's overall food production service supply generally met local demand, with an improving supply-demand ratio that increased from 134% to 246.38% in 2010 before declining to 215.90% in 2020. The food production supply initially showed significant growth followed by a slight decrease, while demand notably dropped in 2010 - primarily due to changes in residents' dietary structure leading to reduced staple food consumption. By 2020, food production demand had increased compared to 2010 levels.

Spatially (Figure 4), central and southern townships exhibited relatively lower but improving food production supply-demand levels. For instance, Yicheng improved from Level 2 to Level 3, while Xinjie and Dingshu advanced from Levels 5 and 4 respectively to Level 6. Most other townships maintained high food production balances, consistently remaining at Levels 5 or 6 throughout the study period.

3.1.3 Spatio-temporal dynamics of Nature-based recreation supply and demand

Temporally (Table 2), during 2000-2020, the supply of recreational services in Yixing City generally well exceeded local demand, showing a slight decline in supply-demand balance while remaining at relatively high levels. The supply of recreational services initially increased before decreasing, while demand continued to grow steadily.

Spatially (Figure 4), except for some townships in the northeastern and central areas, Yixing's recreational service supply-demand balance consistently maintained the highest classification level. Qiting showed a continuous decline from Level 4 to Level 2, Yicheng fluctuated between Levels 5 and 6, while Wanshi persistently remained at the relatively low Level 2 throughout the study period.

3.1.4 Spatio-temporal dynamics of Water provision supply and demand

Temporally (Table 2), from 2000 to 2020, the water yield service supply in Yixing City generally met local demand, with an overall improvement in the supply-demand balance over the two decades. The water yield supply showed a steady increase throughout the period, while demand initially rose before declining, resulting in lower demand in 2020 compared to 2000.

Spatially (Figure 4), most townships in Yixing exhibited improved water yield service supply-demand levels. The central townships of Yicheng and Qiting rose from Level 2 and Level 3 to Level 5 respectively, while all other townships achieved the highest classification level for water yield service balance.

3.1.5 Spatio-temporal dynamics of Water purification supply and demand

Temporally (Table 2), from 2000 to 2020, the supply-demand balance of water purification services in Yixing City showed gradual improvement, though supply still fell short of local demand. The supply-demand ratio increased from 68.24% in 2000 to 85.19% in 2020, with water purification supply steadily increasing while demand gradually decreased.

Spatially (Figure 4), townships in southwestern Yixing generally exhibited higher and improved water purification service supply-demand levels compared to central and northeastern areas, reaching Level 5 or Level 6. However, many central and northern townships remained at Level 4. Some southeastern townships showed improvement, such as Xinzhuang rising from Level 3 to Level 4, while Dingshu and Zhoutie advanced from Level 4 to Level 5, essentially achieving supply-demand balance.

Table 2 Supply and Demand Ratio of Various Ecosystem Services in Yixing City from 2000 to 2020

Year	CSS S-D radio	FP S-D radio	NbR S-D radio	WP S-D radio	Wpu S-D radio
2000	27.24%	134.00%	813.69%	121.74%	68.24%
2010	8.56%	246.38%	823.99%	128.13%	73.78%
2020	9.13%	215.90%	719.29%	226.81%	85.19%

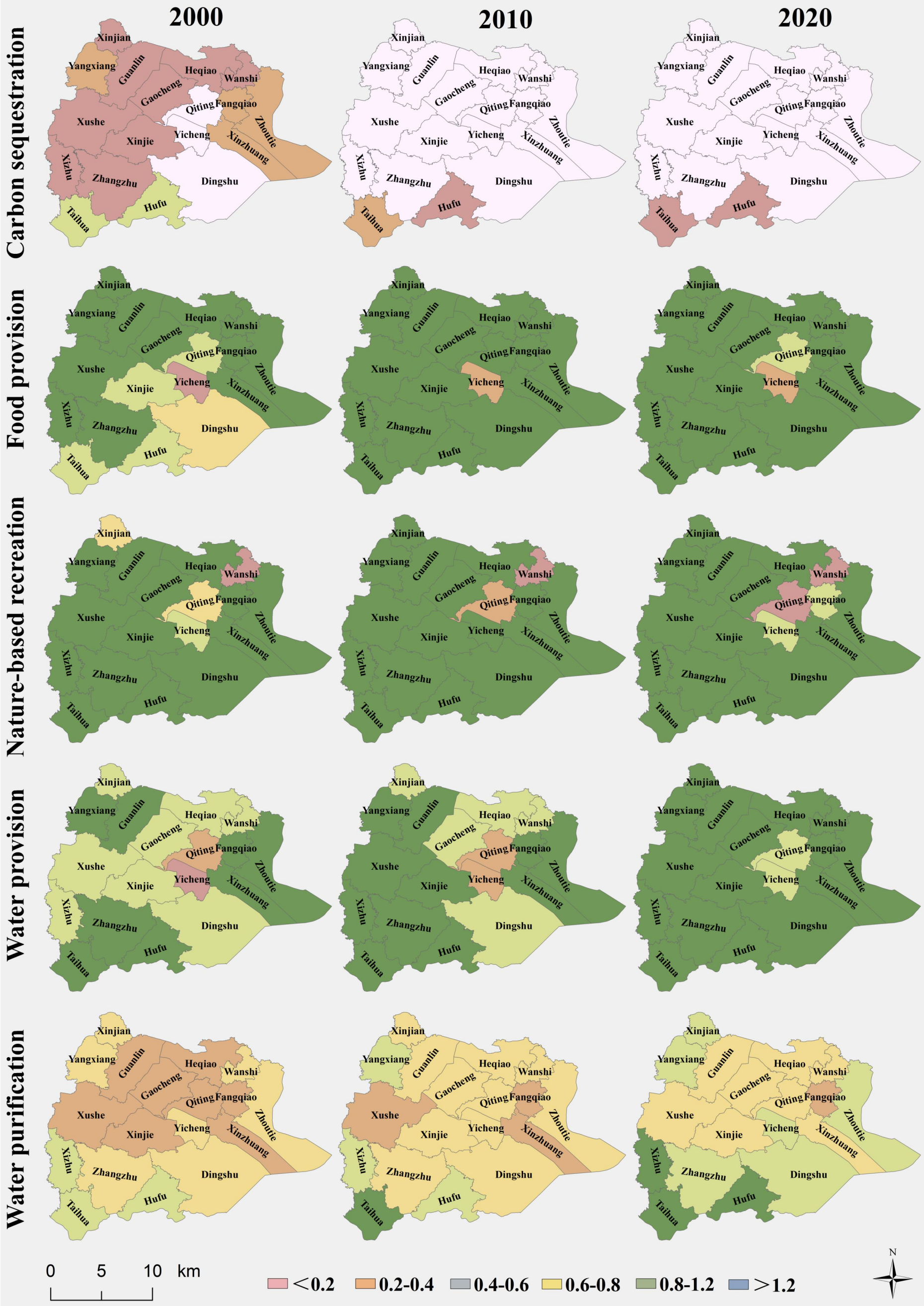

Figure 4 Spatial-Temporal Dynamics of Supply and Demand of 5 Types of Key Ecosystem Services in Yixing City from 2000 to 2020

3.2 Spatial and temporal dynamics of landscape sustainability

In 2000, Xinzhuang exhibited the highest overall SDG attainment level, followed by Zhoutie and Taihua, while Yicheng and Qiting showed the lowest overall SDG performance. Among all SDG targets, SDG 8 (Economic Growth) consistently ranked highest, with SDG 1 (No Poverty) and SDG 14 (Life Below Water) also appearing in the top three. Conversely, SDG 11 (Sustainable Cities) and SDG 9 (Industry, Innovation and Infrastructure) demonstrated relatively lower attainment levels (Figure 5).

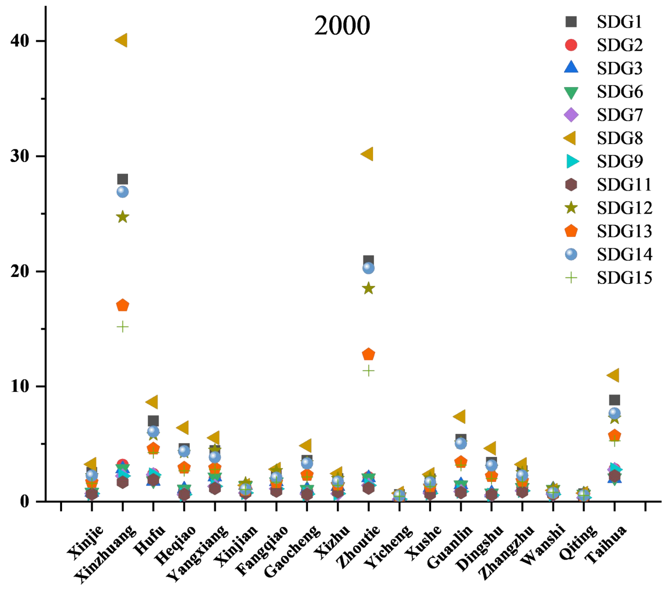

Figure 5 Level of Each SDG in Each Township of Yixing City in 2000

By 2010, Xinzhuang maintained its leading position in SDG performance, with Zhoutie and Taihua remaining second and third respectively, while Yicheng and Qiting continued to rank lowest. SDG 8 still outperformed all other goals, followed by SDG 1, SDG 12 (Responsible Consumption and Production), and SDG 14. The lowest-performing SDGs were SDG 11, SDG 9, and SDG 7 (Affordable and Clean Energy) (Figure 6).

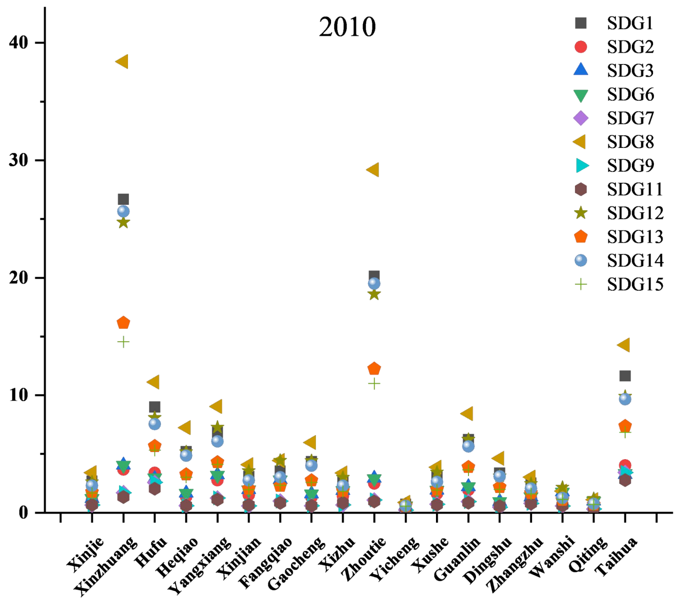

Figure 6 Level of each SDG in Each Township of Yixing City in 2010

In 2020, the top three townships for SDG attainment remained unchanged (Xinzhuang, Zhoutie, and Taihua), with Yicheng and Qiting persistently ranking last. SDG 8 maintained its dominant position, succeeded by SDG 1 and SDG 12, while SDG 11, SDG 9 and SDG 7 consistently showed the poorest performance throughout the study period (Figure 7).

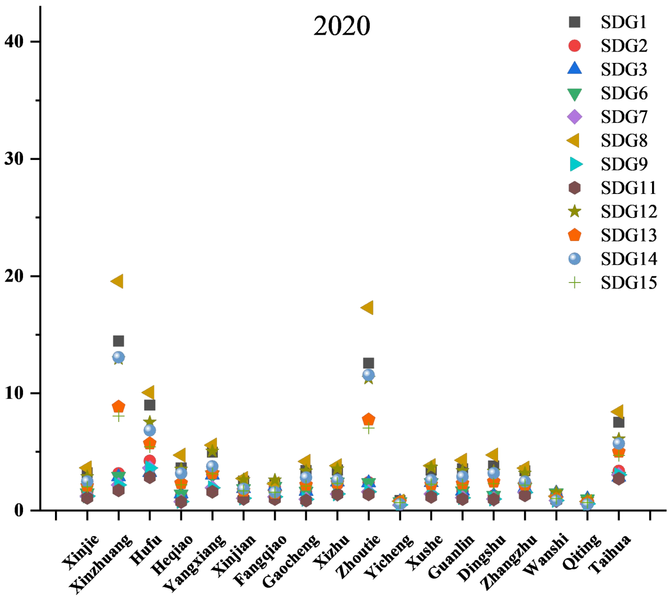

Figure 7 Level of each SDG in Each Township of Yixing City in 2020

Comprehensive assessment of regional landscape sustainability across SDG targets reveals: As shown in Figure 8, Xinzhuang exhibited the highest landscape sustainability level among all townships, followed by Zhoutie and Taihua, though Hufu surpassed Taihua by 2020. The lowest sustainability levels were consistently observed in Yicheng and Qiting.

Among the 18 townships, 12 demonstrated improving trends in landscape sustainability. Notably, Xushe and Xizhu showed remarkable increases of 78.74% and 73.97%, respectively, while Xinjian improved by over 50%. Conversely, 6 townships experienced declines, with Xinzhuang registering the largest reduction (-44.92%), followed by Zhoutie and Guanlin (both exceeding -20%).

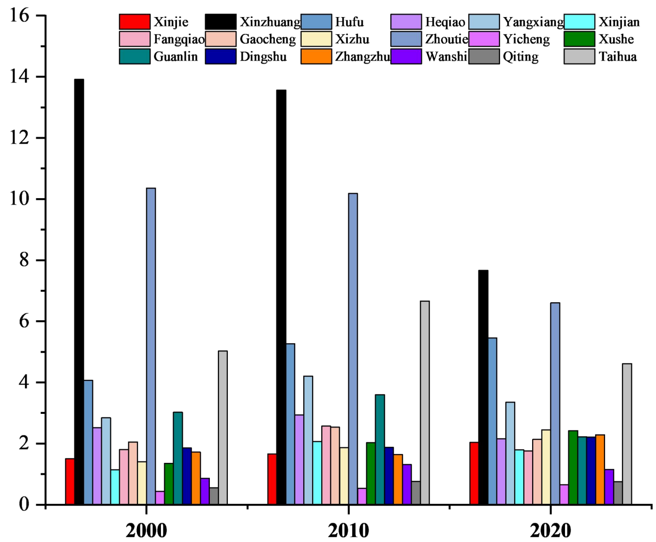

Figure 8 Landscape Sustainability Level of Each Township in Yixing City from 2000 to 2020

4 DISCUSSION AND CONCLUSIONS

4.1 Contributions and Limitations

This study is the first to integrate ecosystem service supply-demand with SDG targets to assess regional landscape sustainability, highlighting the critical role of ecosystem services in supporting sustainable development goals and enhancing regional landscape sustainability. Many sustainable development goals are fundamentally based on the benefits that ecosystem services provide to humans [17, 18]. However, some limitations remain for future research. For example, the ES-SDG linkages were derived from previous studies, but these relationships may vary across regions, necessitating localized ES-SDG assessments in future work. Additionally, using the average of SDG targets to represent regional landscape sustainability overlooks differences in the importance of individual SDGs [15, 19]. Future studies should incorporate varying SDG priorities to better characterize landscape sustainability.

4.2 Conclusions and Policy Recommendations

(1) Regarding ecosystem service supply-demand, food production, recreation, and water yield services in Yixing generally met local demand, while water purification still fell short of balance, and carbon sequestration supply lagged far behind demand. Supply-demand performance varied significantly across townships and over time.
(2) Among SDG targets, SDG 8 (Economic Growth) consistently ranked highest, followed by SDG 1 (No Poverty), SDG 12 (Responsible Consumption and Production), and SDG 14 (Life Below Water). SDG 7 (Affordable and Clean Energy) remained the lowest, while SDG 11 (Sustainable Cities) and SDG 9 (Industry, Innovation and Infrastructure) also performed poorly.
(3) Xinzhuang exhibited the highest landscape sustainability, followed by Zhoutie, Taihua, and Hufu. Yicheng and Qiting ranked lowest. Twelve of the 18 townships showed improving trends, with Xushe and Xizhu demonstrating the greatest gains, while Xinzhuang experienced the largest decline.
(4) To enhance regional landscape sustainability, targeted ecological conservation and restoration measures should address areas with low ecosystem service supply-demand balances. Simultaneously, differentiated SDG priorities must be addressed—particularly improving underperforming SDGs (e.g., SDG 7, 9, 11) and focusing on lagging regions—to achieve comprehensive sustainable development.

COMPETING INTERESTS

The authors have no relevant financial or non-financial interests to disclose.

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