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Dynamic Succession of Ecosystem Services in Rural Areas: Trade-offs, Synergies, and Driving Mechanisms

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ABSTRACT

The intensification of urbanization has exacerbated the conflict between the stability of rural ecosystems and economic development. Understanding the dynamic succession of ecosystem services (ESs) in rural areas is essential for achieving regional ecological sustainability. This study assessed seven ESs in the rural areas of Hangzhou from 2000 to 2020, analyzing their spatiotemporal evolution characteristics, dynamic changes in trade-offs/synergies, and driving mechanisms. The results showed that: (1) ESs exhibited a spatial distribution pattern characterized by “high in the southwest and low in the northeast.” Soil conservation and cultural services showed an overall upward trend, water yield and water purification first increased and then declined, while carbon storage, habitat quality, and food production declined continuously. (2) Among the 21 ES pairs, eight exhibited significant correlations, with notable changes observed in pairs related to food production, cultural services, and habitat quality. (3) Among the prominent trade-off/synergy pairs, socio-economic factors were identified as the dominant drivers of changes in ES trade-offs/synergies in Hangzhou‘s rural areas.

KEYWORDS

Ecosystem services; Rural areas; Trade-offs/synergies; Driving mechanisms.

1. INTRODUCTION

Ecosystem services (ESs) refer to the environmental conditions and benefits derived from ecological structures, functions, and processes that sustain human survival[1]. These services are categorized into four broad types: provisioning services, regulating services, supporting services, and cultural services[2]. During their formation and evolution, ESs are shaped by natural, socio-economic, and anthropogenic factors[3]. ESs exist both independently and interactively, and such interactions manifest as trade-offs or synergies[4]. Trade-offs refer to conflicts between services, where one service increases at the expense of another, while synergies denote mutually beneficial relationships in which services increase or decrease simultaneously[5]. In recent years, intensified human activities have accelerated the degradation of ecosystem service functions, with approximately 60% of global ESs currently in decline[2]. Urban development has weakened the natural support systems upon which rural areas depend for survival and development, thereby restricting their long-term sustainability. Therefore, research on ecosystem services in rural areas is of critical importance.

In recent years, ecosystem services and their trade-offs/synergies have become a focal point in ecology and related fields, with an increasing number of scholars focusing on the driving factors underlying ES trade-offs/synergies. Yuan[6] et al. employed the WAT model to evaluate ESs in karst regions and explore their driving mechanisms. Chen[7] et al. developed a Random Forest–PLS-SEM framework to reveal the drivers of ES interactions in urbanized areas of the Yellow River Basin.

However, existing studies have predominantly focused on major urban development zones, national parks, or ecological protection areas, often assessing single or only a few ESs[8]. Research specifically targeting rural areas remains limited; existing rural studies have mostly addressed spatial patterns of rural development, human settlements, or the coupling of single factors (such as land use, rural development levels, or farmer livelihoods) with ESs, with relatively few investigations into the complex dynamic changes among multiple ESs.

Accordingly, this study employed ArcGIS, R software, and the InVEST model to reveal the spatial distribution patterns and evolution trends of water yield (WY), carbon storage (CS), habitat quality (HQ), food production (FP), water purification (WP), soil conservation (SC), and cultural ecosystem services (CES) in Hangzhou rural areas from 2000 to 2020. Spearman correlation analysis and the optimal parameters-based geographical detector (OPGD) model were used to examine the trade-off/synergy evolution among different ESs and to further investigate the driving factors. The findings aim to provide a scientific basis and actionable policy recommendations for the ecological protection and sustainable development of rural Hangzhou.

2. STUDY AREA AND METHODS

2.1. Study Area

Hangzhou is located on the southeastern coast of China, in the northern part of Zhejiang Province (29°11‘–30°34’ N, 118°20‘–120°37’ E). It borders Huzhou and Jiaxing to the north, connects with Anhui Province via the Tianmu Mountains to the west, adjoins the Qiantang River to the south, and faces Hangzhou Bay to the east, situated in the southern part of the Yangtze River Delta. The topography is high in the northwest and low in the southeast, characterized by plains and hills. The rural areas of Hangzhou were delineated based on the Territorial Spatial Master Plan (2021–2035) of each district, excluding urban built-up areas (refer with: Fig. 1).

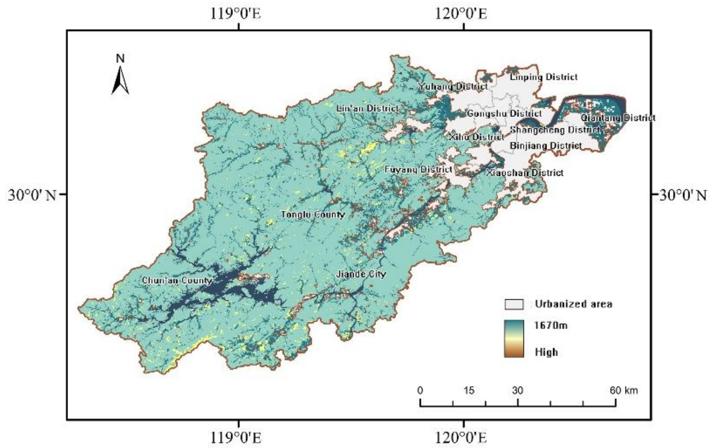


Figure 1. Scope of study area

2.2. Methods

The data used in this study included land use, administrative divisions, road networks, climate, soil, topography, vegetation, and points of interest (POI) data. All data sources were resampled to a uniform resolution of 250 × 250 m and projected using the WGS 1984 World Mercator coordinate system. The spatiotemporal distributions of ESs were calculated using the InVEST model and ArcGIS software.

Based on the seven ESs, Pearson correlation analysis was used to assess correlations among the services. The correlation coefficient r takes 0 as the threshold, where positive values (r > 0) indicate synergy and negative values (r < 0) indicate trade-off. The calculation formula is as follows[9]:

$$r = \frac{\sum x_m y_m (N-1)}{\sqrt{N\sum x_m^2 - (\sum x_m^2)^2}\sqrt{N\sum y_m^2 - (\sum y_m^2)^2}} \quad (1)$$

To further explore the influence of natural, socio-economic, and other driving factors on ES relationships, this study selected slope, elevation, temperature, precipitation, NDVI, population density, and gross domestic product (GDP). The “GD” package in R was used to select optimal parameter combinations, enabling interaction detection among driving factors and their impacts on ESs. The formula is as follows[10]:

$$q = 1 - \sum N_i \alpha_{2i} / N_i \alpha^2 \quad (2)$$

3. RESULTS

3.1. Spatiotemporal Distribution of Ecosystem Services

From 2000 to 2020, the ESs in Hangzhou’s rural areas exhibited significant spatiotemporal heterogeneity and dynamic changes (refer with: Fig. 2). Water yield (WY) showed a pattern of initial increase followed by a decrease. In 2000, high-value areas were mainly located in the southwest; they expanded significantly in 2010 and shifted to the western region by 2020. Over the 20-year period, total water yield increased by 857,964,000 tons, with a mean increase of 183 mm. Chun‘an County and Lin’an District remained the main high-value areas, attributable to their mountainous terrain, high vegetation coverage, and abundant rainfall.

Carbon storage (CS) was closely related to land use types, decreasing by 2,541.66 tons over the 20-year period. Areas with dense river networks exhibited relatively low carbon storage. Habitat quality (HQ) showed mean values of 0.596, 0.589, and 0.581, indicating a slight overall declining trend. Forests and grasslands performed well in maintaining habitat quality, with Chun’an County, Lin‘an City, and Jiande City exhibiting particularly high HQ values. Food production (FP) declined significantly. Although cropland accounted for approximately 16% of land use in Hangzhou, high-yield food production areas were mainly concentrated in Yuhang, Xiaoshan, and Fuyang Districts, highlighting the fragmentation of agricultural land and increasing production pressure amid urbanization.

Water purification (WP) showed a relatively random spatial distribution. High-value WP areas overlapped with food production areas, showing almost identical distribution patterns, while low-value areas were located in the central-southern region. Soil conservation (SC) exhibited a pattern of “low in the northeast and high in the southwest,” with high-value areas distributed at higher elevations. SC showed an overall increasing trend, closely related to the steep terrain and dense vegetation cover of the southwestern mountainous areas. Cultural ecosystem services (CES) showed mean annual values of 2.79, 2.74, and 3.04. High-value areas were concentrated in Xihu District and were strongly associated with road network density, reflecting the significant influence of cultural landscapes and infrastructure on CES provision, particularly in tourism-developed areas.

3.2. Trade-offs and Synergies Among Ecosystem Services

Over the 20-year period, 21 pairs of relationships were identified among the seven ESs, comprising 11 synergies and 10 trade-offs, with no mutual conversion between them. Eight pairs exhibited statistically significant correlations ($p < 0.05$) (refer with: Fig. 3). From a global perspective, significantly positive service pairs included HQ-CS, HQ-WY, FP-WP, and CES-CS. Among these, HQ-CS, HQ-WY, and FP-WP maintained long-term stable synergies, while synergy between CES and CS gradually declined. Among negative relationships, FP-CS and FP-HQ were relatively stable significant trade-offs, with trends gradually weakening over the years. In contrast, trade-offs between CES and WY and between CES and HQ intensified year by year, becoming significant trade-offs.From 2000 to 2010, strong synergies between HQ-CS and FP-WP both intensified, synergy between CES-CS decreased, strong trade-offs between FP-CS and FP-HQ weakened, and trade-offs between CES-WY and CES-HQ increased but remained non-significant. Changes in HQ-WY and other service pairs were not pronounced. From 2010 to 2020, HQ-CS synergy continued to increase, synergy between CES-CS decreased sharply, strong trade-offs between FP-CS and FP-HQ continued to decline, and trade-offs between CES-WY became significant. HQ-WY and FP-WP remained relatively unchanged, while trade-offs between WP-CS more than doubled.

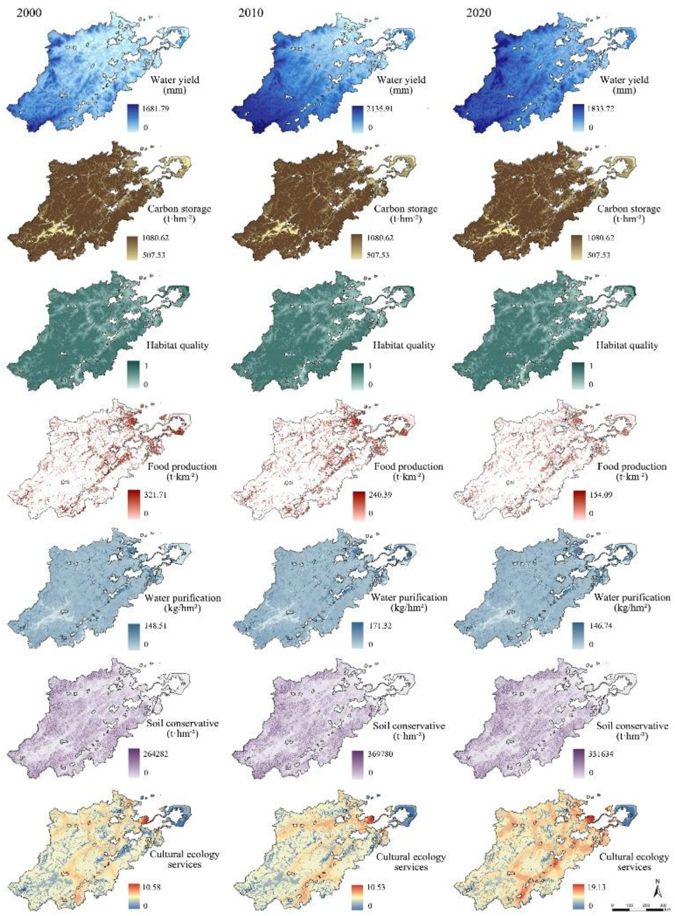
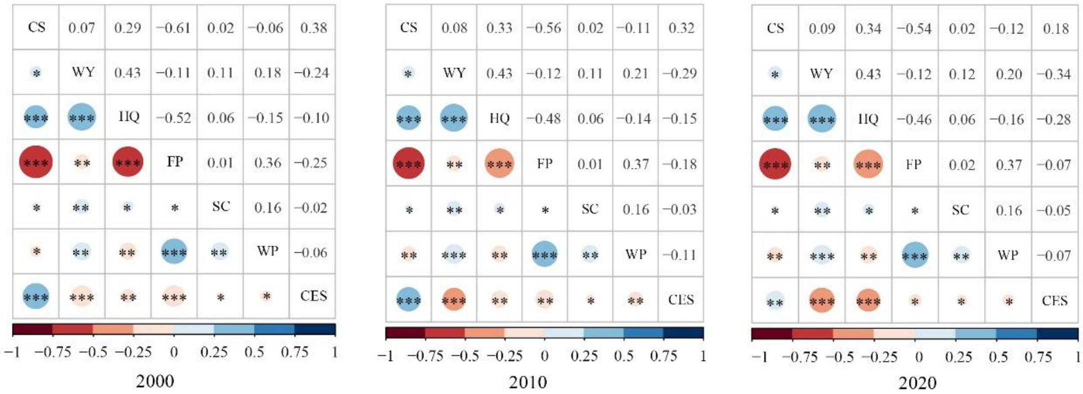


Figure 2. Spatiotemporal distribution map of ecosystem services

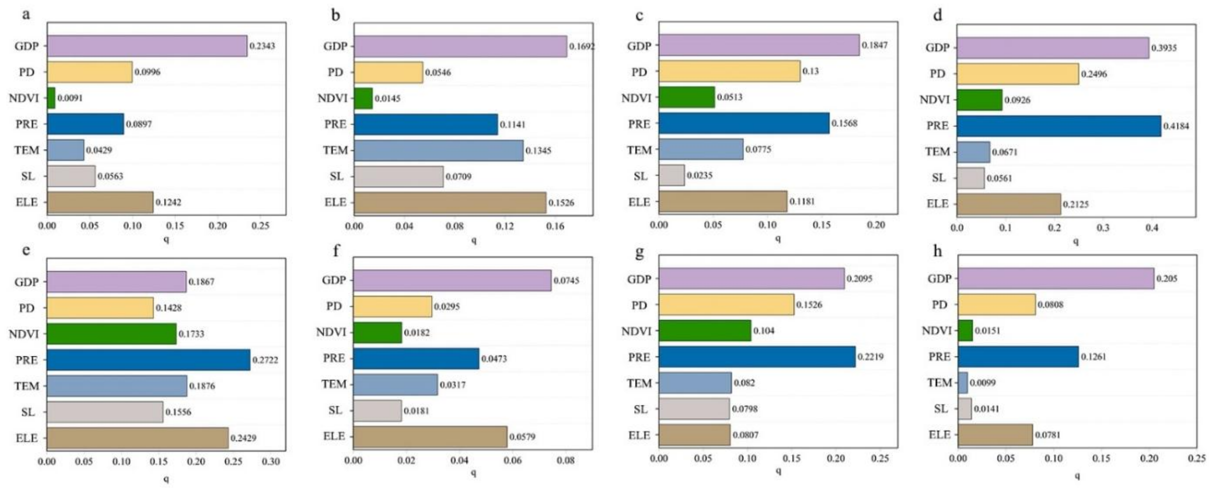
3.3. Analysis of Driving Factors

This study selected several typical natural and anthropogenic factors, including NDVI, mean annual temperature, mean annual precipitation, population density, per capita GDP, elevation, and slope, and used a combination of parameters with high q-values to spatially discretize each factor, then analyzed the influencing factors of the eight significantly correlated trade-off/synergy pairs(refer with: Fig. 4). For the trade-offs that increased, namely HQ-CES and WY-CES, annual precipitation and GDP had the greatest influence, followed by elevation, among which the influence factor of precipitation on WY-CES reached a q-value of 0.418, which is consistent with the findings of Yu[11] et al. For the synergy that decreased most significantly, CS-CES, GDP was the greatest influencing factor, followed by elevation. The trade-offs of CS-FP and HQ-FP were moderated, and it can be seen that annual precipitation and GDP were the greatest influencing factors; for CS-FP, elevation had a greater influence than GDP. Among the pairs with relatively weak influences, FP-WP and WY-HQ, GDP still had the greatest influence. For the synergy of CS-HQ that increased, GDP and elevation were the most obvious factors, followed by mean annual temperature and precipitation.



(CS: carbon storage; WY: water yield; HQ: habitat quality; FP: food production; SC: soil conservation; WP: water purification; CES: cultural ecosystem services; *** p < 0.01; ** p < 0.05; * p < 0.1)

Figure 3. Trade-off and synergy heatmap



(a–h represent CS-CES, CS-HQ, HQ-CES, WY-CES, CS-FP, FP-WP, HQ-FP, and WY-HQ, respectively.)

Figure 4. Driving factors of trade-offs and synergies

4. DISCUSSION

The trade-offs and synergies among ecosystem services are shaped by multiple interacting driving factors, as proposed by Bennett[3] et al. in 2009. This study analyzed the spatiotemporal variations of seven ecosystem services in Hangzhou's rural areas from 2000 to 2020, with a particular focus on the driving mechanisms of eight significantly correlated trade-off/synergy pairs. The results indicate that socio-economic factors, especially GDP[12], are the dominant drivers of changes in ecosystem service trade-offs and synergies, while natural factors such as precipitation, elevation, and temperature also play important roles. Among the prominent service pairs, GDP exerts the greatest influence on the decline of the carbon storage-cultural service synergy, the intensification of the habitat quality-cultural service trade-off, and the easing of the trade-offs between food production and habitat quality as well as between carbon storage and habitat quality. Economic development often comes at the expense of regulating services such as carbon storage and habitat quality, whereas cultural services rely more on artificial infrastructure and improved accessibility, leading to weakened synergies and intensified trade-offs. For the increasing trade-offs between water yield and cultural services and between habitat quality and cultural services, precipitation and GDP have the greatest influence, followed by elevation; notably, the effect of precipitation on the water yield-cultural service pair reaches a q-value of 0.418. Numerous studies have demonstrated that precipitation is the most critical driver of water yield, directly controlling surface runoff and soil moisture to dominate the spatial differentiation of water-related services[13]. For the most prominently decreasing synergy, carbon storage-cultural service, GDP is the dominant factor, followed by elevation. The trade-offs between food production and carbon storage and between food production and habitat quality have eased, with annual precipitation and GDP being the most influential; for the food production-carbon storage pair, elevation has a greater influence than GDP. The increasing synergy between carbon storage and habitat quality is primarily driven by GDP and elevation, followed by mean annual temperature and precipitation. These findings suggest that economic development and urbanization, through land use changes, have weakened regulating and supporting services and intensified conflicts between provisioning services and regulating and supporting services. Meanwhile, the high elevation and abundant precipitation in the western mountainous areas support carbon storage and habitat maintenance[14], but also limit the accessibility of cultural services[15].

Spatially, ecosystem services in Hangzhou's rural areas exhibit a pattern of "high in the southwest and low in the northeast." The southwestern mountainous region is dominated by forests, with relatively high levels of carbon storage, habitat quality, and soil conservation; the northeastern plain is dominated by cropland and built-up areas, where food production and cultural services are relatively concentrated. Carbon storage and habitat quality show synergistic growth in the mountainous region, while food production and water purification exhibit synergy in the agricultural region, albeit with persistent trade-offs against carbon storage and habitat quality[16]. We recommend focusing on the influence of socio-economic factors: controlling cropland fragmentation in areas under high urbanization pressure and promoting ecological agriculture; rationally planning ecotourism in the western mountainous areas to enhance the accessibility of cultural services; paying attention to the exacerbating effect of precipitation fluctuations on the trade-off between water yield and cultural services; and integrating GDP growth with ecological protection objectives in planning, while exploring mechanisms such as eco-compensation. Limitations of this study include[17]: (1) The assessment is based on the InVEST model, and parameters involved (e.g., root depth, biophysical tables) are mainly derived from the model manual and related literature, lacking calibration with field observation data, which may affect the accuracy of the results; (2) The selected study periods are relatively few, and the data are not sufficiently robust; more years and scales should be introduced for empirical validation; (3) The OPGD model fails to reveal nonlinear causal chains among factors. Future research should integrate field monitoring data and introduce structural equation modeling or machine learning to further elucidate the comprehensive driving mechanisms of multiple factors.

5. CONCLUSION

This study explored the trade-off/synergy relationships of ecosystem services and their driving factors in the rural areas of Hangzhou from 2000 to 2020. The results show that most services exhibited a spatial pattern of "high in the southwest and low in the northeast." In Hangzhou's rural areas, food production maintained consistently high trade-offs with carbon storage and habitat quality, which gradually eased over time. Service pairs related to cultural services were more prone to trade-offs. The driving forces were jointly shaped by multiple natural and socio-economic factors. This study provides a scientific basis for rural ecological protection and sustainable development, and also offers important theoretical support for the formulation of future ecological and environmental protection policies .

CONFLICTS OF INTEREST

The authors declare that they have no conflict of interest.

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