Spatiotemporal Variation and Driving Mechanisms of Ecosystem Service Interactions in the Shiyang River Basin (Postprint)

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Abstract

Understanding the spatiotemporal variations of ecosystem services and their internal complex relationships is crucial for ecosystem service management. Taking the Shiyang River Basin as the study area, this study evaluated six ecosystem services for 2010, 2015, and 2020, analyzed the spatiotemporal variations of ecosystem service trade-offs/synergies and ecosystem service bundles at raster and township scales, and explored the driving mechanisms of ecosystem service bundles using a boosted regression tree model. The results show: (1) Significant spatial differentiation exists among various services. Water yield, carbon storage, soil conservation, and habitat quality exhibit a "high in the southwest, low in the northeast" spatial pattern. Food supply is mainly concentrated in cultivated land areas in the central and northern parts of the basin, while high-value recreation areas are distributed in the southern part of the basin and densely populated areas in the central and northern parts. During the study period, all services improved to varying degrees, with soil conservation showing the largest increase and carbon storage and habitat quality showing relatively small increases. (2) The ecosystem service trade-off/synergy relationships show similarity across the two scales, but with differing intensities, generally presenting 12 pairs of synergistic relationships and 3 pairs of trade-off relationships. (3) The spatial patterns of ecosystem service bundles are similar across the two scales. Service bundles dominated by the other five services (excluding food supply) are distributed in the southern part of the basin. In the Minqin oasis area in the central and northern parts of the basin, service bundles dominated by food supply and recreation are distributed. In other areas with relatively harsh ecological environments, the supply of various services within the distributed service bundles is relatively low. During the study period, service bundles exhibited obvious spatial and quantitative transfer changes. (4) Multiple factors play important roles in the changes of ecosystem service bundles in the study

area, with the degree of influence of these factors varying slightly across different years. Among them, land use type, normalized difference vegetation index (NDVI), annual precipitation, and elevation are important driving factors for changes in ecosystem service bundles.

Full Text

Abstract

Understanding the spatiotemporal variation and internal complex relationships of ecosystem services is crucial for ecosystem management. This study evaluates six ecosystem services in the Shiyang River Basin of Gansu Province, China, for the years 2010, 2015, and 2020. Using Pearson correlation analysis, we examine trade-offs and synergies among these services at both grid and township scales. Ecosystem service bundles are identified through self-organizing maps, and their spatiotemporal dynamics are analyzed. A boosted regression tree model is employed to explore the driving mechanisms of ecosystem service bundle changes. The results reveal: (1) Significant spatial heterogeneity exists across all services. Water yield, carbon storage, soil conservation, and habitat quality exhibit a "high in the southwest, low in the northeast" pattern. Food supply is concentrated in cultivated lands in the central and northern parts of the basin, while high-value recreational areas are distributed in the southern region and densely populated areas in the central and northern parts. During the study period, all services showed varying degrees of improvement, with soil conservation increasing most substantially and carbon storage and habitat quality showing more modest gains. (2) Trade-off and synergy relationships display similar patterns across both scales but differ in intensity. Overall, twelve pairs of synergistic relationships and three pairs of trade-off relationships are identified. (3) The spatial patterns of ecosystem service bundles are comparable between scales. In the southern basin, five service bundles dominated by regulating, supporting, and cultural services are identified. The central and northern Minqin oasis areas feature bundles characterized by food supply and recreational services. Other regions with relatively harsh ecological environments show low supply across all services within their bundles. Notable spatial and quantitative transitions in service bundles occurred during the study period. (4) Multiple factors significantly influence the changes in ecosystem service bundles, with land use type, normalized difference vegetation index, annual precipitation, and elevation emerging as the primary drivers, though their relative importance varies slightly across years.

Keywords: ecosystem service bundles; trade-offs and synergies; boosted regression tree model; Shiyang River Basin

1. Introduction

Ecosystem services (ES) represent the various benefits that humans obtain directly or indirectly from ecosystems, encompassing supporting, provisioning, regulating, and cultural services [?, ?]. The Millennium Ecosystem Assessment highlights that global ecosystems are experiencing degradation and destruction, leading to changes in ES that directly impact human well-being [?]. Clarifying the complex interdependencies among ES is therefore essential for promoting sustainable ecosystem management and improving human welfare.

The relationships among ecosystem services are characterized by trade-offs and synergies (TOS), defined as the negative and positive correlations between services, respectively [?]. Current research on TOS has yielded substantial results, employing various methodological approaches including statistical methods [?], spatial analysis techniques [?], scenario simulation analysis [?], and service flow quantification [?]. However, these methods often struggle to reveal the full complexity of ES interactions.

Ecosystem service bundles (ESB) offer a systematic approach to understanding these complex relationships [?]. Defined as sets of multiple ES that co-occur across spatial and temporal scales, ESB reflect the interdependencies among services and provide a comprehensive framework for assessing ecosystem contributions to society [?]. Research on ESB has matured through methods such as clustering algorithms [?], principal component analysis [?], and neural networks [?]. While existing studies have examined ES supply and interactions across various scales, research at the township scale remains limited. Township-level analysis can better reveal associations and interactions among ES tailored to local management needs, making it particularly valuable for policy implementation.

This study addresses these gaps by examining the Shiyang River Basin, a typical arid inland river basin in northwestern China. We quantify six key ecosystem services, analyze their trade-offs and synergies at both grid and township scales, identify ecosystem service bundles using self-organizing maps, and investigate driving mechanisms through boosted regression tree modeling. The findings aim to deepen understanding of ES complex relationships and provide a scientific basis for local ecological management and human well-being improvement.

1.1 Study Area

The Shiyang River Basin ($36°29'–39°27' N$, $101°22'–104°16' E$) is located in the eastern Hexi Corridor, covering an area of 4.16×10^4 km^2 [Figure 1: see original paper]. The terrain slopes from southwest to northeast, with elevations ranging from 1202 m in the northern lowland areas to 5231 m in the southern Qilian Mountains. Situated in an arid and semi-arid region of northwestern China, the basin experiences a temperate continental climate characterized by abundant sunshine, large diurnal temperature variations, and low, concentrated precipitation. The southern Qilian Mountains constitute a high-cold semi-arid humid zone with annual precipitation of 700–1200 mm and annual evapotranspiration of 1300–2000 mm. The central Hexi Corridor plain is an arid zone with 150–300 mm precipitation and 2000–2600 mm evapotranspiration. The northern low hilly area receives less than 150 mm precipitation with evapotranspiration of 300–600 mm. The basin is surrounded by the Badain Jaran and Tengger Deserts, making its ecological environment extremely fragile.

1.2 Data Sources

This study utilizes multiple datasets including land use data, meteorological data, soil data, topographic data, and socio-economic data. All data were projected to the Albers coordinate system and resampled to 100 m resolution. Detailed data sources and specifications are provided in .

1.3 Methods

1.3.1 Ecosystem Service Quantification We selected six ecosystem services for assessment: food supply, water yield, carbon storage, soil conservation, habitat quality, and recreational service. Specific calculation methods are summarized in . Food supply was estimated based on county-level grain production statistics allocated to cropland grids according to NDVI values. Water yield was calculated using the InVEST Water Yield module. Carbon storage was quantified using the InVEST Carbon Storage and Sequestration module with parameters derived from literature. Soil conservation was estimated using the Revised Universal Soil Loss Equation (RUSLE). Habitat quality was assessed via the InVEST Habitat Quality module. Recreational service was evaluated using a model based on net primary productivity, population proximity, and road accessibility.

1.3.2 Trade-off and Synergy Analysis Pearson correlation analysis was applied to examine relationships among ecosystem services at both grid (1 km) and township scales. Positive correlations indicate synergistic relationships, while negative correlations represent trade-offs. The absolute value of correlation coefficients reflects interaction strength.

1.3.3 Ecosystem Service Bundle Identification Self-organizing maps (SOM) were used to identify ecosystem service bundles at both scales. Compared with traditional clustering algorithms, SOM offers advantages including strong memory capacity, robustness, and nonlinear mapping capabilities, enabling effective visualization of classification results [?]. The optimal SOM parameters were determined through iterative training and validation.

1.3.4 Driver Analysis of Ecosystem Service Bundles Boosted regression tree (BRT) modeling was employed to quantitatively analyze the influence of various factors on ecosystem service bundle dynamics [?]. Nine potential drivers were selected: land use type (LULC), normalized difference vegetation index (NDVI), precipitation (PRE), potential evapotranspiration (PET), elevation (DEM), slope, soil type, population density (POP), and gross domestic product (GDP). Model parameters were optimized through grid search and five-fold cross-validation. The relative contribution of each factor was calculated to assess its importance in driving bundle changes.

2 Results

2.1 Spatiotemporal Distribution of Ecosystem Services

Distinct spatial patterns characterize the six ecosystem services in the Shiyang River Basin [Figure 2: see original paper]. Water yield, carbon storage, soil conservation, and habitat quality all decrease from southwest to northeast, with high-value areas concentrated in the southern Qilian Mountains. This pattern aligns with previous research [**?**, **?**] and reflects the influence of topography and climate—higher elevations in the south enhance precipitation and reduce evapotranspiration, while extensive grasslands and forests provide favorable habitat conditions and carbon sequestration capacity. Food supply is predominantly distributed in croplands of the central and northern Minqin oasis, while high recreational values occur in the southern mountains and densely populated central and northern areas.

During 2010–2020, all services exhibited improvement . Soil conservation showed the greatest increase (from 4.53×10^8 t to 7.19×10^8 t), while carbon storage and habitat quality displayed relatively modest gains. Total carbon storage increased from 5.60×10^9 t to 5.64×10^9 t, and mean habitat quality scores rose slightly from 0.48 to 0.49. Water yield, food supply, and recreational service increased by 33.7%, 33.8%, and 35.4%, respectively. These improvements reflect the effectiveness of ecological restoration initiatives implemented since the 2007 Shiyang River Basin Comprehensive Management Plan.

2.2 Scale-dependent Differences in Trade-offs and Synergies

Correlation analysis identified 15 significant relationships among ecosystem services at both scales [Figure 3: see original paper]. At the grid scale, twelve pairs showed synergistic relationships ($r > 0$) and three pairs showed trade-offs ($r < 0$). The strongest synergy occurred between carbon storage and habitat quality ($r = 0.85$, $p < 0.01$), followed by water yield and soil conservation ($r = 0.72$). Trade-offs primarily involved food supply with water yield ($r = -0.42$) and habitat quality ($r = -0.38$), reflecting agricultural water consumption and land use conflicts.

At the township scale, the direction of relationships remained largely consistent, but intensities differed markedly. Synergistic relationships were generally stronger at the township scale, while trade-offs became more pronounced. For instance, the food supply–water yield trade-off strengthened from $r = -0.42$ at grid scale to $r = -0.51$ at township scale, indicating that scale effects amplify the expression of certain ES interactions. Recreational service showed the most variable correlations with other services across scales, suggesting its sensitivity to both ecological conditions and socioeconomic factors.

2.3 Spatiotemporal Dynamics of Ecosystem Service Bundles

Both scales identified distinct ecosystem service bundles with clear spatial patterns [FIGURE:4, FIGURE:5]. At the grid scale, five bundles were delineated: (1) **Regulating-dominant bundle** in the southern mountains, characterized by high water yield, carbon storage, soil conservation, and habitat quality; (2) **Provisioning-dominant bundle** in central and northern oases, dominated by food supply; (3) **Cultural-dominant bundle** in populated areas with high recreational values; (4) **Mixed bundle** showing moderate levels of multiple services; and (5) **Degraded bundle** in arid regions with low supply across all services.

At the township scale, four bundles emerged with similar spatial distribution but different composition. The southern region maintained bundles dominated by regulating, supporting, and cultural services. Central and northern townships featured bundles centered on food supply and recreational services. The most extensive bundle covered environmentally harsh areas with uniformly low service supply.

Significant transitions occurred between 2010 and 2020. At the grid scale, the area of the regulating-dominant bundle decreased by 912 km^2, while the mixed bundle expanded by 1024 km^2, indicating improved ecological functions in previously degraded areas. At the township scale, transitions were most pronounced during 2015–2020, with the provisioning-dominant bundle area decreasing by 562 km^2 as land use efficiency improved.

2.4 Driving Factors of Ecosystem Service Bundle Changes

Boosted regression tree analysis revealed that land use type, NDVI, precipitation, and elevation were the primary drivers of bundle dynamics, with their combined relative contribution exceeding 70% [Figure 6: see original paper]. Land use type showed the highest individual contribution (28.3% in 2010, 26.1% in 2020), followed by NDVI (24.7% in 2010, 25.4% in 2020). Precipitation and elevation contributed 12.8% and 11.5% on average, respectively. Other factors including potential evapotranspiration, population density, GDP, and soil type had relatively minor impacts.

Marginal effect analysis demonstrated consistent response trends across years [Figure 7: see original paper]. For land use types, cropland exerted the strongest influence on bundle changes, followed by grassland and forest. The impact of NDVI increased sharply when values exceeded 0.6, indicating threshold effects of vegetation cover. Elevation effects intensified up to 4000 m before stabilizing. Precipitation effects increased gradually with rainfall amounts but plateaued above 400 mm, reflecting water limitations in this arid environment.

3 Discussion

3.1 Spatiotemporal Patterns of Ecosystem Services

The spatial distribution of ecosystem services in the Shiyang River Basin is shaped by multiple interacting factors [?, ?]. The consistent "high in southwest, low in northeast" pattern reflects the dominant influence of topography and climate. The southern Qilian Mountains, with higher precipitation, lower temperatures, and extensive vegetation cover, provide favorable conditions for regulating and supporting services. Forest and grassland root systems enhance soil stability, reducing erosion, while the high-altitude terrain promotes orographic precipitation. These biophysical conditions create a natural gradient in service provision.

In contrast, the central and northern plains, with flat terrain and intensive agriculture, dominate provisioning services. The Minqin oasis serves as the primary grain production area and human settlement zone, concentrating food supply and recreational services. The ecological restoration policies implemented since 2007, including upstream water conservation, midstream irrigation efficiency improvements, and downstream environmental protection, have significantly enhanced ecosystem services basin-wide [?]. The marked increase in soil conservation and water yield demonstrates the success of these measures in stabilizing the fragile desert-oasis ecosystem.

3.2 Scale-dependent Interactions and Management Implications

The complex interactions among ecosystem services require management strategies that account for both relationship complexity and scale effects [?, ?]. Our findings show that while the direction of trade-offs and synergies remains consistent across scales, their intensity varies significantly. Synergistic relationships are generally stronger at the township scale due to aggregated land use patterns and administrative management units that homogenize ecosystem processes. Trade-offs, particularly between food supply and regulating services, intensify at larger scales because agricultural activities concentrate water consumption and land use pressures [?, ?].

The predominance of trade-offs between provisioning and regulating services reflects fundamental land use conflicts and water scarcity in this arid region. Agricultural expansion for grain production competes with water resources needed for maintaining habitat quality and water yield, creating inherent trade-offs [?]. Conversely, synergies among regulating, supporting, and cultural services arise from shared dependencies on vegetation cover—areas with high NDVI simultaneously support carbon sequestration, soil retention, and recreational opportunities.

Ecosystem service bundles provide a systematic framework for balancing economic, ecological, and social objectives in decision-making [?, ?]. Grid-scale analysis offers a comprehensive regional perspective, while township-scale assessment aligns with administrative boundaries and policy implementation. The expansion of mixed service bundles and the contraction of degraded bundles indicate improving ecosystem multifunctionality, yet the persistence of low-service bundles in harsh environments underscores ongoing management challenges.

Current ES research predominantly focuses on grid, watershed, provincial, or county scales [?, ?]. Township-scale studies remain scarce despite their relevance for targeted policy design. As China' s basic administrative unit, townships require scale-specific research to address local ecological and socioeconomic conditions [?]. Our comparative analysis demonstrates that incorporating scale effects is essential for effective ecosystem planning and management, enabling differentiated policies that match the spatial heterogeneity of service interactions.

4 Conclusion

This study quantifies the spatiotemporal evolution of ecosystem services and their interactions in the Shiyang River Basin from 2010 to 2020. The six assessed services exhibit pronounced spatial heterogeneity, with four regulating/supporting services showing a "southwest high-northeast low" pattern, food supply concentrated in central and northern oases, and recreational services aligned with population distribution. All services improved during the study period, with soil conservation showing the greatest gains.

Trade-off and synergy relationships display scale-dependent characteristics, with twelve synergistic and three trade-off pairs identified. While relationship directions are consistent across scales, intensities differ, with township-scale interactions generally stronger than those at the grid scale. Trade-offs primarily occur between provisioning and regulating services, driven by agricultural water use and land use conflicts. Synergies dominate among regulating, supporting, and cultural services, facilitated by vegetation cover.

Ecosystem service bundles show similar spatial patterns across scales but differ in composition and number. Five bundles are identified at the grid scale and four at the township scale, with clear spatial transitions occurring between 2010 and 2020. The regulating-dominant bundle in the southern mountains contracted, while mixed bundles expanded, indicating ecological improvement.

Land use type, NDVI, precipitation, and elevation are the primary drivers of ecosystem service bundle changes, collectively explaining over 70% of the variation. Their relative contributions vary slightly across years but maintain consistent influence patterns. The threshold effects of NDVI and precipitation highlight the sensitivity of ecosystem service bundles to vegetation cover and water availability in this arid environment.

These findings underscore the importance of scale-sensitive ecosystem management that recognizes both the complexity of service interactions and the dominant role of land use and climate factors. The results provide a scientific basis for optimizing ecological restoration strategies and improving human well-being in the Shiyang River Basin and similar arid inland river basins.

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Note: Figure translations are in progress. See original paper for figures.