Ecosystem Service Value Assessment and Driving Force Analysis in Yinchuan City, 1980–2018: Postprint

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Date: 2021-04-14T00:00:00+00:00

Abstract

Accurate assessment of ecosystem service values (ESV) and analysis of their driving forces are crucial for regional ecological security and economic development. Based on land use data from various districts and counties of Yinchuan City from 1980 to 2018, the ecosystem service values of Yinchuan were calculated using change rate, dynamic degree, sensitivity, and correlation, and the driving factors were analyzed using Geodetector. The results show that the total ESV for different ecosystem service types decreased from 1980 to 2018, with a reduction of 0.753$×$10ˆ9 yuan. Changes in ecosystem service values were relatively minor for most service types, while water regulation exhibited the highest value with significant changes. Water supply displayed the greatest dynamic degree of change and showed an increasing trend; grassland and water body ecosystem service values showed strong sensitivity, and water body demonstrated the strongest correlation with total ecosystem service value. In terms of spatial distribution, Lingwu City had the highest ecosystem service value, while Jinfeng District had the lowest. The main single-factor drivers were Gross Domestic Product (GDP) and Digital Elevation Model (DEM), while among multi-factor interactive drivers, GDP temperature and GDP DEM contributed most to the spatial distribution of ESV in Yinchuan, indicating that the distribution of ecosystem service values in Yinchuan is mainly influenced by the interaction between anthropogenic and natural factors.

Full Text

Value Evaluation and Driving Force Analysis of Ecosystem Services in Yinchuan City from 1980 to 2018

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Abstract

Accurate assessment of ecosystem service value (ESV) and analysis of its driving forces are crucial for regional ecological security and economic development. Based on land use data for various districts and counties in Yinchuan City from 1980 to 2018, this study calculated the ecosystem service value of Yinchuan using change rate, dynamic attitude, sensitivity, and correlation indicators, and analyzed the driving factors using GeoDetector. The results show that from 1980 to 2018, the total ESV of different ecological service types in Yinchuan decreased by 0.755×10^{9} yuan. The ESV of most ecological service types changed only slightly, while hydrological regulation had the highest value and showed significant change. Water resource supply exhibited the greatest dynamic attitude and an increasing trend. Grassland and water body ESVs showed strong sensitivity, and water bodies had the strongest correlation with total ESV. In terms of spatial distribution, Lingwu City had the highest ESV while Jinfeng District had the lowest. The primary single-factor drivers were GDP and DEM. Among factor interactions, GDP DEM contributed most to the ESV distribution, indicating that the spatial distribution of ecosystem service value in Yinchuan is mainly influenced by the interaction between anthropogenic and natural factors.

Keywords: ecosystem service value; driving force analysis; GeoDetector; Yinchuan City

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1. Study Area Overview

Yinchuan City is located in northwestern China, in the central part of the Ningxia Plain. It borders the western edge of the Ordos Plateau to the east and relies on the Helan Mountains to the west, with the Yellow River flowing through the city. As a key commercial town on the ancient Silk Road and the capital of Ningxia, Yinchuan serves as the region' s economic, political, cultural, scientific research, transportation, military, and financial center. It is also a core city in the China-Mongolia-Russia and New Eurasian Land Bridge economic corridors, and a window for China' s opening to the west. The city has an average temperature of approximately 8.6°C, annual precipitation of 200–220 mm, a frost-free period of about 190 days, and annual sunshine hours exceeding 3000 h. Rich in water resources with numerous lakes and wetlands, the city' s diverse soil types are suitable for crop growth. As of 2018, Yinchuan covered a total area of 8874.61 km^2 with a population of 2.25×10^{6}. Its jurisdiction includes three districts (Xingqing, Jinfeng, and Xixia), one county-level city (Lingwu), and two counties (Helan and Yongning). The region has a complete ecosystem, making it ideal for studying heterogeneity in regional natural environments and economic development levels.

2. Data and Methods

2.1 Data Sources

Land use data were obtained from the 30 m resolution land use dataset published by Tsinghua University (http://data.ess.tsinghua.edu.cn/). Digital elevation model (DEM) data were acquired from the Geospatial Data Cloud Platform. Road, railway, and water body data were sourced from OpenStreetMap. Normalized difference vegetation index (NDVI) was calculated from Landsat 8 OLI imagery. Gross domestic product (GDP) and population density data were obtained from the multi-period land use remote sensing monitoring database of the Institute of Geographic Sciences and Natural Resources Research, Chinese Academy of Sciences. The GDP spatial distribution kilometer grid dataset was spatialized using a multi-factor weighting method based on county-level GDP statistics, considering factors such as settlement density, nighttime light brightness, and land use types. Similarly, the population spatial distribution dataset was generated by allocating county-level population data to grid cells while accounting for settlement density, nighttime light brightness, and land use patterns.

2.2 Ecosystem Service Value Calculation

Based on the six periods of land use data and the equivalent factor table for Chinese terrestrial ecosystem service values revised by Xie et al., we calculated value coefficients for Yinchuan's land use types by corresponding different biomes to forest, grassland, farmland (cropland), water body, and bare land. The calculation formula is:

$$ESV = \sum ESV_f = \sum (A_k \times VC_k) = \sum (A_k \times VC_{fk})$$

where ESV represents the total ecosystem service value of Yinchuan (yuan), A_k is the area of the k-th land use type (hm^2), VC_k is the value coefficient of the k-th land use type ($yuan \cdot hm^{-2} \cdot a^{-1}$), ESV_f is the total value of a single ecosystem service (yuan), and VC_{fk} is the value coefficient of a single service function ($yuan \cdot hm^{-2} \cdot a^{-1}$).

Direct application of this method would compromise comprehensiveness and accuracy. Therefore, we adjusted the indicators based on previous research: the cropland VC was calculated as a weighted average of paddy and dry land according to their area ratio in Yinchuan' s 2018 land use statistics; forest VC used shrub values as most of Yinchuan' s forests are shrubland; grassland VC used the average of steppe and meadow; water body VC used the average of water systems and wetlands; bare land VC used bare land values. Built-up land was excluded due to its negligible ecosystem service value. The standard equivalent factor for the improved ecosystem service valuation method was 3.406×10^{3} $yuan \cdot hm^{-2} \cdot a^{-1}$. Based on our selected indicators, we examined 11 secondary ecosystem service types under four primary categories (provisioning, regulating, supporting, cultural). Provisioning services include food production, raw material production, and water supply. Regulating services comprise gas regulation, climate regulation, environmental purification, and hydrological regulation. Supporting services include soil conservation, nutrient cycling maintenance, and biodiversity. Cultural services are primarily aesthetic landscape.

2.3 ESV Change Rate Calculation

The change rate formula for ecological service types is:

$$C = \frac{A_j - A_i}{A_i} \times 100\%$$

where C is the change rate of an ecological service type, and A_i, A_j are the values of a particular ecological service type in Yinchuan for two periods (10^9 yuan).

The dynamic attitude formula for a single ecological service type is:

$$K = \frac{U_b - U_a}{U_a} \times \frac{1}{T} \times 100\%$$

where K is the dynamic attitude of a particular ecological service type during the study period, U_a and U_b are the initial and final values of the service type, and T is the study period length. When T is set in years, K represents the annual change rate.

The comprehensive dynamic attitude formula is:

$$LC = \frac{\sum_{i=1}^{n} |\Delta LU_{i-j}|}{2\sum_{i=1}^{n} LU_i} \times \frac{1}{T} \times 100\%$$

where LC is the annual change rate of ecosystem services, LU_i is the value of the i-th ecological service type at the monitoring start time, ΔLU_{i-j} is the absolute value of the i-th ecological service type converted to non-i type during the monitoring period, and T is the monitoring period length.

2.4 ESV Sensitivity Calculation

The sensitivity model calculates the response of ESV to changes in the value coefficient by adjusting each land use type' s coefficient by $±$50% to observe ESV changes over time and its dependence on the coefficient. The formula is:

$$CS = \frac{(ESV_j - ESV_i)/ESVi}{(VC_{jk} - VC_{ik})/VC_{ik}}$$

where CS is the sensitivity index, ESV is the estimated ecosystem service value, VC is the value coefficient, i and j represent initial and adjusted values ($±$50% adjustment), and k represents land use type. When $CS < 1$, ESV is inelastic to VC; when $CS > 1$, it is elastic. A larger CS indicates greater importance of the coefficient' s accuracy.

2.5 GeoDetector Principle

GeoDetector, proposed by Wang et al., is a statistical method for quantitatively detecting spatial stratified heterogeneity and revealing its driving forces. It comprises four modules: factor detection, interaction detection, risk detection, and ecological detection. This study focuses on factor and interaction detection for analyzing ESV driving forces.

Factor detection uses the q value to measure how much a factor X explains the spatial stratified heterogeneity of attribute Y, with $q \in [0, 1]$. A larger q indicates stronger explanatory power. The expression is:

$$q = 1 - \frac{SSW}{SST}, \quad SSW = \sum_{h=1}^{L} N_h \sigma_h^2, \quad SST = N\sigma^2$$

where SSW and SST are the sum of within-stratum variances and total variance, respectively; $h = 1, 2, ..., L$ represents strata of variable Y or factor X; N_h and N are unit numbers in stratum h and the entire region; σ_h^2 and σ^2 are variances of Y in stratum h and the entire region.

Interaction detection evaluates whether factors X_1 and X_2 interact to increase or decrease explanatory power for dependent variable Y. It compares individual q values ($q(X_1)$, $q(X_2)$) with their interactive q value ($q(X_1 \cap X_2)$). The relationships are classified as: non-linear weakening, single-factor non-linear weakening, dual-factor enhancement, independent, or non-linear enhancement.

3. Results

3.1 ESV Changes by Ecological Service Type

Based on the per-unit-area value equivalent coefficients and corresponding land type areas for different years, we obtained the ESV for various ecological service types in Yinchuan (Table 3). The results show that from 1980 to 2018, different ecological service types exhibited varying degrees of change. Water resource supply showed the most significant change, with consistently negative values reaching a minimum in 2018. Hydrological regulation had the largest proportion among all service types and changed significantly, demonstrating water' s critical role in ecosystems. Climate regulation, gas regulation, biodiversity, and soil conservation also showed notable changes. As a complex integrated system, ecosystem dynamic balance requires coordinated components. However, during the study period, most ecological service types showed decreasing ESV trends, indicating diminishing value from ecosystems and intensifying human disturbance. Some categories, such as food production and nutrient cycling maintenance, showed slight increases with fluctuations, suggesting substantial impacts from socio-economic development and human activities on secondary ecological service types in Yinchuan.

In terms of total magnitude, Yinchuan' s overall ESV decreased from 2.173×10^{9} yuan to 2.097×10^{9} yuan, indicating reduced total ecological value provision. To illustrate temporal trends, Figure 2 plots different ecological service types' ESV against time. The figure reveals that water resource supply and food production showed the most pronounced changes, with opposite trends after 2000. Hydrological regulation, climate regulation, and water resource supply exhibited the greatest variation during 2000–2010, coinciding with significant land use changes and reflecting how land policies simultaneously affect land types and ecological service values. The varying change rates of hydrology and climate—elements closely related to human life—underscore the need for policy adjustments to promote mutualism between natural elements and humans while building a beautiful, green Yinchuan. Ensuring clean, adequate water resources and pleasant climate conditions is essential. Additionally, maintaining nutrient cycling, biodiversity, and aesthetic landscapes will prevent economic growth from sacrificing ecological value, enabling coordinated development between land resources and ecosystems.

3.2 ESV Change Rate and Sensitivity

Applying formula (2), we calculated annual change rates for different land use types in Yinchuan (Table 4). The results show significant inter-annual variation, with cropland and water bodies increasing, particularly cropland at a much higher rate than water bodies. Forest, grassland, and bare land decreased, with bare land showing the largest annual reduction rate, followed by grassland and forest. Different land types exhibited alternating change patterns across years. Overall, bare land and forest showed continuous decline, cropland and water bodies showed continuous growth, while grassland showed significant fluctuation with a maximum reduction rate of 10.716% (1990–2000), likely related to rapid economic growth causing environmental degradation.

Beyond change rates and dynamic attitudes, sensitivity is another crucial indicator. Table 6 presents sensitivity indices after adjusting value coefficients by $\pm$50%. The sensitivity index' s sign corresponds to coefficient changes, with larger absolute values indicating stronger sensitivity. Most indices are below 1, showing inelasticity. Grassland and water bodies have larger values, indicating stronger sensitivity and greater importance of coefficient accuracy, which also highlights their significant role in Yinchuan' s ecosystem. Cropland and forest show moderate sensitivity with similar values across years, while bare land has the smallest sensitivity (minimum 0.004), suggesting lower accuracy requirements but non-negligible influence due to its specific ecological functions and areal proportion.

Correlation analysis further reveals relationships between different land types and total ESV (Table 8). Water bodies show the highest correlation, followed by cropland, indicating water resources' critical importance for both drinking water supply and ecosystem services in Yinchuan. While utilizing water resources, conservation and waste prevention are essential. Cropland, fundamental for food security, also provides important ecological functions and should be maximally protected from salinization or abandonment. To optimize ESV provision, land use and ecology should develop in balanced coordination.

4. Driving Force Analysis of Ecosystem Service Value

4.1 Single-Factor Detection of ESV

To detect Yinchuan' s ESV driving factors, we selected six natural factors (elevation, slope, NDVI, temperature, precipitation) and five anthropogenic factors (GDP, population density, distance to roads, railways, and waterways). The study area was divided into 2 km$\times$2 km grids using ArcGIS 10.5. Each grid' s geometric center generated vector points to extract reclassified data as GeoDetector X variables, with ESV and service categories as Y variables. Natural breaks classification was applied to elevation, slope, temperature, precipitation, GDP, population density, and distance variables.

Single-factor detection revealed GDP contributed most to ESV distribution (Figure 3), followed by DEM, with other factors contributing less. The lowest contribution came from distance to roads. Figure 4 shows high-ESV areas distributed in Lingwu City, Xixia District, and parts of Xingqing District, where ecosystem service quality is generally high. Jinfeng District showed low ESV, with value provision far below average. Helan and Yongning counties had similar high-ESV area sizes, but Helan had broader low-ESV ranges. Overall, high-ESV areas concentrate in southeastern Yinchuan (especially Lingwu), central areas show generally low values (especially Jinfeng), and northwestern areas exhibit significant heterogeneity (especially Xixia).

Low-ESV areas mainly occur at elevations of 1059–1819 m, dominated by built-up land and bare land with small equivalent factors. High-ESV areas concentrate at 1819–3534 m, where cropland, forest, and grassland dominate with high equivalent factors. Yinchuan' s gentle slopes (all below 25°) suit urban and agricultural development, which depends heavily on temperature and precipitation affecting vegetation distribution and growth. Precipitation is concentrated in eastern and western areas with higher elevations, extensive forest and grassland distribution, and high ESV. Higher temperatures in Jinfeng, Xixia, and Xingqing districts correspond to more developed economies with high GDP but low ESV, showing significant negative correlation between GDP/population density and ESV. Road, railway, and waterway distances are indispensable factors affecting ESV, as transportation infrastructure enhances accessibility and attracts population flow while influencing ecological land patterns. Dense transportation networks in Jinfeng, Xixia, and Xingqing districts correlate with low

ESV, while sparse networks in other areas correspond to high ESV. These patterns suggest ESV distribution results from multiple interacting factors rather than single-factor effects.

4.2 Interaction Detection of ESV

Interaction detection examines whether two factors act independently or interactively, and whether interactions enhance or weaken effects. All factor pairs showed enhanced interactive effects on ESV distribution (Table 9), indicating non-independent influences. The interaction between GDP DEM was strongest (q = 0.412), consistent with findings that anthropogenic factors directly affect land use changes and thus ESV distribution. Natural and anthropogenic factor interactions alter vegetation distribution, human activity scope and intensity, indirectly affecting Yinchuan’ s ESV. GDP, population density, and distances to infrastructure cause frequent human activities, forming land use patterns dominated by impervious surfaces and bare land. Precipitation, temperature, NDVI, and slope are closely related to land use, with anthropogenic and natural drivers jointly influencing Yinchuan’ s ESV.

5. Discussion and Conclusions

5.1 Discussion

Various methods have been proposed for ESV assessment, but Xie’ s method based on Costanza’s research is widely accepted. Using 30 m resolution land use data as regional revision coefficients, we comprehensively calculated Yinchuan’ s ESV from 1980–2018 through change rate, dynamic attitude, sensitivity, and correlation. Our results are consistent with Yang’ s calculations for Yinchuan, validating our approach. High-resolution land use data improves accuracy and feasibility.

GeoDetector quantitatively analyzed 11 driving factors for Yinchuan’ s ESV, revealing contributions and interactions between anthropogenic and natural factors. Anthropogenic elements are the primary drivers, consistent with studies in eastern Sichuan. The interaction between GDP and DEM significantly influences ESV distribution, demonstrating that human activities directly impact land use while natural factors mediate these effects indirectly.

5.2 Conclusions

1) From 1980 to 2018, total ESV of different ecological service types in Yinchuan decreased by 0.755$×10^{9}$ yuan. Hydrological regulation had the highest mean value with significant temporal change, while water resource supply showed the smallest mean with a slight increasing trend.

2) ESV distribution is uneven: high-value areas concentrate in southeastern Yinchuan (especially Lingwu), central areas show generally low values (es-

pecially Jinfeng), and northwestern areas exhibit significant heterogeneity (especially Xixia).

3) Bare land and forest ESVs continuously decreased, while cropland and water bodies increased. Grassland showed significant fluctuation with maximum reduction rate of 10.716% (1990–2000). Grassland and water bodies showed strong sensitivity, making their value coefficients critical. Regulating services were most strongly associated with water bodies.

4) GDP and DEM were the main single-factor drivers. Among factor interactions, GDP DEM contributed most to ESV distribution, indicating that Yinchuan' s ecosystem service value distribution is predominantly influenced by interactions between anthropogenic and natural factors.

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