Trade-offs and Synergies of Ecosystem Services in Ningxia under Land Use Change (Postprint)

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Abstract

Research on land use change and its impacts on ecosystem services can provide a scientific basis for improving regional ecological environments; however, previous studies have predominantly focused on historical changes in ecosystem services, with insufficient analysis of future scenario predictions and the trade-offs and synergies among these services. Therefore, this study takes the Ningxia region as a case study, employs the PLUS model to simulate land use conditions under future natural scenarios, farmland protection scenarios, and ecological protection scenarios, and uses the InVEST model to quantify four ecosystem services—carbon storage, soil conservation, water yield, and food production—under different land use types, while investigating the trade-off and synergy relationships among ecosystem services at different spatial scales. The results indicate that water yield under all three future scenarios decreases compared to the baseline year, soil conservation and carbon storage are maximized under the ecological protection scenario at 7.98$×107*tand*4.72×108*trespectively*, *andfoodproductionismaximizedunderthefarmlandprotectionscenari* at the provincial scale, only carbon storage and soil conservation services exhibit a high synergy relationship, whereas at the regional and county scales, the synergy relationship between water yield and carbon storage services is also significant.

Full Text

Ecosystem Services Trade-offs and Synergies Driven by Land-use Changes in Ningxia

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Abstract

Research on land-use change and its impacts on ecosystem services provides a scientific basis for improving regional ecological environments. However, previous studies have primarily focused on historical changes in ecosystem services, lacking predictions of future ecosystem services and analyses of their trade-off and synergistic relationships under future scenarios. Therefore, this study takes Ningxia as a case study, employs the PLUS model to simulate future land-use conditions under three scenarios (natural development, farmland protection, and ecological protection), and uses the InVEST model to quantify four ecosystem services (carbon storage, soil conservation, water yield, and grain production) under different land-use types. The trade-offs and synergies among ecosystem services were analyzed at multiple spatial scales. The results show that: (1) Future water yield under all three scenarios decreases compared to the baseline year, while soil conservation and carbon sequestration reach their maximum values (7.98×10^{7} t and 4.72×10^{7} t, respectively) under the ecological protection scenario. Grain production peaks under the farmland protection scenario at 1.52×10^{7} t. (2) At the provincial scale, only carbon storage and soil conservation exhibit a strong synergistic relationship. However, at regional and county scales, synergistic relationships between water yield and carbon storage services also become significant.

Keywords: land use; ecosystem services; trade-offs and synergy; spatial scales; Ningxia

1.1 Study Area Overview

Ningxia is located between 35°14 –39°23 N and 104°17 –107°39 E, covering a total area of 6.64×10^{4} km^2. It borders Shaanxi Province to the east, Inner Mongolia to the west and north, and Gansu Province to the south. The elevation ranges from 956 to 3531 m, showing an overall trend of higher terrain in the south and lower in the north [Figure 1: see original paper]. The Yellow River flows through Ningxia from Zhongwei City to Shizuishan area. The region has a typical temperate continental climate characterized by long winters, short hot summers, rapid spring warming, cool autumns, drought with little rainfall, abundant sunshine, and strong evapotranspiration. Annual precipitation ranges from 150 to 600 mm, and mean annual temperature varies between 7.5 and 10.2 °C. Under the combined influence of climate and topography, the dominant vegetation types are farmland, desert, and grassland, with some coniferous and broadleaf forests distributed in the southern and northern mountainous areas.

1.2.1 Quantitative Assessment of Ecosystem Services

This study selected four primary ecosystem services for evaluation: carbon storage, soil conservation, water yield, and grain production. The InVEST model was used to quantify these services under different scenarios.

Carbon Storage: The InVEST Carbon Storage and Sequestration module divides carbon pools into four components: aboveground biomass, belowground biomass, dead organic matter, and soil carbon. Total carbon is calculated as:

$$C_{total} = C_{above} + C_{below} + C_{dead} + C_{soil}$$

Given that dead organic matter carbon constitutes a small proportion and is difficult to obtain, this component was excluded from the analysis [18]. Following previous research [19], we modified national carbon density data using the following formulas to obtain carbon densities for different land-use types in Ningxia:

$$C_{SP} = 3.3968 \times e^{0.0054 \times MAP} + 3996.1 \quad (R^2 = 0.11, P < 0.1)$$
$$C_{BP} = 6.798 \times e^{0.0054 \times MAP} + 398 \quad (R^2 = 0.70, P < 0.1)$$
$$C_{BT} = 28 \times e^{0.0054 \times MAT} + 398 \quad (R^2 = 0.47, P < 0.1)$$
$$K_{BP} = \frac{C_{BP}}{C_{BP\_China}}$$
$$K_{BT} = \frac{C_{BT}}{C_{BT\_China}}$$
$$K_S = \frac{C_{SP}}{C_{SP\_China}}$$

where C_{SP} is soil carbon density ($\mathrm{t \cdot hm^{-2}}$) derived from annual precipitation; C_{BP} and C_{BT} are biomass carbon densities ($\mathrm{t \cdot hm^{-2}}$) derived from annual precipitation and mean annual temperature, respectively; MAP is mean annual precipitation (mm); MAT is mean annual temperature (°C); K_{BP} and K_{BT} are correction factors for biomass carbon density; and K_S is the correction factor for soil carbon density. The resulting carbon densities are shown in .

Water Yield: The InVEST Annual Water Yield module assesses water production. The calculation formula is:

$$Y(x) = \left(1 - \frac{AET(x)}{P(x)}\right) \times P(x)$$

where $AET(x)$ is actual annual evapotranspiration and $P(x)$ is annual precipitation for grid cell x. The actual evapotranspiration is calculated as:

$$AET(x) = \frac{P(x) \times \omega(x) \times PET(x)}{P(x) + \omega(x) \times PET(x)}$$

where $PET(x)$ is potential evapotranspiration, and $\omega(x)$ is a non-physical parameter representing natural climate-soil properties.

Soil Conservation: The InVEST Sediment Delivery Ratio model evaluates soil erosion and conservation. Soil conservation (SD) is calculated as:

$$SD = USLE_{potential} - USLE_{actual}$$

where $USLE_{potential}$ is potential soil erosion and $USLE_{actual}$ is actual soil erosion, calculated using the Revised Universal Soil Loss Equation.

Grain Production: County-level grain production statistics were obtained from the *Ningxia Statistical Yearbook*. Grain yield was downscaled from county to pixel scale using NDVI data:

$$G_{ij} = \frac{NDVI_{ij}}{NDVI_{mean,j}} \times G_j$$

where G_{ij} is grain yield for pixel i in county j; $NDVI_{ij}$ is the normalized difference vegetation index for pixel i in county j; $NDVI_{mean,j}$ is the mean NDVI for all cropland pixels in county j; and G_j is the total grain yield for county j from statistical yearbooks.

1.2.2 Land-Use Change Simulation

The PLUS (Patch-generating Land Use Simulation) model, derived from the CA (Cellular Automata) model, integrates spatial factors affecting land-use change with geographical cellular dynamics to enhance spatiotemporal expression and prediction capabilities [22]. The model extracts training samples from transitions between two periods of land-use data, calculates development probabilities and driver contributions for each land-use type using a random forest algorithm, and combines these with a random patch generation module and user-defined transition matrices to determine future land-use patterns.

Driving Factors: We selected topographic, environmental, geographic location, and socioeconomic factors as drivers of land-use change in Ningxia. Topographic factors include slope, aspect, and elevation. Environmental factors are represented by annual precipitation and mean annual temperature. Geographic location factors include distances to roads, towns, and rivers. GDP and population density were selected as socioeconomic factors [Figure 2: see original paper].

Scenario Design: Using 2015 data for calibration, the PLUS model was validated against actual 2020 land-use maps, achieving a Kappa coefficient of 0.73

and overall accuracy of 85.4%, meeting research requirements. Three scenarios were then designed for 2035:

1. **Natural Development Scenario:** No restrictions on land-use transitions.
2. **Farmland Protection Scenario:** Cropland cannot be converted to other land-use types.
3. **Ecological Protection Scenario:** Forest and grassland cannot be converted to other land-use types.

1.2.3 Trade-offs and Synergies Among Ecosystem Services

To eliminate errors from inconsistent units, all ecosystem services were standardized at the pixel scale:

$$ES_{std} = \frac{ES_{obs} - ES_{min}}{ES_{max} - ES_{min}}$$

where ES_{std} is the standardized value, ES_{obs} is the original value, and ES_{max} and ES_{min} are the maximum and minimum values, respectively.

Spearman correlation coefficients were used to determine trade-off and synergistic relationships [21]. Positive correlations indicate synergy, while negative correlations indicate trade-offs. Correlation analysis was performed using the "corrplot" package in R 4.0 software.

1.3 Data Sources

Data sources are summarized in . Land-use and NDVI data (30 m resolution) were obtained from the Chinese Academy of Sciences Resource and Environment Data Center. Meteorological data came from the China Meteorological Data Service Center, including daily observations from 15 stations in and around Ningxia, which were interpolated to monthly data using Kriging in ArcGIS. Soil data were from the Second National Land Survey at 1:1,000,000 scale. Socioeconomic data were extracted from the *Ningxia Statistical Yearbook* (2015–2020).

2 Results and Analysis

2.1 Land-Use Change Analysis

Cropland and construction land are mainly distributed in the northern Yellow River irrigation area. Grassland is uniformly distributed across the region but most concentrated in the central area. Forest land is primarily located in the southern Liupan Mountains and northern Helan Mountains [Figure 3: see original paper]. Under all three scenarios, cropland and grassland remain the dominant land-use types, accounting for approximately 34.2%–35.0% and 44.1%–44.6% of the total area, respectively .

Compared to the baseline year, the natural development scenario shows decreasing trends in cropland, forest, and grassland, with grassland decreasing most severely (197.0 km^2). Construction land increases by 185.6 km^2. Under the farmland protection scenario, forest and grassland decrease (grassland by 194.7 km^2), while cropland and construction land increase. Under the ecological protection scenario, forest and grassland increase (by 119.1 km^2 and 114.5 km^2, respectively), while other land-use types decrease. Unused land decreases under all three scenarios.

2.2 Quantitative Prediction of Ecosystem Services Under Different Scenarios

Carbon Storage: Spatially uniform across the region, total carbon storage remains stable at 4.60$\times10^{\{7\}-4.72\times10}\{7\}$ t. The ecological protection scenario yields the highest carbon storage (4.72$\times10^{7}$ t), while the natural development scenario yields the lowest (4.60$\times10^{7}$ t). Counties with larger areas and more forest/grassland (Tongxin, Haiyuan, Yanchi) have the highest carbon storage, while counties with poor vegetation cover and smaller areas (Yongning, Huinong, Dawukou) have the lowest.

Soil Conservation: Strongly related to vegetation cover, land management practices, and human activities. High soil conservation capacity is found in southern areas with high vegetation cover and the northern Helan Mountains. The ecological protection scenario achieves the best soil conservation (7.98$\times10^{7}$ t). Xiji, Pengyang, and Jingyuan counties show the best soil conservation performance, while Qingtongxia, Yongning, and Litong districts show the poorest.

Water Yield: Shows a clear spatial gradient with more water in the south and less in the north. All future scenarios project lower water yield than the baseline, with the ecological protection scenario showing the greatest reduction (1.76$\times10^{8}$ m^3). The difference between the ecological protection scenario and baseline is smallest in counties like Zhongning and Yuanzhou (0.2$\times10^{8}$ m^3). Changes in water yield vary by county and scenario but are not statistically significant ($P < 0.05$).

Grain Production: Shows distinct clustering characteristics, with high-yield areas concentrated in the northern irrigation area and parts of southern Ningxia due to flat terrain, large cropland area, and favorable hydrothermal conditions. Except under the farmland protection scenario, grain production decreases in future scenarios, reaching its minimum (1.47$\times10^{7}$ t) under ecological protection. At the county level, Shapotou, Xiji, and Pingluo have the highest production, while Jingyuan, Dawukou, and Longde have the lowest. All counties show significant changes compared to baseline ($P < 0.05$) [FIGURE:4, FIGURE:5].

2.3 Multi-Scale Analysis of Trade-offs and Synergies

Provincial Scale: Overall, ecosystem services show synergistic relationships, particularly between soil conservation and water yield (R = 0.49). Synergistic relationships are stronger in future scenarios than in the baseline. Regulating services (carbon storage, soil conservation, water yield) show weak trade-offs or synergies with provisioning services (grain production) [Figure 6: see original paper].

Regional Scale: Based on topography and climate, the study area was divided into three regions: northern irrigation area, central wind-sand area, and southern hilly area . Trade-off and synergistic relationships remain consistent across scenarios. The northern irrigation area shows synergies primarily between soil conservation and carbon storage. The synergy between soil conservation and carbon storage is strongest under ecological protection in the central wind-sand area (R = 0.71). The southern hilly area shows the strongest trade-off between grain production and water yield (R = -0.54).

County Scale: Relationships among ecosystem services vary by county. Yongning County shows predominantly synergistic relationships, while Pengyang County shows trade-offs. The synergy between water yield and carbon storage is strongest in Jinfeng District (R = 0.97) and weakest in Dawukou District (R = -0.65). Counties with good water-carbon synergy include Jingyuan, Xiji, and Zhongning. The relationship between soil conservation and water yield is synergistic in Helan and Xixia districts. The northern irrigation area shows synergies between carbon storage and soil conservation, which weaken in the central wind-sand area and become trade-offs in the southern hilly area [FIGURE:7, FIGURE:8].

3 Discussion

Ecosystem services are influenced by land use and climate, exhibiting different trade-offs and synergies across scenarios [30]. Our results show that synergistic relationships mainly occur among carbon storage, water yield, and soil conservation, consistent with previous studies [6, 10]. However, trade-offs occur among regulating services in the northern irrigation area due to its dry climate (annual water yield < 35.21 m^3). The presence of forestland facilitates carbon sequestration but creates trade-offs between carbon storage and water yield. Additionally, good soil conservation effects in the northern area interact with vegetation distribution to affect runoff generation, creating trade-offs between soil conservation and water yield.

Furthermore, trade-off and synergistic relationships vary across scales [24]. At the provincial scale, only carbon storage and soil conservation show strong synergy, while at regional and county scales, synergy between water yield and carbon storage becomes significant. This occurs because dominant driving factors and land-use changes may vary across scales, altering ecosystem service relationships [31]. Additionally, sampling methods and intensity affect the detection of these relationships when analyzing regional or county-scale patterns from provincial-scale data. Vegetation promotes soil conservation, and forest distribution in the Helan Mountains enhances synergy between these services in northern Ningxia.

In land-use planning and management, decision-makers consider ecosystem functions and structures, making ecosystem service-based optimization a valuable strategy [32]. Our results show that different ecosystem services increase or decrease under different scenarios. Under ecological protection, carbon storage and soil conservation increase synergistically, while water yield and grain production decrease. Increased forest area enhances carbon storage and soil conservation but negatively impacts water yield through increased evapotranspiration [29]. Due to varying economic, natural, and social conditions, identical management measures may produce different outcomes [28]. Ecosystem responses to human interventions are often unpredictable, necessitating consideration of spatial heterogeneity in ecosystem services and their trade-offs/synergies when developing management strategies. Measures should not sacrifice one service to enhance another. Decision-makers must formulate region-specific policies based on local characteristics to promote sustainable land-use development.

The PLUS and InVEST models provide a reliable method for simulating land-use change and quantifying ecosystem services, but uncertainties remain. First, incomplete selection of driving factors and omission of policy impacts may cause deviations between simulated and actual land-use patterns. Second, carbon storage is influenced by climate, vegetation cover, and soil properties [25], but the InVEST model only considers land-use type and carbon density, with constant carbon densities across scenarios, potentially reducing accuracy. Future studies should validate carbon densities through field sampling to improve precision.

4 Conclusions

1. **Land-Use Patterns:** Cropland and grassland dominate Ningxia's landscape (34.2%–35.0% and 44.1%–44.6%, respectively). Compared to baseline, the natural development scenario reduces cropland, forest, and grassland; the farmland protection scenario decreases forest and grassland while increasing cropland and construction land; and the ecological protection scenario increases forest and grassland while decreasing other land-use types. Unused land decreases under all scenarios.
2. **Ecosystem Service Quantities:** Carbon storage is spatially uniform and stable at 4.60\$×10$^{\{7\}-4.72\times 10}${7}\$ t. Soil conservation is best in southern vegetated areas and northern Helan Mountains, reaching 7.98\$×10ˆ{7}\$ t under ecological protection. Water yield shows a south-north gradient and decreases in all future scenarios. Grain production is concentrated in the northern irrigation area and parts of southern Ningxia, decreasing in all scenarios except farmland protection, with a minimum of 1.47\$×10ˆ{7}\$ t under ecological protection.

3. **Trade-offs and Synergies:** Synergistic relationships mainly occur among carbon storage, water yield, and soil conservation. However, these relationships vary across scales. At the provincial scale, only carbon storage and soil conservation show strong synergy. At regional scales, the northern irrigation area shows synergies that weaken in the central wind-sand area and become trade-offs in the southern hilly area. At the county scale, relationships vary significantly, with some counties showing synergies and others trade-offs.

These findings provide scientific support for ecosystem protection and restoration in Ningxia, highlighting the need for scale-specific management strategies that consider local conditions and minimize trade-offs while enhancing synergies among ecosystem services.

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