Spatiotemporal Patterns of Ecosystem Service Hot (Cold) Spots in Shanxi Coalfields: Postprint

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Abstract

Based on remote sensing, meteorological, and other data from the Shanxi coalfields for 1986 and 2015, this study utilized the InVEST (Integrated Valuation of Ecosystem Services and Tradeoffs) model to estimate soil conservation and water yield services, the CASA (Carnegie-Ames-Stanford Approach) model to estimate vegetation production services, the RWEQ (Revised Wind Erosion Equation) model to estimate windbreak and sand fixation services, and hotspot analysis to simulate the spatial distribution patterns of ecosystem service hotspots (and coldspots). The results indicate: (1) From 1986 to 2015, the spatial distribution of soil conservation service hotspots remained largely unchanged overall, while coldspot areas primarily shifted from the Qinshui and Huoxi coalfields to the Hedong Coalfield; water yield service hotspots increased significantly in the eastern Qinshui Coalfield, while coldspot areas mainly expanded in the southern Hedong Coalfield; vegetation production service hotspots generally moved from southern to northeastern Qinshui Coalfield, while coldspot areas predominantly shifted from the Xishan and Qinshui coalfields to the Hedong and Datong coalfields; windbreak and sand fixation service hotspots generally transferred from the northwestern to the southeastern region, while coldspot areas mainly shifted from the Qinshui Coalfield to the Huoxi and Hedong coalfields. (2) During 1986–2015, the Qinshui Coalfield in the southeastern study area served as a concentrated zone for multiple ecosystem service hotspots, representing a key functional supply area for ecosystem services; the Hedong and Huoxi coalfields were concentrated regions of change for multiple ecosystem service coldspots. (3) Cropland exhibited relatively high proportions of hotspot area for water yield and vegetation production services, with service levels exceeding those of other services; forestland and grassland possessed the largest hotspot area for soil conservation services, constituting high-function zones for soil conservation services; construction land demonstrated relatively high water yield service levels.

Full Text

Spatiotemporal Pattern of Hotspots (Coldspots) of Ecosystem Services in Coalfields of Shanxi Province

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Abstract: Hotspot analysis can be used to identify spatial clusters of high (or low) value to ecosystem services (ES) in a study area, helping to further explore regions with relatively high or low values of each ES. As one application, this is of great significance to the protection and restoration of the ecological environment in coalfields. In this study, we collected remote sensing data, meteorological data, and soil data (as well as data of other types) from coalfields in Shanxi Province, China from 1986 and 2015 and estimated soil conservation and water yield using the integrated valuation of ES and trade-offs (InVEST) model, vegetation net primary productivity based on the Carnegie-Ames-Stanford approach, and sand fixation service based on the revised wind erosion equation. Furthermore, we identified the spatial distribution of hotspots (and coldspots) of ES using the Getis-Ord Gi* tool of ArcGIS. The results demonstrated the following: (1) From the perspective of individual ES, the overall spatial distribution of hotspots for soil conservation service did not significantly change from 1986 to 2015, whereas the coldspots of soil conservation service were mainly transferred from Qinshui Coalfield and Huoxi Coalfield to the Hedong Coalfield. The hotspots of water yield also increased significantly in the eastern part of Qinshui Coalfield, whereas the coldspots of water yield increased mainly in the southern part of Hedong Coalfield. Overall, the hotspots of vegetation production service moved from the south to the northeast of Qinshui Coalfield, whereas the coldspots of vegetation production service mainly moved from Xishan Coalfield and Qinshui Coalfield to Hedong Coalfield and the Datong Coalfield. The hotspots of sand fixation service transferred from the northwest to the southeast as a whole, and the coldspots of sand fixation service mainly transferred from Qinshui Coalfield to Huoxi Coalfield and the Hedong Coalfield. (2) From the perspective of multiple ES, from 1986 to 2015, Qinshui Coalfield in the southeastern part of the study area, which belongs to the key ecosystem service function supply area, was a hotspot of multiple ecosystem services. Hedong Coalfield and Huoxi Coalfield were also coldspots of multiple ES. (3) From the perspective of different land use types, the hotspots of water yield and vegetation production of cultivated land accounted for a relatively high proportion, meaning their level of service was stronger than those of other services. The hotspots of soil conservation service for forest land and grassland also accounted for the largest proportion of hotspots, meaning the level of soil conservation was high, whereas the water yield of construction land was relatively high. The spatial distribution of ES in coalfields and their changes in terms of hotspots and coldspots were closely related to land use. Accordingly, maintaining a good

coupling state between land use and ES will be helpful to provide a scientific basis for regional ecological reconstruction and the sustainable development of coalfields.

Keywords: coalfields; ecosystem services; hotspot analysis; land use; spatial pattern

Introduction

The concept of ecosystem services was first proposed in the 1970s in the United Nations General Assembly report "The Human Impact on the Global Environment." Since then, Daily and Costanza have conducted specialized research on the concept, classification, and valuation of ecosystem services, clarifying the principles and methods of ecosystem service assessment from a scientific perspective and producing the most influential research results on ecosystem service value. This concept and theory have been rapidly applied to assessments of different scales and ecosystem types, becoming a research hotspot in international ecology. The concept of "hotspots" was initially proposed by Norman Myers and primarily used in biodiversity priority protection areas. Subsequently, scholars at home and abroad supplemented and improved this concept in the context of ecosystem services and applied it to ecosystem service research. For example, previous studies have used hotspot analysis and clustering algorithms to determine farmland protection priorities and functional zoning, while others have simulated the spatiotemporal patterns of hotspots and coldspots for multiple ecosystem services such as soil conservation, vegetation carbon sequestration, water yield, and flood regulation in the Yanhe River Basin. These studies have significantly promoted the identification of regional ecosystem service hotspots and the protection of key ecosystem services.

Coalfields represent typical environmentally vulnerable areas that exert significant effects on terrestrial ecosystems. They can conserve water sources, maintain soil and water, and support vegetation for windbreak and sand fixation, thereby providing a favorable ecological environment for humans. However, due to various human activities, the ecological environment has been severely damaged. The Shanxi Coalfield, which possesses one-quarter of the nation' s coal resources, has experienced particularly serious ecological destruction, with surface subsidence affecting human life and causing loss of habitat for flora and fauna, while cultivation has led to deforestation and soil loss. Currently, many scholars have participated in ecosystem service research, including studies on trade-offs and synergies, ecosystem service values, and changes in ecosystem services and their driving factors. However, research on coalfields as a special ecosystem is relatively scarce. Although some scholars have studied the impacts of mineral resource development on the ecological environment, most have only explored the degree of impact of mining life cycles on ecology from the perspective of land use change, vegetation net primary productivity (NPP), or normalized difference vegetation index (NDVI) spatiotemporal changes. Ecosystems that have been damaged generally cannot be comprehensively reflected through a single indicator. Therefore, multiple ecological service functions in ecosystem services must be comprehensively quantified and evaluated based on multi-source data to provide greater guidance for economic and environmental development in mining areas and land use reclamation decisions.

This study collected remote sensing imagery, meteorological data, and other data from Shanxi coalfields from 1986 to 2015. Using the ArcGIS hotspot analysis tool and spatial analysis methods, we analyzed and evaluated four ecosystem services: soil conservation, water yield, vegetation production, and sand fixation. Our aim is to provide a reference basis for land reclamation and ecological reconstruction in coalfields.

1. Materials and Methods

1.1 Study Area

Shanxi Province has abundant coal resources and is an important coal base in China, being one of the world' s major coal-producing regions. The Shanxi Coalfield is located between 110°14 -114°33 E and 34°34 -40°43 N and belongs to a typical continental climate with four distinct seasons. The annual average temperature ranges from 4 to 13°C, and the annual average precipitation ranges from 400 to 600 mm. Six major coalfields are distributed from north to south across the province: Datong, Ningwu, Hedong, Xishan, Huoxi, and Qinshui, with a total area of nearly 60,000 km^2, accounting for nearly 40% of Shanxi' s total area. Although coal mining has brought great benefits to the national economy, it has also caused significant damage to the regional ecological environment. The ecological environment of coalfields urgently needs improvement to better benefit humanity.

1.2 Data Sources

This study used multi-source datasets to estimate ecosystem services in coalfields, including land use, meteorological, soil, and DEM elevation data. The data sources and processing methods are detailed in .

** Data sources and processing methods**

Data Type	Data Source	Processing Method
Land use data	Resource and Environment Science and Data Center, Chinese Academy of Sciences	Extraction, clipping
Meteorological data (precipitation, temperature, etc.)	China Meteorological Data Sharing Service Network	Inverse distance weighting interpolation

Data Type	Data Source	Processing Method
Soil data	Cold and Arid Regions Science Data Center	Extraction of properties and calculation
DEM data	Resource and Environment Science and Data Center, Chinese Academy of Sciences	Filling depressions, flow direction analysis and correction

1.3 Methods

1.3.1 Ecosystem Service Estimation Based on the characteristics of the study area and data availability, we selected four services as the main ecosystem service types in the study area: soil conservation, water yield, vegetation production, and sand fixation. The calculation methods for each service were consistent across the years 1986–2015. Soil conservation service refers to the function of surface vegetation such as forests and grasslands to prevent and reduce soil erosion, estimated based on the InVEST model. The fundamental principle is to use meteorological data and soil data to calculate potential soil erosion and actual soil erosion, with the difference being the soil conservation amount. Water yield refers to the amount of water produced per unit area in a region within a unit time period, which plays a significant role in climate regulation and water resource supply. It was also estimated based on the InVEST model, using the water balance principle to quantitatively estimate the water supply capacity of different landscape types at the grid scale. The strength of vegetation production capacity was estimated using the CASA model. Sand fixation service refers to the blocking effect of ecosystem vegetation on wind and sand, estimated based on the RWEQ model by calculating the difference between potential sand fixation and actual sand fixation to estimate the weight of fixed sand particles.

1.3.2 Hotspot Analysis Ecosystem service provision hotspots (or coldspots) can be considered as areas where one or multiple ecosystem services have relatively high (or low) provision capacity compared to the average. Understanding ecosystem service hotspot areas can further clarify the spatial patterns among various ecosystem services and provide references for ecosystem conservation priority zoning. Based on the Getis-Ord Gi* tool in ArcGIS, we identified hotspot (or coldspot) regions for each service relative to the average value. The specific formula is as follows:

$$G_i^* = \frac{\sum_{j=1}^{n} w_{ij}x_j - \bar{x}\sum_{j=1}^{n} w_{ij}}{\sqrt{\frac{\sum_{j=1}^{n} x_j^2 - (\bar{x})^2}{n-1}} \cdot \sqrt{n\sum_{j=1}^{n} w_{ij}^2 - (\sum_{j=1}^{n} w_{ij})^2}}$$

where G_i^* is the hotspot (or coldspot) unit value; x_j is the attribute value of unit j; w_{ij} is the weight matrix; n is the total number of units; and $\bar{x}$ is the average of the total ecosystem services across all geographic spatial units.

2. Results

2.1 Spatial Pattern of Individual Ecosystem Service Hotspots (Coldspots)

In 1986, hotspots of soil conservation service were distributed in the northern part of Hedong Coalfield, the northeastern part of Qinshui Coalfield, and locally in the northern part of Ningwu Coalfield, accounting for 18.54% of the study area. Coldspots were concentrated in the southern part of Xishan Coalfield, the northern part of Huoxi Coalfield, and the western part of Qinshui Coalfield, accounting for 25.17% of the study area. By 2015, hotspots of soil conservation service were distributed in the northern part of Ningwu Coalfield, the northern part of Hedong Coalfield, and the northeastern part of Qinshui Coalfield, accounting for 18.54% of the study area. Coldspots were located in the southern part of Hedong Coalfield, the northern part of Huoxi Coalfield, and the southern part of Qinshui Coalfield, accounting for 23.84% of the study area. Overall, the proportion of hotspot area for soil conservation service did not change from 1986 to 2015, and the overall spatial distribution did not show significant changes either. However, the proportion of coldspot area decreased, and the spatial distribution mainly shifted from the central-southern region to the southwestern region [Figure 1: see original paper].

In 1986, hotspots of water yield service were mainly distributed in the northeastern and southeastern parts of Qinshui Coalfield, accounting for 17.88% of the study area. Coldspots were mainly distributed in Xishan Coalfield, the northern part of Huoxi Coalfield, and the western part of Qinshui Coalfield, accounting for 19.87% of the study area. By 2015, hotspots of water yield were distributed in the eastern part of Qinshui Coalfield and the northern part of Hedong Coalfield, accounting for 33.77% of the study area. Coldspots were scattered mostly in the northern part of Datong Coalfield, the central-southern part of Ningwu Coalfield, and the northeastern and central parts of Qinshui Coalfield, accounting for 15.23% of the study area. Coldspots were distributed in the northern part of Datong Coalfield, the central-southern part of Hedong Coalfield, Huoxi Coalfield, and the western part of Qinshui Coalfield, accounting for 19.87% of the study area. Overall, the proportion of hotspot area for water yield service increased from 1986 to 2015, with a more obvious increase in the eastern part of the study area. The proportion of coldspot area also increased, with the spatial distribution mainly increasing from the central region to the southwestern region [Figure 2: see original paper].

In 1986, hotspots of vegetation production service were distributed in the southern part of Hedong Coalfield and the southeastern part of Qinshui Coalfield, accounting for 18.54% of the study area. Coldspots were mainly distributed in the southern part of Ningwu Coalfield, most of Xishan Coalfield, and the western part of Qinshui Coalfield, accounting for 25.17% of the study area. By 2015, hotspots of vegetation production were distributed in most of Qinshui Coalfield, accounting for 17.22% of the study area. Coldspots were distributed in the northern part of Datong Coalfield, the northern part of Ningwu Coalfield, and most of Hedong Coalfield, accounting for 23.84% of the study area. Overall, the proportion of hotspot area for vegetation production service increased from 1986 to 2015, with the spatial distribution generally moving from the southeastern part to the northeastern part of Qinshui Coalfield. The proportion of coldspot area also increased, with the spatial distribution mainly moving from the central region to the western and northern regions [Figure 3: see original paper].

In 1986, hotspots of sand fixation service were mainly distributed in the central and northern parts of Hedong Coalfield and most of Ningwu Coalfield, accounting for 12.58% of the study area. Coldspots were mainly distributed in the central and northeastern parts of Qinshui Coalfield, accounting for 26.49% of the study area. By 2015, hotspots of sand fixation were distributed in the northeastern and central parts of Qinshui Coalfield, accounting for 15.23% of the study area. Coldspots were distributed in the central-southern part of Hedong Coalfield, most of Huoxi Coalfield, and the western part of Qinshui Coalfield, accounting for 18.54% of the study area. Overall, the proportion of hotspot area for sand fixation service also increased from 1986 to 2015, with the spatial distribution generally transferring from the northwestern part to the southeastern part. The proportion of coldspot area increased, with the spatial distribution mainly transferring from the southeastern part to the southwestern part [Figure 4: see original paper].

2.2 Spatial Pattern of Multiple Ecosystem Service Hotspots (Coldspots)

Multiple ecosystem service hotspots (coldspots) were obtained through ArcGIS analysis. The results are as follows: In 1986, areas with four service hotspots accounted for 7.28% of the study area, mainly distributed in the northern part of Hedong Coalfield and the northeastern part of Qinshui Coalfield. Areas with four service coldspots accounted for 11.92% of the study area, mainly located in the southern part of Xishan Coalfield and the western part of Qinshui Coalfield. Areas with three service hotspots accounted for 11.26% of the study area, mainly distributed in the northern part of Ningwu Coalfield, the central part of Hedong Coalfield, and the northeastern and southeastern parts of Qinshui Coalfield. Areas with three service coldspots accounted for 13.91% of the study area, mainly located in the southern part of Ningwu Coalfield, the northern part of Huoxi Coalfield, and the central-northern and central-southern parts of Qinshui Coalfield.

In 2015, areas with four service hotspots accounted for 8.61% of the study area, mainly distributed in the northeastern part of Qinshui Coalfield. Areas with four service coldspots accounted for 9.27% of the study area, mainly located in the central-northern part of Huoxi Coalfield and the western part of Qinshui Coalfield. Areas with three service hotspots accounted for 5.96% of the study area, mainly distributed in the northern part of Hedong Coalfield and the central part of Qinshui Coalfield. Areas with three service coldspots accounted for 16.56% of the study area, mainly located in the southern part of Datong Coalfield, the northern part of Ningwu Coalfield, the northern part of Hedong Coalfield, the central part of Xishan Coalfield, the southern part of Huoxi Coalfield, and the southern part of Qinshui Coalfield.

Overall, the proportion of area with four ecosystem service hotspots increased from 1986 to 2015, with a more obvious increase in the southeastern part. The proportion of area with four ecosystem service coldspots also increased, with a more obvious increase in the western part. The proportion of area with three ecosystem service hotspots decreased significantly, with a more obvious decrease in the southeastern part. The proportion of area with three ecosystem service coldspots increased, with a more obvious increase in the western part [Figure 5: see original paper] and [Figure 6: see original paper].

The distribution of hotspots and coldspots of four ecosystem services in different land use types in the study area is shown in [Figure 7: see original paper]. In 1986, the proportions of hotspot area for soil conservation, water yield, vegetation production, and sand fixation services in cultivated land were 11.74%, 20.69%, 12.14%, and 19.32%, respectively, among which vegetation production service had the highest hotspot area proportion. The proportions of coldspot area were 20.84%, 13.41%, 18.61%, and 28.29%, respectively, among which sand fixation service had the highest coldspot area proportion. In forest land, the proportions of hotspot area for the four ecosystem services were 16.57%, 8.02%, 29.96%, and 22.51%, respectively, among which vegetation production service had the highest hotspot area proportion. The proportions of coldspot area were 15.79%, 15.58%, 8.33%, and 33.86%, respectively, among which sand fixation service had the highest coldspot area proportion. In grassland, the proportions of hotspot area were 19.59%, 11.88%, 10.09%, and 16.20%, respectively, among which soil conservation service had the highest hotspot area proportion. The proportions of coldspot area were 21.45%, 29.93%, 17.50%, and 24.08%, respectively, among which water yield service had the highest coldspot area proportion. In construction land, the proportions of hotspot area were 16.90%, 21.99%, 11.06%, and 17.69%, respectively, among which water yield service had the highest hotspot area proportion. The proportions of coldspot area were 12.43%, 1.80%, 35.35%, and 27.02%, respectively, among which vegetation production service had the highest coldspot area proportion.

From 1986 to 2015, in cultivated land, the proportions of hotspot area for soil conservation and water yield services increased, while those for vegetation production and sand fixation services decreased. The proportions of coldspot area for water yield and sand fixation services increased, while those for soil conservation and vegetation production services decreased. In forest land, the proportions of hotspot area for all four ecosystem services increased, and except for water yield service, the proportions of coldspot area for the other three services all decreased. In grassland, except for soil conservation service, the proportions of hotspot area for the other three services all decreased, while the proportions of coldspot area for all four services decreased except for sand fixation service. In construction land, the proportions of hotspot area for all four services increased except for soil conservation service, and the proportions of coldspot area for all four services decreased.

3. Discussion

Coalfields are affected by human disturbances such as mineral resource exploitation, mining area land reclamation, and the Grain for Green project, as well as by natural conditions. For example, climate change directly affects biotic communities by altering temperature and precipitation levels, thereby further affecting ecosystem functions and services. Land use change also affects ecosystem composition and structure, causing changes in carbon cycling, water cycling, and other biophysical processes, ultimately altering ecosystem service supply levels. Hotspot analysis can specifically identify areas with high or low supply capacity. The hotspot and coldspot spatial distributions of the four ecosystem services obtained in this study showed differences. From the perspective of natural geographical conditions, the northern and southern parts of the study area have obvious climate differences due to latitudinal variation. The northern part is more windy and sandy, with lower temperatures and relatively less precipitation, while the southern part is the opposite. This makes the vegetation production function in the southern coalfields generally better than that in the northern part. Therefore, the southern region with more forest and grassland coverage, higher vegetation coverage, and better hydrothermal conditions is a hotspot aggregation area. Regarding land use types, areas with high vegetation cover also have higher service levels, especially compared with grassland and cultivated land. Forest land has higher biodiversity and soil and water conservation functions, so the southern region with extensive forest land distribution has become a hotspot area. For coldspot areas, as described by Naren et al., coal mining directly destroys surface soil layers and vegetation, resulting in lower soil conservation and hydrological regulation functions, thus becoming coldspot areas.

The multiple ecosystem service hotspot areas in the study area should be centrally utilized and protected, while in multiple service coldspot areas, ecological construction activities such as soil and sand fixation and afforestation should be intensified to improve ecological conditions and better serve humanity. The spatiotemporal patterns of ecosystem services in coalfields and their changes are closely related to land use and other human disturbance activities and surface cover conditions. Therefore, sustainable land use development strategies should be adopted to achieve efficient coupling between land use and ecosystem services in coalfield areas.

4. Conclusion

To understand the spatial distribution of high and low values of ecosystem services in coalfields with significant human disturbance and to provide a scientific basis for ecological protection or key ecological restoration area identification in coalfields, this study systematically investigated the spatiotemporal distribution patterns of ecosystem service hotspots and coldspots in Shanxi coalfields. Using ArcGIS hotspot analysis and spatial analysis methods from the perspectives of individual and multiple ecosystem services and different land use types, we revealed the hotspot and coldspot spatial distribution patterns and their changes of four ecosystem services (soil conservation, water yield, vegetation production, and sand fixation) in the study area from 1986 to 2015. The main conclusions are as follows:

(1) The water yield and vegetation production services of cultivated land were relatively high, with stronger service levels than other services. Forest land and grassland had the largest hotspot area for soil conservation service, belonging to high-function areas for soil conservation. Construction land had relatively high water yield service.

(2) The spatiotemporal patterns of ecosystem services in coalfields and their changes were closely related to land use and other human disturbance activities and surface cover conditions. Therefore, sustainable land use development strategies should be adopted to achieve efficient coupling between land use and ecosystem services in coalfield areas.

This study systematically investigated the spatial distribution patterns of ecosystem service hotspots and coldspots in the six major coalfields of Shanxi, identified high and low functional areas of ecosystem services, and discussed the factors causing their spatial differences. However, it remains a challenge to comprehensively understand the relationships among multiple ecosystem services for ecological sustainable development. Due to various reasons, measured data for ecosystem service estimation are lacking, and model-based estimation still has certain accuracy issues. Moreover, because the relationships among ecosystem services are complex, this study only analyzed the hotspot and coldspot spatial patterns of a limited number of ecosystem services. Different ecosystem services in different regions are subject to interactive influences of various factors such as natural geographical conditions and human activities, so the results will vary. A more comprehensive and in-depth understanding requires investigation at finer scales.

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