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Integrating the impacts of vegetation coverage on ecosystem services to determine ecological restoration targets for adaptive management on the Loess Plateau, China

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Abstract

Achieving sustainable resource management is essential to address the rising demand for ecosystem services. The absence of targeted vegetation restoration based on ecological function positioning has, nevertheless, made it challenging to effectively combat the ecological decline. This study attempted to classify four dominant ecological function areas based on the assessment of water conservation, soil retention, habitat quality, and food supply and determined the vegetation coverage threshold by exploring the trade-offs among ecosystem services and constraint effects between ecosystem services and vegetation coverage. The results highlighted the impacts of ecosystem services on vegetation coverage across the years 1990, 2000, 2010, and 2020 and established differentiated ecological restoration targets. The optimal vegetation coverage in the water conservation area was found to be 58%–63%, in the soil retention area was 52%–56%, in the food supply area was 34%–40%, and in the habitat quality area was 65%–70%. Finally, the study identified the subwatersheds with reasonable vegetation coverage, excessive restoration, and those that failed to reach the optimal vegetation coverage to develop targeted restoration strategies for each subwatershed according to its unique vegetation conditions. This study provides valuable insights into the specification of differentiated vegetation coverage targets and serves as a useful tool for more effective ecosystem planning and management.

KEYWORDS
adaptive management, constraint effect, ecological restoration, ecosystem services, threshold effect, trade-offs

1 | INTRODUCTION

Against the backdrop of a fragile social-ecological system, widespread ecological degradation, and loss of ecosystem services, a series of eco-spatial planning initiatives seek to leverage ecological engineering to adjust land use patterns and achieve sustainable ecological benefits (K. Zhang et al., 2019), but the ecological deficit continues to grow. Optimizing one ecological target may result in the weakening of another, leading to conflicting relations between targets (Griggs et al., 2017; Nilsson et al., 2016). This phenomenon is attributed to both inherent design defects and the severe impacts of human activities (S. X. Cao, 2011); thus, there is an urgent need for action to guide the regular operation of ecosystems to meet the demand for ecosystem services (Gomes et al., 2020).

The Loess Plateau has suffered from some of the most extreme instances of soil erosion and ecological degradation of any region in the world (X. H. Yang et al., 2020). China has taken active measures in response to the challenging ecological problems by implementing extensive vegetation restoration initiatives in the Loess Plateau, with the most notable being the "Grain for Green Program" (Tang et al., 2022). The previous studies found that vegetation restoration initiatives increased soil retention capacity, reduced the loss of water through surface runoff, and created habitats for a wide range of plant and animal species (J. J. Li et al., 2017; Long et al., 2006). Excessive restoration may, however, consume a large amount of water resources and result in depletion of soil moisture (Ma et al., 2021), which indicates that an increase in vegetation coverage does not always result in a corresponding increase in ecosystem services. It is noted the implementation path that clearly focuses on specific vegetation coverage targets can achieve the desired results of the restoration initiative (Han et al., 2021; C. Q. Zhang & Li, 2016), which requires addressing the mismatch between the desire to restore vegetation and the extent of ecological benefits.

The fundamental aspect of ecological restoration planning is to identify the targets for restoration and to maximize the combined benefits of multiple ecosystem services (Sampson et al., 2021). One of the key challenges is determining the optimal vegetation coverage that will not compromise ecosystem services. Relevant studies have shown that the interaction of ecosystem services prevents the simultaneous promotion of multiple ecological benefits (Feng et al., 2020; Y. C. Wang & Li, 2022). This trade-off between ecosystem services highlights the importance of determining the optimal vegetation coverage that balances ecological, social, and economic considerations (Howe et al., 2014; Martin-Lopez et al., 2014). But it can only reveal the extent of trade-offs among ecosystem services and cannot quantitatively describe the point of inflection in their relationship changes (Feng et al., 2020). The relationship among ecosystem services is nonlinear and cannot be simply described as a synergy or trade-off (Jiang et al., 2019). The reason is that there can be an initial synergistic relationship (positive correlation), which is then followed by a trade-off relationship (negative correlation). The combination of trade-offs and constraint effects of ecosystem services can provide both qualitative and quantitative descriptions of their relationships. Previous studies have investigated the relationship between vegetation coverage and ecosystem services, exploring how changes in vegetation coverage can impact the provision of ecosystem services on a specific time scale (T. Li et al., 2019; Y. X. Liu et al., 2019), but this relationship may differ on larger time scales, such as annually (Meng et al., 2018; Zhao et al., 2017). The interplay between vegetation coverage and ecosystem services is influenced by climatic factors and vegetation activity, resulting in annual variations that require further investigation. Such research can serve as a valuable case study for understanding the complexity of ecosystems and developing effective policies and measures to enhance ecosystem services.

The constraint effect between ecosystem services and vegetation coverage can, furthermore, assist in establishing optimal restoration targets and strategies and guiding the practical implementation of vegetation restoration, which has been reported in previous studies (Q. Cao et al., 2015; Lester et al., 2013). According to Jiang et al. (2019), there existed an upper limit of 50% for vegetation coverage to control soil erosion, and the maximum soil retention sharply decreased with increasing vegetation coverage beyond this threshold value. S. K. Li et al. (2021) found that a vegetation coverage of 55% or more was needed to reduce soil wind erosion, with little effect observed below 9%. J. Li (2021) employed a linear programming model to determine the optimized vegetation pattern that would maximize the ecological productivity, which was found to be composed of 86% of shrubs and 14% of grass. These studies have demonstrated the existence of threshold effects, where even slight changes in vegetation coverage can lead to significant variations in ecosystem services once these thresholds are reached. The identified thresholds are, however, only general and cannot account for spatial and functional variations; thus, relying on a "one-size-fits-all" approach to restoration efforts, referring to applying the same restoration targets across the entire region or ecosystem without considering spatial and functional variations, may result in ineffective restoration outcomes and miss opportunities to maximize the provision of ecosystem services in restoration implementation (Jiang et al., 2020; Ma et al., 2021). It illustrates the necessity of establishing differentiated ecological restoration targets for vegetation coverage, and the restoration policies for different areas may be adapted based on the existing vegetation conditions.

To tackle the challenges, this study aims to raise awareness of the importance of considering spatial and functional heterogeneity in ecological restoration and attempts to identify the threshold of ecosystem services on vegetation coverage to inform ecological restoration strategies that cater to the specific requirements and functions of each subwatershed. Restoration efforts can be directed towards subwatersheds that have yet to meet restoration targets, while early warnings can be issued for subwatersheds that are at risk of excessive restoration to prevent undue stress on the ecosystem. The specific objectives of this study were to (1) analyze the spatial and temporal variation of vegetation coverage and ecosystem services, including water conservation, soil retention, habitat quality, and food supply for the years 1990, 2000, 2010, and 2020; (2) establish differentiated ecological restoration targets for dominant ecological function areas by exploring the relationships between ecosystem services and vegetation coverage; (3) evaluate whether subwatersheds have been over-restored or under-restored to provide a theoretical reference for ecosystem-based adaptive management.

2 | MATERIALS AND METHODS

2.1 | Study area

Jingle County (38°08′ N–38°40′ N, 111°43′ E–112°20′ E) is located in the eastern part of the Loess Plateau in China (Figure 1). The study area is characterized by a river between two mountains on either side, ranging from 1118 to 2396 m above sea level. The region covered by forest and grassland is approximately 1387.33 km^2, which accounts for 68.14% of the total area. As an important ecological barrier of the North China Plain, it is listed as a functional area for biodiversity conservation in ecological function regionalization; however, it suffers

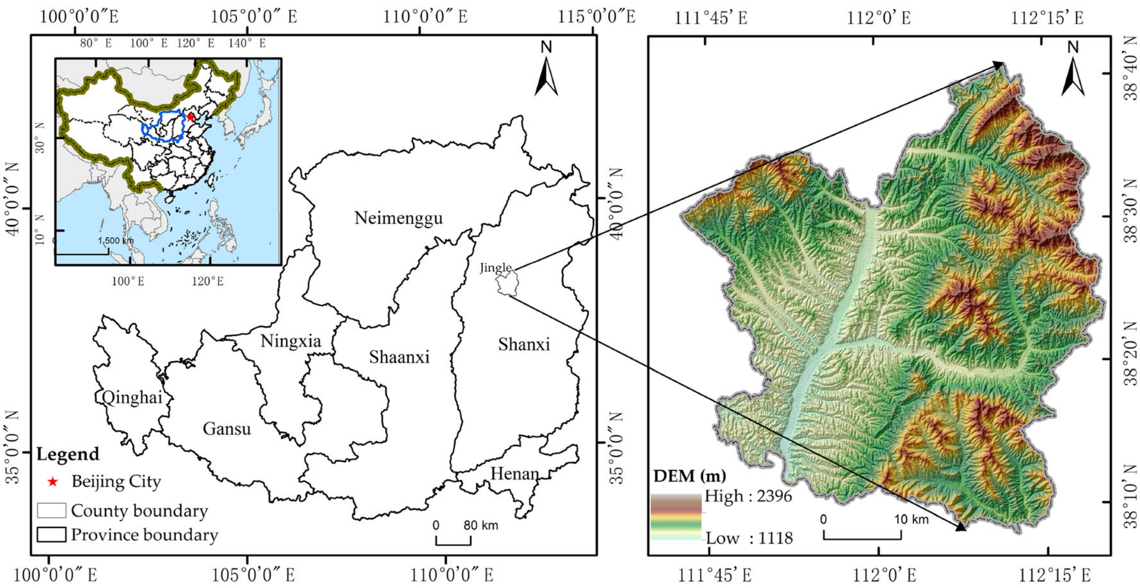

FIGURE 1 Geographical location of Jingle County. DEM, digital elevation model. Wiley acknowledges that the borders within the figure are subject to multiple territorial claims. [Colour figure can be viewed at wileyonlinelibrary.com]

TABLE 1 Description of the dataset used in this study.

Data types	Data description	Data type	Resolution	Data sources
Remote sensing images	Landsat TM and ETM + images for the years 1990, 2000, 2010, and 2020	Raster	30 m	Geospatial Data Cloud (http://www.gscloud.cn/)
Meteorological data	Precipitation for the year 1990, 2000, 2010, and 2020 Temperature for the years 1990, 2000, 2010, and 2020	Point	—	China National Meteorological (http://cdc.cma.gov.cn)
Digital elevation model	The Shuttle Radar Topography Mission (SRTM) digital elevation model	Raster	30 m	Geospatial Data Cloud (http://www.gscloud.cn/)
Soil data	Harmonized World Soil Database	Raster	1 km	International Institute for Applied Systems Analysis and the Food and Agriculture Organization (http://webarchive.iiasa.ac.at/Research/LUC/External-World-soil-database)

from serious soil erosion due to the seasonal concentration of precipitation and the looseness of the soil. Besides, the 564.51 km^2 of farmland supports a population of nearly 120,000. Because of poverty, the local people mainly rely on agricultural reclamation for their livelihoods, which has a negative impact on the environment. Meanwhile, the harsh environment has led to more poverty, so they were trapped in a circle of poverty and poor ecology, facing the conflicting trade-offs between ecological conservation and farmland reclamation (Zhou et al., 2014).

2.2 | Data collection and preprocessing

Given the input parameters required by ecosystem services models, we collected multisource datasets, including remote sensing images, meteorological data, digital elevation model (DEM), and soil data for model calculation (Table 1). The data were preprocessed as follows:

1. Meteorological data were sourced from weather stations in Jingle County and interpolated using the Kriging method into grids for the calculation of ecosystem services.
2. The normalized difference vegetation index (NDVI) and land use/cover map were obtained from remote sensing images. NDVI, obtained by the maximum synthesis method, can further estimate vegetation coverage using the dimidiate pixel model. The formulas of NDVI and vegetation coverage can be found in Gutman and Ignatov (1998) and Carlson and Ripley (1997), respectively.
3. Subwatershed was obtained by extracting terrain features from DEM using the hydrological analysis module of ArcGIS 10.3 (Esri, USA).

4. All data were finally resampled to 100 m resolution before they were input into the assessment models.

2.3 | Overall workflow

The implementation of artificial vegetation restoration measures could significantly impact local ecosystems by altering the composition, configuration, and distribution of land use/land cover (S. Li et al., 2016). The nonlinear changes in ecosystem services and vegetation coverage may reflect the existence of threshold effects (Berdugo et al., 2020; Ma et al., 2021). When thresholds were reached, small changes in vegetation coverage could lead to large changes in ecosystem services (Berdugo et al., 2020); thus, determining an optimal vegetation coverage is critical for the success of territorial ecological restoration planning. This will establish a theoretical basis for practical implementation and enable the formulation of region-specific restoration targets that consider the distinctive ecological features of each subwatershed. First, after the assessment of ecosystem services and vegetation coverage, we divided the dominant ecological function areas to determine ecological restoration orientations. Second, given the interactions between paired ecosystem services and vegetation coverage, the target for ecological restoration was determined by the vegetation coverage thresholds for each dominant ecological function area. Third, regarding the implications for ecological restoration, practitioners can identify the ecosystems to be restored by determining the conservation functions of different ecological planning areas, allowing for more scientific and adaptive ecosystem management for a given conservation or development policy.

2.4 | Assessment of four ecosystem services

Spatial planning for a specific area necessitates the selection of representative and appropriate ecosystem services. The first consideration in our study was to ensure the chosen ecosystem services accurately reflect the ecological issues affecting the Loess Plateau. This region was struggling with a severe environmental crisis, including soil erosion, insufficient water resources, and declining biodiversity, all posing a significant threat. The second factor was the prioritization of key ecosystem services listed in the Ecological Function Zoning. Second, we prioritized the key ecosystem services specified in the Ecological Function Zoning. Our focus was on the upstream region of the Fenhe River, emphasizing the importance of preserving water resources. The area has also been listed as a biodiversity conservation zone and an agricultural development base for corn and beans in Shanxi Province within the Ecological Functional Zoning. Last, the data used in our analysis was both accessible and feasible. Water conservation and soil retention as the regulation service, habitat quality as the support service, and food supply as the supply service were, thus, selected as the evaluation objects. Water conservation, soil retention, and habitat quality were obtained by the integrated valuation of ecosystem services and trade-offs (InVEST) model (Redhead et al., 2016), and food supply was obtained by the corresponding relationship between land use types and food output values for the years 1990, 2000, 2010, and 2020. InVEST models have been parameterized and tested in China (Hao et al., 2019; Ouyang et al., 2016; Peng et al., 2017), and the detailed calculation process used for the quantitative evaluation of ecosystem services has been described in our previous study (He et al., 2020).

The identification of areas with dominant ecological functions was used to clarify the future target and extent of ecological restoration. After standardizing water conservation, soil retention, habitat quality, and food supply, respectively, four ecosystem services were summed for each subwatershed and ranked in descending order, with the highest value representing the dominant ecosystem service.

2.5 | Trade-off and synergy analysis among ecosystem services

The purpose of trade-offs and synergies analysis was to judge the relationships among ecosystem services to provide guidance for the constraint effects adopted in different dominant ecological function areas. To assess the spatial correlation of ecosystem services, we employed both global spatial autocorrelation (Anselin, 1995) and local spatial autocorrelation (Wartenberg, 1985), taking into account the spatial dependence of ecosystem services.

2.6 | Constraint effects analysis between ecosystem services and vegetation coverage

Under the interaction of multiple influencing factors, the relationship between influencing factors takes the form of scattered clouds (Blackburn et al., 1992; Thomson et al., 1996). The constraint line refers to the boundary of the scattered clouds of two variables, which is defined as the maximum point or range of the dependent variable that can be obtained under the limitation of impact factors (Qiao et al., 2019) (Figure 2). To date, the extraction methods of constraint lines mainly include parameters, scatterplot grids, quantile regression, and piecewise quantile regression. The piecewise quantile regression method first proposed by Mills et al. (2006), which can extract the boundary around the scattered clouds, has been proven to be an effective method.

First, this study divided the range of x-axis values into 30 equal intervals and determined the corresponding y-value for each column. To eliminate the influence of outliers, we selected the 99.9th quantile of the corresponding variable on the y-axis to obtain the boundary point and fitted a function between x and y. Finally, based on the shape of scattered clouds and the degree of fit R^2, this study

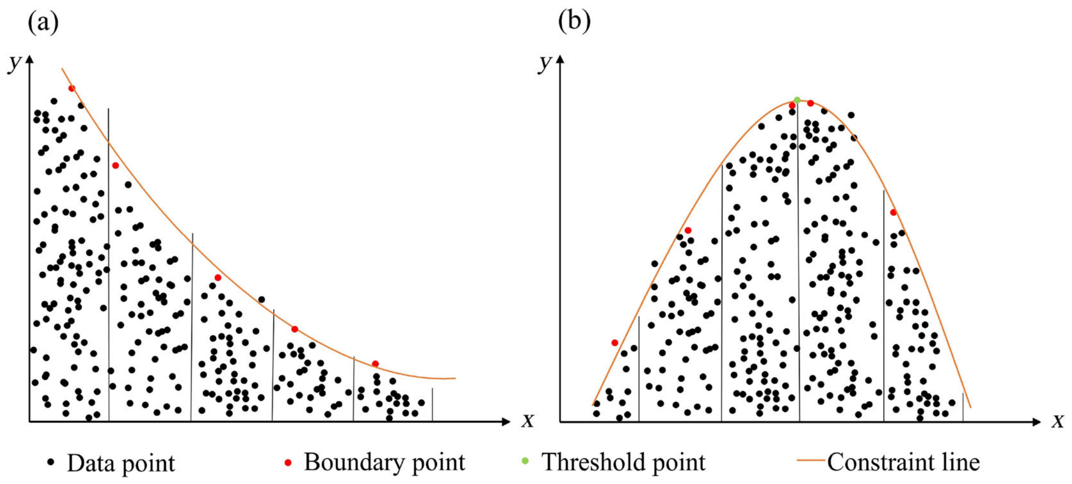

FIGURE 2 The diagrammatic map of constraint lines. [Colour figure can be viewed at wileyonlinelibrary.com]

determined the type of constraint line and identified the threshold when the constraint line exists. The above steps were performed in the MATLAB platform (version 2021b). By employing the constraint line approach, this study uncovered the constraint effect among ecosystem services and also examined the relationships between ecosystem services and vegetation coverage; furthermore, the turning point of constraint effects among variables was recognized as the threshold value, which refers to the point at which ecosystem services undergoes a significant change due to an increase of vegetation coverage. This study attempted to establish the varying ecological restoration target for dominant ecological function areas by applying the threshold to the policy guidelines. If the subwatershed's vegetation coverage fell below the threshold, efforts should be made to increase it to maximize the synergistic benefits of ecosystem services. On the other hand, if the threshold was exceeded, it served as an alert to prevent excessive restoration and allowed for timely adjustments to restoration policies.

3 | RESULTS

3.1 | Spatial and temporal variation of ecosystem services and vegetation coverage

3.1.1 | Spatial and temporal variation of ecosystem services

Figure 3 shows the pixel-level temporal and spatial differentiation of water conservation, habitat quality, soil retention, and food supply for the years 1990, 2000, 2010, and 2020. Water conservation had a similar total and spatial distribution in 2020 and 1990, with amounts of 1.820×10^8 and 1.806×10^8 m^3, respectively. Forests and grasslands dominated the surface, favorably affecting water storage, with a mainly distributed range of 60 mm to 90 mm. Water conservation was, however, lower in 2000 and 2010, which was 1.315×10^8 and 1.274×10^8 m^3, respectively. The concentration of water conservation was primarily between 30 and 60 mm due to the impairment of water retention capacity caused by the conversion of forests to grasslands and croplands. The average habitat quality increased from 0.736 in 1990 to 0.766 in 2020, with the lowest value recorded in 2000. The pattern remained relatively unchanged over time, and habitat quality in the central flat area was lower due to its extensive cultivation. Soil retention in most areas showed an increasing trend, owing to the implementation of ecological programs in the past 30 years, and it changed from 1.310×10^8 t in 1990 to 2.626×10^8 t in 2020. Spatially, soil retention was weaker in valleys, stronger on slopes, and higher in areas with minimal human activity. Although ecological policies such as Grain for Green Program continued to encroach on cropland, food supply in most areas exhibited an upward trend, with its concentration growing on a larger scale, possibly as a result of both the impact of climate change and advancements in agricultural technology.

To establish differentiated restoration targets, we partitioned four dominant ecological function areas based on the results of the ecosystem services assessment. It was observed that the spatial distribution of dominant ecological function areas was relatively concentrated (Figure 4). The areas with dominant ecological functions in water conservation, habitat quality, soil retention, and food supply were divided into 12, 13, 6, and 13 subwatersheds, respectively.

3.1.2 | Spatial and temporal variation of vegetation coverage

Figure 5 illustrates the spatial distribution of vegetation coverage in 1990, 2000, 2010, and 2020, with corresponding values of 56.5%, 43.28%, 60.56%, and 52.19%, respectively. The findings indicated a pattern of decreasing vegetation coverage in 2000, followed by

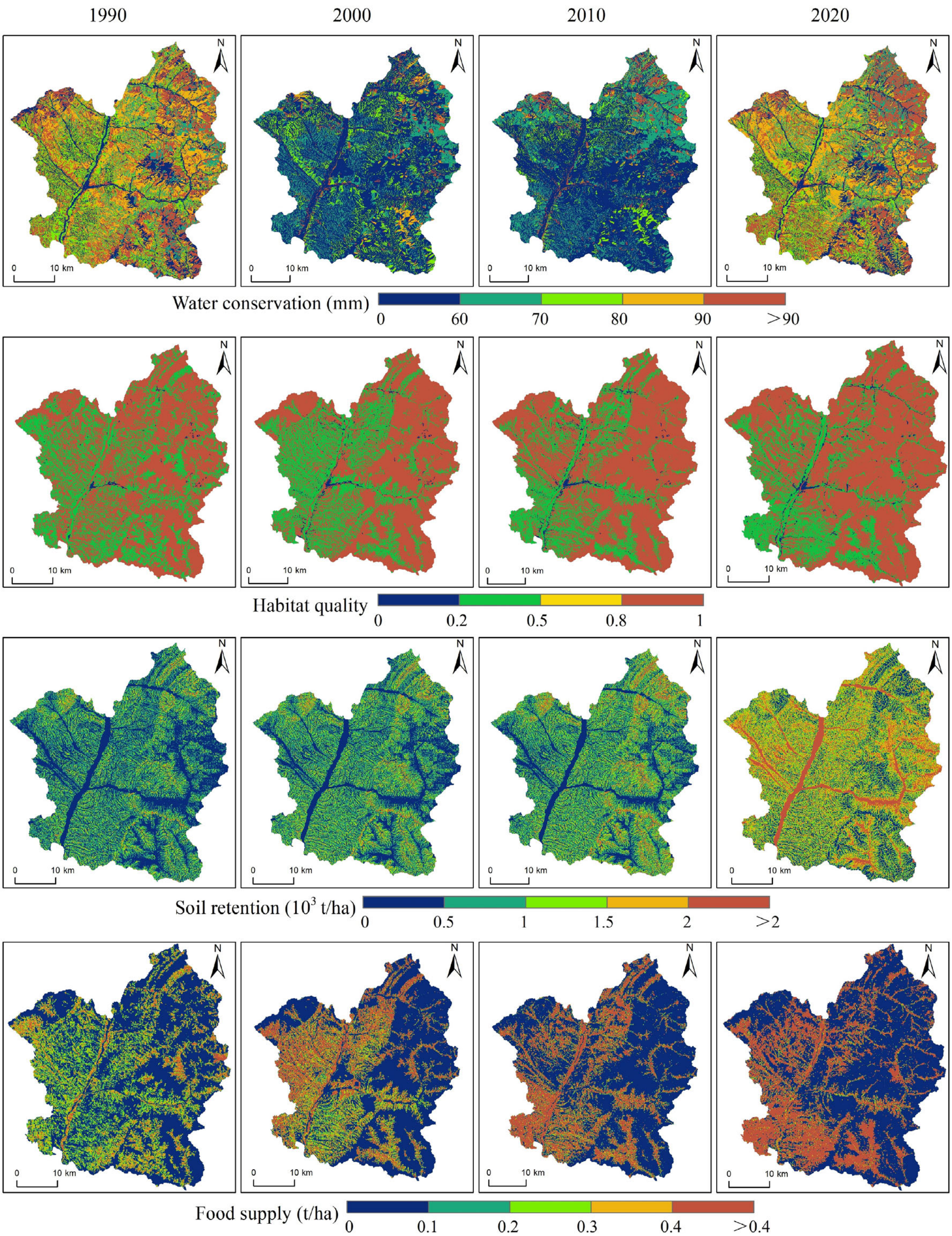

FIGURE 3 The temporal and spatial distribution of four ecosystem services in 1990, 2000, 2010, and 2020. [Colour figure can be viewed at wileyonlinelibrary.com]

a sharp increase in 2010 and a subsequent decrease in 2020, with the peak occurring in 2010. During this period, the majority of areas exhibited vegetation coverage values above 30%. The distribution area with vegetation coverage greater than 60% showed a trend of high value to low value in the years 2010, 1990, 2020, and 2010, respectively. In terms of spatial distribution, the eastern areas exhibited higher vegetation coverage, whereas the central areas showed more severe degradation.

3.2 | Relationships between ecosystem services and vegetation coverage

3.2.1 | Trade-offs between paired ecosystem services

As shown in Table 2, Global Moran's *I* showed two of six pairs of ecosystem services were negatively correlated (soil retention-food supply and food supply-habitat quality), and four were positively correlated (water conservation-soil retention, water conservation-food supply, water conservation-habitat quality, and soil retention-habitat quality); however, water conservation-food supply and water conservation-habitat quality had the weaker synergy, and food supply-habitat quality had the strongest trade-offs.

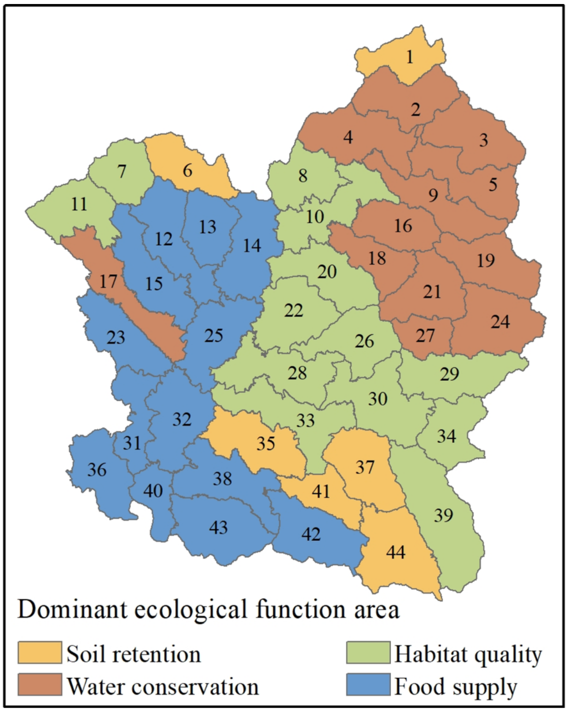

FIGURE 4 Spatial distribution map of dominant ecological function area in Jingle County. [Colour figure can be viewed at wileyonlinelibrary.com]

To better understand the trade-off effect, this study analyzed the spatial heterogeneity among ecosystem service pairs using LISA agglomeration maps (Figure 6). Then, this study calculated the areas of trade-off and synergy at the grid scale. The proportion of synergistic areas of water conservation-soil retention, water conservation-food supply, water conservation-habitat quality, soil retention-food supply, soil retention-habitat quality, and food supply-habitat quality was 20.23%, 18.07%, 18.11%, 11.74%, 25.92%, and 2.89%, respectively. The proportion of trade-off areas was 13.58%, 12.52%, 20.94%, 18.84%, 13.14%, and 36.17%. Soil retention-habitat quality showed the largest synergistic area, while food supply-habitat quality presented the largest trade-off area. The spatial distribution of water conservation-soil retention, water conservation-habitat quality, and soil retention-habitat quality revealed a synergistic effect along both sides of the main stream of the Fenhe River. In contrast, the trade-off effect of food supply-habitat quality was more significant in lower altitude areas where crops grew, such as in the southwest of the study area.

Six pairs of ecosystem services were calculated with subwatersheds as units to determine the optimal vegetation coverage for each subwatershed. As shown in Figure 7, the subwatersheds had different trade-offs among ecosystem service pairs. In 93% of the subwatersheds, food supply-habitat quality had the largest trade-off, which was also confirmed by the correlations of ecosystem services across the study area. The pair of ecosystem services with the largest synergy was soil retention-habitat quality in 50% of watersheds and water conservation-soil retention in 27% of subwatersheds. In the four dominant ecological function areas, the trade-offs and synergistic pairs of ecosystem services were the same, but the correlations were different. In food supply areas, the strongest trade-off effect was between water conservation and habitat quality, and the strongest synergistic effect was between water conservation and food supply.

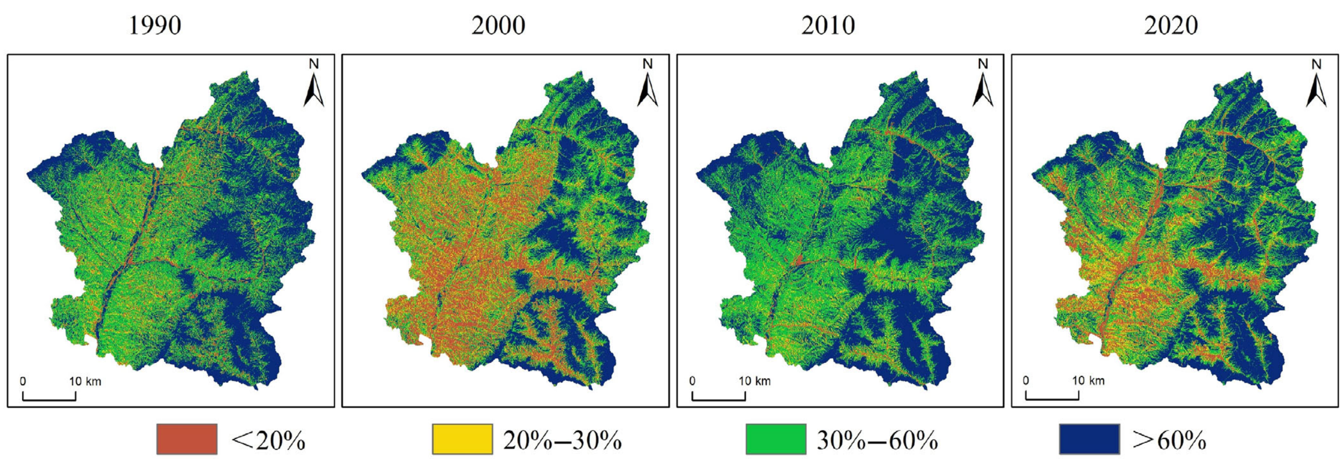

FIGURE 5 The temporal and spatial distribution of vegetation coverage in 1990, 2000, 2010, and 2020. [Colour figure can be viewed at wileyonlinelibrary.com]

TABLE 2 Bivariate global Moran's *I* Index between water conservation, soil retention, habitat quality, and food supply.

Paired ecosystem services	*p* Value	*Z*	Moran's *I*
Water conservation–soil retention	0.001	115.241	0.136
Water conservation–food supply	0.001	3.464	0.034
Water conservation–habitat quality	0.001	46.947	0.054
Soil retention–food supply	0.001	−114.882	−0.136
Soil retention–habitat quality	0.001	204.292	0.240
Food supply–habitat quality	0.001	−391.909	−0.551

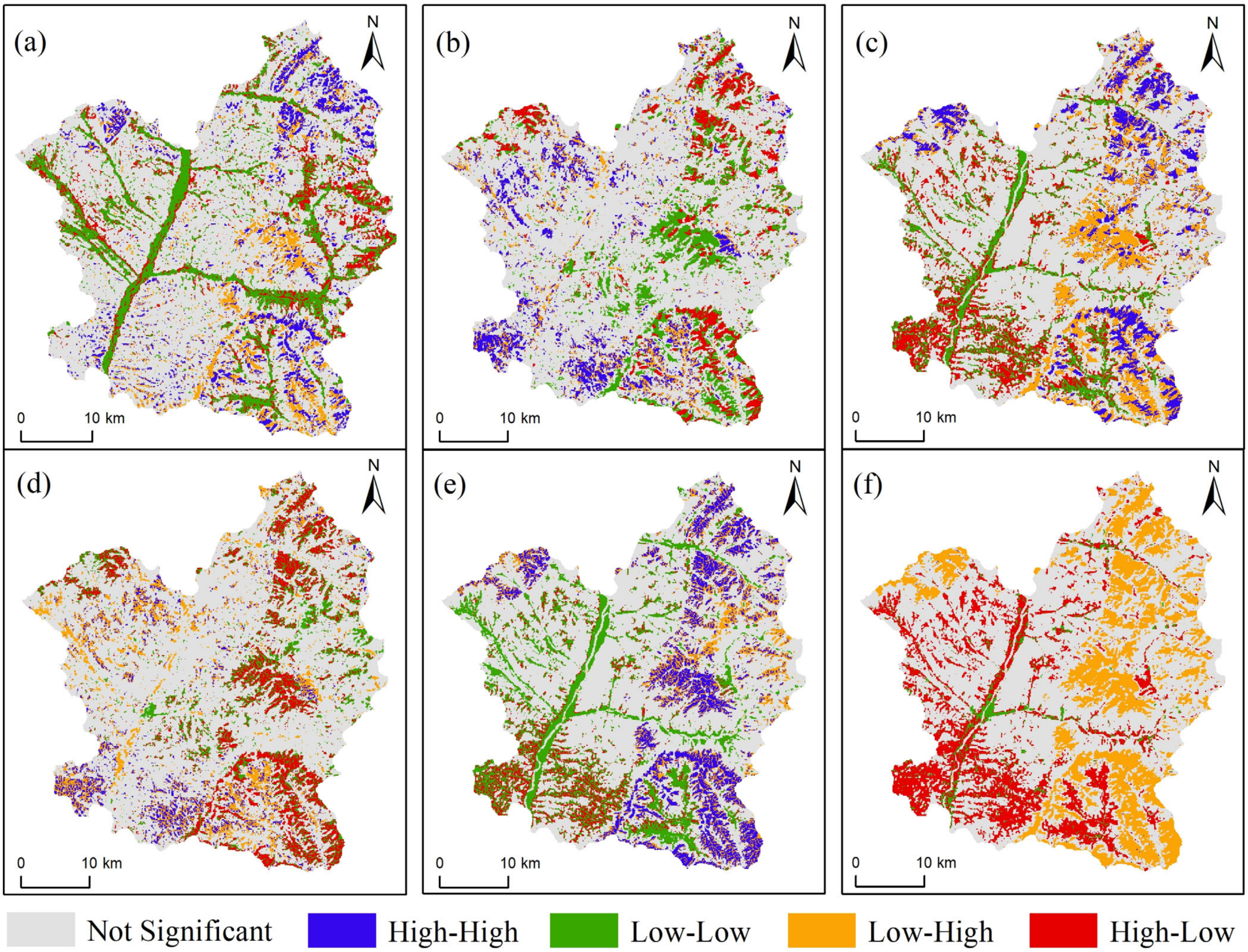

FIGURE 6 LISA agglomeration maps of bivariate spatial autocorrelation of ecosystem services: (a) water conservation and soil retention; (b) water conservation and food supply; (c) water conservation and habitat quality; (d) soil retention and food supply; (e) soil retention and habitat quality; (f) food supply and habitat quality. [Colour figure can be viewed at wileyonlinelibrary.com]

The strongest trade-off effects in soil retention areas were between soil retention and food supply and between habitat quality and food supply, while the largest synergistic effect was between soil retention and habitat quality. This suggests that this area should better deal with the relationship between habitat quality and food supply, while less attention needs to be paid to the relationship among other ecosystem services.

3.2.2 | Constraint effects of ecosystem services and vegetation coverage

The trade-off effect qualitatively reveals the negative relationship among ecosystem services, but the constraint effect provides a quantitative description of their relationship trend. This study extracted the constraint lines among ecosystem services and between

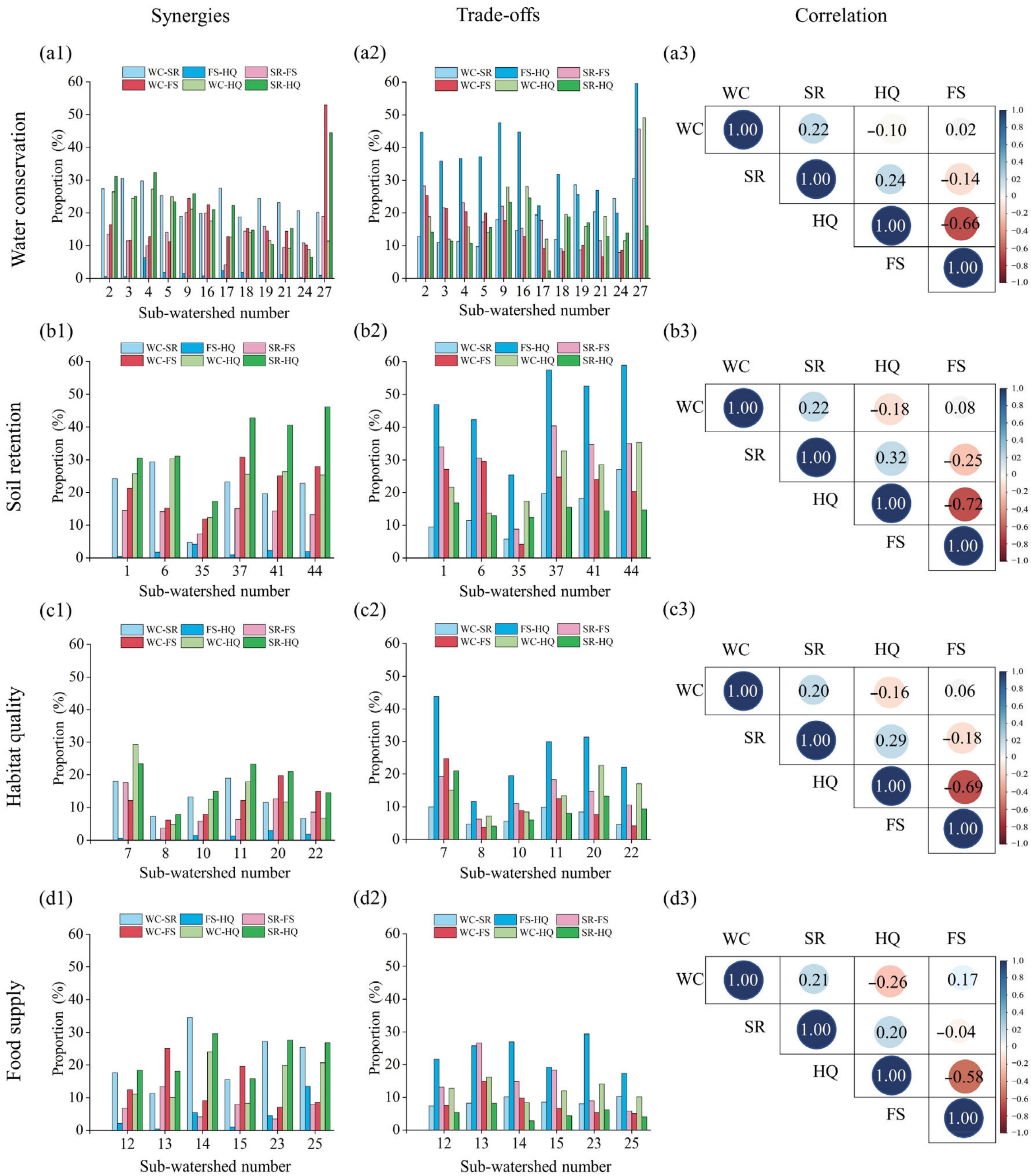

FIGURE 7 The trade-offs, synergies, and correlation relationships of WC (water conservation), SR (soil retention), HQ (habitat quality), and FS (food supply) in 44 sub-watersheds and four dominant ecological function areas. [Colour figure can be viewed at wileyonlinelibrary.com]

ecosystem services and vegetation coverage in 1990, 2000, 2010, and 2020, as shown in Figure 8. The constraint curve of vegetation coverage and water conservation was a downward parabola, with vertices at (65%, 210 mm) in 1990, (58%, 153 mm) in 2000, (75%, 157 mm) in 2010, and (63%, 226 mm) in 2020. The relationship between vegetation coverage and soil retention was depicted by an exponential constraint curve, which improved as vegetation coverage increased. The greatest impact was observed in 2010 when the slope was steepest. The relationship between vegetation coverage and habitat quality followed a positive convex pattern. The vegetation coverage and food supply showed positive convexity in 1990 and 2020 and a downward-opening parabolic shape in 2000 and 2010, with vertices at (40% 1.1 t ha^{-1}) and (65%, 1.3 t ha^{-1}), respectively. Food supply increased with increasing vegetation coverage before decreasing gradually. The relationship between food supply and soil retention was negative and concave, meaning that an increase in food supply resulted in a decrease in soil retention. The constraint curve between water conservation and food supply was negatively convex during 1990 and 2000 but took the form of a downward-opening parabola in 2010 and 2020, with the vertex points of (44 mm,

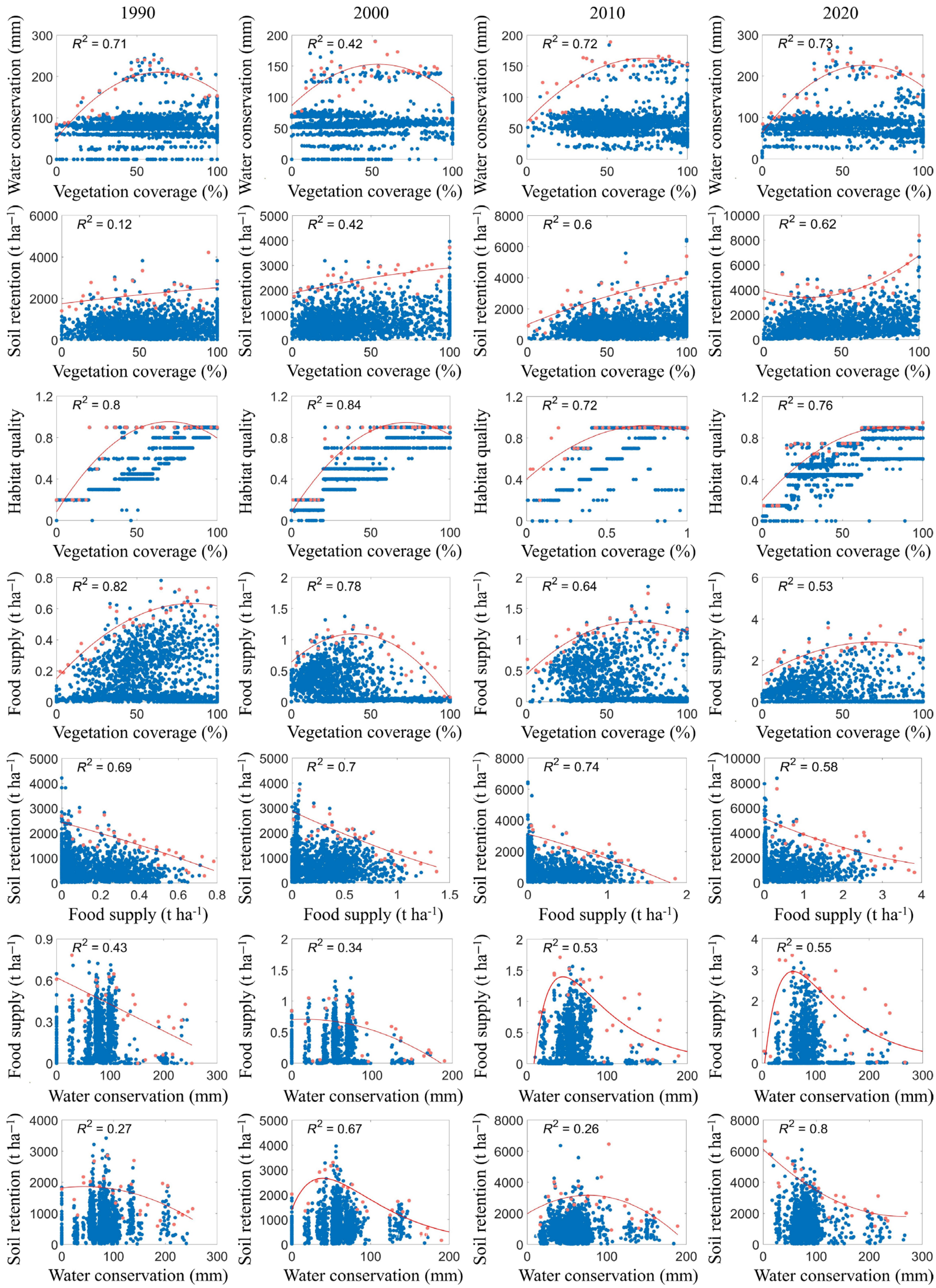

FIGURE 8 Scatter plots (blue), boundary points (red), and constraint lines (red) of paired ecosystem services and vegetation coverage. R^2 represents the goodness of fit. [Colour figure can be viewed at wileyonlinelibrary.com]

1.4 t ha^{-1}) and (57 mm, 2.9 t ha^{-1}), declining rapidly after exceeding the vertex. The constraint curve between water conservation and soil retention in the years 1990, 2000, 2010, and 2020, respectively, was negatively convex, a downward-opening parabolic shape with a vertex of (37 mm, 2600 t ha^{-1}), a downward-opening parabolic shape with a vertex of (80 mm, 3100 t ha^{-1}), and negatively concave.

3.3 | Determination of ecological restoration targets

The changing trends of the constraint line illustrated the threshold phenomenon. For the water conservation area, in 1990, when vegetation coverage was between 50 and 80 mm, water conservation reached its maximum at 200–210 mm. Given the synergistic effects among ecosystem services, water conservation should minimize trade-offs with food supply and maximize synergy with soil retention. A strong negative correlation existed between water conservation and food supply, and when water conservation was greater than 90 mm, soil retention decreased as water conservation increased. To minimize the trade-off, 63% of vegetation coverage corresponding to 200 mm of water conservation was the optimal target for ecological engineering implementation. In 2000, the relationship between vegetation coverage and water conservation showed a downward-opening parabola, with a vertex at 58% of vegetation coverage and 153 mm of water conservation. When water conservation was between 0 and 58 mm, soil retention increased with increasing water conservation and then showed a decline, so the optimal vegetation coverage was 58%. In 2010, when vegetation coverage was between 60% and 80%, water conservation reached the maximum value of 155–160 mm. Within this range, water conservation and food supply and water conservation and soil retention were negatively correlated. To minimize the trade-off, the target value for water conservation was set at 155 mm, which corresponds to 60% of vegetation coverage. Similarly, in 2020, when vegetation coverage was between 58% and 68%, the maximum water conservation was recorded at 220–226 mm. Conserving water conservation at 220 mm can minimize trade-offs with food supply and soil retention, with corresponding vegetation coverage of 58%.

Ecological restoration in the soil retention area should aim to minimize trade-offs between soil retention and food supply and maximize the synergy between soil retention and water conservation. The focus is on maximizing soil retention while considering the relationship with water conservation, as a negative correlation was observed between soil retention and food supply. In 1990, the highest soil retention value of 2200 t ha^{-1} was achieved when water conservation was 90 mm, with vegetation coverage of 56%. In 2000, the relationship between water conservation and soil retention followed a downward parabolic curve, with the maximum soil retention of 2600 t ha^{-1} at water conservation of 40 mm and vegetation coverage of 52%. Similarly, in 2010, the parabolic curve showed a maximum soil retention of 3165 t ha^{-1} at water conservation of 78 mm and vegetation coverage of 56%; however, in 2020, a negative relationship between soil retention and water conservation was observed, with water conservation ranging from 63 to 108 mm. To maximize soil retention, the highest value of 4130 t ha^{-1} was achieved at water conservation of 63 mm, with vegetation coverage of 52%.

For the food supply area, in 1990, the food supply increased as vegetation coverage increased. To maximize food supply and minimize the trade-off with water conservation and soil retention, most of the scatter points of water conservation were basically less than 110 mm, with a maximum food supply of 0.43 t ha^{-1}, corresponding to vegetation coverage of 35%. In 2000, the relationship between food supply and vegetation coverage followed a downward parabolic curve, with vegetation coverage of 40% at the maximum food supply. In 2010, an initial increase and then a decrease in food supply was observed as vegetation coverage increased, which was similar to the synergistic relationship followed by a trade-off between food supply and water conservation. Water conservation was mostly below 85 mm, and the maximum food supply was 1.1 t ha^{-1}, with vegetation coverage of 38%. Similarly, in 2020, the highest food supply of 2.45 t ha^{-1} was achieved when water conservation was 108 mm, with vegetation coverage of 34%.

The constraint relationship between habitat quality and other ecosystem services was unclear and not established during our study period. The optimal vegetation coverage was, therefore, determined based on the correlation between vegetation coverage and habitat quality. They were positively correlated, reaching 70%, 65%, 65%, and 70% of vegetation coverage in 1990, 2000, 2010, and 2020, respectively, with less increase in habitat quality.

Overall, the optimal vegetation coverage was found to be 58%–63% for the water conservation area, 52%–56% for the soil retention area, 34%–40% for the food supply area, and 65%–70% for the habitat quality area.

3.4 | Localized evaluation at subwatershed levels

We calculated the current average value of vegetation coverage in each subwatershed and compared it with the established vegetation coverage threshold (Figure 9). In the water conservation area, three subwatersheds exceeded the optimal range, while two fell below it. In the soil retention area, one subwatershed was below the threshold and others were above it. In the food supply area, six subwatersheds exceeded the threshold and seven were below it. In the habitat quality area, one subwatershed exceeded the threshold, three were within the optimal range, and 11 fell short. In total, 13 subwatersheds had reasonable vegetation coverage, while 10 showed excessive restoration, which could have negative impacts on ecosystem services and serve as a warning for ecosystem services integration. On the whole 21 subwatersheds fell short of the optimal threshold, requiring further attention to enhance greening and quality.

4 | DISCUSSION

4.1 | Application of trade-offs and constraint effects to determine the optimal vegetation coverage

The importance of minimizing trade-offs among ecosystem services has been acknowledged as a crucial aspect of successful ecological restoration (Lin et al., 2019). Regulating services exhibited a synergistic relationship, as supported by the results of earlier studies using Pearson correlation and cluster analysis of ecosystem services (Shen

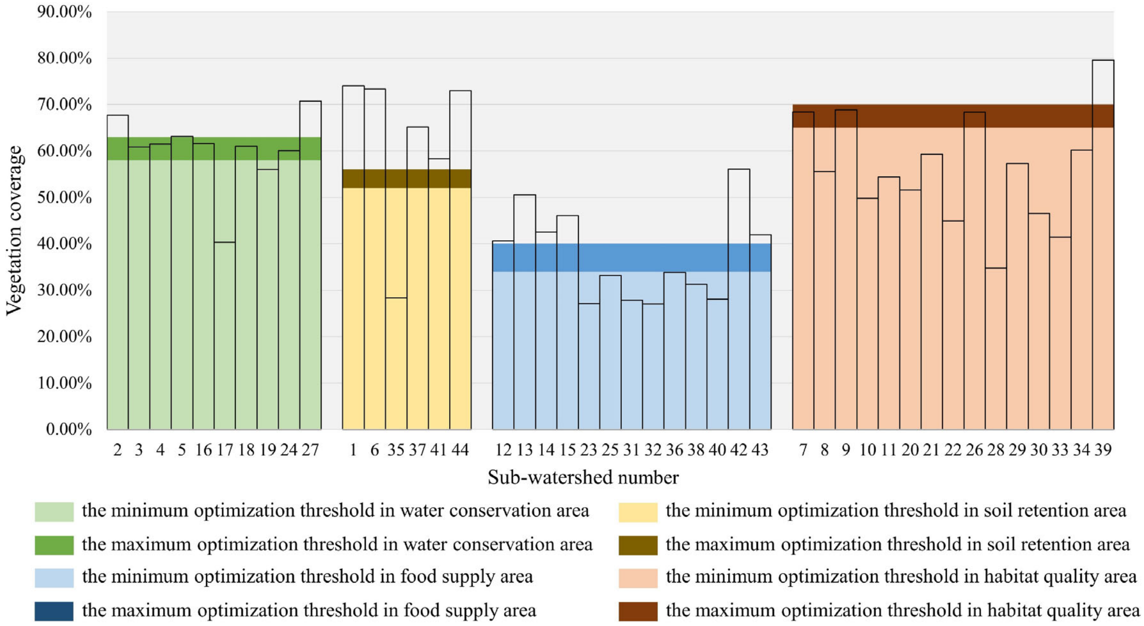

FIGURE 9 The real value and the optimization threshold range of vegetation coverage in each subwatershed for four dominant ecological function areas. [Colour figure can be viewed at wileyonlinelibrary.com]

et al., 2020; Y. Y. Yang et al., 2019). Our findings also highlighted the negative impact of excessive restoration on food supply, which may give a clue that regulating services were mutually reinforcing and the increase in provisioning services resulted in a decline in regulating services. Increasing evidence showed that the trade-off and synergistic relationships among ecosystem services changed in gentle hilly areas and mountainous areas (Gao et al., 2021), which was also seen in our study with different relationships among ecosystem services in different sites. In other words, this relationship depends on spatial heterogeneous and stochastic biogeophysical processes (Stosch et al., 2019). Stakeholders can leverage ecosystem-based strategies to make informed decisions about land use and the provision of specific ecosystem services, such as sustainable ecological land use or increased vegetation coverage. The simultaneous provision of ecosystem services and minimization of trade-offs can result in positive outcomes for biodiversity, soil conservation, and water management (Geng et al., 2020). It is, however, important to note that supplying specific ecosystem services may temporarily solve ecological problems, but human preferences for land use can be unpredictable and potentially harmful in the long term, leading to negative outcomes. Further investigation is required to determine the feasibility of various combinations of ecosystem services and the potential trade-offs of proposed land use changes (Ruijs et al., 2013).

The constraint analysis provides a useful approach for formulating appropriate vegetation restoration measures (C. Wang et al., 2022). The trade-offs among ecosystem services can be further reduced by incorporating the constraint effect and the threshold effect of vegetation restoration into ecological restoration criteria. In arid and semi-arid areas, owing to the scarcity of water resources, water conservation is a critical factor for sustaining vegetation growth and controlling soil erosion (Mohammed & Scholz, 2017), but exceeding a certain threshold would lead to a decline in vegetation carrying capacity and a reduction in water conservation and food supply (Wu et al., 2020). Increasing vegetation coverage to improve the interception and infiltration reduces the flow of surface water into rivers, storing and seeping water to increase the amount of groundwater (G. X. Zhang et al., 2020). Nevertheless, the results indicated that water conservation decreased when the vegetation coverage increased to more than a certain threshold, reaching the constraint effect. This is similar to the constraint effect of NPP-SC implemented in the wet or arid regions of China (Jiang et al., 2019; Sampson et al., 2021). The constraint effect of vegetation coverage on water conservation is extremely critical for optimizing the supply and management of ecosystem services, which may be due to the coexistence of restorative growth and low vegetation carrying capacity. Jiang et al. (2019) found that 50% vegetation coverage can result in optimal water conservation (350 mm) on the Loess Plateau. This study, however, suggested that the highest value of water conservation was recorded as 226 mm when the vegetation coverage reached 63% in 2020 and only 153 mm when the vegetation coverage was 58% in 2000. A more plausible explanation is different research scales and significant differences in precipitation and topography (Jiang et al., 2018; Lavorel et al., 2011). Additionally, it was shown that 52%–56% vegetation coverage was the optimal threshold for the dominant ecological function area of soil retention, differing from the proposal to control vegetation coverage of the Loess Plateau to no more than 50%. This is because the focus of the study was to determine the optimal threshold from the perspective of the relationship between multiple ecosystem services and vegetation coverage rather than exploring soil erosion control from a limited water resource perspective (Gilby et al., 2021). Differences in vegetation restoration targets over time emphasize the need for comprehensive consideration of the impacts of climate, soil, and land use modifications on vegetation requirements in upcoming ecological restoration efforts.

4.2 | The recommendation for better adaptive management

At present, in China, lower-level departments usually rely on achieving targets to report to higher-level departments (Han et al., 2021), leading to the adoption of the same restoration targets across their jurisdiction, disregarding the geospatial heterogeneity (M. D. Li et al., 2018). To maximize ecological benefits and sustainable ecosystem management, it is crucial to end the "one-size-fits-all" management approach and fully consider the trade-offs among ecosystem services within the region. This study proposed the spatial strategy to scientifically guide the specific practice of ecological restoration, linking the ecological threshold warnings and ecosystem management, thereby facilitating better planning and management of ecosystems in different subwatersheds. Although the actual effect of future implementation is still uncertain, it is possible to identify appropriate restoration targets according to local conditions for better restoration effects.

For the subwatersheds that exceed the threshold, the relationship among ecosystem services is not contributing to the improvement of ecological benefits. Many tree species exhibit growth of only 20% of normal height, indicating that too much vegetation was planted and soil water has been consumed too much (Jia et al., 2017). Hence, it is imperative to implement management strategies like thinning or altering land use in excessive restoration areas to maintain a balanced relationship between soil water availability and plant usage of water (Fava et al., 2016). Whether the carrying capacity of vegetation has been exceeded requires further study to establish the relationship between vegetation indices and environmental factors based on long-term hydrological and vegetation field data. For subwatersheds in urgent need of restoration, future reforestation efforts should consider soil textures and elevations with the greatest potential because of the strong spatial variability of soil and topographical features (Brown et al., 2018; Rezende & Vieira, 2019). Precipitation also plays a crucial role in vegetation restoration on the Loess Plateau, but declining precipitation calls for the optimization of vegetation resources (W. Liu & Sang, 2013). Reforestation may involve both native and nonnative vegetation. Native vegetation should be preserved because it adapts to local arid and semiarid sites, which greatly contributes to the success of afforestation (Meli et al., 2018; Thomas et al., 2014). The latter should be carefully evaluated in terms of their impact on the vegetation's threshold, with special focus on combining trees and shrubs to create a stable biotope for soil erosion control (Potzelsberger et al., 2020). To restore vegetation on the Loess Plateau, it is highly recommended to use *Caragana korshinskii* and *Robinia pseudoacacia* species.

Overall, the practice of ecological engineering can benefit from taking into account the vegetation restoration threshold, allowing for the setting of targets for each dominant ecological function area. To avoid irreversible changes resulting from ecosystems exceeding the threshold, policymakers can establish specific targets and make well-informed decisions based on defined thresholds. Besides, the different implementation intensities can be adopted by referring to the vegetation coverage threshold to achieve higher ecosystem services. The threshold effect can be used in land assessment and monitoring activities to evaluate land health and productivity. It can also be applied to monitor the impact of climate change on ecosystems, enabling the identification of the critical threshold for climate factors like temperature, precipitation, and carbon dioxide concentrations, beyond which ecosystems undergo significant changes. Of course, regular monitoring of ecological benefits is necessary to make timely adjustments to the ecological restoration plan and changing ecosystems must also be updated accordingly, reflecting real-time data collected through monitoring. Nevertheless, this approach remains practical and effective.

4.3 | Limitations and prospects

This study sheds light on the impact thresholds of vegetation coverage on ecosystem services and provides valuable insights for determining the optimal vegetation coverage for different dominant ecological function areas; however, we noted that some uncertainties remained in this study. The lack of data availability resulted in the focus being on provisioning and regulating services but not on supporting and cultural services. Further research should consider a more comprehensive and representative set of ecosystem services for more effective implementation and optimization. The extraction of constraint lines also presented some subjectivity, with outliers and the choice of quantiles in each column, as well as the number of columns, being open to interpretation. Striking a balance between the number of data points and columns is crucial for fitting the regression line accurately (Peng et al., 2017). Additionally, trade-offs of ecosystem services and their threshold constraints on vegetation coverage can vary at different scales (Bai et al., 2020). Research could be advanced by considering threshold effects at random points or various grid cell sizes to illustrate the differences in the relationship between vegetation coverage and ecosystem services using various spatial units or scales, especially for the thresholds of vegetation coverage response to ecosystem services. It would be, furthermore, worthwhile to apply the threshold of influence factors specifically to vegetation coverage specifically and to further implement ecological engineering based on the specific impact threshold of different factors on the distribution of vegetation coverage.

5 | CONCLUSIONS

With a focus on integrating differentiated policies for different subwatersheds into ecosystem management and practice, this study attempted to explore the relationship between ecosystem services and vegetation coverage and determined the optimal vegetation coverage threshold for dominant ecological function areas. Subsequently, the over-restored and under-restored subwatersheds were distinguished. Several results have been found in this study. (1) From 1990 to 2020, water conservation and habitat quality initially declined and subsequently increased, while soil retention and food supply showed a trend of increasing volatility. The vegetation coverage exhibited an initial decline, followed by a significant increase, and then a subsequent decline. (2) The degree of trade-offs varied among subwatersheds, but in general, soil retention-food supply and food supply-habitat quality were negatively correlated, and water conservation-soil retention, water conservation-food supply, water conservation-habitat quality, and soil retention-habitat quality were positively correlated. The relationship between ecosystem services and vegetation coverage, as depicted by the constraint curve, has changed over the years in 1990, 2000, 2010, and 2020. (3) The optimal vegetation coverage was found to be 58%–63% for the water conservation area, 52%–56% for the soil retention area, 34%–40% for the food supply area, and 65%–70% for the habitat quality area. (4) Out of 44 subwatersheds, 13 had appropriate vegetation coverage, but 10 had excessive restoration, which could negatively impact ecosystem services and serve as a caution for ecosystem services integration. The remaining 21 subwatersheds failed to reach optimal vegetation levels; thus, additional attention is needed to improve greening and quality. This study is expected to serve as a reference for confronting the essential challenge of sustainable social-ecological systems and further guidelines on ecological restoration measures.

AUTHOR CONTRIBUTIONS

Juan He: Conceptualization; investigation; software; writing—original draft; writing—review and editing. **Yao Li**: Writing—reviewing and editing. **Xueyi Shi**: Resources; writing—original draft; writing—review and editing. **Haiyan Hou**: Software.

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CONFLICT OF INTEREST STATEMENT

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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