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Land Use Zoning Management to Coordinate the Supply–Demand Imbalance of Ecosystem Services: A Case Study in the City Belt Along the Yellow River in Ningxia, China

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The imbalance between the supply and demand of ecosystem services (ESs) is one of the main reasons for ecological degradation, which significantly impacts human well-being and ecological safety. Spatial heterogeneity of ES supply–demand, ES tradeoffs, and the socioecological environment calls for zoning management, while few studies have combined the above three aspects in dividing management zones and proposed strategies. Using the City Belt along the Yellow River in Ningxia in northwestern China as a case study, this study quantified the supply and demand for five key ESs (crop production, carbon sequestration, nutrient retention, sand fixation, and recreational opportunity), analyzed ES tradeoffs/synergies and bundles through correlation analysis and the self-organizing map (SOM) method, and investigated their socioecological driving mechanisms through a random forest model and the SOM method. Management zones were proposed and differentiated suggestions were provided through overlaying ES bundles and driver clusters. The results suggested that crop production, carbon sequestration, and nutrient retention mostly correlated to the same intrinsic ecological process, resulting in consistent synergies among these three ESs at both supply and demand sides. On the contrary, the variance in interactions between the two ESs of sand fixation and recreational opportunity and the other three ESs is due to the low similarity of their intrinsic ecological processes and external driving mechanisms. Fourteen socioecological factors could effectively explain the spatial heterogeneity of ES supply, demand, and match degree. Fourteen management zones with similar ecological problems and socioecological environments were delineated, and differentiated suggestions were provided for each zone. Adopting both ES characteristics and the socioecological environment into zoning management could effectively detect ecological problems and help to promote management suggestions in different socioecological contexts. This framework could offer new insights for integrating ESs into actual decision-making and ecosystem management.

Keywords: ecosystem service, zoning management, socioecological environment, supply and demand, tradeoff

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1 INTRODUCTION

Ecosystem services (ESs), the direct and indirect goods and services provided by ecosystems to human society, can effectively bridge the natural environment and human society (Costanza et al., 1997; Wang et al., 2017; Huang et al., 2020). Studies show that ecosystems can only provide limited ESs, while human society has increased demand for ESs, driven by rapid population growth and socioeconomic development, especially in developing countries (Birge et al., 2016; Wei et al., 2017). Almost 60% of the global ecosystem is deteriorating at an unprecedented rate, caused by the surpassing of demand compared to supply and their spatial mismatches (MEA, 2005; Bagstad et al., 2013). Therefore, how to effectively manage ecosystems to minimize the supply–demand mismatches of ESs is critical for improving human well-being and sustainable development (Furst et al., 2013; Chang et al., 2021).

An ecosystem can provide multiple ESs simultaneously, while ESs are not independent of each other, as they may be related to the same ecological process or influenced by the same socioecological factors (Meacham et al., 2016). Complex relationships exist among multiple ESs, especially the tradeoff that one ES decreases with the increase of another ES, which is the main challenge in improving multiple ESs simultaneously (Spake et al., 2017; Peng et al., 2019b). Understanding the interactions among multiple ESs and their socioecological driving mechanisms has been proven to be useful and critical in developing management policies related to land use, vegetation restoration, and spatial planning (Chen et al., 2019; Schirpke et al., 2019). Fu et al. (2017) provided management suggestions for different subregions by analyzing the impacts of land use change and climate change on ESs, such as planting grasslands with high coverage in the oasis zone and establishing protected areas in the mountain and desert zones. However, most existing studies have focused on the supply side but neglected the demand side, which has a closer connection to human society (Meng et al., 2020; Chang et al., 2021).

Existing studies have suggested that not only the ES supply–demand match degree but also their relationships would change with different socioecological contexts (Xu et al., 2017; Sun et al., 2019). For example, three ESs of crop production, climate regulation, and recreation had higher demand in cropland and urban areas but higher supply in natural forests and olive orchards (Lorilla et al., 2019). Crop production and carbon sequestration represent tradeoffs in mountain regions but synergy in plain irrigation areas (Zhou et al., 2017; Lyu et al., 2019). Thus, zoning management would be an effective method to improve human well-being while maintaining ecosystem function and resilience, especially for regions with high spatial heterogeneity (Xu L.-X. et al., 2019; Zeng et al., 2020; Chang et al., 2021). Most existing studies tended to classify zones through either environmental characteristics or ecological function and ESs. The former classification is mainly based on natural ecological features and scarcely considers the role of humans in the ecosystem (Xu et al., 2020; Yu et al., 2021). The latter classification is beneficial to identify the ecological problem and optimization goal but fails to consider the socioecological contexts and make niche-targeting suggestions. For example, both excess fertilizer in plain irrigation and lack of riparian buffer could result in water pollution; thus, different suggestions should be made for different regions for water purification (Lyu et al., 2019). Till now, rare studies have combined natural ecological features and ESs to divide the management zones.

ES bundles, sets of ESs that repeatedly appear together across space or time, can effectively represent the spatial heterogeneity of ESs and their interactions (Raudsepp-Hearne et al., 2010; Cord et al., 2017). In this study, we proposed a new framework to classify ecological zones and propose management suggestions for the identified problems by quantifying the status of ES supply–demand, their bundles, and socioecological drivers. The City Belt along the Yellow River in Ningxia (CBYN), located in the upstream part of the Yellow River basin, has a fragile ecological environment with various landscape types—deserts, oases, and mountains. CBYN faces severe conflict between rapid socioeconomic development and ecological protection. In this study, taking CBYN as the study area, we quantified the supply and demand of five critical ESs, identified their interactions and socioecological driving mechanisms, classified the ecological zones, and provided specific suggestions. This study aimed to 1) estimate the supply–demand status of multiple ESs in a spatially explicit manner; 2) clarify ES tradeoffs/synergies and their driving mechanisms at different sides; and 3) develop a comprehensive approach to combining the socioecological environment and ESs into zoning management. The results are expected to provide a scientific foundation for land use planning and decision-making for sustainable ecosystem management.

2 MATERIALS AND METHODS

2.1 Study Area

Located in the northwestern Ningxia Hui Autonomous Region, China, the CBYN (36°54′30″–39°23′23″N, 104°17′7″–106°58′13″E) covers approximately 22,000 km^2 at the intersection of the Loess Plateau, the Mongolian Plateau, and the Tibetan Plateau (**Figure 1**). It borders the Tengger, Maowusu, and Ulanbuh deserts in the west, east, and north directions, respectively, with elevations ranging from 956 to 3,544 m. It has a continental climate characterized by low precipitation, abundant sunshine, high evapotranspiration, and four distinct seasons of a late windy spring, short summer, early autumn, and long cold winter. The average annual precipitation in 1989–2017 was 191.38 mm, which falls mostly in June–August, with an average annual temperature of 10.38°C. The Yellow River flows from southwest to northeast through Zhongwei City, Wuzhong City, Yinchuan City, and Shizuishan City, fostering the formation of irrigation for agricultural production and providing abundant water resources for human life, agriculture, and industrial production.

Driven by global climate change and rapid socioeconomic development, several ecological problems have emerged in the

TABLE 1 | Sources of the primary data.

Types	Resolution	Year	Source
Land use data[a]	30 m	2019	Landsat OLI images through object-oriented interpretation in eCognition software (http://www.ecognition.com/)
Monthly NDVI images	30 m	2019	Landsat OLI images through band math in ENVI 5.3 software (http://www.harrisgeospatial.com/Software-Technology/envi.aspx/)
DEM	30 m	—	ASTER GDEM dataset in the Geospatial Data Cloud (http://www.gscloud.cn/)
Monthly climate data	23 points	2019	China Meteorological Data Sharing Service System (http://data.cma.cn/)
Socioeconomic data	Counties	2019	Ningxia Statistical Yearbook published by China Statistics Press Statistical Bulletin on Ningxia's Tourism Economic Development
Hydrological observation records	Points	2019	Ningxia Water Conservancy

[a] *There are six land use types including cropland, forest land, grassland, water area, built-up land, and unused land. Based on sample points derived from a field survey and maps from Google Earth, the Kappa index of land use data was 0.84, indicating high reliability of the results.*

CBYN, such as food security, water pollution, and global warming. Unique landscapes and a rich cultural background also generate abundant tourism resources in the CBYN. Thus, based on ecological problems, data availability, and the feasibility of assessment methods, four ESs with high relevance to stakeholder welfare were selected, including one provision service (crop production), two regulating services (carbon sequestration and nutrient retention), and one cultural service (recreational opportunity). The main datasets used in this study are listed in **Table 1**.

The spatial distribution of population, a critical and essential factor in calculating ES demand, was simulated through census data at the county scale and for influencing factors using the random forest model. First, the influencing factors of population distribution were selected through a literature review (Qi et al., 2015; Stevens et al., 2015; Tan et al., 2017), including elevation, slope, distance to water, distance to the Yellow River, distance to transportation, distance to railways, distance to roads at the province level, distance to the city center, built-up percentage. These factors were resampled to 30 m. Next, the relationship between population density and the average value of influencing factors at the county level was explored through a random forest model, in which the explained variance of the derived model reached 88.24%. Thus, the established random forest model could effectively simulate population spatialization. At last, a population distribution map at 30 m was generated based on the derived model and the distribution maps of the influencing factors. The details are listed in **Supplementary Material Section S1**.

2.2 Methodology

This study was conducted in four steps. First, the supply and demand of five key ESs (crop production, carbon sequestration, nutrient retention, sand fixation, and recreational opportunity) were quantified in a spatially explicit manner. Second, interactions among the ESs were quantified at three sides of supply, demand, and match degree through correlation analysis and a self-organizing map (SOM) method. Third, the socioecological driving mechanisms were explored for the supply and demand of each ES through random forest analysis and the SOM method. Fourth, zoning management and corresponding measures were proposed by combining ES bundles and socioecological driver clusters. The technical roadmap is shown in **Figure 2**.

2.2.1 Mapping ES Supply and Demand

The flat topography and opulent sunshine in the CBYN provide favorable conditions for agricultural production (Lyu et al., 2018). Thus, it has become one of the most critical grain production bases in northwestern China but also suffers from serious nonpoint pollution (Dong and Ma, 2012; Li et al., 2017). The CBYN is surrounded by deserts on three sides, while Helan Mountain provides great benefits in preventing wind erosion and sandstorms (Xu J. et al., 2019). Carbon sequestration and emission play a critical role in mitigating global warming (Ito et al., 2016). Besides that, a multiethnic culture and unique landscape provide the CBYN with abundant opportunities for ecotourism (Zhou and Yan, 2009; Lyu et al., 2018). According to the environmental characteristics, ecological problems, method feasibility, and data availability in the CBYN, the following five ESs were selected and estimated at a spatial resolution of 30 m in 2019: one provision service of crop production, three regulating services of carbon sequestration, nutrient retention, and sand fixation, and one cultural service of recreational opportunity.

2.2.1.1 Crop Production

The supply of crop production was calculated based on the statistical data of the main crop output at the county scale obtained from the Ningxia Statistical Yearbook, including rice, wheat, corn, tubers, and soybeans. By referencing the method used by Hu et al. (2018), the crop output value was allocated to cropland at the grid scale (30 m) based on the linear relationship between crop yield and NDVI. It was calculated from **Eq. 1**:

$$S_{CPi} = \frac{NDVI_i}{NDVI_{sum}} \times G_{sum} \tag{1}$$

where S_{CPi} is the supply of crop production in pixel *i* (kg), G_{sum} is the total crop output in each county, $NDVI_i$ is the normalized NDVI value in pixel *i*, and $NDVI_{sum}$ is the sum of the normalized NDVI value in cropland for each county.

The demand for crop production was calculated through the per capita food demand and population distribution. According to the per capita food demand based on the average grain pattern of China and the Ningxia Statistical Yearbook, the annual

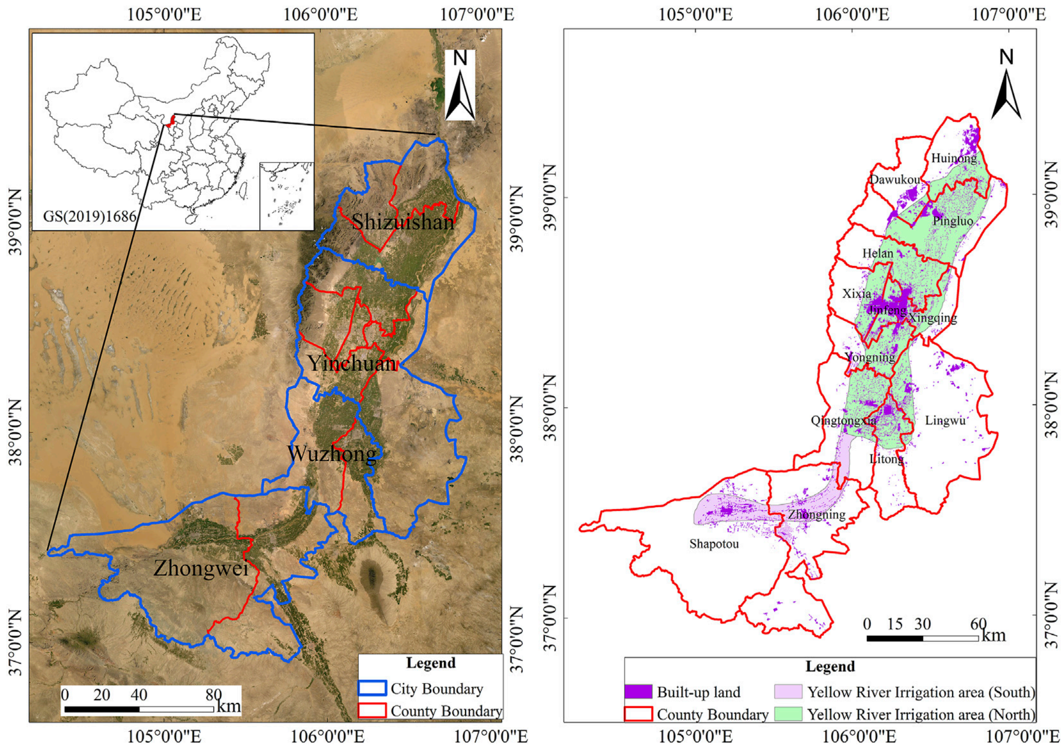

FIGURE 1 | Location of the study area.

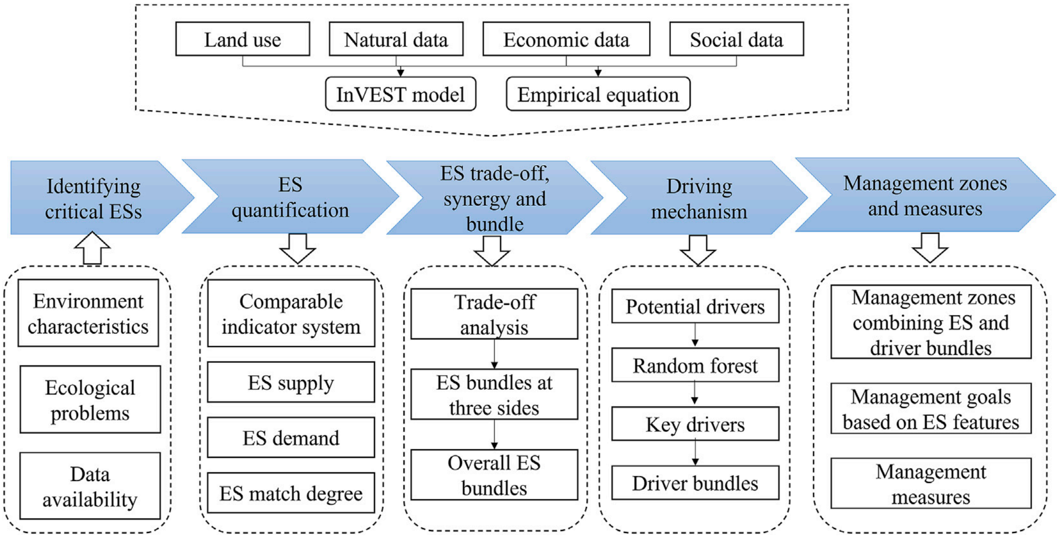

FIGURE 2 | Framework for dividing management zones and proposing measures based on ES supply–demand, tradeoffs, and environmental characteristics.

consumption of major foods by urban and rural households is 112.1 kg per capita. It was calculated as follows:

$$D_{CPi} = POP_i \times 112.1 \tag{2}$$

where D_{CPi} is the demand for crop production in pixel *i* (kg), and POP_i is the population in pixel *i*.

2.2.1.2 Carbon Sequestration

The supply of carbon sequestration was estimated through the net primary productivity (NPP) (Zhou et al., 2017), which was calculated through the CASA model as follows:

$$NPP = APAR \times \varepsilon \tag{3}$$

TABLE 2 | Carbon and nutrient emission factors of livestock in the CBYN.

	Cattle	Pig	Sheep
Live weight (kg/head)	300	160	60
Carbon emission factor (tC/kg)	0.0226	0.0035	0.01845
TN emission factor [kg/(head·a)]	1,288.45	78.5925	63.7947
TP emission factor [kg/(head·a)]	91.25	15.855	16.8703

$$ARAR = SOL \times FPAR \times 0.5 \tag{4}$$

$$\varepsilon = T_{\varepsilon 1} \times T_{\varepsilon 2} \times W_{\varepsilon} \times \varepsilon_{max} \tag{5}$$

where NPP is the net primary productivity, APAR is the canopy-absorbed incident solar radiation over a time period (MJ/m^2), ε is the light utilization efficiency (gC/MJ), SOL is the total solar radiation (MJ/m^2), FPAR is the canopy-absorbed fraction of photosynthetically active radiation, $T_{\varepsilon 1}$ and $T_{\varepsilon 2}$ are temperature stress coefficients, W_{ε} is a water stress coefficient, and ε_{max} is the maximum light-use efficiency of vegetation (gC/MJ). For related parameters, refer to Zhu et al. (2007).

The demand for carbon sequestration was assessed by carbon emissions in the ecosystem, mainly coming from industrial fossil-fuel consumption, human respiration, cropland soil respiration, and livestock farming. It was calculated as follows:

$$D_{CS} = C_i + C_h + C_l + C_c \tag{6}$$

$$C_I = Output_I \times F_I \tag{7}$$

$$C_P = POP \times F_P \tag{8}$$

$$C_L = N_{Lj} \times W_{Lj} \times F_{Lj} \tag{9}$$

$$C_C = S_c \times F_C \tag{10}$$

where D_{CS} is the total carbon emissions by ecosystem (tC/a), and C_I, C_P, C_L, and C_C are the carbon emissions caused by industrial production, human respiration, livestock farming, and cropland soil respiration, respectively. $Output_I$ is the industrial output value in each county, and F_I is the carbon emission ratio for industrial output (0.54 tC/10000 yuan) (Cui et al., 2019). *POP* is the population, and F_P is the carbon emission factor per person per year (0.13797 tC) (Zhang et al., 2014). *Sc* is the area of cropland (km^2), and F_C is the carbon emission factor (tC/km^2) (Li et al., 2010). N_{Lj} is the number of *i*th livestock, W_{Lj} is the live weight of *i*th livestock (kg), and F_{Lj} is the carbon emission factor per kilogram of *i*th livestock (Zhang et al., 2014) (**Table 2**). For the spatialization of carbon emissions, C_I and C_L in each county were allocated equally into the built-up land and grassland, respectively.

2.2.1.3 Nutrient Retention

The supply of nutrient retention refers to the contribution of vegetation and soil to water purification through the removal of nonpoint nutrient pollutants from runoff. It was calculated through the InVEST NDR model with input data of topography, surface runoff, land use type, pollution load, and empirical parameters derived from relevant literature (Redhead et al., 2018). It was assessed as follows:

$$NE_i = ALV_i \times f_j \tag{11}$$

$$ALV_i = \frac{\lambda_i}{\lambda_{\bar{w}}} \times pol_i \tag{12}$$

where NE_i is the nutrient retention amount in pixel *i* (kg/pixel), f_j is the retention capacity of land use *j*, *ALVi* is the adjusted loading value in pixel *i*, *poli* is the exported coefficient in pixel *i*, λ_i is the runoff index in pixel *i*, and $\lambda_{\bar{w}}$ is the mean runoff index.

For the model calibration and validation, data on nitrogen concentration, phosphorus concentration, and river flow in three gauging stations were derived from Ningxia Water Conservancy. Annual nutrient retention was calculated through the nutrient load difference between the inlet and outlet in the basin; then, it was compared to simulated data from the InVEST NDR model, indicating the high reliability of the simulation results for nitrogen retention but low reliability for phosphorus retention (**Supplementary Figure S3**). As the amount of nitrogen retention was nearly 10 times that of phosphorus retention, the underestimation of phosphorus retention did not significantly impact the accuracy of the overall assessment of nutrient retention.

The demand for nutrient retention was assessed by nonpoint nutrient emission from an ecosystem including total nitrogen (TN) and total phosphorus (TP), mainly including three sources: agricultural production, human living, and livestock breeding.

$$D_{NR} = NE_C + NE_P + NE_L \tag{13}$$

$$NE_C = S_C \times R_C \tag{14}$$

$$NE_P = W_P \times R_P \tag{15}$$

$$NE_L = N_{Lj} \times R_{Lj} \tag{16}$$

where D_{NR} is the total nutrient emission by ecosystem in each pixel (kg/a), and NE_C, NE_P, and NE_L are the nutrient emissions caused by agricultural production, human living, and livestock farming, respectively. *Sc* is the area of cropland (km^2), and F_C is the nutrient emission factor of cropland [19.04 kg/(km^2·a) of TN and 0.75 kg/(km^2·a) of TP] (Yinlu Yang et al., 2011). W_P is the wastewater discharge from daily life (L), and R_P is the nutrient emission factor of wastewater (23.02 mg/L of TN and 3.74 mg/L of TP) (Yinlu Yang et al., 2011). N_{Lj} is the number of *i*th livestock, and R_{Lj} is the nutrient emission factor of *i*th livestock [kg/(head·a)] (Yinlu Yang et al., 2011) (**Table 2**). For the spatialization of carbon emissions, NE_L in each county was equally allocated to grassland, while NE_P in each county was allocated to built-up land based on the population distribution.

2.2.1.4 Sand Fixation

Wind erosion, the root cause of desertification in arid and semiarid regions, decreases soil productivity and threatens human health and ecological safety (Su et al., 2020). The ecosystem could reduce it through surface vegetation, steep slopes, and low soil erodibility. The supply and demand of sand fixation were calculated through the Revised Wind Erosion Equation. This method can comprehensively consider the impacts of climate variability, topography, soil contexts, and vegetation coverage. The supply and demand of sand fixation were assessed as follows:

$$\Delta Q = Q_0 - Q_v \tag{17}$$

TABLE 3 | Attributes, variables, and weights used to assess the supply of recreational opportunities.

Attribute	Indicator	Weight	Spatial Treatment
Accessibility	Road network	0.7	Euclidean distance
	Station (airports, railway, and bus stations)	0.3	Euclidean distance
Tourism use aptitude	Land use	—	Normalized values assigned to each land use type
Scenic beauty	Public and private protected areas	0.33	Euclidean distance
	National park	0.33	Euclidean distance
	Tourism area	0.34	Euclidean distance
Civilization	Archaeological sites	—	Euclidean distance

[a]*The normalized values assigned to each land use type referred in* ***Table 1***.

TABLE 4 | Potential activities in each land use type in the CBYN.

	Horseback Riding	Mountain Climbing	Recreational Fishing	Kayaking	Camping	Scientific Tourism	Scenic Beauty	Shopping	Total
Cropland	0	0	0	0	0	1	0	0	1
Forest	1	1	0	0	1	1	1	0	5
Grassland	1	1	0	0	1	0	1	0	4
Water	0	0	1	1	0	1	1	0	4
Built-up land	0	0	0	0	0	1	1	1	3
Unused land	0	0	0	0	0	0	1	0	1

$$Q(x) = Q_{max}\left\{1 - \exp\left[-\left(\frac{x}{S}\right)^2\right]\right\} \tag{18}$$

$$Q_{max} = 109.8 \times WF \times EF \times K \times SCF \times VC \tag{19}$$

$$S = 150.71 \times (WF \times EF \times K \times SCF \times VC)^{-0.3711} \tag{20}$$

where ΔQ is the supply amount of sand fixation [t/(ha·yr)], Q_0 is the potential soil erosion without vegetation coverage [t/(ha·yr)], Q_v is the actual soil erosion under current coverage and management and the demand amount of sand fixation [t/(ha·yr)], $Q(x)$ is the amount of soil transported by the wind past a point x, Q_{max} is the maximum amount of soil at downwind, S is the critical filed length at which the transported soil is 63.2% of Q_{max}, WF is the weather factor calculated based on wind speed, air density, soil wetness, and snow cover factor, EF is the erodible fraction calculated through soil contexts, SCF is the soil crust factor calculated through soil clay and organic matter content, K is the soil roughness factor calculated, and VC is the vegetation coverage factor. For details, see Jiang et al. (2016).

2.2.1.5 Recreational Opportunity

The supply of recreational opportunity refers to the potential for recreation and ecotourism provided by an ecosystem. It was calculated by the characteristics, properties, and potential activities of the landscape, including four types of indicators: accessibility, tourism aptitude, scenic beauty, and civilization (**Tables 3** and **4**) (Nahuelhual et al., 2017). The relative weights of each indicator were calculated through the analytical hierarchy process based on interviews with 15 academics and postgraduate students familiar with the tourism industry in the study area. All the raster maps were first normalized to 0–100 and then summed up with their weights to calculate the supply amount.

The demand for recreational opportunities was assessed by the distribution of beneficiaries, including residents and tourists. The number of tourists was derived from the Statistical Bulletin on Ningxia's Tourism Economic Development in 2019. The number of tourists was firstly divided into each county based on the distribution and level of tourist attractions and then equally allocated to built-up land in each county. It was converted into permanent resident equivalent by dividing by the number of nights (365) and added to the raster map of residents. At last, the demand for recreational opportunity was simulated by the rescaled addition map from 0 (low) to 1 (high).

2.2.2 Calculation of Spatial Mismatches Between Supply and Demand for Each ES

The ecological supply–demand ratio was used to quantify the degree of spatial match between the supply and demand of different ESs, as is widely done in similar studies (Cui et al., 2019; Lorilla et al., 2019). It was calculated as follows:

$$\text{ESDR} = \frac{S - D}{(S_{max} + D_{max})/2} \tag{21}$$

where S and D are the supply and demand of each ES, respectively, and S_{max} and D_{max} are the maximum values of supply and demand for a specific ES. A positive value of ESDR indicates that the supply of a specific ES is larger than its demand; a negative value indicates that the supply does not meet its demand, while a value of zero means that its supply and demand are balanced.

2.2.3 Analysis of ES Interactions and Bundles

Spearman correlation analysis and principal component analysis (PCA) were used to investigate the interactions among the ESs. The

TABLE 5 | Potential and selected driving factors for ES supply, demand, and match degree.

Type	Code	Potential driving factor	Selected factor
Ecological	DEM	Elevation	√
	slope	Slope	—
	temp	Annual average temperature	—
	prec	Annual average precipitation	√
	humid	Relative air humidity	—
	sun	Sunshine hour	—
	soil	Soil type	√
	wind	Wind speed	√
Social	landuse	Land use distribution	√
	urban	Built-up land distribution	√
	NDVI	Vegetation coverage	√
	discity	Distance to city center	√
	dissub	Distance to county center	—
	disgrass	Distance to grassland	√
	disroad	Distance to transportation	√
	diswater	Distance to water area	—
	disurban	Distance to built-up land	√
	discrop	Distance to cropland	√
	GDPden	GDP density	√
	perGDP	Per capital GDP	√

SOM method was used to identify ES bundles, while the optimal number of clusters was determined according to the results of PCA and NbClust functions. The above analyses were performed by differentiating supply, demand, and the match degree through the "raster," "corrgram," "psych," "NbClust," and "kehonen" packages in the R statistical software (https://www.r-project.org/).

2.2.4 Exploring the Socioecological Driving Mechanism of ES Supply and Demand

First, we identified critical driving factors for ES supply and demand from a complex socioecological environment through random forest analysis. The potential socioecological driving factors of ES supply and demand were collected from five sources: public recognition, expert knowledge, ES assessment, environmental characteristics, and relevant literature (Hauck et al., 2015; Mouchet et al., 2017; Spake et al., 2017; Li and Wang, 2018; Lyu et al., 2018; Lyu et al., 2019). Twenty potential factors were originally selected (**Table 5**). To avoid multicollinearity, Pearson's correlation analysis was first applied to all the variables, and the results showed that there were no high correlations among them. Then, the random forest model was applied to identify the most important factors for the supply, demand, and match degree of each ES, which was performed in the "randomForest" package in the R software. Fourteen factors were finally selected that could effectively simulate the spatial heterogeneity of the supply, demand, and match degree of the four ESs (**Table 5**). To explore the socioecological background of ES mismatches and bundles, these 14 driving factors selected were clustered based on their similarities in spatial distribution using the SOM clustering method, which was performed using the "kohonen" and "raster" packages in the R software. Then, driving factor clusters were overlaid with ES bundles to investigate the socioecological context of the ES bundles.

2.2.5 Zoning Management Based on ES Bundles and Socioecological Driver Clusters

In our study, zoning management combined ES characteristics and the socioecological environment, which was convenient to put forward measures of ecosystem management and achieve the goal of sustainable supply of multiple ESs. First, ES bundles for all the three components (supply, demand, and supply–demand match degree) in **Section 2.2.2** and driver clusters in **Section 2.2.3** were overlaid to propose management zones. Second, based on the characteristics of ES supply, demand, and match degree, and the interactions among ESs, we identified the main ecological problem and optimization objective. Then, combining the different socioecological conditions that had significant impacts on ESs, management measures were proposed to achieve the management goals. In specific, management zones less than 1,000 km^2 were eliminated, and there were 14 zones in total.

3 RESULTS

3.1 Spatial Distribution of ES Supply and Demand

Significant differences existed in the spatial distribution of ES supply, demand, and match degree (**Figure 3**). Among the three sides of ESs, supply and match degree had a similar pattern for each ES, while higher supply only partly overlapped with higher demand for the five ESs except crop production. The total supply of crop production in the CBYN reached 223.52 × 10^7 kg in 2019, much higher than its total demand of 50.84 × 10^7 kg, suggesting the critical role of the CBYN as a crop production base. The unsatisfied demand for crop production was mainly distributed in urban and rural areas with human settlements, while its excess supply was mainly distributed in cropland in the central plain, with lower excess supply in Dawukou District. For carbon sequestration, its total supply (173.61 × 10^{10} gC) was far less than its total demand (950.61 × 10^{10} gC), while excess supply was mainly located in the forest land, with unsatisfied demand in urban and rural areas. The total supply of nutrient retention reached 2.17 × 10^7 kg, which was lower than the total demand of 3.13 × 10^7 kg. Its excess supply mainly lied in the croplands in Xixia District, Jinfeng District, Xingqing District, Dawukou District, Huinong District, and Lingwu City, while the unsatisfied demand was located in urban and rural areas and in grassland with low vegetation coverage in the north region. For sand fixation, its total supply (8.686 × 10^8 t/ha) was lower than its total demand (10.871 × 10^8 t/ha), resulting in the occurrence of sand and dust storms and further threatening human well-being, especially in the transition region between the central plain and the fringe mountains without vegetation coverage. For recreational opportunity, the unsatisfied demand was mainly in the south fringe area with low accessibility and low aesthetics, while the excess supply was in the areas with natural beauty and forest gardens.

3.2 Interactions Among ESs Based on Supply, Demand, and Match Degree

3.2.1 Correlation Coefficients Among ESs in Different Sides

Spearman's correlation coefficients of paired ESs were different among the three sides of supply, demand, and match degree

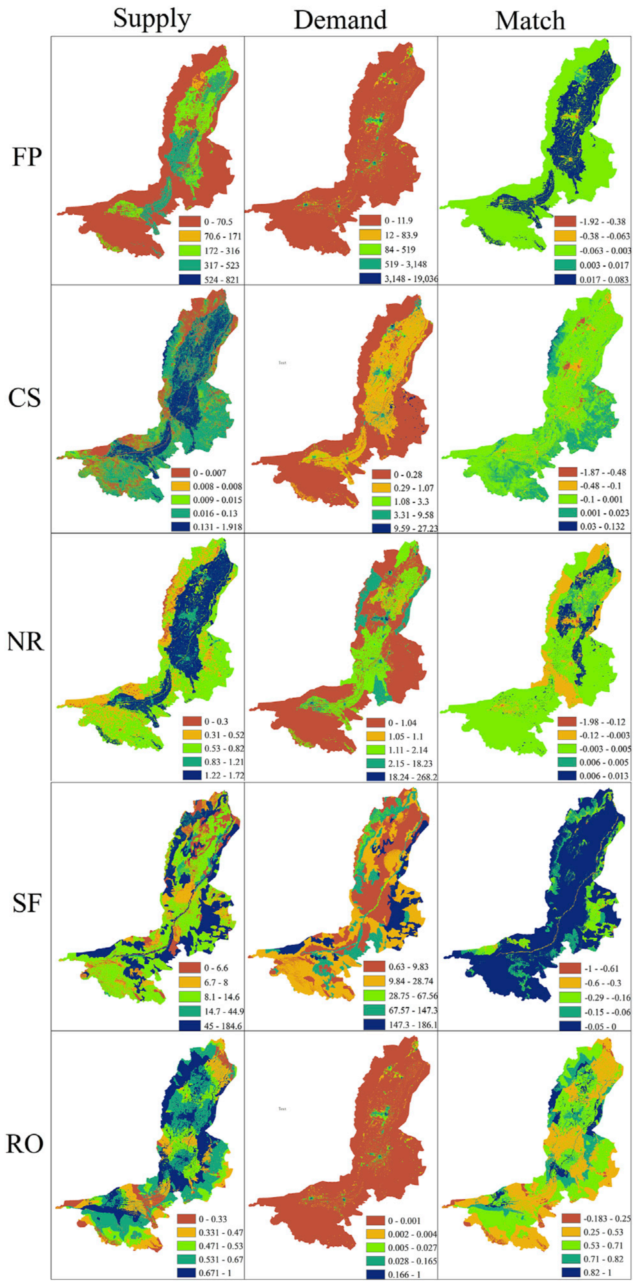

FIGURE 3 | Spatial distribution of ES supply, ES demand, and ESDR in 2019.

(**Figure 4**). Among the 10 pairs of ESs, only one pair (crop production and nutrient retention) exhibited consistent synergies with different strengths across the three sides. Three pairs (crop production vs carbon sequestration, carbon sequestration vs nutrient retention, sand fixation vs nutrient retention) exhibited opposite correlations between the supply and demand sides and the match side. Sand fixation and other ESs exhibited weak correlations at the supply and demand sides but strong synergies with crop production and nutrient retention and strong tradeoffs with carbon sequestration and recreational opportunity. Recreational opportunity and the other three ESs (crop production, carbon sequestration, and nutrient retention) exhibited strong tradeoff relationships at the supply side, but showed synergy relationships at demand side.

3.2.2 Spatial Distribution and Characteristics of ES Bundles

As indicated by the results of PCA (**Figure 5**) and the Calinski criterion of the K-means clustering method, 3, 3, 3, and 6 bundles were suggested for the five ESs at supply, demand, match degree, and all the three above components, respectively (**Figure 6**). At the supply side, the central plain covered by cropland (ESB 3) could provide higher levels of crop production, carbon sequestration, and nutrient retention but lower levels of the other two ESs. The transition region between the central plain and the fringe area with lower vegetation coverage (ESB 3) provided higher levels of sand fixation but lower levels of the other ESs; the fringe area and central built-up land (ESB 2) mainly provided higher recreational opportunity. At the demand side, the central urban and rural areas (ESB 3) had the highest demand for the discussed ESs except for sand fixation, while the transition region between the central plain and the fringe area with lower vegetation coverage (ESB 1) had the highest demand for sand fixation. At the supply–demand match degree side, the urban and rural areas (ESB 3) exhibited the lowest match degree for crop production, carbon sequestration, and nutrient retention but the highest match degree for recreational opportunity; the transition region had the lowest match degree for sand fixation. For all the three sides of these five ESs, the whole region can be divided into six regions, with different characteristics in ES supply, demand, and match degree. The inner urban and rural areas had the highest demand and lowest match degree of the discussed ESs except for sand fixation among the whole region, while the outer urban and rural areas had lower demand and higher match degree compared to the inner urban and rural areas. In specific, the outer urban and rural areas had the highest match degree of recreational opportunity across the whole region. ESB 2 and ESB 5 are both located in the central cropland with the highest supply of crop production, carbon sequestration, and nutrient retention, while ESB 5 also had the highest supply of sand fixation.

3.3 Driving Mechanisms of ES Supply, Demand, and Match Degree

Twenty possible socioecological factors were selected to analyze the driving mechanisms of ES distribution and interactions. Using random forest analysis, we tried to identify the most critical factors of ES supply, demand, and match degree by comparing their relative impacts and explained variance for ES distribution. Then, 14 factors were selected, including dem, prec, wind, soil, discity, discrop, disgrass, disurban, disroad, GDPden, perGDP, NDVI, land use, and urbanland (**Table 6**).

To explore the socioecological background of the ES bundles, these 14 factors were clustered using the SOM clustering method and then overlaid with the ES bundles (**Figure 7**). The results suggest that the study area could be divided into six different

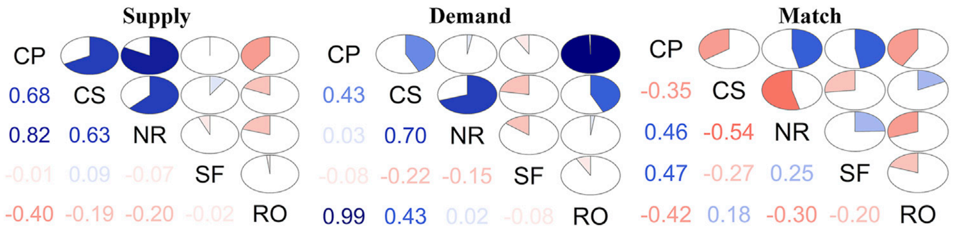

FIGURE 4 | Correlation coefficients among ESs at three sides of supply, demand, and match degree (blue for positive correlation, red for negative correlation; CP—crop production, CS—carbon sequestration, NR—nutrient retention, SF—sand fixation, RO—recreational opportunity).

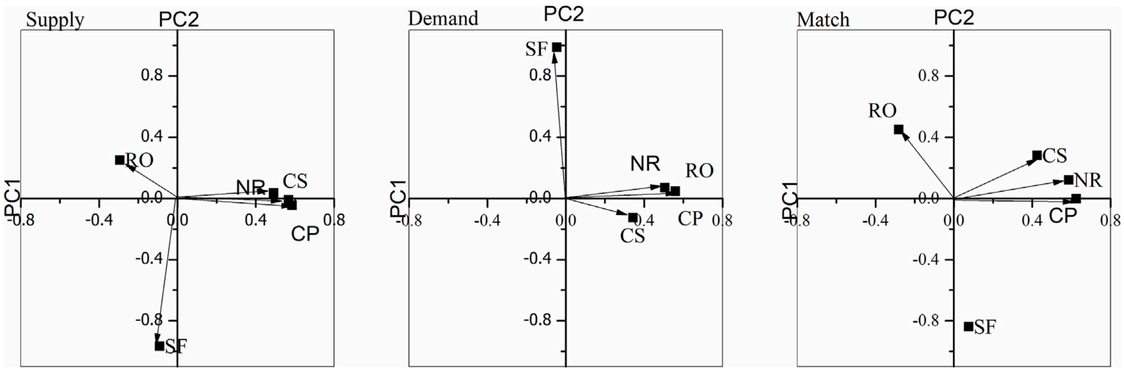

FIGURE 5 | Principal component analysis result among ESs at three sides of supply, demand, and match degree.

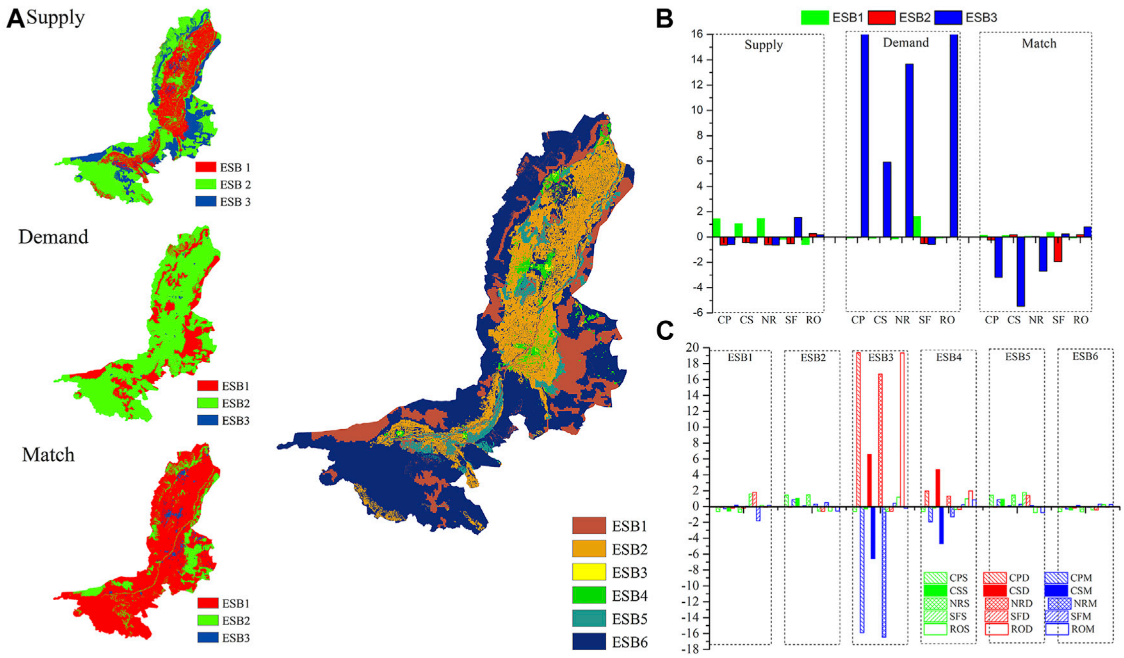

FIGURE 6 | Spatial distribution of ES bundles for supply, demand, match degree, and all three ES components **(A)**, and z-score values of ESs in each bundle **(B)** and **(C)**.

TABLE 6 | Selected socioecological factors for ES supply, demand, and match degree and their explained variances.

Ecosystem Service	—	Explained Variance (%)	Selected Factor
CP	Supply	91.05	landuse/discrop/NDVI
	Demand	88.82	perGDP/discity/urban
	Match	88.82	perGDP/discrop/landuse
CS	Supply	83.53	NDVI/landuse/prec/dem
	Demand	86.56	disurban/perGDP/prec
	Match	96.33	prec/GDPden/disurban
NR	Supply	99.14	landuse/discrop/dem
	Demand	80.72	perGDP/landuse/GDPden
	Match	80.7	perGDP/landuse/GDPden
SF	Supply	94.5	soil/NDVI/wind
	Demand	93.2	soil/prec/wind
	Match	93.7	soil/NDVI/prec
RO	Supply	81.04	discity/landuse/disroad/disgrass
	Demand	88.54	perGDP/discity/urban
	Match	80.57	discity/landuse/disroad/disgrass

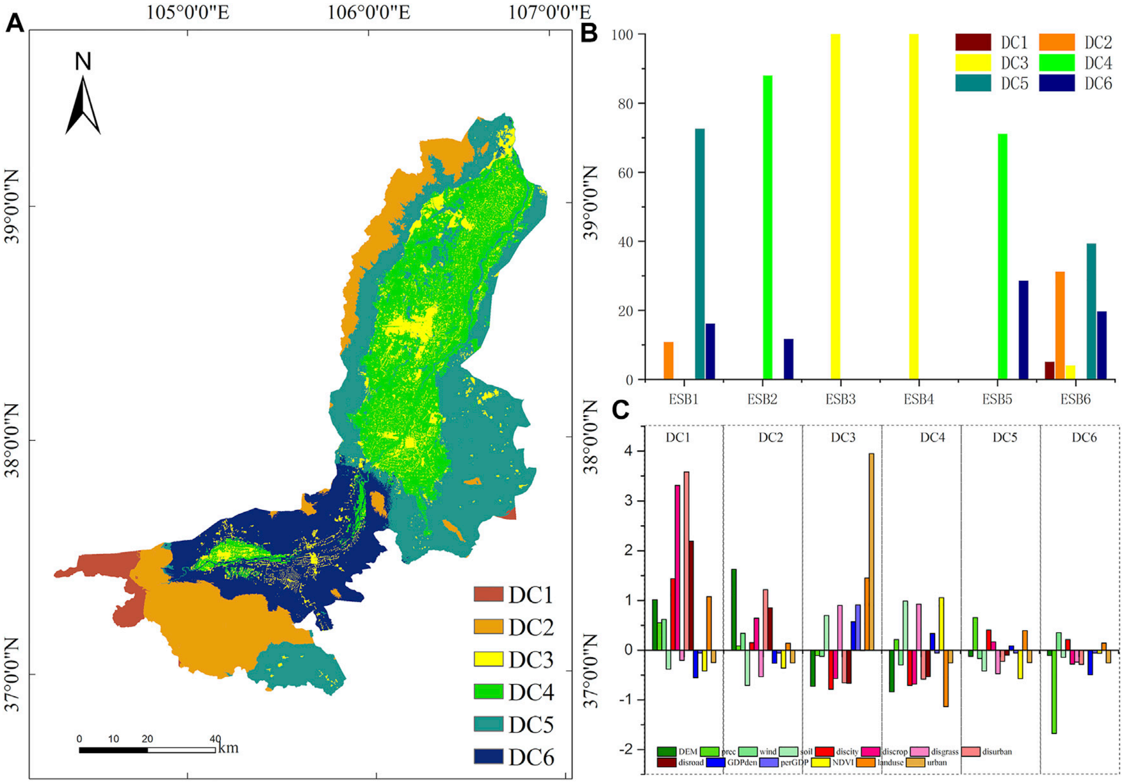

FIGURE 7 | Spatial distribution of driver clusters **(A)**, overlap percentage of driver clusters and ES bundles **(B)**, and z-score values of each driver in different clusters **(C)**.

clusters according to the spatial pattern of these socioecological factors. Driver cluster 1 (DC 1) was in the southern part of the CBYN with the highest distance to artificial and semiartificial facilities, such as city centers, cropland, and transportation. DC 2 was distributed in the southern and northern mountains with the highest elevation and the second-largest distance to artificial and semiartificial facilities. DC 3 and DC 4 were both distributed in the central plain with lower elevation and were closer to city centers, cropland, and urban areas but far away from grassland; DC 3 was concentrated in urban and rural areas with the highest per GDP, and DC 4 was in cropland with the highest NDVI values. DC 5 and DC 6 were both distributed in the transition region between the central plain and the fringe mountains; the former was in the northern part with the highest precipitation

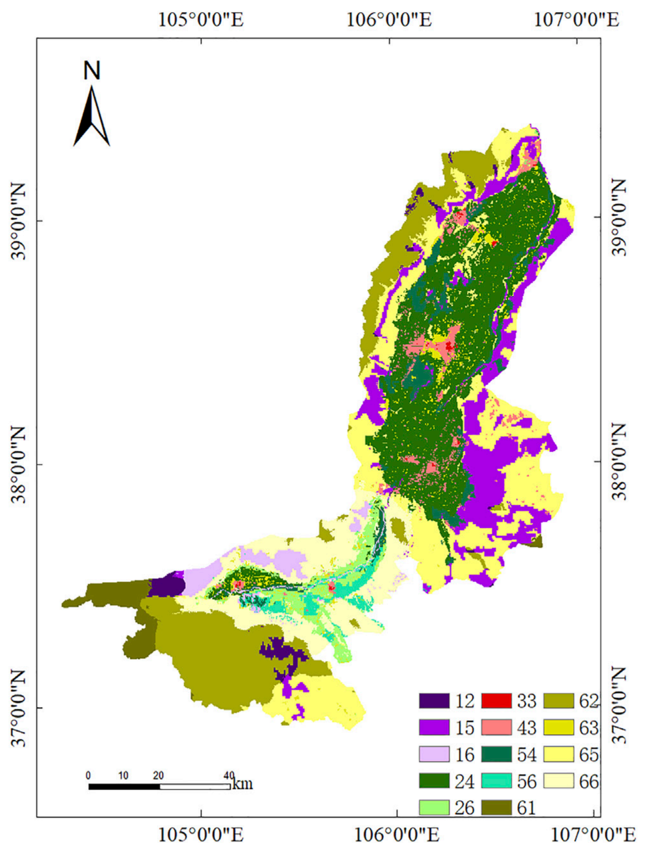

FIGURE 8 | Zoning management in the CBYN.

and moderate GDP density, and the latter was in the southern part with the lowest precipitation and lowest GDP density. As indicated by the results of the overlay analysis (**Figure 7B**), ESB 3 and ESB 4 mostly overlapped with DC 3, while ESB 2 and ESB 5 had a higher overlap percentage with DC 4 and DC 6. ESB 1 mainly overlapped with DC 5 (66.248%) and overlapped little with DC 6 (15.301%) and DC 2 (10.844%), while ESB 6 overlapped with DC 5 (82.799%), DC 2 (30.395%), and DC 6 (19.992%). Overall, ES supply–demand characteristics can be predicted by the socioecological environment to some extent, while different socioecological environments generate the same ES supply–demand characteristics.

3.4 Ecosystem Zoning Management and Measures

To maintain the sustainable supply of multiple ESs, the socioecological system must be managed in a manner that can balance ES supply and demand. By combining the characteristics of ES supply and demand, their tradeoffs and bundles, and the socioecological environment, zoning management was conducted, as shown in **Figure 8**. According to the characteristics of different zones, combining the driving mechanism of each ES, zoning management measures were proposed, as shown in **Table 7** below.

4 DISCUSSION

4.1 Spatial Mismatches of ES Supply and Demand

In the CBYN, high supply and low demand of ESs exist in croplands with high human utilization in the central plain, with low supply and high demand in grassland with a more natural environment. This is inconsistent with the findings in the European, which suggested that hotspots of ES supply exist in more natural mountain regions, with high demand in urbanized areas or intensive agricultural areas in the lowlands (Schirpke et al., 2019). This can be explained by the characteristics of the study area. Low precipitation in arid and semiarid regions limits vegetation coverage and growth (Georganos et al., 2017), resulting in large areas of sparse grassland and even bare land or deserts, which have low supply and low demand of ESs. Thus, the natural environment does not equate to hotspots of ES supply, or the low supply and demand of ESs, especially in arid and semiarid regions.

Land use patterns directly impact the configuration and magnitude of ESs and further affect the sustainability and resilience of the ecosystem (Marques et al., 2019; Zhou et al., 2021). They play a critical role in determining the spatial pattern of ES supply, which is consistent with the findings in other studies (Meacham et al., 2016; Spake et al., 2017; Xu et al., 2018), but cannot explain all the variance. For ES supply, cropland distribution and vegetation coverage have the second largest impacts, suggesting the ecological importance of cropland management in the CBYN. The Yellow River goes through the CBYN, providing abundant water resources for agricultural production and for sustaining the cropland with a high and intensive vegetation cover. The management of the cropland is critical for future sustainable development, especially in the Yellow River basin. Mountain areas with forest coverage and steep terrains could provide a high supply of regulating and cultural services, i.e., carbon sequestration, sand fixation, and recreational opportunity, especially in arid and semiarid regions (Fu et al., 2017). Moreover, this area also has a high supply of wind prevention and sand fixation, which has great importance in building good living conditions for human settlement in the central plain (Lyu et al., 2018). The exclusion of human intervention also makes the mountain areas a low-demand area for ESs. Therefore, even in arid and semiarid regions, the mountains remain ecological hotspots with strong positive spillover effects (Wei et al., 2018; Chen et al., 2019).

Lorilla et al. (2019) suggested that excess ES demand can inhibit the supply of other ESs. In our study, high demand and low supply of ESs existed in the urban areas, especially in the city center with the densest settlement. Thus, the compact city, which has been widely promoted in urban planning due to its advantages in social cohesion and land efficiency, would have negative impacts on ES conservation, especially for provision and regulating services. This is consistent with the "paradox of the compact city" in Berlin (Larondelle and Lauf, 2016). Green spaces in urban areas would be a solution to tackle this paradox and turn it into a win–win situation, as indicated by the higher supply and lower demand of ESs in the outer city (Guan et al., 2020). Dense settlement in the city center is closely correlated with high imperviousness of the land surface, which has been suggested as a critical driver for the low ES supply in urban areas (Zhang et al., 2017; Tao et al., 2018). Minimizing the paved area in settlements

TABLE 7 | Ecosystem zoning management measures.

Zone	Location and Area Percentage	ES Characteristics	Management Objective	Socio-Ecological Environment Characteristics	Management Suggestions
12	Mainly in the northwestern and southeastern part of Shapotou District, dominated by unused land and grassland 1.693%	The highest supply and demand of sand fixation, with low supply and demand of other ESs	The highest elevation, highest soil erodibility, and moderate distance to human activities	The highest elevation, highest soil erodibility, and moderate distance to human activities	Increase vegetation coverage to reduce wind erosion and increase soil retention
15	Mainly in the transition region between central plain and mountains, dominated by grassland and unused land 10.93%	—	—	The lowest vegetation coverage, highest precipitation, higher soil erodibility, lower wind speed, moderate elevation and socio-economic development	Increase vegetation coverage, promote trickle irrigation and protect this from intensive development or utilization to improve the supply of ESs and decrease their demand
16	Mainly in the northern part of Dawukou District and southwestern part of Wuzhong City, dominated by grassland and water area 2.473%	—	—	The lowest precipitation and socio-economic development, and moderate wind speed and distance to human activities	Restore the original natural ecosystem, and control the scale
24	In Yinchuan Plain and north part of Weining Plain, mainly covered by cropland 21.183%	The highest supply and match degree and moderate demand of crop production, carbon sequestration and nutrient retention, with lower level of sand fixation and recreational opportunity	Ensure the sustainable development of supply capacity of provision and regulating ESs	The highest vegetation coverage, lowest elevation and wind speed, moderate distance to human activities and socio-economic development	Promote fertigation and tickle irrigation to improve the supply of crop production and carbon sequestration and reduce the demand of nutrient retention
26	Mainly in Weining Plain and covered by cropland 2.949%	—	—	The lowest precipitation and socio-economic development, and moderate wind speed and distance to human activities	Promote tickle irrigation to replenish agricultural water consumption
33	In the core region of urban area 0.160%	The highest demand and lowest supply of ESs except sand fixation among the whole region	Reduce the demand pressure of ESs	The lowest elevation, highest socio-economic development, distance to grassland and distance to human activities	Reduce human density and perfect the structure of urban green land to decrease ES demand
43	In the outer region of urban area 2.664%	Higher demand and lower supply of ESs except sand fixation among the whole region	Reduce the demand pressure of ESs and improve ES supply capacity	The lowest elevation, highest socio-economic development, distance to grassland and distance to human activities	Control the size of urban expansion and population distribution to satisfy ES demand and avoid overdevelopment
54	In the fringe area of 3.806%	The highest supply and match degree of ESs except recreational opportunity	Maintaining the existing supply and demand of ESs and steadily improve ES supply capacity	The highest vegetation coverage, lowest elevation and wind speed, moderate distance to human activities and socio-economic development	Promote high-quality agriculture and control the scale of urbanization
56	Mainly in the eastern part of Weining Plain 1.595%	—	—	The lowest precipitation and socio-economic development, and moderate wind speed and distance to human activities	Promoting tickle irrigation and high-quality agriculture to improve the supply capacity of ESs
61	In the southwestern fringe region of the CBYN 2.125%	Higher supply and match degree of recreational opportunity, with low supply and demand of other ESs	Improve the supply capacity of ESs	Higher elevation, precipitation and wind speed, moderate soil erodibility, lowest socio-economic development, and the highest distance to human activities	Planting xerophyte vegetation to improve the supply capacity of other ESs
62	Mainly in the north Helan Mountain and south Sikouzi Mountain 15.385%	—	—	The highest elevation, highest soil erodibility, and moderate distance to human activities	Encouraging ecological tourism while maintaining the original natural ecosystem to increase the supply of recreational opportunity
63	Dispersed in Yinchuan Plain and Weining Plain, dominated by built-up land 2.075%	—	—	The lowest elevation, highest socio-economic development, distance to grassland and distance to human activities	Perfect the structure of urban green land to increase its availability and spatial equity to further satisfy human demands
	—	—	—	—	Control the scale of urban expansion and population

(Continued on following page)

TABLE 7 | (*Continued*) Ecosystem zoning management measures.

Zone	Location and Area Percentage	ES Characteristics	Management Objective	Socio-Ecological Environment Characteristics	Management Suggestions
					distribution to avoid overdevelopment and decrease ES demand
65	Mainly in the west region of Yinchuan Plain, the transition region between Helan Mountain and Yinchuan Plain, and the southern part of Zhongning County 19.524%	—	—	The lowest vegetation coverage, highest precipitation, higher soil erodibility, lower wind speed, moderate elevation and socio-economic development	Restoring the original natural ecosystem and encouraging to plant xerophytic vegetation to improve the supply capacity of ESs
66	Mainly in the north and south region of Weining Plain, dominated by grassland, 10.091%	—	—	The lowest precipitation and socio-economic development, and moderate wind speed and distance to human activities	Promoting tickle irrigation to decrease water consumption and improve vegetation coverage to further improve the supply capacity of ESs

would be helpful in the sustainable planning of city centers. On the other hand, urban land also has a high supply and high match degree for cultural services, especially in the outer city. This also is another promising future for urban development, i.e., utilizing tourism resources and building scenic spots.

4.2 Tradeoffs and Synergies Among ESs

Tradeoffs/synergies among ESs mainly come from two resources. The first is ESs intrinsically correlated with the same ecological process or those that benefit stakeholders, e.g., the photosynthesis process in vegetation growth would increase the carbon sequestration service but decrease water resources, resulting in the tradeoff between carbon sequestration and water yield (Zhou et al., 2017); crop production and recreational opportunity both aim to satisfy the demand of the same stakeholders (Stålhammar and Pedersen, 2017; Ala-Hulkko et al., 2019). The second is ESs externally impacted by the same socioecological factors, e.g., high elevation is beneficial for wind prevention and sand fixation but harmful for crop production, contributing to their tradeoff (Shi et al., 2009; Li and Wang, 2018). In our study, synergies among crop production, carbon sequestration, and nutrient retention in supply may be caused by their close correlation with vegetation growth. In specific, crop production and nutrient retention have a closer relation to crop growth in the central plain, while carbon sequestration is also impacted by forest growth, as indicated by the hotspots in the mountain areas and the high impacts of precipitation and elevation. These factors finally result in a stronger synergy between food production and nutrient retention and a weaker one between carbon sequestration and the other two services. Overall, the closer to the same ecological process or the same stakeholders, the stronger the relationship between the two ESs.

Recreational opportunity supply and sand fixation had greater differences from the other three ESs in the related ecological process and estimation method, while they only had similarities in their driving mechanisms to a certain extent, with the common influencing factors of land use pattern and NDVI. The lack of intrinsic correlation and low similarity of the external driving mechanisms finally result in a weak correlation between the former two ESs and the other three ESs on the supply side, which is consistent with the findings in relevant studies (Obiang Ndong et al., 2020; Lyu et al., 2021). The same situation occurs at the match and demand sides. The unstable tradeoffs or synergies among ESs mainly result from the lack of intrinsic relations or similar calculation methods among ESs at the match side, as ES demand comes from the recalculation of ES supply and demand. In our study, the ES demand was calculated with significant differences: two from the requirements of human beings (crop production and recreational opportunity), two from pollutants emitted in the ecosystem (carbon sequestration and nutrient retention), and one from an ecological process (sand fixation). Among them, stronger relationships exist among ESs in the same group at the demand side, while weaker relationships exist among ESs in different groups. Cui et al. (2019) also suggested the same conclusion. Overall, the synergies and tradeoffs among ESs can be partly predicted based on the similarity of calculation methods and intrinsic ecological processes. Moreover, per capita GDP, a good comprehensive indicator for economic development and population growth, has the most critical impact on the four ESs on the demand side except for sand fixation, which contributes to the stronger synergies among ES demands at the county scale. This should be taken into consideration in land use policy-making.

4.3 Integrating ES Supply–Demand and the Socioecological System Into Ecosystem Zoning Management

Significant spatial heterogeneities exist in different zones, including key environmental issues, social conditions, and ecological environment, which calls for differentiated, targeted management policies (Ai et al., 2015; Li et al., 2021). Zoning management can satisfy this need at multiple scales for different protection targets (Dubrova et al., 2015). For example, the U.S. Environmental Protection Agency developed a water ecological zoning in the mid-1980s at the national scale, which has been successfully applied to protect the entire hydroecological system and water quality (Xu et al., 2020). In China, the Ecological Red Line system has been launched to classify strict protection areas with special and critical ecological functions to maintain national ecological security. However, the delineation of the Ecological Protection Red Line has conflicted with the boundary of Permanent Basic Arable land and the need for economic development (He et al., 2018). A more rational zoning management method is desired at the local scale.

This study presented an integrated framework to integrate ESs and the socioecological environment in zoning management, including mapping the supply and demand of multiple ESs, assessing interactions among ESs, quantifying their socioecological mechanisms, and finally overlaying ES bundles and socioecological driver clusters to classify zones and provide management suggestions. By considering both the supply and demand sides of multiple ESs in the framework, we can identify the ecological problems from the comprehensive insights of natural, ecological, social, and economic systems, which is beneficial for balancing environmental protection and socioeconomic development (Peng et al., 2019a). Through quantifying the socioecological driving mechanisms of ESs, differentiated management strategies have been designed for different zones to adapt to local conditions. The strategy of one-size-fits-all is unsuitable for land use planning and ecosystem management (Zhou et al., 2019).

Numerous studies have focused on avoiding irrational human activities and protecting natural capital (Bradford and D'Amato, 2012; Cai et al., 2017; Fernandino et al., 2018). The urgent challenge is integrating research results into actual actions through social policy and decision-making (Gong et al., 2021). Based on the analysis results of ES bundles and socioecological driver clusters, the CBYN can be divided into 14 zones with different ES supply–demand characteristics, ES tradeoffs/synergies, and socioecological conditions. Differentiated management strategies have been suggested for different zones to enhance the ES supply–demand match degrees and synergies among ESs and reduce tradeoffs (**Table 7**).

4.4 Limitations and Directions

In this study, the key ESs were selected by considering not only the natural environment but also human well-being, while their supply and demand were quantified and mapped through widely accepted models and equations. Data in this study were readily obtained, including remote sensing images, meteorological observations, and social statistics. As for the approach to identifying ecological problems and management objectives, spatial neighborhood impacts were taken into consideration rather than directly overlaying multiple ESs. This approach could contribute to identifying spatially aggregated multiple ESs rather than isolated grids with high or low values of ESs through the SOM method. Besides that, Spearman's rank correlation analysis has been confronted as a simple but effective method for analyzing correlations among ESs. However, there are still some limitations.

First, tradeoffs/synergies among ESs are scale-dependent, that is, they are likely to change with the spatial unit. The results of ES interactions might only be applicable at a specific temporal or spatial scale in the study (Peng et al., 2019a). Future research would focus on comparative analysis at multiple scales. Second, this study did not include institutional and cultural factors in building a socioecological driver system, which has important impacts on socioeconomic development and human demands, especially in China. Future studies should focus more on finer and deeper identification of key drivers of ES tradeoffs/synergies, such as the impacts of management practices, landscape patterns, and soil characteristics.

5 CONCLUSION

This study established a framework for systematically proposing a zoning management method by exploring the spatial relationships among ESs and their driving mechanisms at both supply and demand sides. The results suggest that significant differences exist in ES spatial distribution at different sides of supply, demand, and match degree. High values of ES supply were mainly concentrated in the central plain, which was mostly impacted by land use patterns, cropland distribution, and vegetation coverage. Meanwhile, high ES demand was mainly concentrated in urban areas, especially the city center, which was mainly driven by per capita GDP. Spatial interactions among ESs varied greatly among the three sides of supply, demand, and match degree, especially between the two ESs of sand fixation and recreational opportunity and the other three ESs. Significant synergies existed among crop production, carbon sequestration, and nutrient retention, which kept consistent at different sides of supply and demand. This was caused by the similarities in their intrinsic ecological processes and beneficiaries. On the other hand, the lack of intrinsic correlation and low similarity of the external driving mechanisms resulted in weak and unstable interactions between the two ESs of sand fixation and recreational opportunity and the other three ESs at different sides. Overlay analysis of ES bundles and driver clusters is a useful way to identify management zones with relatively consistent ecological problems and socioecological environments, and differentiated management suggestions were provided to sustain the supply–demand match degree of multiple ESs simultaneously.

DATA AVAILABILITY STATEMENT

The original contributions presented in the study are included in the article/**Supplementary Material**; further inquiries can be directed to the corresponding author.

AUTHOR CONTRIBUTIONS

RL: conceptualization, data curation, methodology, formal analysis, writing, project administration; XT: methodology, resources, software; WZ: supervision, validation, visualization; JP: data analysis, visualization; JZ: funding acquisition, investigation, supervision.

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SUPPLEMENTARY MATERIAL

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fenvs.2022.911190/full#supplementary-material

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