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Research on ecological management zoning in Jilin Province based on a human well-being framework

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Taking Jilin Province in 2020 as the study area, this research categorizes ecosystem service supply and demand by integrating ecosystem service functions with a human well-being framework. The study evaluates the supply and demand of ecosystem services and examines their spatial distribution characteristics. To further delineate ecological management zones, the SC K-means clustering algorithm and the coupling coordination degree model are employed. The results reveal significant regional disparities in the availability and necessity of six ecosystem services. Food production services exhibit a spatial pattern characterized by an increase in the central region while declining in the eastern and western areas. In contrast, the supply of the other five ecosystem services generally follows a "low in the west, high in the east" trend. Additionally, except for soil conservation, the demand for ecosystem services demonstrates a distribution pattern of being high in the central region and lower in the surrounding areas. The overall supply of ecosystem services gradually increases from west to east, reaching its peak in the eastern region, whereas the comprehensive demand is highest in the central region and lower in both the eastern and western areas, with central cities and their surrounding counties exhibiting the most pronounced demand. Based on the dynamics of supply and demand, Jilin Province is divided into five ecological management zones. The ecological potential zone, where supply–demand coordination transitions from low to high, is suited for developing green agricultural economies and optimizing industrial structures. The ecological restoration zone, experiencing a shift from high to low supply–demand balance, faces imbalances that necessitate efforts to alleviate human-land conflicts and enhance the equilibrium between social development and ecological conservation. The ecological consolidation zone, which maintains a high-to-low supply–demand trend with relative stability, requires continued efforts in preserving its natural environment. The ecological adjustment zone, characterized by an imbalanced high-to-low supply–demand transition, should focus on industrial restructuring and eco-tourism development. Lastly, the ecological coordination zone, which maintains a well-balanced supply–demand relationship, should leverage its economic foundation to advance environmental protection technologies and strengthen conservation efforts. This study provides a systematic evaluation of the spatial patterns of ecosystem service supply and demand in Jilin Province and offers targeted ecological management strategies to promote sustainable environmental development.

Keywords Supply and demand for ecosystem services, Ecological management zone, Maslow's hierarchy of needs, Spatially constrained K-means, Jilin Province

Rapid economic growth, urbanization, land use changes, and climate change have significantly contributed to ecosystem degradation and the decline of ecological functions[1]. Over half of the world's ecological functions are deteriorating, threatening the sustainable development of human societies due to inadequate ecosystem management. To address this challenge, ecological management zoning has been proposed as a strategic approach to enhance ecosystem structure, restore ecological integrity, and ensure a sustainable supply of ecosystem services[2–4]. However, current ecological zoning initiatives primarily focus on natural elements, often

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overlooking the dynamic interactions between human demands and ecological functions. This imbalance can lead to inefficiencies in ecological management and land use planning.

Since the late 1970s, scholars have explored ecological zoning methodologies, with early contributions from Bailey[5] and Rowe and Sheard[6] focusing on ecosystem-based regional delineation. Subsequent research has examined zoning at different scales, including forests, farmlands, and wetlands[7–9], as well as national, regional, and watershed levels[10–12]. However, most studies have concentrated on assessing the supply capacity of multiple ecological functions rather than the interplay between the availability and demand for these services. This gap underscores the need for a zoning approach that integrates both ecological function provision and human needs.

Recent international studies have increasingly emphasized the importance of integrating supply–demand interactions in ecosystem service evaluations. For example, studies in arid and semi-arid regions have highlighted water scarcity as the dominant constraint on ecological functions[13], whereas research in industrialized regions often focuses on pollution control and environmental restoration[12]. Additionally, traditional ecological zoning frameworks have been criticized for their reliance on static assessments that fail to capture temporal shifts in ecosystem service dynamics[14,15]. In contrast, newer approaches advocate for dynamic monitoring systems that adapt to changing environmental conditions[10].

To bridge this gap, this study employs a human well-being framework as a foundation to evaluate the demand for ecological functions, ensuring that zoning decisions align with human quality of life and sustainable development. Unlike Human well-being framework, which provides a rigid hierarchical structure, the human well-being approach allows for a more dynamic and multidimensional perspective, emphasizing the role of ecosystem services in sustaining livelihoods, enhancing environmental security, and promoting socio-economic stability. The SC K-means model, a spatially constrained clustering method, is utilized to delineate ecological management zones in Jilin Province. This study assesses the availability and demand for six key ecological functions—water production, carbon sequestration, food production, soil conservation, habitat quality, and recreation services—at the county level in Jilin Province, identifies spatial variations and mismatches between ecological function supply and human demand, and applies the coupled coordination degree model and SC K-means clustering to establish an optimized ecological management zoning framework. By integrating ecological service assessments with human well-being considerations, this research provides a scientific foundation for improving land use planning and ecological management in Jilin Province, offering practical insights for policymakers to enhance regional sustainability and ecosystem resilience.

Materials and methods
Study area
As shown in Fig. 1, situated at the core of Northeast China, the Jilin Province is positioned between 121° 38′ –131° 19′ east longitude and 40° 50′–46° 19′ north latitude. The province's eastern region includes the ChangBai Mountain range, famed for its elevated landscape, thick woodlands, and abundant greenery, along with a substantial segment of the Songhua River Basin, a source of plentiful water resources. Characterized by its level landscape and rich soil, the central area is an essential center for agriculture. Conversely, the western region features steppe wetlands that stretch from the Horqin steppe, serving as a transitional area between moist forest-steppe ecosystems and the semi-arid steppe and desert. This region enjoys a mild continental weather pattern, characterized by monsoon showers, four separate seasons, and harmonized rainfall and heat throughout the growth period. Nonetheless, modern human actions have progressively disturbed the ecological setting, resulting in regular environmental disturbances. Consequently, performing a scientific evaluation of ecological function supply and demand, along with the application of ecological management zoning, is vital for improving ecological conservation and fostering sustainable economic development in Jilin Province. This research utilizes maps from the Ministry of Natural Resources Standard Map Service's website (Standard Map No. GS4308), without altering the foundational map.

Data sources
This study incorporates multiple datasets, including the Digital Elevation Model (DEM), land use data, meteorological records, soil data, hydrological data, and socioeconomic statistics, to support the ecological management zoning analysis. To maintain consistency and scientific rigor, all datasets were projected to a unified spatial reference system and standardized to a 1 km × 1 km resolution. The 1 km × 1 km resolution was chosen to balance spatial accuracy and computational efficiency, ensuring effective modeling of ecosystem services over Jilin Province. This resolution is widely used in regional-scale ecological assessments, aligning with standard datasets such as MODIS NDVI and FAO soil databases, ensuring data consistency. It captures landscape-level variations while avoiding excessive computational complexity, making it suitable for large-area spatial analysis and policy applications. The sources, purposes, accuracy, and collection time of the datasets used are presented in Table 1. The software used in this study includes ArcGIS 10.2, with the URL https://www.esri.com/zh-cn/arcgis/products/arcgis-desktop; MATLAB 2021, with the URL https://www.mathworks.com/products/matlab.html; and Origin 2021, with the URL https://www.originlab.com/index.aspx?go=Products/Origin.

Research methodology
Measuring supply for ecosystem services
This study selects water production, carbon sequestration, food production, soil conservation, habitat quality, and recreational services based on their essential role in ecosystem functions, as well as their relevance to the ecological and socioeconomic characteristics of Jilin Province. Jilin Province, located in Northeast China, exhibits a distinct east–central–west ecological gradient. The eastern region, dominated by the Changbai Mountain forest ecosystem, has strong water conservation capabilities, high carbon sequestration potential, and superior habitat quality, making it crucial for regional biodiversity protection and climate regulation. The central plains serve as
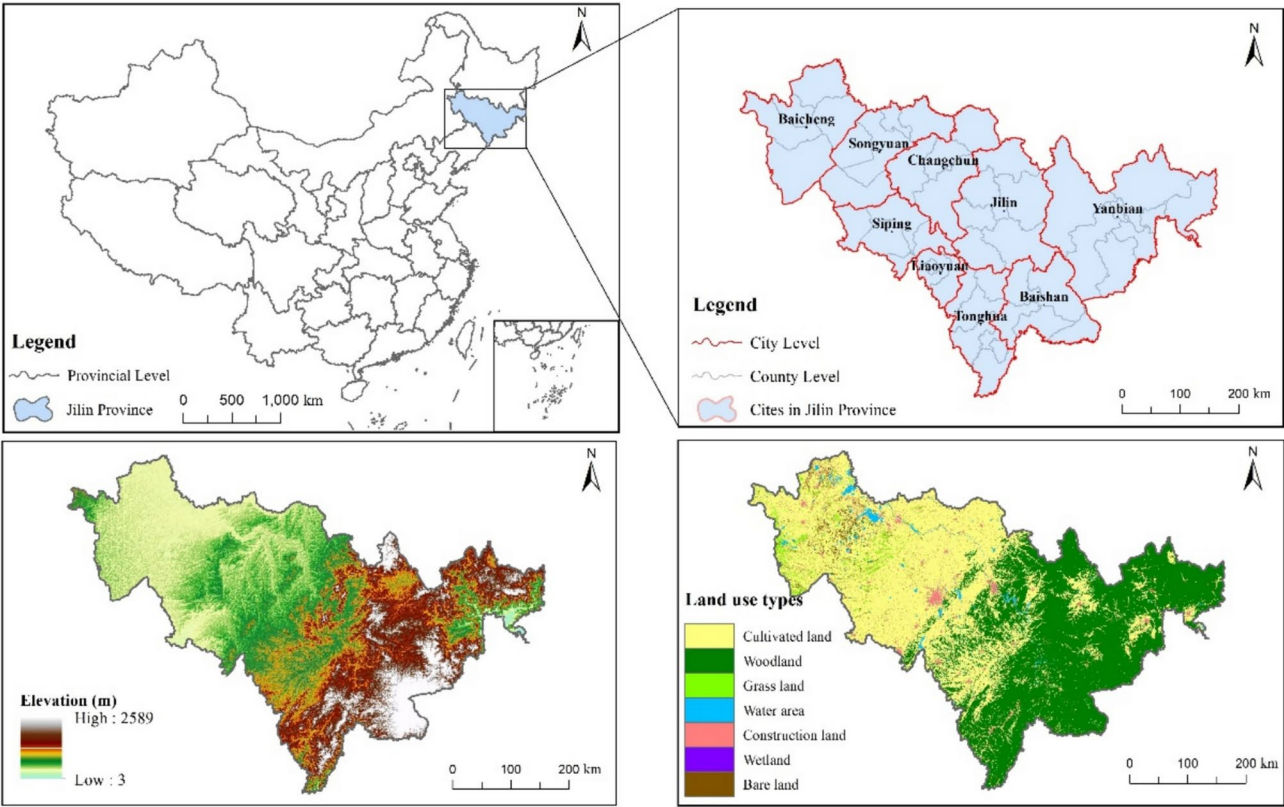
Fig. 1. Geographic location and land use in Jilin Province.

	Data type	Source	Purpose	Accuracy	Collection time
1	Data on the digital elevation model (DEM)	Resource Environment Science and Data Centre, CAS	Terrain analysis and elevation assessment	30 m resolution	Latest available data (2020)
2	Administrative boundaries	Resource Environment Science and Data Centre, CAS	Study area delineation	Official administrative boundaries	Latest available data (2020)
3	Land utilization	National Data Centre for the Tibetan Plateau	Land use classification and ecosystem analysis	30 m resolution	2020
4	Weather patterns	National Data Centre for the Tibetan Plateau	Climate impact assessment	Meteorological station data with spatial interpolation	2020
5	Evapotranspiration (ET)	National Data Centre for the Tibetan Plateau	Water balance and ecological function analysis	MODIS-derived with an accuracy of ± 5%	2020
6	Normalized Difference Vegetation Index (NDVI)	National Data Centre for the Tibetan Plateau	Vegetation coverage and ecosystem health assessment	MODIS-derived with an accuracy of ± 5%	2020
7	Soil data	World Soil Database (HWSD), FAO	Soil quality and classification	1 km resolution	Latest available data (FAO)
8	Water system data	Landsat 8 OLI (Processed via PIE Remote Sensing Software)	Hydrological analysis and water resources evaluation	30 m resolution	2020
9	Social statistics	China Urban Statistical Yearbook, China County Statistical Yearbook, Jilin Provincial Statistical Yearbook	Socioeconomic and demographic analysis	Official statistical data	2019–2020

Table 1. Data sources and specifications.

the province's primary agricultural production area, characterized by fertile soils and high grain yields. However, long-term agricultural activities and human interventions have led to increased soil erosion risks, making soil conservation and sustainable agriculture key concerns for ecological management. The western semi-arid region experiences low precipitation and high evaporation, resulting in significant water supply–demand imbalances and fragile ecological conditions, emphasizing the critical role of water production and soil conservation in this area. Additionally, Jilin Province is home to abundant natural landscapes, such as Changbai Mountain and Songhua Lake, which significantly contribute to regional economic and social development through eco-tourism and recreational activities. Therefore, recreational services, as a vital component of cultural ecosystem services, are also included in this study's assessment framework[16]. Each of the six ecosystem services was selected based

Land use code	Land use type	C_{above}	C_{below}	C_{soil}	C_{dead}
01	Cultivated land	4.7	7.52	64.28	2.84
02	Woodland	41.05	23.18	408.56	7.02
03	Grass land	0.91	5.57	142.26	1.05
04	Water area	0	0	249.71	0
05	Construction land	0	0	0	0
06	Wetland	5.59	0	31.75	0
07	Bare land	0.71	5.02	95.38	0

Table 2. Carbon density table by site type/(t/hm^2).

Land use type	Cultivated	Woodland	Grass	Water	Construction land	Wetland	Bare land
C	0.27	0.01	0.06	0	0.21	0.06	0.35
P	0.29	0.71	0.53	0.22	0.16	0.53	0.27

Table 3. C and P values for different land-use types.

Threat	Max_dist	Weight	Decay
Cultivated land	4	0.61	Linear
Construction land	8	0.98	Exponential
Bare land	6	0.52	Linear

Table 4. Maximum distance of influence, weights, and type of spatial decline of threat elements.

on its fundamental role in sustaining ecological integrity and human well-being. Their inclusion aligns with widely accepted ecosystem service classification frameworks, such as the Millennium Ecosystem Assessment (MEA) and the Common International Classification of Ecosystem Services (CICES).

Water production service supply   The provision of water yield services is a crucial element of ecosystem services, significantly impacting agricultural progress, industrial growth, and socio-economic development in a specific region. Moreover, these services can dramatically enhance social welfare in various ways[12,13]. This paper employs the water yield module of the InVEST model, which is based on integrating Budyko's coupled hydro-thermal equilibrium assumption equation.

Carbon sequestration service supply   This study employs the InVEST model to quantify the carbon stock in Jilin Province, thereby indicating the capacity for ecosystem carbon sequestration services. The carbon stock comprises four components: aboveground biomass, belowground biomass, soil carbon, and dead organic matter. The carbon densities vary across different land use types, with the densities presented in this paper sourced from pertinent literature[12] (Table 2).

Food production service supply   This paper allocates the grain production of cities and counties in the study area to agricultural land using NDVI data based on pertinent studies[2–4].

Soil conservation service supply   The soil retention capacity of an ecosystem indicates its capability to retain sediment[17]. This study quantifies this capability by utilizing the sediment transport ratio module of the InVEST model alongside the *Technical Specification for National Ecological Condition Survey and Assessment of Ecosystem Service Functions* published by the Ministry of Environment of China (Eq. 4). This paper establishes specific figures based on pertinent literature (Table 3).

Habitat quality service supply   This study utilizes the InVEST model, particularly its habitat quality assessment module, to determine the habitat quality index in the research area. The InVEST model evaluates habitat quality by analyzing land use data, the proximity and nature of threat impacts, and the vulnerability of various land types to these threats. The parameters are derived from a synthesis of three components, with the model parameters established based on relevant literature[18] (Tables 4 and 5).

Leisure and entertainment service supply   Recreational services constitute a fundamental component of the ecosystem's socio-cultural benefits to humanity. This paper articulates the sum of the ratio of recreational land per unit area to grid area[19], which offers a consolidated representation of the ecosystem's recreational services.

Land use code	Land use type	Habitat	Cultivated land	Construction land	Bare land
01	Cultivated land	0.42	0	0.82	0.43
02	Woodland	0.98	0.63	0.53	0.19
03	Grass land	0.82	0.55	0.55	0.12
04	Water area	0.73	0.52	0.72	0.18
05	Construction land	0	0	0	0.11
06	Wetland	0.81	0.51	0.91	0.63
07	Bare land	0.23	0.63	0.32	0

Table 5. Habitat quality suitability of different land use types and their sensitivity to threat elements.

Demand for ecosystem services	Calculation formula	Variable comments
Demand for water production services	$D_w = f_{pewc} \times P_{pop}$	D_w for water production services demand f_{pewc} is per capita water consumption P_{pop} is population density
Demand for carbon sequestration services	$D_c = c_{pecc} \times P_{pop}$	D_c for carbon sequestration service demand c_{pecc} is carbon emissions per capita P_{pop} is population density
Demand for food production services	$D_f = f_{pefc} \times P_{pop}$	D_f for food production service demand f_{pefc} is per capita food consumption P_{pop} is population density
Demand for soil conservation services	$Q_{se\_a} = R \times K \times L \times S \times C \times P$	R is the rainfall erosion factor K is the soil erodibility factor L and S are the topographic factors (slope length and slope gradient) C is the vegetation cover factor P is the soil conservation initiative factor
Demand for habitat quality services	$D_q = \overline{q_{xj}}$	D_q for habitat quality service demand $\overline{q_{xj}}$ is the average level of habitat quality
Demand for leisure and recreation services	$D_l = l_{pelc} \times P_{pop}$	D_l for leisure and recreation service demand l_{pelc} is recreational land area per capita P_{pop} is population density

Table 6. Methodology for calculating demand for ecosystem services.

Measuring demand for ecosystem services
Given that humans are the primary beneficiaries of ecosystem services, it is essential to analyze the demand for these services from society[14]. This paper analyzes six facets of demand related to a specific ecosystem service supply: water production, carbon sequestration, food production, soil conservation, habitat quality, and recreation. The evaluation techniques are detailed in Table 6.

The per capita water consumption was referenced against the 2020 national water consumption data from the *China Water Resources Bulletin to compare the different calculation methods*. Likewise, the per capita carbon emissions were sourced from the China Carbon Accounting Database (https://www.ceads.net.cn/). In contrast, the per capita food demand was derived from data supplied by the National Bureau of Statistics (NBS). This figure was obtained from the 2020 per capita food consumption data released by the National Bureau of Statistics (NBS). An average level of habitat quality was presumed to adversely impact the demand for this ecosystem service[15]. The per capita recreational land area was cited from prior studies.

Integrated ecosystem services supply and demand assessment based on the hierarchy of demands theory
This study integrates a human well-being framework into ecosystem service assessment to systematically illustrate how different ecological functions contribute to various well-being dimensions. Unlike Maslow's hierarchy, which assumes a sequential progression of needs, the human well-being framework recognizes the interdependent and context-specific nature of ecosystem services in supporting human life. The selected ecosystem services are classified into three main dimensions:

1. Basic environmental needs: Water production, food production, and soil conservation ensure fundamental survival by securing access to clean water, food security, and stable land conditions.
2. Health and environmental security: Carbon sequestration and habitat quality enhance environmental stability, mitigate climate risks, and support biodiversity conservation, directly impacting long-term human well-being.
3. Cultural and socioeconomic well-being: Recreational services fulfill socio-cultural demands, promoting psychological well-being, eco-tourism, and aesthetic appreciation, while also contributing to economic sustainability.

This classification ensures that the zoning methodology accounts for both ecological integrity and human well-being, facilitating a more adaptive and policy-relevant approach to ecosystem management. The results provide actionable insights for regional planning, environmental policy-making, and sustainable development strategies.

This study integrates Human well-being framework into ecosystem service assessment to systematically illustrate how different ecological functions meet human needs at various levels. Basic needs (physiological and safety needs) are fundamental for human survival, with water production ensuring access to drinking water, agricultural irrigation, and industrial use, food production securing food supply and agricultural sustainability, and soil conservation maintaining soil fertility and preventing erosion, thereby ensuring long-term land productivity and environmental safety. Intermediate needs (well-being and security) pertain to the role of ecosystems in enhancing quality of life and ensuring environmental stability. Carbon sequestration mitigates climate change by regulating atmospheric carbon levels, improving air quality, and reducing the risks of extreme weather events, while habitat quality supports biodiversity and ecosystem resilience, ensuring ecological balance and long-term sustainability. Higher needs (social and self-actualization needs) relate to the cultural and recreational benefits provided by ecosystems. Recreational services fulfill human aspirations for aesthetic enjoyment, cultural enrichment, and leisure activities, while also promoting eco-tourism, social interaction, mental well-being, and cultural heritage preservation. This framework underscores the role of ecosystem services in addressing human needs across multiple dimensions, making ecological management more people-centered, precise, and aligned with sustainable development goals. A thorough evaluation of the supply and demand for ecosystem services was performed by allocating appropriate weights to each service based on its supply level (Eqs. 1 and 2).

$$TES_p = \sum_{i=1}^{j} (6 - L_i) \times ES_{ip} \tag{1}$$

$$TES_d = \sum_{i=1}^{j} (6 - L_i) \times ES_{id} \tag{2}$$

In the equation, TES_p denotes the aggregated supply of ecosystem services, while TES_d indicates the aggregated demand for ecosystem services. L_i represents the level at which ecosystem services are positioned, ES_{ip} suggests the supply of the ith ecosystem service, and ES_{id} signifies the demand for the ith ecosystem service.

z-score normalization and coupling coordination degree
The supply and demand of ecosystem services are interdependent. To examine this relationship, this study employed the z-score standardization method[20] (Eq. 3) alongside the coupled degree of coordination model[21] (Eq. 3).

$$X = \frac{x_i - \frac{1}{n}\sum_{i=1}^{n} x_i}{\sqrt{\frac{1}{n}\sum_{i=1}^{n} (x_i - \overline{x})^2}} \tag{3}$$

In Eq. (3), X denotes the supply and demand of ecosystem services after z-score standardization. The term x_i denotes the supply and demand of the ith raster. The symbol $\overline{x}$ denotes the mean supply and demand of ecosystem services in Jilin Province. The variable n denotes the aggregate quantity of evaluation units. A two-dimensional coordinate system was established, with standardized ecosystem service supply depicted on the x-axis and ecosystem demand illustrated on the y-axis. Quadrant I depicts a situation of low supply and high demand, quadrant II demonstrates a scenario of high supply and high demand, quadrant III signifies a condition of low supply and low demand, and quadrant IV denotes a context of high supply and low demand.

$$D = \sqrt{\sqrt{\frac{P_s \times P_d}{[(P_s \times P_d)/2]^2}} \times (\alpha P_s \times \beta P_d)} \tag{4}$$

In Eq. (4), D denotes the coupling coordination degree, P_s represents the normalized ecological service supply, and P_d signifies the normalized ecological service demand. The coefficients α and β are employed to weight supply and demand, with $\alpha = \beta = 0.5$ in this analysis.

Cluster identification of supply and demand for ecosystem services
This study employed the Spatially Constrained K-means (SC K-means) clustering method to delineate clusters of supply and demand for ecosystem services. This method enhances the traditional K-means clustering by incorporating a spatial constraint term, S, to reflect the spatial relationships among data points[2–4,22] (Eqs. 5 and 6).

$$\text{minimize} \sum_{k=1}^{K} \left(\sum_{x_i \in C_k} \|x_i - \mu_k\|^2 + \lambda S \right) \tag{5}$$

$$S = \sum_{x_i, x_j \in C_k, i \neq j} (1 - w_{ij}) \tag{6}$$

In the equation. x_i represents the data point; μ_k signifies the centroid of cluster C_k; $\|x_i - \mu_k\|$ denotes the Euclidean distance from point x_i to centroid μ_k; w_{ij} indicates the spatial proximity of point i to point j; λ serves as a balancing factor to modulate the spatial constraint weights.

Results

Supply and demand analysis of different ecosystem services in Jilin province

Figure 2 demonstrates a notable spatial heterogeneity in the supply of ecological functions across Jilin Province. The eastern and southern areas of Jilin Province are distinguished by the presence of primary forests on ChangBai Mountain, featuring high vegetation cover, low population density, an ideal ecological environment, and a substantial supply of ecological functions. A more significant percentage of uncultivated land, diminished vegetation cover, and a deterioration in ecological quality mark the western region. The central region is marked by elevated population density, considerable ecological degradation due to anthropogenic activities, and a restricted availability of ecological functions. Among the six categories of ecosystem service provisions, water production services, carbon sequestration services, soil conservation services, habitat quality services, and recreational services demonstrate a distribution pattern characterized by lower levels in the west and higher levels in the east. The supply of food production services is greatest in the center, followed by the west, with the east exhibiting the lowest levels. The central region of Jilin Province features a level topography, nutrient-rich soil, elevated agricultural yield, and robust food production service capabilities. The capacity for food production services is comparatively robust. The primary land use categories are agricultural and developed land, distinguished by intensive human activities and lacking soil conservation services. A decrease in the quantity of land designated for recreational activities and a deterioration in the quality of recreational services; A decline in vegetation cover
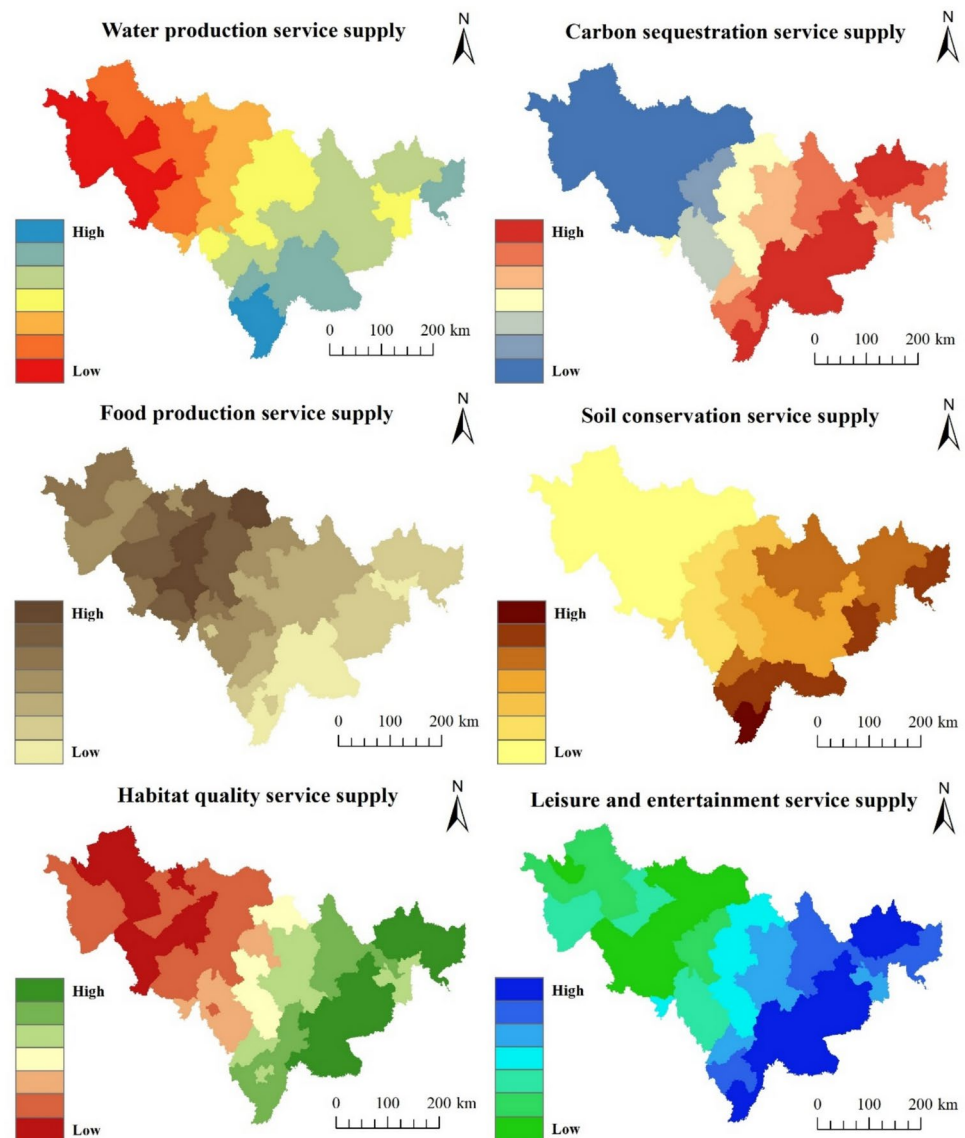

Fig. 2. Spatial distribution of ecosystem service supply in Jilin Province.

and a diminishment in the provision of carbon sequestration services; Human activities significantly impact the ecosystem, causing considerable disruption and a decline in habitat quality services. The western region of Jilin Province is marked by aridity and low precipitation, significant soil salinization, and a scarcity of tall vegetation, such as forests, which hinders soil conservation. Moreover, the region demonstrates a restricted ability for water generation and soil preservation services.

A correlation exists between the supply of ecological functions and the distribution of water production service capacity, resembling that of soil conservation service capacity. Both exhibit a diminished distribution in the central western area of Jilin Province, a median distribution in the eastern sector, and an elevated distribution in the southern region. The ChangBai Mountain Range is known for its abundant flora and heavy precipitation, which improve its ability to produce water and preserve soil. The southeastern ChangBai Mountain Range exhibits high values for carbon sequestration services, which are comparable to leisure and recreation services. A significant supply of leisure and recreation services is produced by the region's hilly terrain and abundance of natural spaces, which also improve carbon sequestration and support the local tourism sector. The quality of habitat services and the supply capacity of food production services are negatively correlated. Both factors are directly correlated with population density and the extent of arable land. Regions characterized by substantial food production service capacity and extensive arable land exhibit flat topography and high population density. This leads to significant human interference, extensive alteration of the natural environment, and a comparatively low capacity for habitat quality service supply.

Figure 3 demonstrates that the demand for ecological functions in Jilin Province is significantly associated with regional population density. Elevated values are noted in regions of high population density, especially in the central area, where the demand for water, carbon sequestration, food production, and recreational services
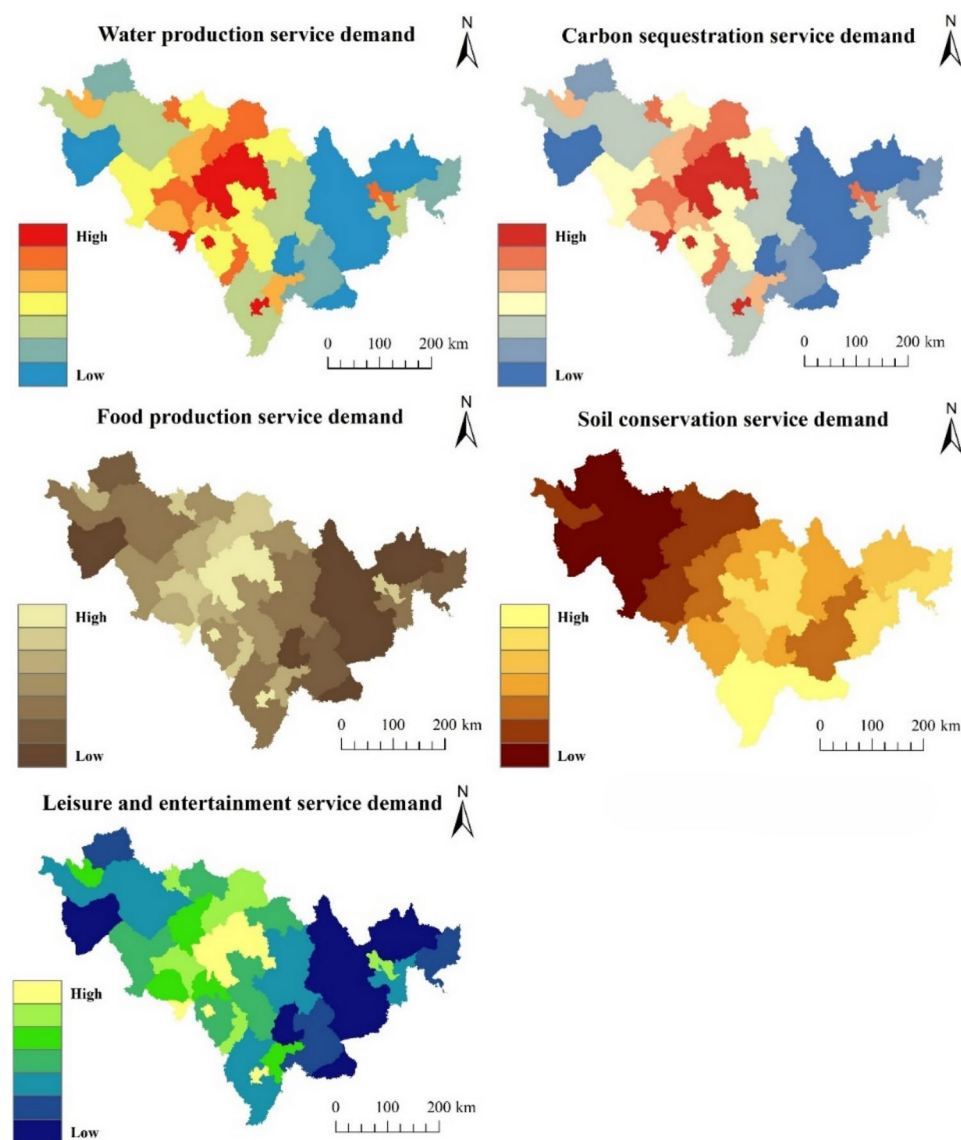

Fig. 3. Spatial distribution of ecosystem services demand in Jilin Province.

is significantly pronounced. These services are distributed in the densely populated central region, which is highly urbanized and densely populated. In addition to concentrated businesses, more carbon emissions, and a greater requirement for sequestration services, this region also shows increasing demand for food, water, and recreational services. Conversely, the eastern region, characterized by a relatively low population density and more abundant natural resources, exhibits diminished demand for these four ecological functions. The demand for soil conservation services is predominantly elevated in the eastern and southern regions, characterized by more undulating terrain susceptible to soil erosion. Low values are predominantly found in the west, characterized by flat terrain and minimal demand for soil conservation services. The ChangBai Mountain Range region, despite its mountainous topography, also exhibits high vegetation cover and a comparatively low demand for soil conservation services. There is no established methodology for quantifying the demand for habitat quality services. It assumes that the average habitat quality level corresponds to the demand for these services, with Jilin Province's demand quantified at 0.508768, indicating a relatively average demand for habitat quality services.

Analysis and quadrant division of supply and demand of comprehensive ecosystem services in Jilin Province

Figure 4 demonstrates that the regional layout of integrated ecosystem service supply in Jilin Province shows a noticeable regional increase from west to east. The area exhibiting elevated supply values is situated in the east and south. This includes most of Baishan City, the majority of Tonghua City, Helong City, Wangqing County, and Hunchun City. These regions are located within the ChangBai Mountain Range. They display extensive vegetation cover and a resilient ecological environment. Furthermore, these regions are defined by diminutive urban areas, low population densities, and reduced anthropogenic environmental alterations. The moderate supply volume is situated in the central and selected eastern regions. The region is distinguished by various ecological mountains and vegetation, with Jiaohe City and Tumen City as prominent examples. Nevertheless, specific regions demonstrate elevated population density or vast cultivable land, coupled with significant human alteration of the natural landscape. Yanji County, Yu Shu City, and Huinan City exemplify this phenomenon. The center and western regions are where the reduced supply value is located. High population density, high rates of urbanization, vast tracts of agricultural land, and a significantly impacted natural environment are the characteristics of the central area. These regions include the Changchun urban area, the Jilin urban area, Nongan County, and Meihekou City. In the western region, despite a relatively low population density and a diminished impact on the natural environment, the foundational aspects of the ecosystem are more susceptible, natural resources are limited, and the supply of ecological functions is suboptimal. The demand for ecological functions in Jilin Province demonstrates a clear intra-regional layout pattern, characterized by lower levels in the eastern and western regions and elevated levels in the central and southern areas. Regions exhibiting significant demand for ecological functions are predominantly located in urban centers of major cities, marked by elevated population density, vigorous economic activity, and substantial demand for ecological functions. Regions characterized by a typical demand for ecological functions comprise arable land. These regions are chiefly accountable for food production activities and exhibit a considerable demand for ecological functions. In the east, increased vegetation cover correlates with lower population densities, reduced arable land, and diminished pressures on the natural environment. The western region possesses a deficient natural environment characterized by subpar soil conditions, a sparse population, and limited arable land, resulting in minimal demand for ecological functions. In summary, the demand for the regional integrated ecosystem is substantially influenced by two primary factors: the region's population size and the agricultural land area.

A quadrant analysis of the availability and requirement for integrated ecological functions in Jilin Province is delineated according to the hierarchy of demand theory. Figure 5 demonstrates that the quantity of counties and cities in quadrants I and II is comparatively low, whereas those in quadrants III and IV are relatively high. Figure 6 depicts nine counties and cities in Quadrant I, primarily in the central area. These include urban regions and counties characterized by a comparatively high population density. They demonstrate a high economic status, a degraded ecological environment, considerable anthropogenic disruptions, and a land use composition that includes construction and agricultural land. This leads to a diminished supply of ecological functions and an elevated demand for them. Quadrant II consists of three counties and cities: Tonghua City
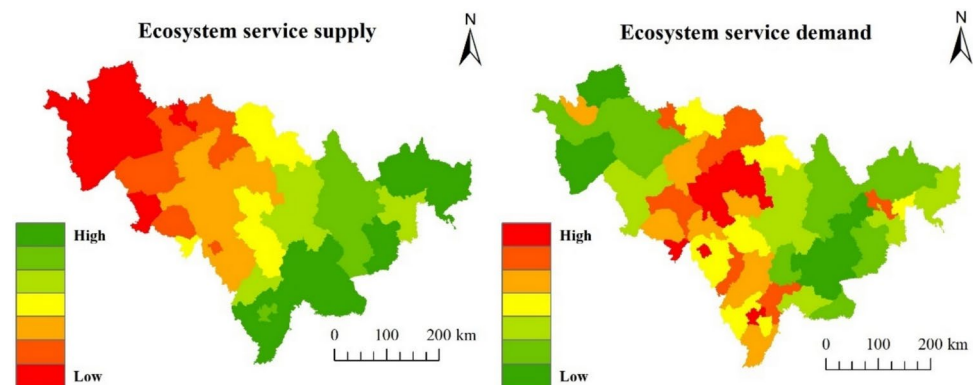

Fig. 4. Spatial distribution of supply and demand for integrated ecosystem services in Jilin Province.
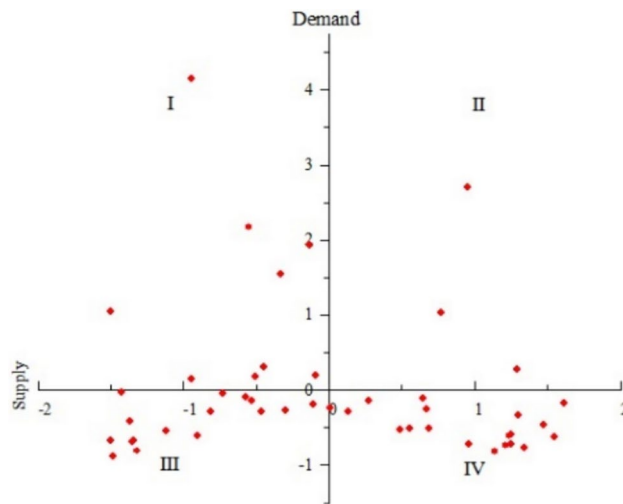
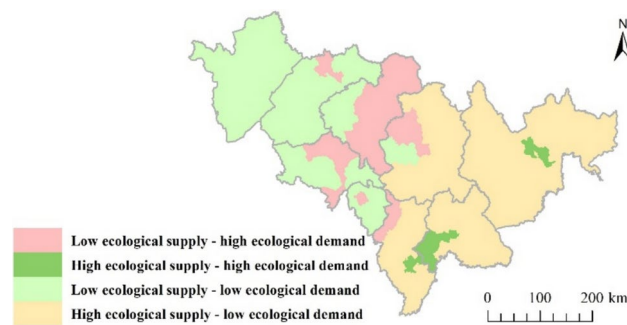**Fig. 5**. Quadrant map of ecosystem services supply and demand in Jilin Province.

Fig. 6. Spatial distribution of ecosystem service supply and demand quadrants in Jilin Province.

District, Baishan City District, and Yanji City. Notwithstanding the elevated population density, the region is distinguished by substantial vegetation cover, leading to a significant availability and requirement for ecological functions. Quadrant III consists of 16 counties and districts, primarily situated in the western and central areas of the nation. This region's primary land use is agriculture, accompanied by wetlands and barren land. A relative deficiency of natural resources marks a degraded ecological environment and minimal vegetation cover. Nonetheless, the population density is comparatively low, resulting in a correspondingly feeble demand for the natural environment. As a result, both the availability and requirement for ecological functions are minimal; Quadrant IV encompasses 19 counties and districts, collectively covering the predominant eastern and southern areas of Jilin Province. These regions are distinguished by elevated topography, dense vegetation, and a landscape primarily consisting of forests and grasslands. Furthermore, the region's urban footprint is comparatively limited and characterized by low population densities, which results in an abundant supply of ecological functions and a correspondingly low demand.

Ecological management zoning

This paper utilizes the availability and requirement of ecological functions, along with the coupled coordination degree value of availability and requirement across various counties and cities, as the clustering subject. The optimal number of clusters was ascertained through the Calinski-Harabasz Criterion (CH value)[23], Davies-Bouldin Criterion (DB value)[24], Gap value, and Silhouette Coefficient (SC value)[25]. The samples were systematically grouped into 1–16 classes utilizing MATLAB software for each parameter, with each clustering executed over multiple iterations until convergence was achieved. Figure 7 illustrates the SC, DB, Gap, and CH values. The SC value measures the extent of similarity between a specific point and other points within the same cluster, ranging from -1 to 1. Figure 8 demonstrates that a more significant contour coefficient signifies improved clustering performance. When K = 5, the SC value demonstrates a significant upward trend and surpasses 1; the DB value measures the ratio of intra-cluster distance to inter-cluster distance. The ideal clusters demonstrate reduced DB values, as shown in Fig. 8, which indicates the initial point of decline when K = 5. The Gap value is utilized to ascertain the optimal number of clusters by assessing the difference between empirical data's clustering effectiveness and random data's expected clustering effectiveness. A reduced Gap value signifies a more effective clustering outcome, as demonstrated in Fig. 8, which shows that the Gap value is lowest when K = 4. The CH
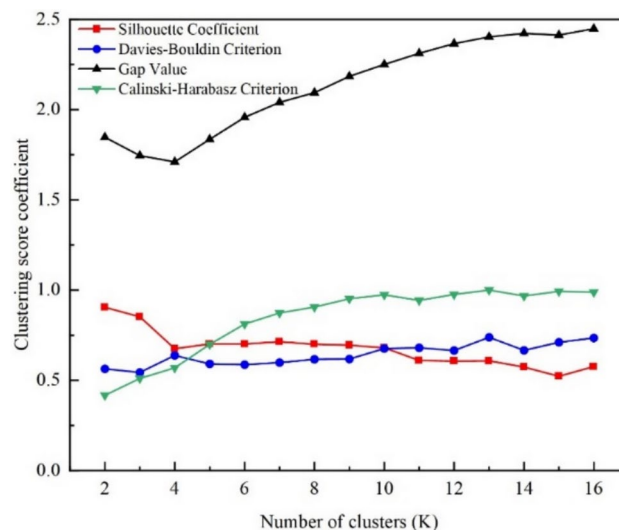
Fig. 7. SC value, DB value, Gap value, and CH value for each iteration of the sample point.
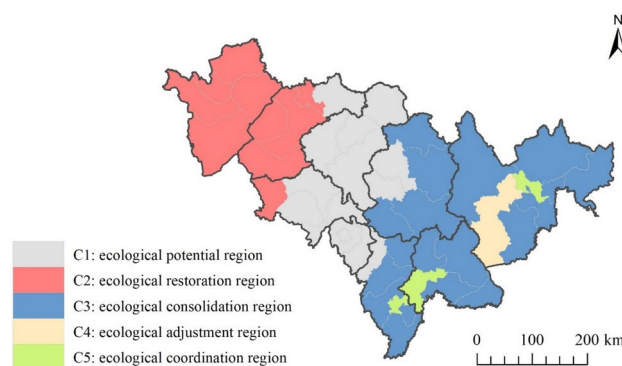

Fig. 8. Ecosystem services management zoning in Jilin Province.

value denotes the ratio of inter-cluster variance to total intra-cluster variance. A more significant inter-cluster variance and a lesser overall intra-cluster variance characterize an optimal clustering K value. As depicted in Fig. 8. The CH value demonstrates the most significant increase when K = 5. Integrating the four criteria mentioned above demonstrates that the optimal clustering effect is attained when K = 5. Utilizing SC K-means, the cluster count was established at 5, resulting in the identification of ecological management zones in Jilin Province through multiple iterations of the availability and requirement for comprehensive ecological functions, with regional characteristics reflected in the vocabulary of the areas. This paper categorizes the regions based on the SC K-means clustering methodology to clarify the differences among the various ecosystem management zones. This methodology relies on the average coordinated relationship between the availability and requirement of integrated ecological functions across various ecosystem management zones (Figs. 8, 9, 10, 11, 12, 13). The resultant zones are as follows:

The C1 ecological potential region, comprising 15 counties and cities, is located in the central areas. It encompasses all of Changchun City, Liaoyuan City, and most of Siping City. At the raster scale, ecological functions are often scarce, with high levels of supply located in the north and east, where vegetation cover is quite dense, and low levels concentrated in urban and agricultural areas. The demand for ecological functions peaks in the central regions of major cities, exhibiting a gradual decrease in distribution as distance from the city center increases. The districts and counties in the ecological potential zone contain vast agricultural areas, reduced ecosystem service capacity, and significant human-induced disturbances. Simultaneously, the region is marked by increased urban centers, high population densities, and heightened demand for ecological functions. The mean value of the supply–demand coupling coordination is 0.532, indicating that the relationship between availability and requirement is reluctantly coordinated. This zone is suitable for developing a green agricultural economy and optimizing industrial structures. The C1 ecological potential region is the most densely populated region, with the highest population density (797 people/km^2) and a relatively high GDP per capita. This zone is situated in a low-altitude area (1176 m) with relatively low forest coverage (20.92%) and a high soil erosion risk (0.62). The economy is primarily driven by the tertiary industry (67.44%), followed by a balanced presence of
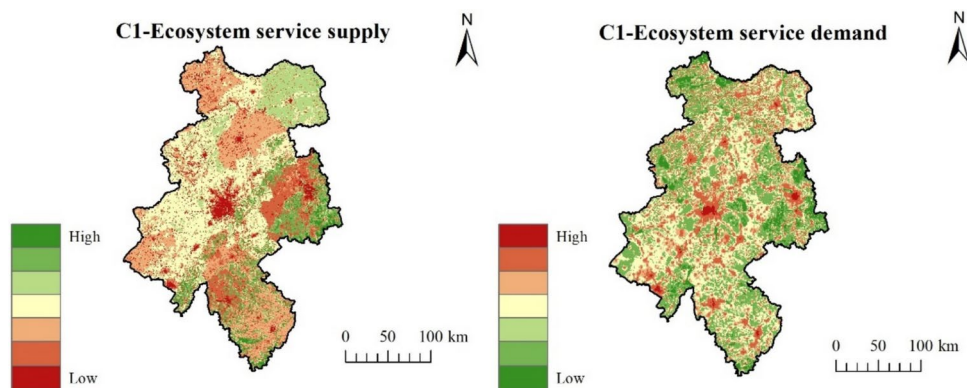
Fig. 9. Spatial distribution of ecosystem services supply and demand for in C1-ecological potential region at the raster scale.
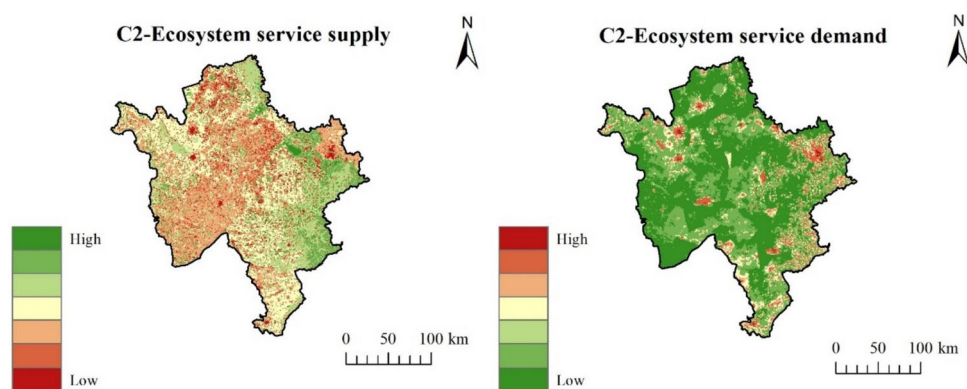

Fig. 10. Spatial distribution of ecosystem service supply and demand in C2-ecological restoration region at the raster scale.
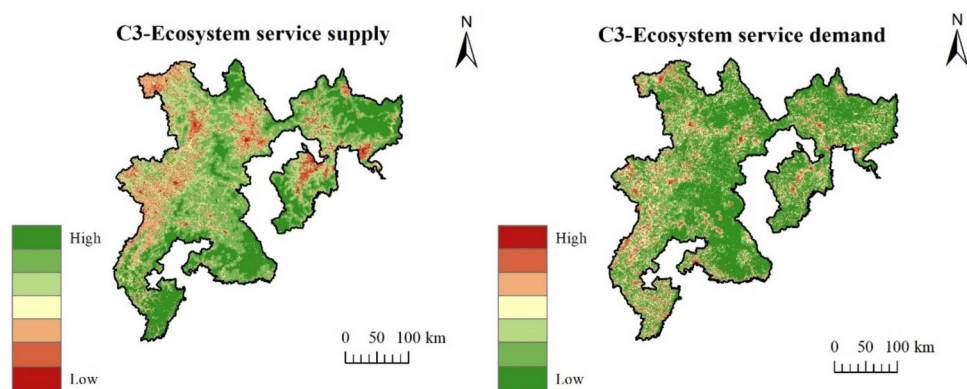

Fig. 11. Spatial distribution of ecosystem services supply and demand in C3-ecological consolidation region at the raster scale.

agriculture (24.65%) and industry (43.70%). Due to high human activity and ecological degradation risks, this region should focus on sustainable urban expansion, industrial upgrading, and ecological restoration initiatives, particularly in water resource conservation and soil protection.

The C2 ecological restoration region, comprising ten counties and cities, is located in the western parts. It encompasses Baicheng City, most of Songyuan City, and Shuangliao City. The supply of ecological functions at the raster scale is generally minimal, with low values predominantly located in the central region and a few areas in the east. In contrast, elevated values are situated in the eastern section of the region, and the supply generally escalates progressively from west to east. The demand for ecological functions is typically low across most regions,
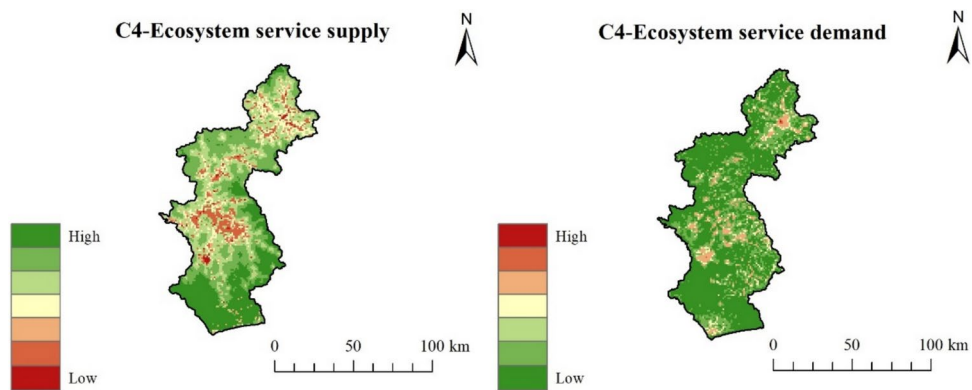
Fig. 12. Spatial distribution of ecosystem service supply and demand in C4-ecological adjustment region at the raster scale.
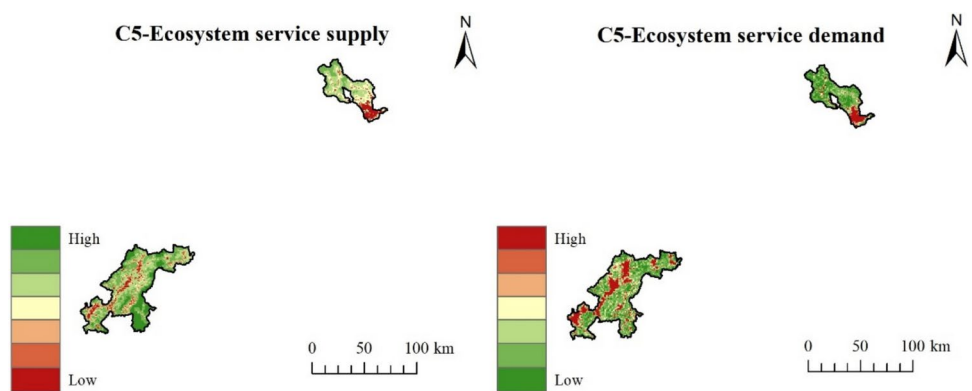

Fig. 13. Spatial distribution of ecosystem service supply and demand in the C5-ecological coordination region at the raster scale.

with elevated values primarily concentrated in western and central urban centers and fragmented distribution of high values in the eastern areas. The soil quality of the region determines how land use categories are distributed within the districts and counties. The region is marked by a scarcity of agricultural land, predominantly grassland, wetland, and barren land. These ecosystems exhibit a restricted ability to deliver ecological functions. Furthermore, the region demonstrates a low population density and a feeble economy, resulting in a concomitant low demand for ecological functions; the average value of the supply–demand coupling coordination is 0.238, signifying a moderately dysfunctional supply–demand relationship. The C2 ecological restoration region is a high-altitude region (1180 m) with the lowest forest coverage (14.07%) and the highest soil erosion risk (0.78), indicating a fragile ecological environment. Annual precipitation is 460 mm, and the population density is 610 people/km^2, with a strong reliance on agriculture (41.41%) and industry (44.30%). Due to the combined pressures of economic activities and a vulnerable natural environment, conservation efforts should focus on strengthening soil erosion control, afforestation programs, and sustainable land-use strategies.

The C3 ecological consolidation region, encompassing 18 counties and cities, is located in the eastern and southern areas. It includes most of Jilin City, the majority of Tonghua City, most of Baishan City, and the eastern and southern regions of Yanbian Prefecture; the availability and requirement of ecological functions are fundamentally inversely related. The region's topography is predominantly elevated, with woodland and grassland as the primary land use types. It has a substantial capacity to provide ecological functions, is rich in natural resources, and has a solid ecological base. Simultaneously, the population density is comparatively low, and the extent of arable land constitutes a small fraction of the total area, leading to a minimal demand for ecological functions. The mean value of the supply–demand coupling coordination is 0.603, indicating a primary coordination between availability and requirement. The C3 ecological consolidation region has an elevation, relatively high forest coverage (52.08%), and moderate soil erosion risk (0.33). Annual precipitation is 613 mm, and the population density is 524 people/km^2. Agriculture (30.57%) and industry (22.60%) are relatively balanced, while the tertiary industry has the lowest share (24.88%). Given its strong ecological foundation and balanced economic structure, this zone should leverage its economic resources to strengthen environmental protection technologies, promote sustainable development policies, and advance ecological conservation strategies.

The C4 ecological adjustment region, comprising Antu County, is located in the eastern parts and is intersected by the ChangBai Mountain Range. The regional layout of ecosystem service provision exhibits low values in

the central region and elevated values in the peripheral areas. The elevated values range from the north to the center, whereas the diminished values are predominantly concentrated in the south. The demand for ecological functions is comparatively low, exhibiting significant fragmentation in the distribution of high-value services; the region is distinguished by extensive vegetation cover, a robust ecological foundation, and a substantial capacity to provide ecological functions. Simultaneously, the area exhibits a sparse population density and a consequently diminished demand for ecological functions. The mean value of the supply–demand coupling coordination is 0.38, indicating a mild dysfunctional supply–demand relationship. The C4 ecological adjustment region has an elevation, the highest forest coverage (70.63%), and relatively high soil erosion risk (0.70). Annual precipitation reaches 759 mm, and the population density is 610 people/km2. The tertiary industry share (35.23%) is the lowest, while agriculture (17.99%) and industry (26.82%) dominate. This region is well-suited for eco-tourism development, strengthening ecosystem function protection, and promoting industrial restructuring.

The C5 ecological coordination region includes three counties and cities in the eastern and southern parts: Yanji City, Baishan City, and Tonghua City. The ecological coordination region is divided into the northeast and the southwest. The regional layout of ecological availability and requirement differs between the two segments. In the northeastern region, diminished ecosystem service provision is concentrated in urban areas, whereas the rest demonstrates a more excellent supply. The diminished values in the southwestern section of the supply are arranged in bands throughout the central region, demonstrating a distinct high-low–high distribution pattern. The demand for ecological functions is significantly elevated in both areas and demonstrates a strong negative correlation with their supply; the region possesses enhanced ecological attributes and a greater capacity to provide these services. Furthermore, it shows better economic growth and a more just industrial structure, which can help protect the environment while having little effect on natural systems. The regional average for the coupling and coordination of availability and requirement is 0.756, signifying a moderate coordination between availability and requirement dynamics.

To better illustrate the classification of ecosystem service areas, the C1 Ecological Potential Zone in central Jilin Province serves as an example. This zone encompasses Changchun City, Liaoyuan City, and most of Siping City, areas characterized by intensive agricultural activities, high population density, and significant human-induced ecological disturbances. The supply of ecosystem services in this zone is generally low, particularly for soil conservation and water production, due to extensive land cultivation and urbanization. However, food production services exhibit relatively high levels, given the fertile soils and large-scale agricultural operations. On the demand side, this region exhibits the highest demand for ecosystem services in Jilin Province, particularly for water resources, carbon sequestration, and recreational services, driven by urban expansion and economic activities. The supply–demand coupling coordination analysis reveals that this zone has a moderate imbalance, with high ecosystem service demand exceeding available supply. Based on this assessment, the C1 Ecological Potential Zone is classified as an area requiring green agricultural transformation, industrial optimization, and targeted ecological restoration efforts to enhance ecosystem function and sustainability.

This example demonstrates how the classification process integrates quantitative analysis of supply and demand, spatial clustering (SC K-means), and regional ecological characteristics to delineate distinct management zones. By using this framework, other ecological zones were classified based on their unique environmental conditions, supply–demand relationships, and strategic management needs.

Discussion

This study systematically analyzes the ecological management zoning of Jilin Province by integrating the supply–demand relationship of ecosystem services, the human well-being framework, and the spatially constrained K-means (SC K-means) clustering method. Compared with traditional ecological zoning approaches, this study not only focuses on the supply capacity of ecological functions but also incorporates human demand, making the zoning results more practical and applicable[7–9]. In recent years, ecological zoning research has been widely applied to ecosystem management at various scales[10–12], however, most studies have predominantly focused on supply-side assessments, often overlooking the demand dimension of ecosystem services. This study reveals that the supply–demand relationship of ecosystem services in Jilin Province follows a spatial pattern of "high in the east, low in the west," with particularly pronounced mismatches in the central agricultural-intensive regions. This phenomenon aligns with the characteristics of agricultural-dominated ecosystems globally[2–4,26].

In comparison to prior works, such as those conducted on ecosystem service zoning in China[2–4,8] and Europe[26], this study uniquely integrates the human well-being framework to categorize ecosystem services into different levels of human needs. This allows for a more nuanced understanding of ecosystem functionality and its implications for policy-making. Furthermore, unlike previous research that often employs simple overlays of supply and demand indices, the combined use of SC K-means clustering and the coupling coordination model in this study provides a more refined classification of ecological management zones, enhancing the applicability of zoning outcomes in land-use planning and environmental governance. Additionally, this study reveals that the ecological potential region in Jilin Province exhibits significant supply–demand mismatches similar to those observed in other intensive agricultural regions worldwide. However, unlike studies conducted in arid and semi-arid regions where water scarcity dominates supply–demand conflicts[13], Jilin Province's ecological stressors are more closely related to soil degradation, industrial pollution, and urban expansion. This finding underscores the necessity of region-specific management approaches rather than generalized ecological zoning strategies. Moreover, while previous research has focused on static assessments of ecosystem service provision, this study acknowledges the dynamic interplay between ecological supply and anthropogenic pressures, suggesting that zoning frameworks should incorporate long-term monitoring and adaptive policy mechanisms.

This study commenced with the ecological functions availability and requirement relationship as its foundation. The human demand for ecological functions was integrated into the zoning system, categorized these services into various tiers based on human well-being framework. This facilitated the acquisition of a

thorough availability and requirement analysis of ecological functions, which was subsequently integrated with the coupled coordination model and SC K-means clustering to define the ecological management zones of Jilin Province. Compared to the ecosystem service provision derived from simple superposition, the varying division levels illustrate the multifaceted demand for ecological functions. As a result, the outcomes are no longer affected by the extreme values of availability and requirement for a singular ecosystem service. Rather, they fluctuate based on humans' diverse demands for ecological functions. The incorporation of human demand for ecological functions has led to a shift in focus from the traditional zoning strategy, which just takes degradation levels and ecosystem supply potential into account. The novel approach recognizes the interconnection between human society and the natural environment, considering human demand for ecological functions across multiple levels. This has resulted in establishing ecological management zones in Jilin Province, which correspond to the availability and requirement of ecological functions, yielding a more pragmatic outcome. Using the SC K-means algorithm to cluster the availability and requirement of ecological functions in Jilin Province is more effective in maintaining the spatial continuity of these clusters than the conventional K-means clustering algorithm. This is crucial for analyzing geographic data that emphasizes spatial continuity, as it enhances the probability that the partitioning results will constitute a cohesive whole rather than being fragmented. Ecological management policies are established and executed by various administrative districts. Ecological management zones are segmented into counties and districts as fundamental units, facilitating the precise execution of ecological management by the designated authorities. This structure allows local administrators to develop various management programs or protection policies tailored to specific zones.

The ecological potential region is defined by extensive agricultural land, a large population, considerable industrial environmental impact, groundwater over-exploitation, soil erosion, and insufficient soil resource conservation. Nevertheless, the region is a vital agricultural zone, making it more challenging to improve the environment from this standpoint. The regional strategy for ecological management must emphasize minimizing pesticide and chemical fertilizer usage, optimizing groundwater resource utilization, and fostering a sustainable agricultural economy. Simultaneously, the industrial framework must be refined, and development strategies with minimal environmental impact should be implemented to enhance the region's ecological potential. Certain regions within the designated ecological restoration area face several challenges, such as land desertification and resource depletion. To resolve these issues, it is imperative to employ effective ecological management tools to harmonize the conflicting interests of humans and the environment. This should encompass the creation of natural resource protection zones and implementing stringent regulations to avert the disruption of the natural environment by construction activities. Moreover, augmenting investment in ecological restoration and environmental management is essential to rectifying the disparity between social development and ecological preservation. The ecological management instruments in the ecological consolidation region must be predicated on consolidating current accomplishments in ecological protection, preserving ecological integrity, safeguarding the native environmental system, and augmenting the value of natural resources. Moreover, there should be a reasonable use of abundant natural resources in the region. The region should be developed into a tourist destination, utilizing natural resources as a catalyst for economic advancement. Simultaneously, investment in environmental protection should be augmented, establishing a virtuous cycle in which economic development and ecological preservation are simultaneously elevated. Ecological adjustment regions should preserve ecosystem functions, enhance biodiversity protection, alter the industrial framework, and promote eco-tourism. This strategy will guarantee a seamless amalgamation of economic and environmental advantages. The ecological coordination region must prioritize the preservation of synergy between ecological protection and socio-economic development. This involves equilibrating the availability and requirement of ecological functions and enforcing stringent regulations to avert urban development from adversely affecting the local ecological environment. Moreover, the region ought to utilize a strong economic base to promote ecological protection technologies, improve the safeguarding of the natural environment, and ensure the simultaneous progress of economic development and ecological preservation.

While this study focuses on ecological management zoning in Jilin Province, the methodology and findings have broader applicability to regions with diverse ecological gradients and human–environment interactions. The integration of Human well-being framework with ecosystem service supply–demand assessments provides a replicable framework for understanding and managing ecological functions in other areas. For instance, the classification approach used in this study—combining SC K-means clustering with coupling coordination analysis—can be adapted to different regional conditions, including arid, temperate, and tropical landscapes. However, certain uncertainties and limitations must be acknowledged when applying these results to other regions. The availability and accuracy of input data (e.g., land use, climate conditions, socioeconomic statistics) may vary across different study areas, influencing the precision of ecosystem service assessments. Additionally, human demand for ecosystem services is shaped by region-specific socioeconomic and cultural factors, which may differ significantly from those in Jilin Province.

Future research should explore cross-regional and multi-scale comparisons to test the robustness of this approach in different ecological and socioeconomic contexts. Comparing ecosystem service supply–demand dynamics across multiple provinces or countries would help refine the classification criteria and enhance the transferability of ecological management zoning frameworks. Furthermore, integrating climate change scenarios and longitudinal data analysis would improve the understanding of temporal variations in ecosystem service demand and supply, ensuring that zoning strategies remain adaptive to environmental and socioeconomic changes.

This paper exhibits the following deficiencies: (1) The challenges associated with data acquisition have led to an inadequately comprehensive selection of indicators for assessing the availability and requirement of ecological functions. As a result, the assessment framework for the availability and requirement of ecological functions in Jilin Province may lack the capacity to quantify these services thoroughly. It is advisable to enhance

the evaluation system for the availability and requirement of ecological functions in the future to incorporate the multi-tiered demands of individuals for these services; (2) Current research has primarily concentrated on the disparities in the availability and requirement of ecological functions across various counties and cities, with insufficient emphasis on the transferability of ecological functions and the interrelations between their availability and requirement across different regions. There is a necessity for enhanced research on ecosystem service flows, particularly regarding the connections between alterations in ecological functions across various counties and cities; (3) Despite the suggestion of management strategies for distinct subregions from an ecological management viewpoint, there is a lack of inquiry into the factors affecting the availability and requirement of ecological functions in each region. Therefore, it is essential to compile subsequent ecological indicators across various regions to investigate the primary driving factors in each area.

Conclusions

This study provides a novel approach to ecological management zoning in Jilin Province by integrating Human well-being framework theory with ecosystem service supply and demand assessments. Unlike traditional ecological zoning methodologies that focus solely on ecological functions, our study incorporates human demand for ecosystem services, enabling a more comprehensive and practical zoning framework. The application of the SC K-means clustering algorithm and the coupling coordination degree model has facilitated the delineation of five distinct ecological management zones, offering targeted strategies for sustainable development and ecological conservation.

The scientific added value of this research lies in its methodological innovation and interdisciplinary integration. By categorizing ecosystem services based on human needs, we establish a theoretical framework that aligns ecological conservation with socioeconomic development. The use of advanced clustering algorithms ensures the spatial continuity of ecological management zones, which enhances the applicability of the findings for land use planning and regional environmental governance. Additionally, this study contributes to the growing body of research on ecosystem service supply–demand dynamics by providing empirical evidence on spatial heterogeneity and ecological imbalances in Jilin Province.

The practical implications of our findings extend beyond Jilin Province, offering a replicable model for other regions facing similar ecological and socioeconomic challenges. The proposed zoning strategies—ranging from ecological restoration and consolidation to potential enhancement—serve as a guideline for policymakers to optimize land use, mitigate human–environment conflicts, and promote green economic transformations. The ecological coordination zone, in particular, demonstrates the feasibility of achieving a balanced supply–demand relationship through sustainable economic development and technological innovation in environmental protection.

Despite these contributions, this study has certain limitations. First, the selection of ecosystem service indicators was constrained by data availability, which may not fully capture the complexity of ecological interactions. Future research should expand the evaluation framework by incorporating additional ecological and socioeconomic variables to refine supply–demand assessments. Second, while this study focuses on static ecosystem service supply and demand relationships, future research should explore the dynamic changes in these relationships under climate change and land use transformation scenarios. Third, a deeper investigation into ecosystem service flows and their spatial interactions across administrative boundaries would enhance the accuracy and applicability of ecological management zoning.

In conclusion, this study provides a scientifically robust and practically relevant approach to ecological zoning that bridges the gap between ecosystem functionality and human needs. By advancing a people-centered ecological management strategy, this research contributes to the broader discourse on sustainable development and environmental governance, offering valuable insights for ecological conservation, urban planning, and regional sustainability.

Data availability

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B.H. Zhang and J.F. Liu wrote the main manuscript text; Z.Y. Zhang prepared Fig. 1, Y. Zhu prepared Fig. 2, and B.H. Zhang prepared Figs. 3–14. All authors reviewed the manuscript.

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