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RESEARCH ARTICLE

Spatiotemporal assessment of ecosystem services supply–demand relationships to identify ecological management zoning in coastal city Dalian, China

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Abstract

Integrating ecosystem services supply–demand relationships into ecological management zoning is a hot topic. Most studies have focused on the matching relationship between the supply and demand of ecosystem services. However, the extent to which both are coordinated at different matching levels is ignored, that is, whether ecosystem services supply and demand tend to reinforce each other at high levels or constrain each other at low levels. Therefore, taking Dalian as an example, this study constructed a research framework for ecological management zoning by integrating the matching and coupling coordination relationship of ecosystem services supply–demand. We found that the supply of ecosystem services in Dalian decreased by 23.70% and the demand increased by 22.54% from 2005 to 2019. There was an obvious mismatch and disharmony in the supply and demand of ecosystem services, and the matching and coordination often did not exist simultaneously. Overlay analysis was used to divide Dalian into four ecological management zones: eco-conservation, eco-development, eco-improvement, and eco-restoration zones. This study helped in integrating the matching and coupling coordination relationship of ecosystem services supply–demand into the environmental management system, which has practical significance for the sustainable development of ecosystem services.

Keywords Ecosystem services · Supply and demand · Matching · Coupling coordination · Ecological management zoning

Introduction

Ecosystem services (ESs) form the basis for human survival and development (Millennium Ecosystem Assessment 2005; Lorilla et al. 2019). Rapid urbanization has increased people's demand for ESs, which has profoundly affected the sustainable development of ESs, a more serious phenomenon in urban with rapid economic development (Peng et al. 2020; Wei et al. 2023). In this context, ecological management zoning provides an effective approach to managing ESs, which are the regional units divided into different ESs states (Xin et al. 2021). ESs supply and demand show that ESs have both natural and socioeconomic properties (Burkhard et al. 2012; Xu et al. 2022). However, the differences between natural and human factors may cause spatial and temporal differences between ESs supply and demand (Sun et al. 2019). Therefore, the current challenge in ecological management zoning is identifying and spatializing ESs supply–demand relationships.

Current research on urban ecological management zoning based on ESs can be divided into two categories. The

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first category supports the functional enhancement of ecosystems. Some studies classified areas based on ecological assessments, including climate, hydrology, land use, and indicators such as ecological functions (Kazemi and Hosseinpour 2022; Zhang et al. 2022; Zhao and Huang 2022), emphasizing the natural attributes of ecological management zoning. For example, Luan et al. (2021) implemented ecological management zoning through land use suitability assessment. ESs are an important link between socioeconomic and natural systems (Burkhard et al. 2012). As the role of ESs in human well-being receives attention, more and more studies are applying ESs to planning and decision-making (Sun et al. 2020; Longato et al. 2021; Bian et al. 2022; Fang et al. 2022; Han et al. 2022). For example, Karimi et al. (2021) and Sun et al. (2022a) utilized ESs bundles. However, these studies only looked at enhancing ESs supply, ignoring urban ecosystem demand for ESs.

The second type of principle supported is the mismatch between the supply and demand of ESs in cities. In fact, ESs supply–demand mismatch is often a common phenomenon in urban areas, especially in coastal cities, due to the spatial heterogeneity of ESs supply and demand as well as the role of human disturbances (Zhai et al. 2020). Some studies often explored the characteristic of ESs supply–demand mismatch in terms of quantitative equilibrium and spatial distribution patterns, identifying areas of mismatched supply and demand of ESs (Li et al. 2021b; Chen et al. 2022; Guo et al. 2022; Zhou et al. 2022). The matching relationship between the supply and demand of ESs has become a powerful tool for ecological management zoning (Lorilla et al. 2019). Although these studies recognized the importance of ESs supply–demand relationships in ecological management zoning, they ignored the dynamic coupling mechanisms between supply and demand, making the results difficult to apply to practical management.

In summary, it can be concluded that the existing studies on urban ecological management zoning considered ESs supply and ESs supply–demand relationships. It is feasible to carry out ecological management zoning from the perspective of ESs, and ecological management zoning is aimed at increasing ESs supply and enhancing human well-being. In other words, exploring the relationship between the supply and demand of ESs in ecological management zoning is necessary. Although some studies have focused on this issue, they have concentrated on the exploration of the matching relationship of ESs supply–demand, ignoring the dynamic coupling mechanism between the supply and demand of ESs. This may raise a series of sustainability issues. In this context, coupled coordination relationships of ESs supply–demand provide a new perspective on this challenge and can measure the degree of coherence and benign interactions between the two supply and demand systems (Yang et al. 2022), reflecting the sustainability of regional ESs (Guan et al. 2020). Unfortunately, applied studies on the coupling coordination of the ESs supply–demand relationships are scarce. Therefore, ecological management zoning should be identified based on further research on the ESs supply–demand relationships to achieve effective management of ecosystems.

The main purpose of this study was to construct and apply an ecological management zoning framework based on ESs supply–demand relationships. Dalian was chosen as the case study in this application. After, the model, value, and index methods were combined to analyze the spatial and temporal characteristics of ESs supply and demand in Dalian from 2005 to 2019. Secondly, the quadrant matching method and coupled coordination degree model were applied to explore the ESs supply–demand matching and coordination relationships. Thirdly, the overlay method was used to delineate ecological management zones.

Materials and methods

Study area

A case study was carried out in Dalian, China. Dalian is located in the south of Liaodong Peninsula (Fig. 1). It comprises four counties (Pulandian, Zhuanghe, Wafangdian, and Changhai) and three districts (Central Dalian, Jinzhou, and Lvshunkou) and is bordered by three cities (Yingkou, Anshan, and Dandong). Dalian is an important port city in the Bohai Rim city group with a coastline of 2211 km. Its western region is near the Bohai Sea, and its eastern region is near the Yellow Sea. Waterways crisscross Dalian, and there are large areas of national nature reserves and forest parks in the north, center, and west of Dalian. These are important ecological protective screens for Dalian. Additionally, there are many types of land use, and farmland (41%) and forests (32%) were the dominant land use types in 2019 (Fig. 1).

Conceptual framework

There is an interaction between ESs and ecological zoning management (Fig. 2). ESs, as a bridge between the ecosystem and socioeconomic system, are influenced by both (Fisher et al. 2009). On the one hand, ESs supply depends on the structure and function of ecosystems to maximize the satisfaction of human demands (Müller 2005; Burkhard et al. 2012). On the other hand, human well-being is based on the consumption of ESs (Villamagna et al. 2013). At this time, the supply and demand of ESs may have different scales and development levels, that is, the ESs supply–demand relationship changes, which may lead to ecological and environmental problems such as pollution, ecological destruction, and

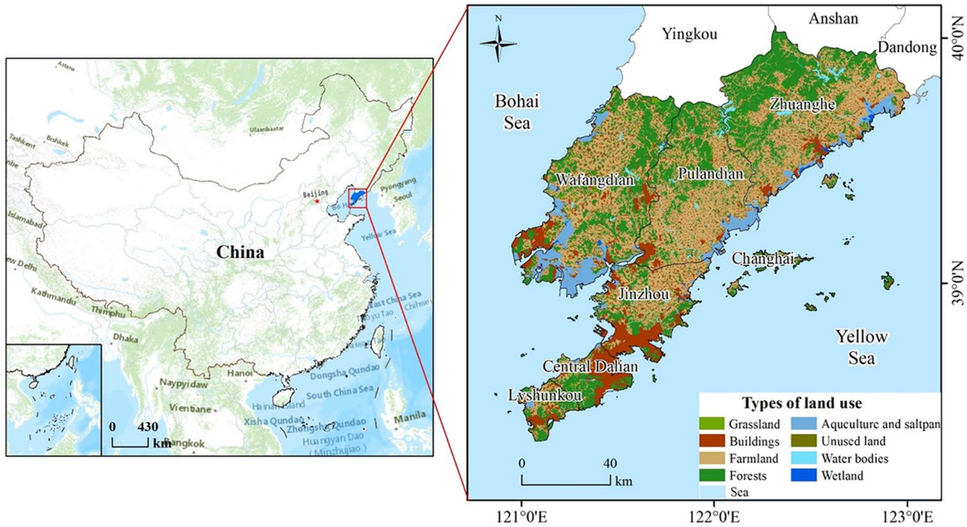

Fig. 1 Study area in China and land use classification in 2019

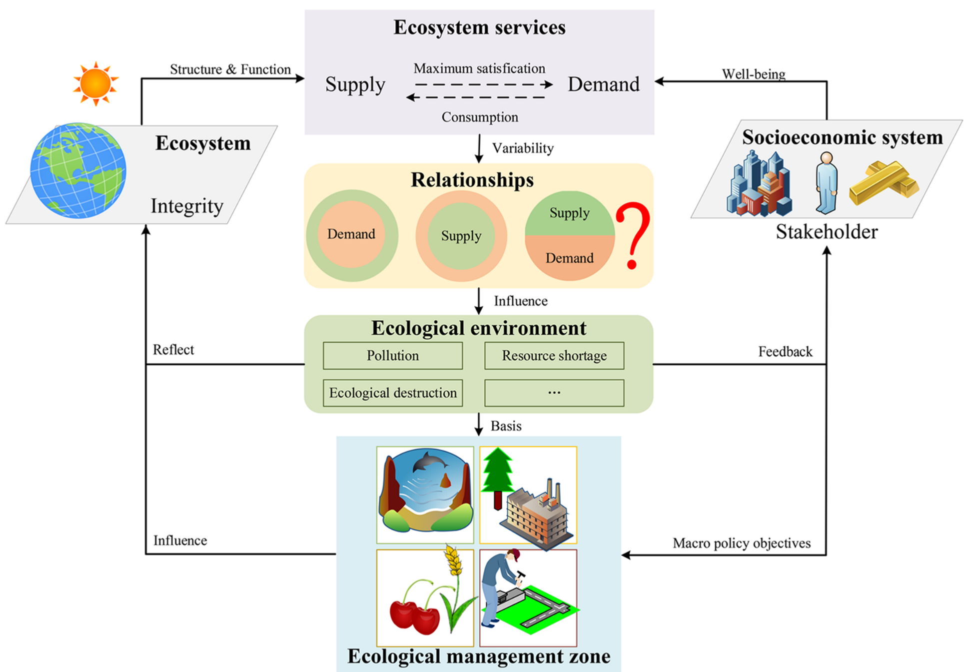

Fig. 2 Relationships between ecological zoning management and ecosystem services

resource shortage. Thus, managers and policymakers weigh the supply and demand of ESs in combination with macro-policy objectives to perform planning and management (e.g., ecological management zoning). Based on this, the research framework of this paper is shown in Fig. 3: (1) We built a database. Four periods (2005, 2010, 2015, and 2019) of land use, normalized difference vegetation index (NDVI), digital elevation model (DEM), soil property, spatial population, spatial gross domestic product (GDP), and meteorological and socioeconomic data were used in this study. Information on the data is shown in Table 1, and all data were resampled to 30 m. (2) We selected six types of ESs and appropriate indicators to qualify ESs supply and demand. (3) We formulated two indexes—the coupling coordination degree and the quadrant matching of ESs supply–demand—to analyze the relationships between ESs supply and demand. (4) We performed ecological management zoning by overlaying the two results of part (3).

Selection of ecosystem services

According to the natural and socioeconomic conditions of Dalian, six types of ESs were selected using the following criteria: (1) In current natural conditions, Dalian is surrounded by the sea on three sides, with rich and varied landscapes such as mountains, seas, and islands (Yang et al. 2018). It is an

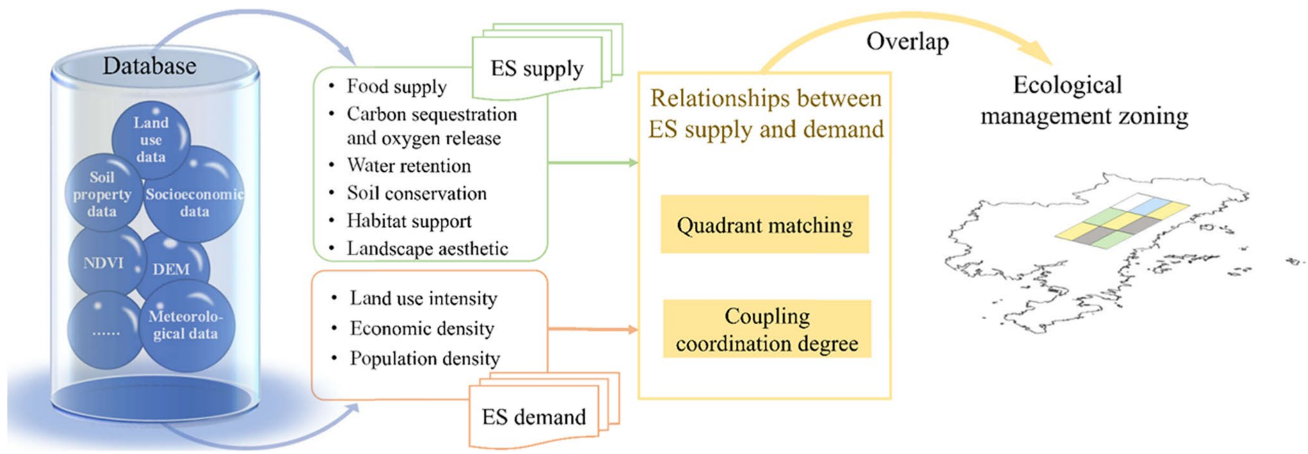

Fig. 3 Conceptual research framework

Table 1 Data and sources

Data	Spatial resolution	Periods	Sources
Land use data	30 m	2005, 2010, 2015, and 2019	Interpretation of Landsat remote sensing images
NDVI	250 m	2005, 2010, 2015, and 2019	https://www.nasa.gov/
DEM	30 m	–	http://www.gscloud.cn/
Soil property data	1 km	–	http://www.ncdc.ac.cn
Meteorological data	–	2005, 2010, 2015, and 2019	http://data.cma.cn/
Spatial population data	1 km	2005, 2010, 2015, and 2019	http://www.resdc.cn/
Spatial GDP data	1 km	2005, 2010, 2015, and 2019	http://www.resdc.cn/
Socioeconomic data	–	2005, 2010, 2015, and 2019	http://www.stats.gov.cn/

important water conservation area and a biological habitat. The diversity of the landscape facilitates diverse cultural ESs as well. (2) In current economic conditions, food security is important for regional sustainable development (Viana et al. 2022). Dalian is a metropolis with a large population and a massive demand for food items. And its geographical advantage of being surrounded by the sea on three sides results in great potential for fishery development. Moreover, Dalian is a famous coastal tourist city in China, which has developed tourism and attracted many tourists from all over the world. However, economic and population growth and extensive food production methods have contributed to land degradation and CO_2 emission in Dalian (Du et al. 2019). Considering the above reasons, we selected six key ESs: food supply (FS), carbon sequestration and oxygen release (CSOR), water retention (WR), soil conservation (SC), habitat support (HS), and landscape aesthetic (LA).

Quantification of ecosystem services supply and demand

Mapping the ecosystem services supply

We used biophysical spatial ESs models and monetary valuation methods to map the supply of six key ESs in Dalian (Table 2), and the specific calculation formulas were in Supplementary Part 1. To eliminate the impact of price changes in each period, we adopted 2015 constant prices. Furthermore, models were validated by comparing our results with other similar studies and datasets (Supplementary Part 2). Afterward, we generated the ESs supply

Table 2 The ESs supply valuation methods

Ecosystem services	Valuation methods		Variables
	Biophysical	Economic	
FS	The food yield per unit area	Market value	Food unit yield (t/ha); the market price of food (CNY/t); margin on food sales (%)
CSOR	Improved CASA model (Zhu et al. 2005)	Carbon tax rate and industrial oxygen production (Wang et al. 2016)	NPP (g/m^2); price of oxygen (CNY/t); price of carbon (CNY/t)
WR	InVEST-water yield model	Avoided damage cost (Remme et al. 2015)	Water yield (mm); reservoir construction cost (CNY/m^3); velocity coefficient; terrain index; soil saturated water conductivity (cm/d)
SC	RUSLE model	Opportunity cost, market value, and replacement cost (Wang et al. 2016)	Soil retention of the grid (t/ha); reservoir construction cost (CNY/m^3); soil bulk density (g/cm^3); average soil thickness (m); average forestry income (CNY/ha); average price of a nutrient element (CNY/t); average content of N, P, K, and organic matter in the soil (%)
HS	InVEST, habitat quality model	Value transfer	Habitat quality index; HS equivalent value per unit area in China (CNY/ha)
LA	–	Chinese ESs equivalent value per unit area (Xie et al. 2015)	Average tourism income (CNY/ha); national average tourism revenue (CNY/ha); LA equivalent value per unit area in China (CNY/ha)

of Dalian ecosystems by summing the total supply of each ESs type based on the following formula:

$$ES_S = \sum_{i=1}^{6} S_i \times A \quad (1)$$

where ES_S is the total ESs supply in Dalian (CNY), S_i is the i th ESs supply (CNY), and A is the area of the grid (ha).

Mapping ESs demand

Economic and social development inevitably involves the environment of the ecosystem or its products and services. However, different economic and social development conditions have different requirements for ESs. Therefore, we selected three indicators—land use intensity, population density, and economic density—to map the ESs demand in Dalian. The land use intensity was calculated using a quantitative method (Li et al. 2013); this indicator directly reflects the differences in people's use of land resources; the higher the value, the higher the ES demand. Population density reflects the demand for ESs. Economic density was calculated in this work as the gross domestic production (GDP) per area. It can indirectly reflect the preference for ESs demand. Due to the large difference between the average economic density and population density in the north and south of Dalian, the natural logarithm was used to avoid the impact of severe fluctuations. The following calculation formula was used:

$$ES_D = L \times lnP \times lnG \quad (2)$$

where ES_D is the demand for ESs (dimensionless), L represents land use intensity (%), P represents population density (people/km^2), and G represents economic density (10^4 CNY/km^2).

Analysis of relationships between ecosystem services supply and demand

We standardized ES supply and demand on a scale of 0–1 using maximum–minimum methods, with Eq. (3) for comparison. After obtaining the standardized supply and demand map for ESs, we created a fishnet (1000 m; $n = 14{,}573$) covering the surface of Dalian and extracted the values of the ESs supply and demand for each grid to analyze the relationship between these values. The coupling coordination degree model and z-score method were used to quantify and explore the coordinated development level and the matching relationship between ESs supply and demand.

$$X_j = \frac{x_{ij} - min(x)}{max(x) - min(x)} (j = 1, 2) \quad (3)$$

where X_j is the standardized value for the j th indicator and $j = 1$ or 2 represent the ESs supply or ESs demand, respectively. x_{ij} is the value of the j th indicator of tnit i.

The specific formulas for the coupling coordination degree model are as follows:

$$D = \sqrt{C \times T} \tag{4}$$

$$C = \sqrt{\frac{X_1 \times X_2}{\left(\frac{X_1 + X_2}{2}\right)^2}} \tag{5}$$

$$T = \alpha \times X_1 + \beta \times X_2 \tag{6}$$

where D is the coupling coordination degree of the ESs supply and demand, with $D \in [0, 1]$. The greater the coupling coordination degree, the better the coupling and coordination between ES supply and demand. C is the coupling degree, which refers to ESs supply and demand affecting each other through various interactions (Cheng et al. 2019). T is the degree of coordination. Considering ESs supply and demand are equally important, their weights are $\alpha = \beta = 0.5$ (Li et al. 2021a). Using the equal division method, combined with the actual situation of Dalian, the classification of D is given below:

$$D = \begin{cases} [0.0, 0.2], & \textit{Extreme disharmony} \\ (0.2, 0.3], & \textit{Moderate disharmony} \\ (0.3, 0.4], & \textit{Slight disharmony} \\ (0.4, 0.5], & \textit{Near disharmony} \\ (0.5, 0.6], & \textit{Basic coordination} \\ (0.6, 0.7], & \textit{Slight coordination} \\ (0.7, 0.8], & \textit{Moderate coordination} \\ (0.8, 1.0], & \textit{Good coordination} \end{cases}$$

We divided ESs supply and demand into four quadrants based on their z-scores, with the X-axis representing the ESs demand and the Y-axis representing the ES supply. The first quadrant represents high supply and high demand (HSHD); the second quadrant, high supply and low demand (HSLD); the third quadrant, low supply and low demand (LSLD); and the fourth quadrant, low supply and high demand (LSHD). The z-score was calculated as follows:

$$x = \frac{x_i - \bar{x}}{s} \tag{7}$$

$$\bar{x} = \frac{\sum_{i=1}^{n} x_i}{n} \tag{8}$$

$$s = \sqrt{\frac{\sum_{i=1}^{n} \left(x_i - \bar{x}\right)}{n}} \tag{9}$$

where x is the standardized value for ESs supply or ES demand, x_i is the value for ESs supply or ES demand of the ith evaluation unit, $\bar{x}$ is the average of the study area, n is the total number of grids, and s is the standard deviation of the study area.

Ecological management zoning

The coupling coordination and matching of ESs supply and demand were spatially superposed to obtain 22 combinations (Table 3), and the software of ArcGIS10.2 was used to process fragmented units. Based on the consistency and comprehensiveness of these combinations, the ecological management zones of Dalian were obtained and divided into four first-level types: eco-conservation, eco-development, eco-improvement, and eco-restoration.

Results

Supply of ecosystem services over time

Figure 4 shows that over time, the total supply of ESs in Dalian increased from 56.48 billion CNY in 2005 to 64.59 billion CNY in 2010, but then declined to 46.97 billion CNY

Table 3 Ecological management zones in Dalian

First-level zones	Secondary zones	ESs supply–demand relationships	
		Matches	Coupling coordination
Eco-conservation zone	Eco-conservation zone	HSLD	ND, BC, SC
Eco-development zone	Priority eco-development zone	HSLD	ED, MD, SD
	Key eco-development zone	HSHD	MD, SD, ND
	General eco-development zone	HSHD	BC, SC
Eco-improvement zone	Priority eco-improvement zone	LSHD	ND, BC, SC
	Key eco-improvement zone	LSLD	ND, BC
	General eco-improvement zone	LSLD	ED, MD, SD
Eco-restoration zone	Eco-restoration zone	LSHD	ED, MD, SD

ED extreme disharmony, *MD* moderate disharmony, *SD* slight disharmony, *ND* near disharmony, *BC* basic coordination, *SC* slight coordination, *MC* moderate coordination

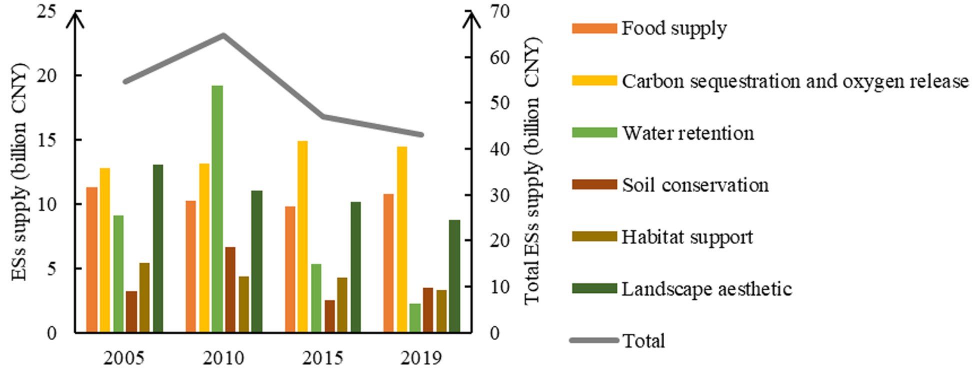

Fig. 4 Temporal changes of the ESs supply in Dalian

in 2015 and continued from 2019 to 43.10 billion CNY, with an overall decrease in of RMB 11.58 billion CNY. Each of the six ESs also changed from 2005 to 2019. On the whole, FS, WR, HS, and LA showed a downward trend, while CSOR and SC showed a negative trend.

The spatial pattern of ESs supply per unit area in Dalian for 2005–2019 showed that high values were concentrated in the east-west coastal areas, and in the north and south Dalian, especially in areas with dense mountains, while most urban areas and interior plains showed low levels (Fig. 5). This spatial pattern remained unchanged from 2005 to 2019. However, except for the increase in north Dalian in 2010, the supply of ESs decreased significantly from 2005 to 2019, especially in the centers of all districts and counties.

Demand for ecosystem services over time

Figure 6 shows that ESs demand in most parts of southern Dalian and some dense urban areas is at a high level, with values exceeding 16,969.60. Conversely, the regions with lower ESs demand are mainly concentrated in the northern mountains with values below 8864.75. From 2005 to 2015, the high-demand ESs regions expanded from the south to the north, and this change was even more obvious during 2005–2010 than during 2010–2015. From 2015 to 2019, the high ESs demand area in northern Dalian shrank, while the southern ESs demand continued to rise, especially in Central Dalian.

The demand for ESs in Dalian increased period by period from 2005 to 2015 and decreased slightly in 2019 (Fig. 7a), and the growth rate slowed down, with an average annual growth rate of 1.46% from 2005 to 2019 (Fig. 7b). This is mainly due to the decline in economic density. During this period, the average annual growth rate of economic density was −1.19%, which is not unrelated to COVID-19. In terms of specific indicators, economic density has the highest average annual growth rate of 13.23% and is consistent with the trend of demand for

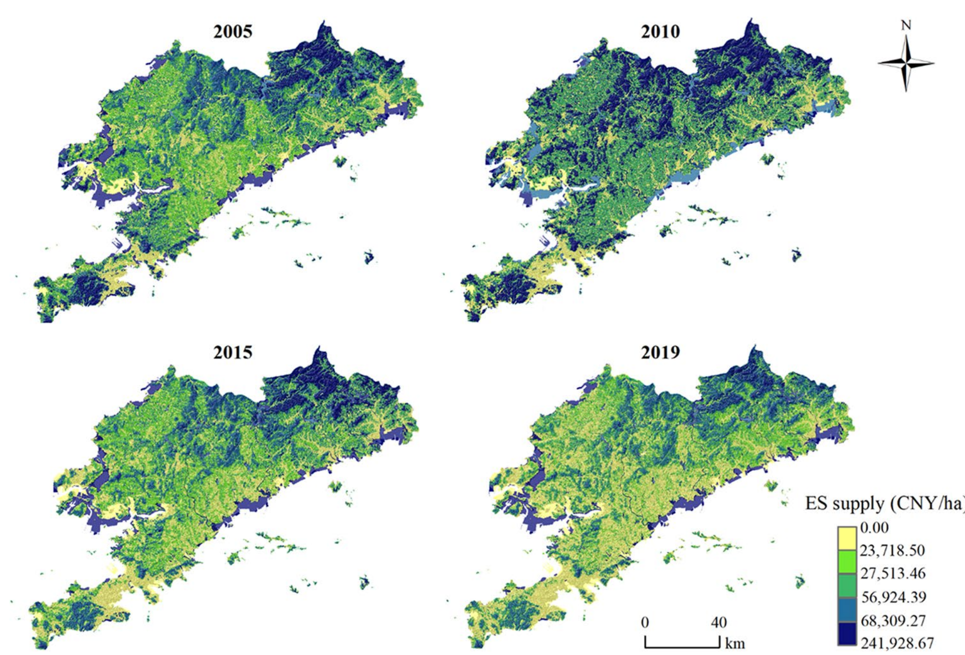

Fig. 5 Distribution of ESs supply in Dalian

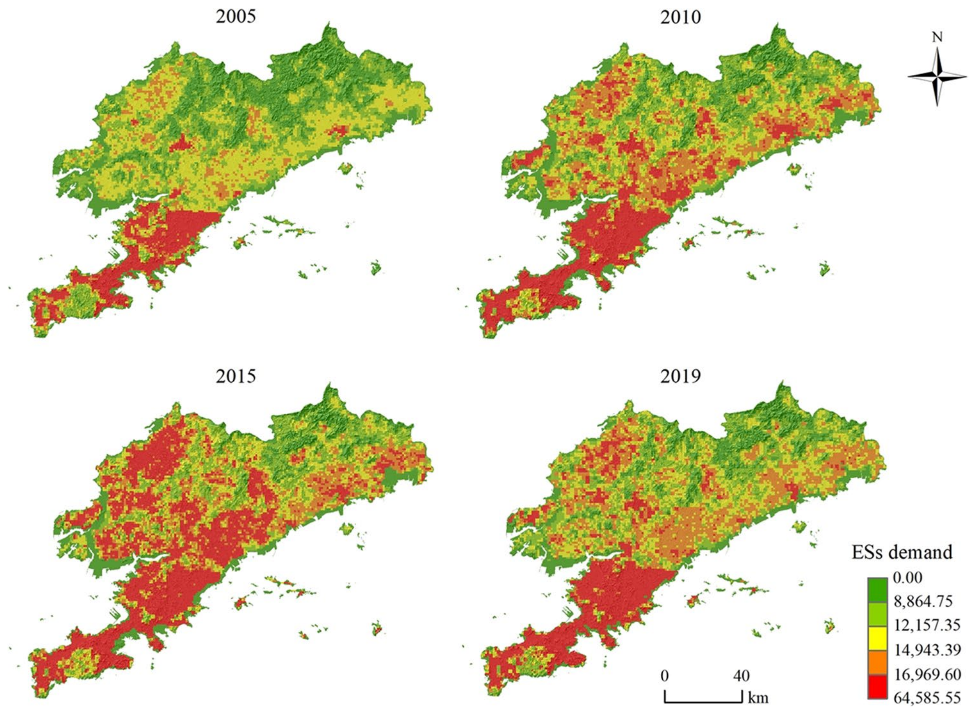

Fig. 6 Distribution of ESs demand in Dalian

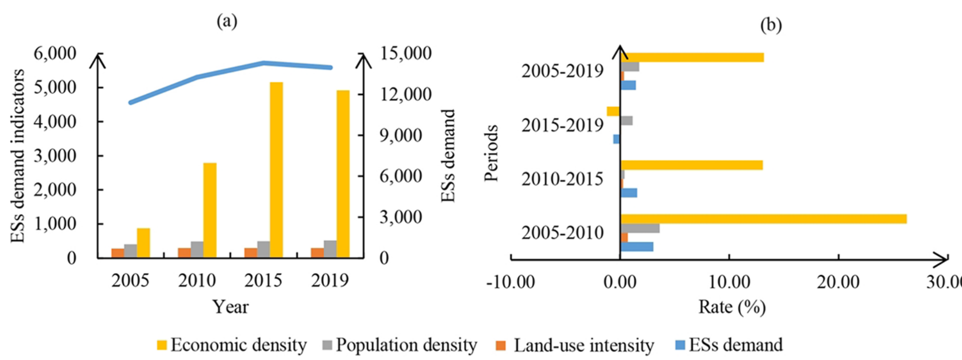

Fig. 7 Mean (**a**) and average growth rate per annum (**b**) of each ESs demand indicator

ESs. In addition, land use intensity and population density in Dalian show an increasing trend over time, with the highest growth rate from 2005 to 2010.

Spatiotemporal changes in the coupling coordination degree of ecosystem services supply–demand

Generally, the overall coupling coordination of the ESs supply–demand relationships for Dalian in 2019 was lower than that in 2005, 2010, and 2015 (Fig. 8), suggesting that ESs demand development occurred at the cost of ESs supply conservation. Based on the previous classification of coupling coordination of the ESs supply–demand relationships, ESs supply and demand showed a slight disharmony (0.41) in 2005. Relative to that in 2005, the relationships between ESs supply and demand dropped to near disharmony levels in 2010 (0.39), 2015 (0.38), and 2019 (0.37). From 2005 to 2010, the basic coordination of the ESs supply–demand area and the slight disharmony expanded significantly for the northern part of the study area. However, the basic coordination area was gradually replaced by the near disharmony area and expanded clearly during 2010–2019. Compared with other types, there were significantly more areas of near disharmony in terms of ESs supply–demand relationships, while slight and moderate coordination were less obvious. The area for each coupling coordination type has changed over the past 10 years. Among them, slight disharmony and near disharmony areas expanded, being more obvious in 2010–2019, especially in northern Dalian. Moreover, The ESs supply–demand coordinated regions shrank significantly.

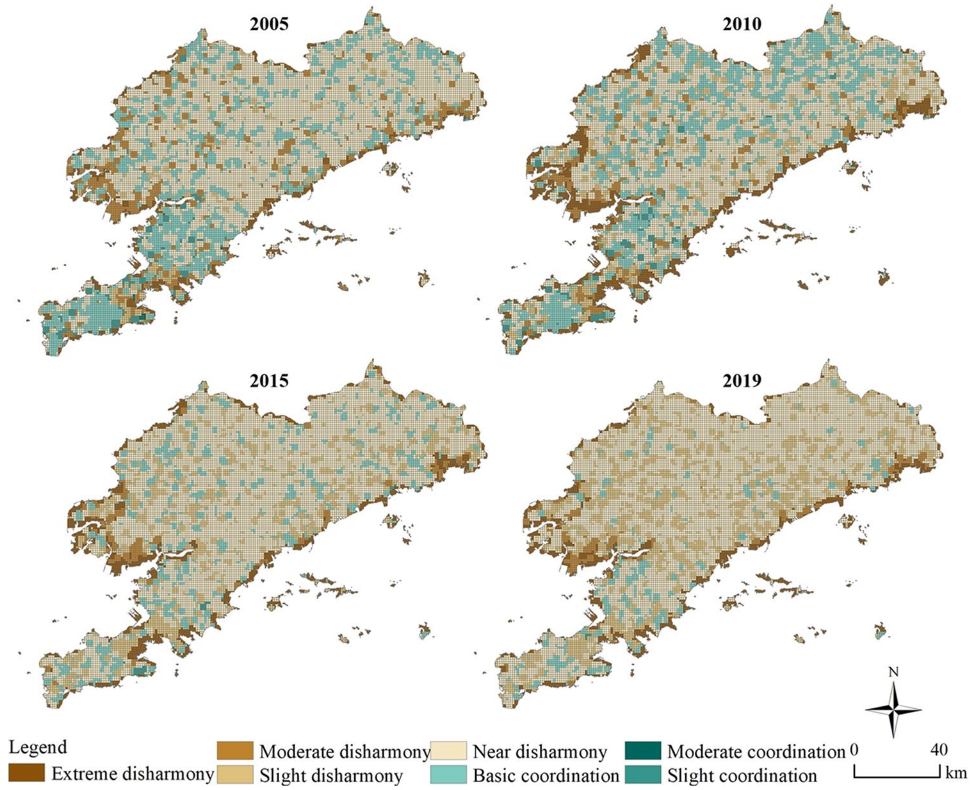

Fig. 8 Spatial distribution of the ESs supply and demand coupling coordination degree

Spatiotemporal changes in the matching types of ecosystem services supply–demand

The results in Fig. 9 indicate that most of the study area was in HSLD and LSHD, while the remaining parts were in LSLD and HSHD, thus indicating an overall mismatch between ESs supply and demand in Dalian during the study period. From the perspective of spatial patterns, the HSLD regions were mainly concentrated on the forests in the north and south and the coastal areas in the east and west. The LSHD area was mainly distributed in the inland plain, similar to the distribution of farmland and buildings. The distributions of HSHD and LSLD were mainly scattered in the transition zones of the former two types. From 2005 to 2015, the HSLD area shrank gradually and expanded in 2019, especially in the northern part of the study area, while the LSHD area was the opposite. From 2005 to 2019, the area of LSLD expanded phase by phases, such as the junction of Wafangdian and Pulandian. And the HSHD area showed a fluctuating downward trend, especially in the southern forests edge of Dalian. In addition, the types of HSLD and LSHD remained unchanged in 42.73% of the study area, indicating that the mismatch between supply and demand was still severe.

Ecological management zoning of Dalian

Figure 10 shows that the eco-conservation zone was mainly distributed in the northern and southern forests of the study area and accounted for 25.10% of the total area. The ecological background of the area was good with HSLD and coordinated supply–demand relationships. The eco-development zone showed high supply and disharmonious supply–demand relationships and was mainly distributed in coastal Dalian. These areas included priority eco-development zone, key eco-development zone, and general eco-development zone. The eco-restoration zone was mainly distributed in urban areas. There was LSHD with poor ecological background, serious disharmony between ES supply and demand, and dense economic activities, accounting for 15.23% of Dalian. The eco-improvement zone included the priority eco-improvement zone, key eco-improvement zone, and general eco-improvement zone, accounting for 39.52% of the total area. These zones were widely distributed and consisted mostly of farmland with low supply.

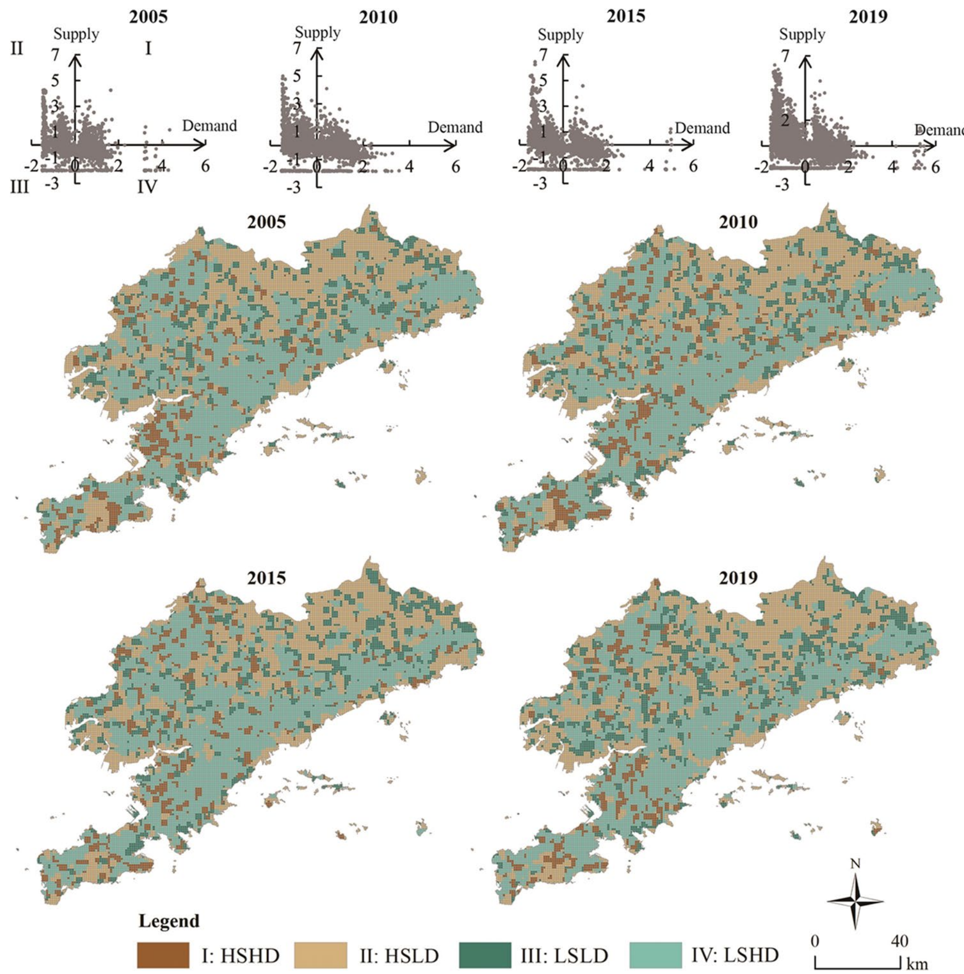

Fig. 9 Matching patterns of ES supply and demand. *Notes:* I, HSHD is high supply and high demand in the first quadrant; II, HSLD is high supply and low demand in the second quadrant; III, LSLD is a low supply and low demand in the third quadrant; and IV, LSHD is a low supply and high demand in the fourth quadrant

Discussion

Impact of land use/land cover change on the ESs supply–demand relationships

The impact of land use/land cover change (LULC) on the ESs supply–demand relationships has been widely recognized (Schirpke et al. 2019; Wang et al. 2019; Wei et al. 2020). Through the analysis of LULC in Dalian from 2005 to 2019 (in Supplementary Part 3), it can be seen that the LULC in Dalian were mainly from natural landscapes (e.g., forests and sea) to semi-natural (e.g., farmland, aquaculture, and saltpan) and artificial landscapes (e.g., buildings) and semi-natural to artificial landscapes, especially in the coastal areas and central districts and counties. It was more evident in the first 5 years than in the second nine. This study found that forests and the sea have strong ESs supply capacity, while the ESs supply capacity of built-up, aquaculture, and saltpan was extremely weak, which was generally consistent with the findings of Cui et al (2022). Therefore, LULC inevitably weakens the ESs supply capacity and worsens the relationship between ESs supply and demand. LULC is driven by multiple factors (Liang et al. 2021). The mismatch and disharmony between the supply and demand of ESs are then not caused by a single factor. It is a common phenomenon caused by the complex interaction of various natural, social, and economic factors (Larondelle & Lauf 2016; Mehring et al. 2018; Xu et al. 2021), such as population density, road network, and relief (Pinto et al. 2022). In addition, in a certain period, the ESs supply–demand match and the ESs supply–demand coordination in the same unit do not necessarily exist at the same time. Therefore, it is necessary to comprehensively consider the matching and coupling coordination relationship of ESs supply–demand, to provide a decision-making basis for managers. Managers would give full play to their subjective initiative and balance and coordinate the relationship between ESs supply and demand through policy intervention and management, to achieve sustainable development and improve human well-being.

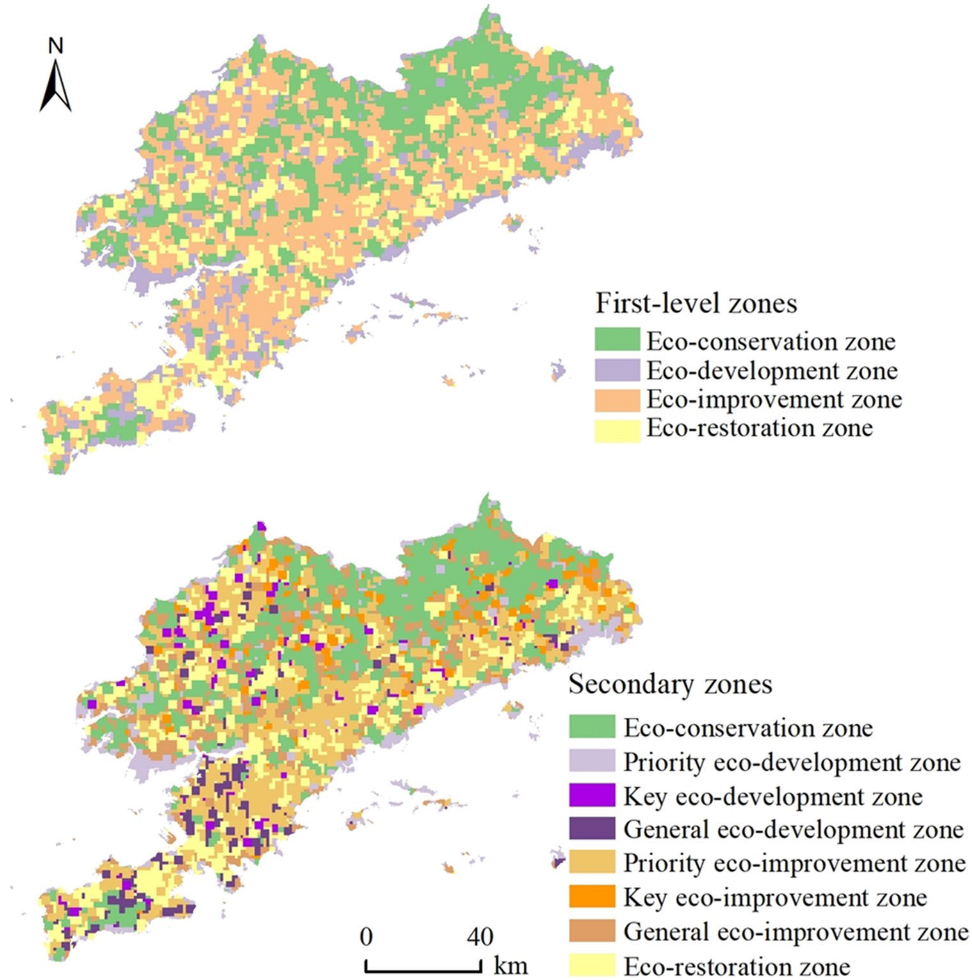

Fig. 10 Ecological management zoning

Insights and applications based on the ecological management zoning framework

Urban space is heterogeneous, and it urgently needs differentiated zoning control facing climate change and anthropogenic disturbances (González-García et al. 2020). Some countries have recognized the importance of zoning. For example, the main function of zoning implemented in China is based on the current ecological status and the development intensity and potential of the region, which aims to achieve sustainable regional development. This ecological policy has significantly promoted key performance indicators (e.g., biodiversity, green space rate, and soil erosion) (Bryan et al. 2018; Sun et al. 2022b). To some extent, this coincides with this study. Nevertheless, based on the ESs supply–demand relationships, this study proposed an ecological management zoning framework that defined control units from the integrated perspective of matching and balancing the supply and demand for ESs, providing a new perspective on ecosystem management. In the context of specific planning systems and governance requirements, this framework can provide a methodical methodology for sorting out complex fundamental linkages and assisting with policy formation. First, accounting for ES supply and demand involves several difficult elements, including both macroeconomic development and microscale ecological processes, necessitating the integration of several models, approaches, and techniques. Second, ESs supply and demand are the results of complex interactions between ecosystems and human culture, entailing a multi-perspective evaluation of both. The final step in zoning planning is a combination of qualitative cognitive judgment and quantitative technical analysis. As a result, a linked "social-ecological" governance paradigm is required to ensure sustainable development of ESs supply and demand. It is important to note that ESs supply and demand sustainability is not a requirement for a static alignment of supply and demand spatially, but a dynamic alignment of the development levels of both, where large scale is not necessarily efficient. Taking the area around the central city of Dalian as an example, the zoning results were combined with the actual current situation to determine effective countermeasures for land use planning (Fig. 11).

(1) In the eco-conservation zone (i.e., A), there is excess supply but the supply and demand are in harmony, indicating

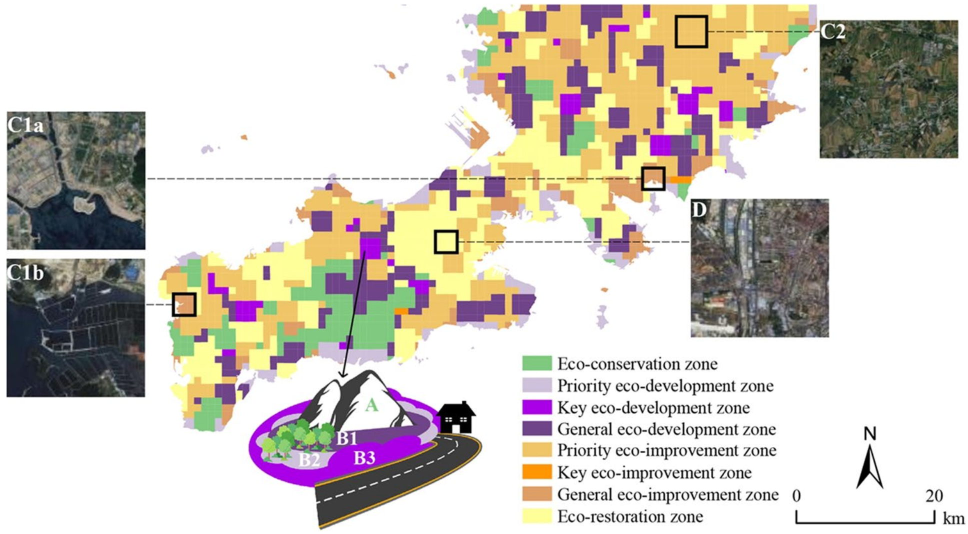

Fig. 11 Spatial distribution of typical ecological management zones: Eco-conservation zone (A), eco-development zones (B1, B2, and B3), eco-improvement zones (C1a, C1b, and C2), and eco-restoration zone (D)

that people and ecology form a positive interaction, so the development measure is to maintain the existing ecological level. (2) In the eco-development zone, supply and demand show a high-low state and extreme imbalance, implying that the ecological utilization efficiency of the area is low. Thus, the ecological utilization rate should be improved to enhance human well-being. Among them, the priority eco-development zone (i.e., B2), which differs from the other two eco-development zones (i.e., B1 and B3) in that it has a mismatch between ESs supply and demand, should be integrated to safeguard ecology and prioritize the improvement of ecological efficiency. The general eco-development zone (i.e., B1) may be thought of as a transition zone between the eco-conservation zone and the eco-development zone since it accomplishes both matching and a benign interplay of ESs supply and demand, and it should be both fully protected and moderately developed. (3) Within the eco-improvement zone, ESs supply and demand are low–high but coordinated, indicating a high ecological input–output rate but not a large ecological scale. It should prioritize the restoration of degraded landscapes (e.g., returning farmland to forests and aquaculture to the beach), while weighing food security. In this respect, C2 and C1b are typical. Furthermore, priority areas (i.e., C2) differ from the other two eco-improvement zones in that they have high-demand characteristics and are more ecologically fragile in comparison. It is important to note that the general eco-improvement zone (i.e., C1) was a special area that also required ecological development because, despite low supply and low demand, supply was high in comparison to demand. (4) In the eco-restoration zone (i.e., D), there is excess demand and an extreme imbalance between ESs supply and demand, which mainly occurs in the urban center, but it is unrealistic to increase ecological land in large quantities. It is necessary to take advantage of the spatial spillover effect of other zones such as the external eco-conservation zone and produce a better coupling of ESs supply and demand through the increase of landscape connectivity inside and outside the city. This could provide a reference for land use planning in Dalian, and even this perspective could be cited for cities worldwide.

Limitations and prospects

In this study, we comprehensively consider the spatiotemporal characteristics of ESs supply–demand matching and coupling coordination relationships for ecological management zoning. The results of the study can provide a feasible approach to ecological zoning in coastal areas worldwide and provide an effective reference for regional land use planning. However, some limitations of this study have to be acknowledged. The supply and demand matching of ESs in this study focuses on spatial matching, not absolute matching. However, ESs has scale effects (Raudsepp-Hearne and Peterson 2016), and decisions often occur at multiple scales, which may require a more complex multi-scale assessment (Scholes et al. 2013). There may be differences in ESs supply and demand at watershed and administrative unit boundaries, which do not match grid boundaries. At different temporal and spatial scales, issues such as data availability, data accuracy, and method applicability for ESs supply and demand assessment limit the scale effect analysis. Moreover, the ecological management zoning we set aims to ensure the sustainable supply of regional ESs and improve human well-being, that is, to achieve the matching and coordinated development of ESs supply–demand. However, ESs also interact with each other, and there may be a trade-off relationship, so the reduction of ESs is likely to lead to the inability to meet demand due to insufficient supply, that is, the trade-off feature will affect the ESs supply–demand relationship (Feng et al. 2021). Therefore, future research needs to deeply explore the ESs scale effect but also pay attention to the trade-off relationships within the ESs, to provide a more objective reference for regional sustainable development.

Conclusions

In this study, an ecological management zoning framework based on the supply–demand relationship of ESs was developed, and the temporal and spatial changes in the supply, demand, and supply–demand relationships of ESs were analyzed using Dalian as an example, and ecological management zones were developed to balance and coordinate the natural ecosystem and the socio-economic system. The results show that (1) ESs supply decreases and ESs demand increases from the periphery of Dalian to the central. Over the past 14 years, high-supply areas have shrunk, while high-demand areas have expanded significantly, especially in major urban and coastal areas. (2) The mismatch and imbalance between the supply and demand of ESs are becoming more and more obvious, which is manifested in that the ESs supply–demand matching is dominated by high-supply–low-demand and low supply–high demand, and the ESs supply–demand coupling coordination has gradually dropped from slight disharmony to near disharmony levels in the period of 2005–2019. (3) Comprehensive analysis divides Dalian into four first-level ecological management zones and eight second-level ecological management zones. Adopt differentiated management strategies for each ecological zone to achieve regional sustainable development. The analytical framework proposed in this study provides a new perspective and method for us to understand ecosystems' carrying capacity and sustainability. On this basis, the future will pay more attention to the discussion and application of the ESs supply–demand relationships in multi-scale, multi-type, and their internal trade-offs of ESs.

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Data availability The datasets used and/or analyzed during the current study are available from the corresponding author upon reasonable request.

Declarations

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Consent to participate Not applicable.

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