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# Spatial–temporal variation and correlation analysis of ecosystem service values and ecological risks in winter city Shenyang, China

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Ecosystems in winter cities are complex and fragile, experiencing significant changes due to climate variations and human construction activities. Previous studies on the assessment of overall ecosystem service value (ESV) and ecological risk index (ERI) in winter cities are scarce. In this study, we constructed ESV and ERI measurement models using land use data in 2000, 2010, and 2020 using the improved value per unit area factor method and the landscape pattern index method, respectively, to reveal their spatial and temporal change characteristics. Geographic detectors were used to explore the driving roles of natural and artificial factors on the changes of ESV and ERI. The combination in ESV and ERI can then provide a more quantitative and accurate basis for policy decisions, identify priority areas for urban ecological restoration, and reduce the risk to ecosystems. The results of the study show that the total ESV of Shenyang city decreased from  $273.97 \times 10^8$  CNY to  $270.38 \times 10^8$  CNY during 2000–2020. Although the decrease is not large, the ESV changes structurally with the advancement of urbanization. During the 20 years, the construction land with the lowest ecological service function continues to expand, increasing by  $354 \text{ km}^2$ , the grassland decreased by  $215.9 \text{ km}^2$ , and the arable land decreased by  $196.6 \text{ km}^2$ . The ecological service function of the water area is the strongest, with an increase of  $51.3 \text{ km}^2$  in the water area, ensuring that there is no significant decline in ESV. The size of the ERI is Very high, High, and Medium value zones remained relatively stable, while the size of the Very Low-value zone decreased by 12.78% and the size of the Low-value zone increased by 13.21%. The interaction factors that contributed most to the changes in ESV and ERI were annual evapotranspiration (EVP)/ Normalized Difference Vegetation Index (NDVI) and Annual sunshine hours (SSD)/ Digital Elevation Model (DEM), respectively. There was a spatial correlation between ESV and ERI. The areas with the highest ESV supply capacity and at the same time facing severe ecological risks to the landscape pattern are distributed in the northeastern hilly lands. This area should be prioritized to develop planning and control measures to prevent further erosion of forest lands and grasslands and reduce ecological risks. These results provide a theoretical basis for ensuring ecological security and sustainable development in winter cities.

**Keywords** Winter city, ESV, ERI, Geographic detectors, Ecological restoration, Shenyang

Ecosystems provide human beings with provisioning, regulating, cultural, and support services, and are the environment and material basis on which human survival and development depend. However, with the growth of the global population and the rapid progress of urbanization and industrialization, the well-being provided by ecosystems is gradually diminishing as a result of people's uncontrolled solicitation of resources from ecosystems, the emission of pollutants, and the irrational use of land and other resources. On the other hand, global climate change has a more significant impact on ecology, and ecosystems are challenged by changes in the vertical distribution of species, a decrease in biodiversity, and an increase in extreme weather such as heavy rainfall, drought, and typhoons. How to maintain ecological balance, improve ecosystem services, and reduce ecological risk exposure has become a common concern for scholars around the world.

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ESV is the benefits that humans derive from ecosystems, which support human survival and development and are of immense value to human well-being<sup>1–5</sup>. Ecosystem services include provisioning services, regulating services, supporting services, and cultural services<sup>1,6,7</sup>. ESV is the basis for city governments to make environmental protection, ecological red line delineation, and ecological compensation<sup>8</sup>. Based on the valuation model proposed by Costanza<sup>9</sup>, Xie et al.<sup>10</sup> proposed an equivalence table of ecosystem service values (ESV) per unit area for different terrestrial ecosystems in China, and studies by Jiang et al.<sup>11</sup> and Zhang et al.<sup>12</sup> emphasized that ecosystem service values increased significantly over time in regions such as the Tibetan Plateau and Xinjiang, respectively. Msofe et al.<sup>13</sup> in the alluvial plain of the Kilombero Valley and Wang et al.<sup>14</sup> in the upper reaches of Xiong'an New Area explored the impacts of land use/cover change on the value of ecosystem services, while Hou et al.<sup>15</sup> in the city of Xi'an, and Han et al.<sup>16</sup> in the eastern part of Sichuan Province, China, also explored the spatial characteristics and relationships between landscape patterns and the value of ecosystem services. Xiao et al.<sup>17</sup> in the Shanghai-Hangzhou Bay metropolitan area and Li et al.<sup>18</sup> in the Sichuan-Yunnan ecological barrier explored the interactive coercive relationship between urbanization and ecosystem service values. In addition, Wu et al.<sup>19</sup> discussed the valuation of ecosystem services in different watersheds in their studies of the Yellow River Basin and Yangtze River Basin, and Cao et al.<sup>20</sup> analyzed the balance between economic development and ecosystem service values in the process of terrestrial urbanization with a focus on terrestrial urbanization in China. In addition, Pan et al.<sup>21</sup> explored the spatial differentiation and driving mechanisms of ecosystem service values in arid regions in their study of the Shule River Basin. Currently, valuation methodologies used to compute ESV are primarily based on the unit area values factor method<sup>22–24</sup>, which monetizes the many services supplied by diverse ecological processes. Another method is based on the assessment of ecological service functions, such as water production, carbon sequestration, and biodiversity<sup>8,25,26</sup>. This method assesses ecological services from multiple perspectives, but it does not mean that the method is more reasonable. Some scholars have argued that the first method is more intuitive and less data-demanding than it is<sup>27</sup>, and more importantly, it can effectively relate the quality of ecological services to the well-being of the population<sup>28</sup>. In summary, these studies provide valuable insights into the dynamics of ecosystem service values, the impacts of human activities on the environment, and the importance of sustainable land use practices in maintaining ecosystem services. The quantitative analysis of the value of ecological ecosystem services can help to provide support for correcting irrational human development behaviors, reducing the probability of ecological risks, and providing support for the accurate formulation of ecological restoration strategies.

The ecological impacts of climate change vary from region to region, and different regions face different ecological risks. In 1986 the International Winter Cities Forum in Edmonton proposed that a winter city is a city with an average January temperature of 0 °C (32 °F) or lower and located in an area above 45° latitude. Later, some scholars believe that the latitude of winter cities can be lowered to 40° N latitude<sup>29</sup>. Winter cities are characterized by low winter temperatures, short days, and marked seasonal changes<sup>30</sup>. Leng et al.<sup>31</sup> focused on the influencing factors of outdoor activities in cold land settlements and proposed optimization strategies from the perspectives of optimization objectives, optimization mechanisms, and environment creation. Li et al.<sup>32</sup> construct an index system of stay activity intensity and cold micro-spatial environmental elements, and explore the influencing factors affecting stay activity. Zhu et al.<sup>33</sup> selected a typical small-scale community park in a Chinese winter city to study how landscape elements affect restoration benefits by setting up a seasonal virtual scene. Zhai<sup>34</sup> compared the ability of common tree species in winter urban parks to withstand urban flooding. Cheng et al.<sup>35</sup> Analysis of the drivers of severe winter haze in Harbin. It is not difficult to find that the existing research focuses more on the impact of cold climate on human activities in micro-space, with more qualitative analysis, and a large number of conclusions come from people's subjective feelings, and lack of more accurate and objective quantitative analysis. The city is a complex giant system, and it is difficult to optimize the whole system through micro-improvement of small-scale space. Winter city ecological protection strategies and territorial spatial planning depend on quantitative evaluation of the overall ecosystem functioning.

As a typical winter city, Shenyang is an important node in the Bohai Rim Economic Zone. 2022 Shenyang's urbanization rate has reached 85.12%, much higher than the national average of 63.9%. The growth of the urban population and the expansion of construction land in the process of urbanization have brought about LUCC, which promotes changes in the value of ecological services and a surge in ecological risks. The ecological risks faced by Shenyang are universal and unique. First, Shenyang has the universal ecological risks faced by other regions. For example, ecological risks such as reduced forest cover, reduced biodiversity<sup>36</sup>, increased soil erosion, desertification, and increased carbon emissions. At the same time, Shenyang has unique ecological risks due to its unique natural and industrial characteristics. First, the risk of forest fires caused by the dry climate in winter and spring. The winter and spring seasons in the city are dry, with sparse rainfall and high winds. Areas with fragmented landscapes and mixed cultivated and forested areas are very prone to forest fires. Second, the risk of crop pests and diseases caused by irrational agricultural cultivation. The long sunshine time, rain and heat at the same time, and good irrigation conditions in the cold land are conducive to the energy enrichment of food crops, which is an important base for the production of commercial grains<sup>37</sup>. Wang Hui et al.<sup>38</sup> pointed out that crop intercropping can increase yields and reduce pests. In order to increase the efficiency of agricultural machinery and boost agricultural production, large areas have been planted with mono-crops, leading to an increase in pests and diseases, which in turn leads to an increase in the use of pesticides, creating new ecological risks. Third, there is a risk of severe air pollution in winter and spring due to coal-fired heating, etc. For example, Jinsang Jung et al.<sup>39</sup> found for two East Asian cities that PM2.5 concentrations were four times higher than usual in both cities during the occurrence of hazy weather. Fourth, the risk of heavy metal pollution due to industrialization. Industrialization began in northeastern China as early as the beginning of the twentieth century, and studies have found that due to long-term mining and industrial production, more toxic and harmful substances have been enriched in cold soils and rivers<sup>40</sup>. Jiao Xudong et al.<sup>41</sup> measured the content of multiple heavy metals in 42 samples from the Shenyang industrial area and found that the average concentrations were higher than the

background values, suggesting that the pollution hotspots may be caused by human activities such as smelters and sewage irrigation. Quantitative landscape ecological risk assessment can make urban ecological governance policies more precise and is the basis for spatial control of territorial spatial planning.

Landscape Ecological Risk Assessment is an extension of landscape ecology, a methodology for monitoring and assessing the negative impacts of human activities and the natural environment on ecosystem structure and function<sup>42</sup>. The landscape ecological risk index determines the influence of landscape spatial patterns on ecological risk processes and functions, with typical spatial heterogeneity. It mainly focuses on measuring and evaluating landscape patterns, and then using the findings to illustrate ecological hazards in the landscape either directly or indirectly<sup>43</sup>. Scholars have applied this method to study ecologically vulnerable areas such as mines<sup>44</sup>, wetlands<sup>45</sup>, and drought-prone areas<sup>46</sup>, and the results have shown that ERI can accurately characterize the ecological risks of ecologically vulnerable areas. In recent years, there has been a growing body of literature on landscape ecological risk assessment in various regions of China. Zhang et al.<sup>47</sup> studied 48 coastal cities in China, focusing on the impacts of urbanization on ecosystems. Li et al.<sup>48</sup> incorporated an ecological risk index into a multi-process MCRE model to optimize the ecological security pattern of a semiarid region with intensive coal mining. Li et al.<sup>49</sup> also analyzed the impact of landscape multifunctionality change on landscape ecological risk in Beijing, and the results showed that there was a negative correlation between these two factors. Hou et al.<sup>50</sup> used the landscape ERA method to assess the ecological risk of LUCC-based alpine wetland ecosystems in the Zhuozhi Plateau. Xu et al.<sup>51</sup> constructed a landscape ecological network for large-scale opencast coal mining areas based on landscape ecological risk assessment, and the results showed that with land reclamation, the ecological risk of large-scale opencast coal mining areas would be reduced. Wang et al.<sup>52</sup> evaluated the spatial-temporal pattern of landscape ecological risk assessment in Baishuijiang National Nature Reserve based on the change of LULC. Ju et al.<sup>53</sup> explored the spatial-temporal pattern of ecological risk in coastal areas centered on the Shandong Peninsula. Zhang et al.<sup>54</sup> predicted landscape ecological risks under localized shared socio-economic pathways in the Fujian delta region. Ai et al.<sup>55</sup> assessed the dynamic landscape ecological risks and their drivers in an island city, particularly on Hainan Island, China. Karimian et al.<sup>56</sup> used spatial autocorrelation and geodetector methods to analyze landscape ecological risks and drivers in the East River Basin over forty years, providing valuable insights for environmental quality management. Together, these studies contribute to the understanding of landscape ecological risk assessment in various regions of China, emphasizing the importance of considering factors such as urbanization, land use change, and ecosystem services when assessing and managing ecological risks.

To our knowledge, winter cities face the challenges of urbanization. Previous studies are rich and meaningful for the micro-ecology of the region, but there is a relative lack of quantitative assessment of ecological service functions and exposure to ecological risks from the macro-spatial scale of the city, and from the multi-temporal time scale. This study attempts to jointly portray the spatial and temporal trends of urban ecological changes from the dimensions of ecological service outputs and ecological risks, and to find the driving factors, that can more rationally formulate sustainable development strategies and reduce the risk of ecological risk exposure. The study chooses Shenyang, a typical winter city, as the study area. The region has a high level of urbanization, and the contradiction between people and land is relatively prominent, with a large amount of arable land and grassland converted to urban construction land. The change in landscape pattern catalyzes landscape ecological risk. The primary questions to be addressed in this dissertation are: (a) What is the spatial and temporal variation pattern of ESV and ERI in Shenyang? (b) What are the drivers of ESV and ERI changes? (c) How can ESV and ERI be combined to identify key areas for urban ecological protection?

## Materials and methods

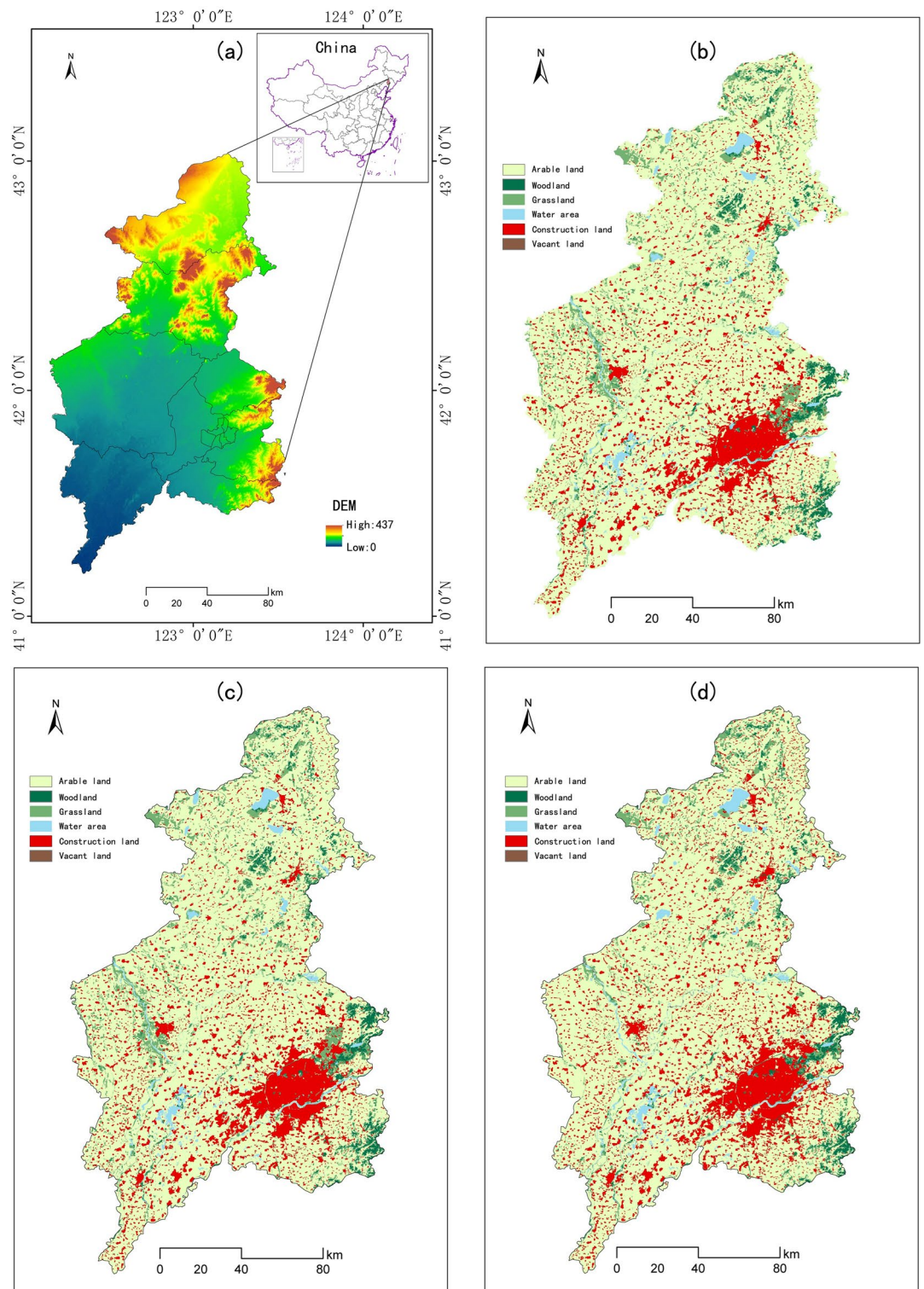
### Research area overview

Shenyang is the capital of Liaoning Province, situated in northeastern China and central Liaoning Province. It has a total area of 12,860 km<sup>2</sup> and a population of 9,073,000 people (2022). Geographically, Shenyang is situated between 41° 11' 51" to 43° 2' 13" north latitude and 122° 25' 9" to 123° 48' 24" east longitude. The region is mainly characterized by plains with relatively flat terrain, averaging an elevation of about 50 m. Mountains are mainly concentrated in the northeast and southeast. To the west lies the alluvial plain of the Liao River and Hun River, gradually sloping from east to west. Shenyang has a temperate semi-humid continental climate, with an average annual temperature of 9 °C and an average annual precipitation of 700 mm. The frost-free period ranges from 155 to 180 days throughout the year. Winter, from December to February, experiences an average temperature of − 10 °C, with January temperatures averaging at − 12.5 °C, 5 mm of precipitation, and 186 h of sunshine. The winters are long, cold, and dry, reflecting the city's typical characteristics as a winter city. Shenyang administers 13 county-level administrative regions. As of the end of 2020, its GDP reached 657.16 billion CNY, with the primary, secondary, and tertiary industries constituting 4.62%, 32.87%, and 62.51% of the total, respectively (Fig. 1).

### Data source and processing

The main data source of this research is the 30-m precision land use data of Shenyang City in 2000, 2010, and 2020. This data is obtained from the Global Land Cover Data Products Service website of the National Basic Geographic Information Center (<http://www.globeland30.org/>) (DOI: 10.11769). The vector data for administrative boundaries is sourced from the Geographic National Conditions Monitoring Cloud Platform (<http://www.dsac.cn/>). Other basic data come from the multi-year Shenyang Statistical Yearbook (<http://tjj.shenyang.gov.cn/>).

The GlobeLand30 data were simplified and reclassified into six categories: arable land (AL), forest land (FL), grassland (GL), water area (WA), construction land (CL), and unused land (UL) using the ArcGIS 10.2 program, based on the "Classification of Land Use Status (GB/T 21010-2017)". The land use within the study area is then resampled using 1 km × 1 km evaluation unit grids, resulting in 13,395 evaluation units.



**Figure 1.** Location of the study area (a) Location and Elevation; (b) Land use in 2000; (c) Land use in 2010; (d) Land use in 2020; (created by Arcgis 10.2, <http://desktop.arcgis.com/cn/>).

### ESV evaluation model

The research refers to the ESV model proposed by Costanza et al.<sup>9</sup>. Based on the ESV equivalent scale developed by Xie Gao Di et al.<sup>57,58</sup>, one standard equivalent was defined as 1/7 of the net profit of food production per unit area of farmland. The small size of the study area and the relatively homogeneous natural geographic characteristics and agricultural production practices make it suitable for ESV accounting using the above methodology. The specific calculation model is:



$$ESV_k = \sum A_k \times VC_k \quad (1)$$

$$ESV = \sum_f ESV_f \quad (2)$$

In the above equation ( $ESV_k$ ) and ( $ESV$ ) represent the ecosystem service values and total service values of the  $k$ -th land type in the research area, in CNY. ( $A_k$ ) represents the area of the  $k$ -th land use type in the research area, in  $hm^2$ . ( $VC_k$ ) represents the values coefficient of the  $k$ -th land use type, in CNY/ $hm^2$ . ( $ESV_f$ ) represents the values of the  $f$ -th type of ecosystem service, in CNY.

Referring to<sup>8,59,60</sup>, a method for revising the ratio of grain yield can be used to reflect the differences in service values between the research area and the national average state. The adjustment model is as follows:

$$\lambda = \frac{Q}{Q_0} \quad (3)$$

$$E_i = \lambda \times E_{0i} \quad (4)$$

In the equation,  $\lambda$  is the regional correction factor for ecological service equivalence, and  $Q$  and  $Q_0$  represent the grain yield per unit area in the study area and the national grain yield per unit area, respectively.  $E_i$  is the ecological service equivalent of the  $i$ -th land use type after regional correction,  $E_{0i}$  is the national average ecological service equivalent of the  $i$ -th land use type, where  $i = 1 \dots 6$ , representing AL, FL, GL, WA, CL, and UL, respectively. The correction results are shown in Table 1.

### ERI evaluation model

The degree of external perturbations to regional ecosystems and the extent of their internal resilience determine the ecological risk. Different biological functions within ecosystems result from changes in the spatial area ratios and spatial interactions between various land-use patterns. These variations then influence the ecosystems' resistance to external shocks<sup>61</sup>. Drawing on existing research<sup>62,63</sup> and considering the characteristics of winter city areas, In this study, the Landscape Disturbance Index, Vulnerability Index, and Loss Index were selected to construct a model to assess the risk of loss of ecological service functions.

#### Landscape disturbance index ( $E_i$ )

Based on the landscape pattern analysis, the landscape fragmentation index ( $C_i$ ), landscape separation index ( $N_i$ ), and landscape subdimension ( $D_i$ ) were chosen to build the  $E_i$  model<sup>64</sup>. Its expression is Eq. (5).

$$E_i = aC_i + bN_i + cD_i \quad (5)$$

According to the relevant references<sup>65</sup>, the weights applied to the three indicators,  $a = 0.5$ ,  $b = 0.3$ , and  $c = 0.2$ .

$$C_i = \frac{n_i}{A_i} \quad (6)$$

$$N = \frac{A}{2A_i} \sqrt{\frac{n_i}{A}} \quad (7)$$

$$D_i = \frac{Q_i + M_i}{4} + \frac{L_i}{2} \quad (8)$$

Level 1 class	Level 2 class	AL	FL	GL	WA	CL	UL
Supply services	Food production	1	0.33	0.43	0.89	0	0.02
	Raw material production	0.39	2.98	0.36	0.59	0	0.04
Regulation services	Gas regulation	0.72	4.32	1.5	2.92	0	0.06
	Climate regulation	0.97	4.07	1.56	15.61	0	0.13
	Hydrological regulation	0.77	4.09	1.52	32.21	0	0.07
	Waste disposal	1.39	1.72	1.32	29.25	0	0.26
Support services	Soil maintenance	1.47	4.02	2.24	2.4	0	0.17
	Maintaining biodiversity	1.02	4.51	1.87	7.12	0	0.4
Cultural services	Providing aesthetic landscapes	0.17	2.08	0.87	9.13	0	0.24
Total		7.9	28.12	11.67	100.12	0	1.39

**Table 1.** Revised ecological value service equivalents.

### Landscape vulnerability index ( $F_i$ )

The expert scoring approach was used to categorize the susceptibility of the various land use categories into six levels, ranging from low to high: UL, WA, AL, GL, FL, and CL, in light of the actual conditions in the research region. The vulnerability index  $F_i$  for each kind of terrain was generated after normalization.

### Landscape loss index ( $R_i$ )

$R_i$  reflects the degree of loss of natural attributes of ecosystems represented by different landscape types under both natural and anthropogenic disturbances.

$$R_i = E_i \times F_i \quad (9)$$

### Landscape ecological risk index (ERI)

Landscape spatial structure is converted into spatial ecological risk using the ERI model, which is built based on  $E_i$  and  $F_i$ .

$$ERI_i = \sum_{i=1}^N \frac{A_{ki}}{A_k} R_i \quad (10)$$

where  $ERI_i$  represents the ERI of the  $i$ -th risk subarea,  $A_{ki}$  represents the area of the  $i$ -th landscape type in the  $k$ -th risk subarea,  $A_k$  represents the area of the  $k$ -th risk subarea.

## Geographic detectors

Geographic detectors are spatial analysis methods that detect spatial dissimilarities and reveal the driving forces behind them, and are widely used to conduct driver analysis and factor analysis. It has two major advantages: first, geographic detectors can detect both numerical and qualitative data; second, they can detect two-factor interactions on the dependent variable<sup>66</sup>. In this study, ESV and ERI are used as dependent variables, and 10 independent variables are selected from the dimensions of natural and human factors, as shown in Table 2 as follows.

All independent variable factors were categorized into 5 categories using the natural breakpoint method and transformed into type quantities. Dependent variables Y1 for ESV, Y2 for Y2 are numerical quantities.

## Bivariate correlation analysis model

Spatial correlation modeling captures the extent to which certain factors are correlated in terms of spatial location. In this study, Moran's I index was used to reflect the spatial correlation between ESV and ERI in winter cities. The formula is as follows:

$$I = \frac{n \sum_i \sum_j \omega_{ij} (Y_i - \bar{Y})(Y_j - \bar{Y})}{\left( \sum_{i \neq j} \omega_{ij} \right) \sum_i (Y_i - \bar{Y})^2} \quad (11)$$

The LISA index can show the degree and significance of difference between localized areas and adjacent areas within the study area.

$$I_i = \frac{Y_i - \bar{Y}}{S^2} \sum_{j \neq i}^n \omega_{ij} (Y_j - \bar{Y}) \quad (12)$$

$$S^2 = \frac{1}{n'} \sum (Y_i - \bar{Y})^2 \quad (13)$$

	Data number	Data name	Data content	Data source
Natural factors	X1	DEM	Digital Elevation Model	<a href="http://srtm.csi.cgiar.org/srtmdata/">http://srtm.csi.cgiar.org/srtmdata/</a>
	X2	EVP	Annual evaporation	Resource and Environmental Science Data Registry and Publishing System ( <a href="http://www.resdc.cn/">http://www.resdc.cn/</a> )
	X3	NDVI	Normalized Difference Vegetation Index	
	X4	PRE	Annual rainfall	
	X5	SSD	Annual sunshine hours	
	X6	TEM	Average annual temperature	
	X7	RIVER	Distance to river	
Human factors	X8	ROAD	Distance to road	National Geographic Information Resources Catalogue Service System ( <a href="https://www.webmap.cn/main.domethod=index">https://www.webmap.cn/main.domethod=index</a> )
	X9	GDP	Gross domestic product	Resource and environmental science data platform ( <a href="http://www.resdc.cn/">http://www.resdc.cn/</a> )
	X10	POP	Population	

**Table 2.** Driving forces.

## Results

### Characterization of spatial–temporal variations in ESV

The research area's overall ESV dropped from 27.397 billion CNY to 27.038 billion CNY between 2000 and 2020, with a change rate of  $-1.31\%$ . The per unit area ESV decreased from  $21,304.50$  CNY/hm<sup>2</sup> to  $21,025.33$  CNY/hm<sup>2</sup>. The following represents the percentage of ESV for different forms of land use: AL > WA > FL > GL > UL > CL (Tables 3, 4). The service value ranking of various ecological functions is as follows: Hydrological regulation > Waste treatment > Climate regulation > Maintaining biodiversity > Soil maintenance > Gas regulation > Providing aesthetic landscapes > Raw material production > Food production (Table 5). The values of ecological services produced by each category are shown in Table 5. The total ESV has declined slightly over the two decades.

The ecological supply service functions as a whole show a high level. The very high-value zone has 366 units, accounting for 2.8% of the total, and is distributed in the eastern and northern mountainous areas. The high-value zone has 6744 units, accounting for 51.8%, and is very widely distributed, mainly in the central and western plains suitable for farming. The very low-value area has 1118 units, accounting for 8.6%, distributed in the main

Time		AL	FL	GL	WA	CL	UL
Area (km <sup>2</sup> )	2000	9699.1	424.6	822.9	275.6	1637.6	0
	2010	9532.9	438.4	875.7	275.3	1737.5	0
	2020	9502.4	425.8	607.0	326.8	1991.6	6.1
Area of change (km <sup>2</sup> )	2000–2020	-196.6	1.2	-215.9	51.3	354.0	6.1
Change rate (%)		-2.03	0.28	-26.24	18.60	21.62	-

**Table 3.** Changes in the spatial structure of land use, 2000–2020.

		ESV (billion CNY)			ESV change rate (%)	
		2000	2010	2020	2000–2010	2010–2020
AL	ESV	187.50	184.28	183.69	-1.71	-0.32
	Rate	68.44	67.94	67.94		
FL	ESV	29.22	30.16	29.30	3.25	-2.87
	Rate	10.66	11.04	10.84		
GL	ESV	23.50	25.01	17.33	6.42	-30.69
	Rate	8.58	9.15	6.41		
WA	ESV	33.76	33.72	40.04	-0.11	18.73
	Rate	12.32	12.34	14.81		
CL	ESV	0	0	0	0.00	0.00
	Rate	0.00	0.00	0.00		
UL	ESV	0	0	0.02	0.00	0.01
	Rate	0.00	0.00	0.01		
Total	ESV	273.97	273.18	270.38	-0.29	-1.02
	Rate	100.00	100.00	100.00		

**Table 4.** ESV structure and change in different land use types, 2000–2020增加.

Level 1 class	Level 2 class	AL	FL	GL	WA	CL	UL	Total
Supply services	Food production	2447	807.51	1052.21	1088.915	0	48.94	5444.575
	Raw material production	954.33	7292.06	880.92	721.865	0	97.88	9947.055
Regulation services	Gas regulation	1761.84	10,571.04	3670.5	3572.62	0	146.82	19,722.82
	Climate regulation	2373.59	9959.29	3817.32	19,098.835	0	318.11	35,567.145
	Hydrological regulation	1884.19	10,008.23	3719.44	39,408.935	0	171.29	55,192.085
	Waste disposal	3401.33	4208.84	3230.04	35,787.375	0	636.22	47,263.805
Support services	Soil maintenance	3597.09	9836.94	5481.28	2936.4	0	415.99	22,267.7
	Maintaining biodiversity	2495.94	11,035.97	4575.89	8711.32	0	978.8	27,797.92
Cultural services	Providing aesthetic landscapes	415.99	5089.76	2128.89	11,170.555	0	587.28	19,392.475
Total		19,331.3	68,809.64	28,556.49	122,496.82	0	3401.33	

**Table 5.** Composition of the value of various ecosystem services in the study area in 2020 Unit: billion CNY.

urban area of Shenyang, as well as the urban construction areas in the sub-centers of Liaozhong, Xinmin, Faku, Kangping, and so on. The overall level of restoration service functions is not high, and the spatial distribution of different grades is significantly differentiated. There are 101 units in the very high-value area, accounting for 0.8%, and 129 units in the high value area, accounting for 1%, distributed in large lakes, reservoirs, rivers, and urban wetlands. The very-low value area has 11,723 units, accounting for 88.2% of the total, and is distributed in the central and western plains, which are dominated by cultivated land and have weak ecological restoration functions. There are 433 units, accounting for 3.3%, in the very high value zone of ecological support services, and 1275 units, accounting for 9.8%, in the high value zone, which is distributed in the woodland and grassland-covered areas in the eastern and northern mountainous regions. As well as the Liaohe, Puhe, and Hunhe river basins, especially Pearl Lake wetland in western Shenyang and Lotus Lake wetland in northern Shenyang. There are 1366 units in the very low zone, accounting for 10.5% of the total, which is highly overlap with the urban construction area. The overall level of cultural service functions is not high. There are 114 units, or 0.9%, in the very high-value area, and 212 units, or 1.6%, in the very high-value area, which are mainly located in the river, lake, and wetland areas. The remaining areas are mostly very low-value areas. Extremely low-value areas are widely distributed, with 10,988 units, accounting for 82.7% of the total (Fig. 2).

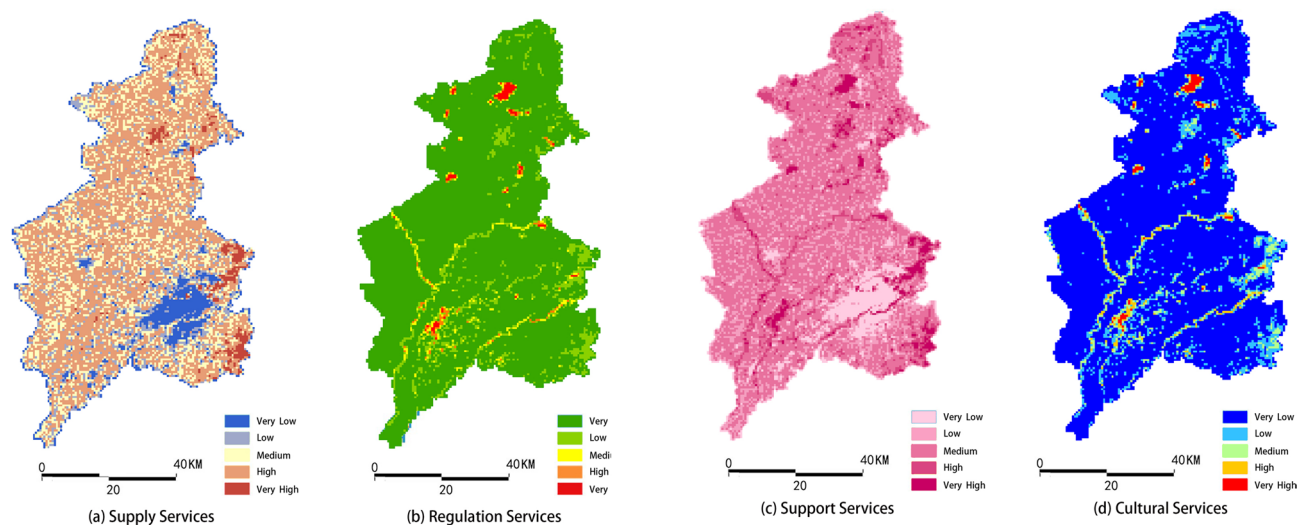
In summary, the contribution of urban construction land to all ecological services is very small, and reasonable control of the scale of construction land will be conducive to the enhancement of people's ecological well-being. Woodlands, grasslands, and waters contribute greatly to all ecological service functions. Effectively protecting forest land, grassland, and waters from being encroached upon by other land use types with low ecological service value will promote the overall improvement of ecological service value. Cultivated land is the basis of the food security strategy. However, the ecological functions of arable land are relatively homogenous, contributing greatly only to the ecological supply functions, but less to the other three types of ecological service functions.

By calculating the ESV of the evaluation unit, it can be categorized into five levels: Very low [0, 100], Low (100, 150], Medium (150, 200], High (200, 250], and Very high (250,  $\infty$ ). As shown in Fig. 3 and Table 6, The Medium, High, and Very high levels account for 47.70%, 16.25%, and 15.22% of the total area, respectively. The High level has the largest change in area with a decrease of  $-19.98\%$ . Low level and Very low levels increased by 18.98% and 17.48% respectively.

Figure 4 shows that the Hun, Liao, and Liu River basins, as well as the hilly areas in the southeastern and northeastern sections of the research region, have High or Very high ESV. Cropland in the Central Plains is the main distribution area for medium ESV. CL is mainly distributed in the central and southern plains of the study area. The terrain here is flat and the transportation conditions are good. The main urban area of Shenyang and the four urban sub-centers of Liaoyang, Xinmin, Kangping, and Faku highly overlap with the ESV's very low-value area. In order to control further expansion in these areas, appropriate town planning policies need to be developed. For example, the total amount of urban construction land should be controlled and urban construction land growth boundaries should be delineated. The development of the urban economy should also change the crude way of expanding construction land in the past. The potential of the stock of land should be fully tapped, and low-utility land should be fully revitalized to increase the GDP per unit area of land output.

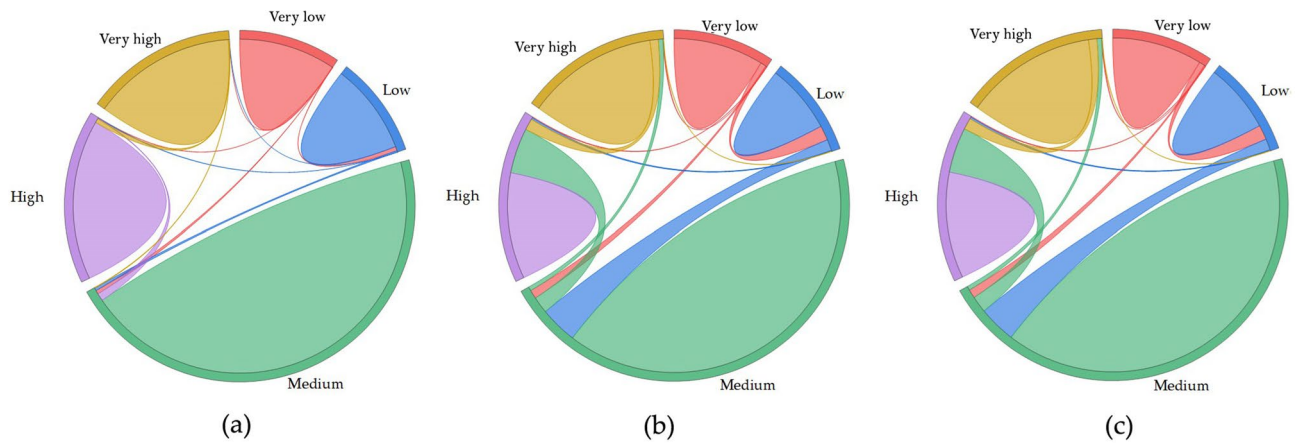
### Analysis of the drivers of ESV change

In the single-driver factor detection analysis, the factors with large driving forces on ESV changes were X1 (DEM), X10 (GDP), X8 (ROAD), and X4 (PRE), which were 0.35, 0.22, 0.19, and 0.21, respectively, but none of them exceeded 0.5 (Table 6).



**Figure 2.** Distribution of various ecological service functions in 2020 (a) Supply Services; (b) Regulation Services; (c) Support Services; (d) Cultural Services; (created by Arcgis 10.2, <http://desktop.arcgis.com/cn/>).

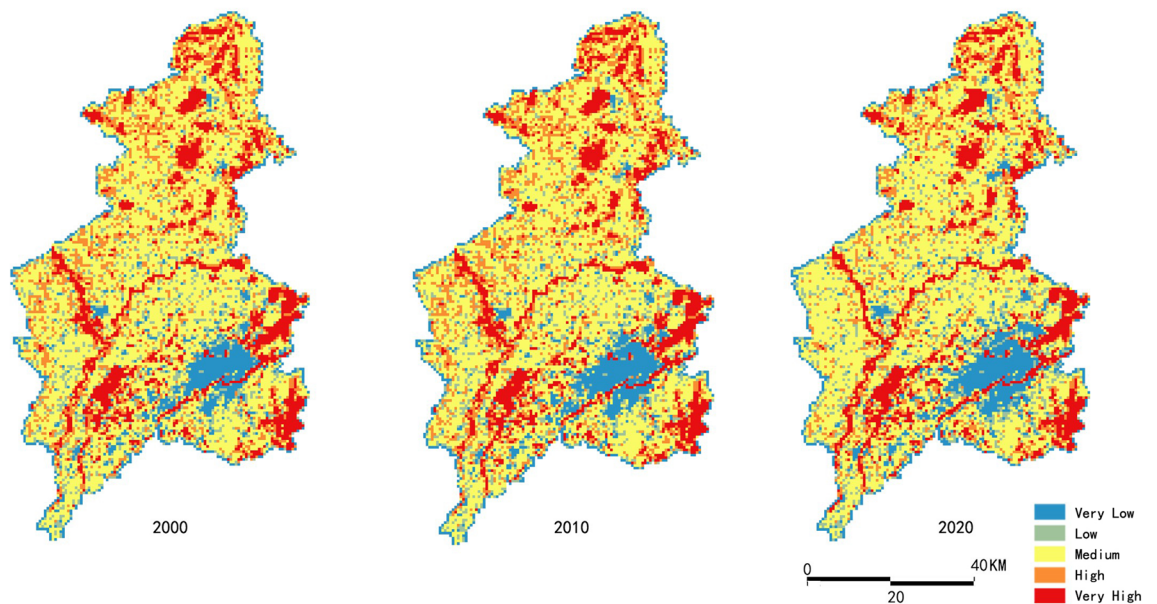




**Figure 3.** (a) Chord diagram of ESV changes, 2000–2010; (b) Chord diagram of ESV changes, 2010–2020; (c) Chord diagram of ESV changes, 2000–2020 (created by Oringin2022, <https://www.originlab.com/>).

	X1	X2	X3	X4	X5	X6	X7	X8	X9	X10
q statistic	0.35	0.16	0.09	0.19	0.09	0.18	0.06	0.21	0.15	0.22
p value	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00

**Table 6.** Drivers of ESV changes.

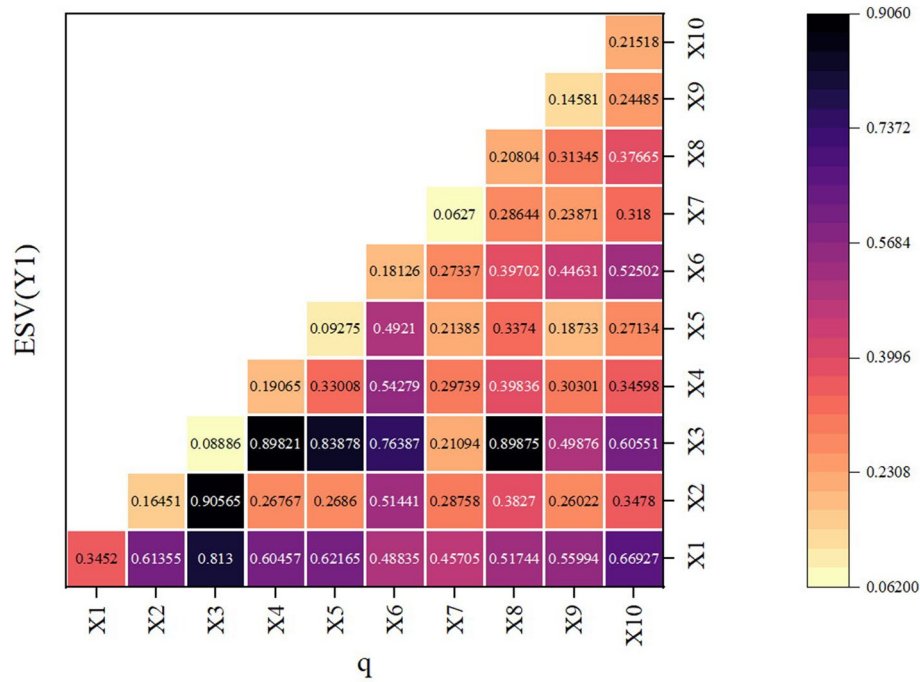


**Figure 4.** Spatial pattern of ESV in the study area, 2000–2020 (created by Arcgis 10.2, <http://desktop.arcgis.com/cn/>).

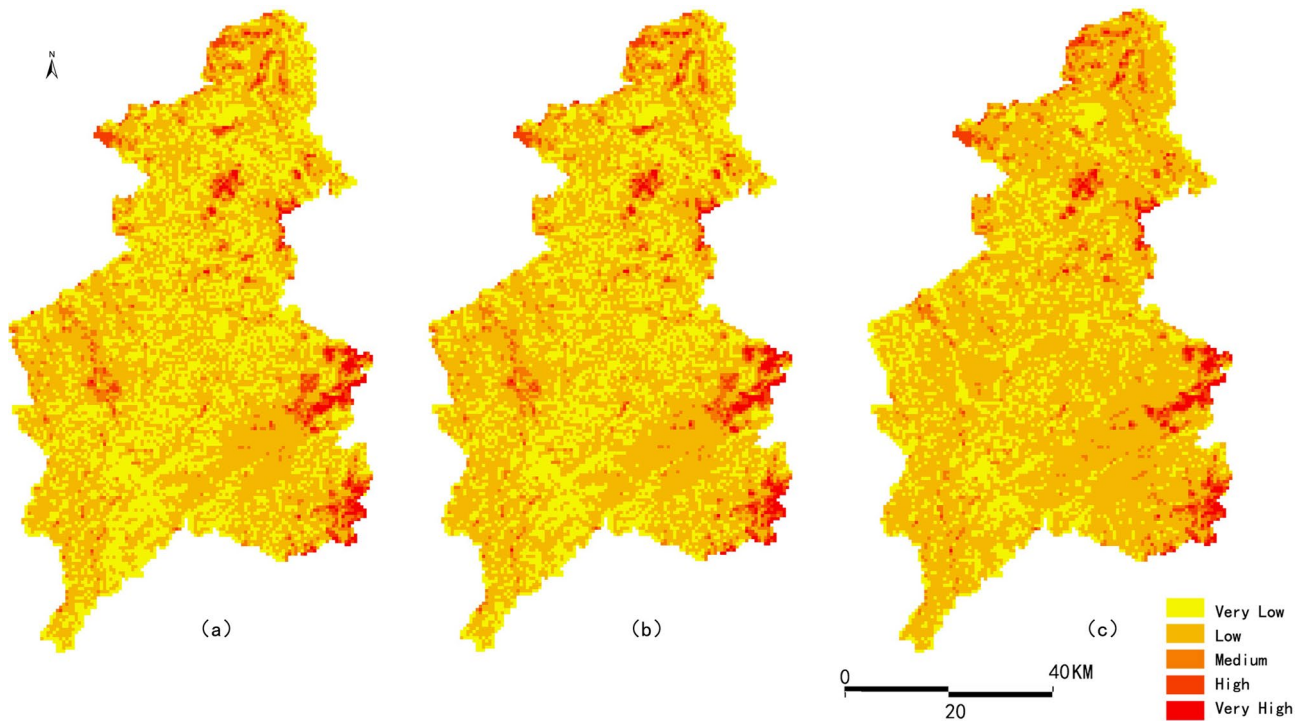
In the factor interaction detection analysis, the interaction of each driving factor on ESV change was nonlinearly enhanced or two-factor enhanced, and there were no independent, two-factor attenuated, or nonlinear attenuated factors (Fig. 5). The interaction drivers with greater explanatory power were X2/X3 (0.90565), X4/X3 (0.89821), X8/X3 (0.89875) X5/X3 (0.83878). The interaction of X2 (EVP), X4 (PRE), X8 (ROAD), and X5 (SSD) with X3 (NDVI) showed a nonlinear enhancement effect.

### Characterization of spatial–temporal variations in ERI

The ERIs of the three periods ranged from 0.007 to 0.170. To facilitate the comparative analysis of the spatial distribution of ecological risk in the three periods, the ERI of each period was divided into five levels with the following thresholds: Very high (0.12, ∞), High (0.09, 0.12], Medium (0.06, 0.09], Low (0.03, 0.06] and Very low [0, 0.03]. On this basis, the spatial pattern of ERI was mapped (Fig. 6).



**Figure 5.** Heatmap of interaction detection results for drivers of ESV change (created by Oringin2022, <https://www.originlab.com/>).



**Figure 6.** Spatial pattern of ERI in the study area (a) 2000; (b) 2010; (c) 2020 (created by Arcgis 10.2, <http://desktop.arcgis.com/cn/>).

The spatial distribution of ERI has shown an overall uneven pattern over the 20 years, showing a fragmented layout. Generally, the central and southern regions showed lower ERI, while the eastern and northern regions exhibited higher ERI. Very high ERI were primarily found in the eastern mountainous areas and northern hilly regions of Shenyang. These areas are prone to dual disturbances from natural and human activities, leading to a Very high ERI. On the one hand, the region's high slopes cause natural disasters such as landslides, flash floods,

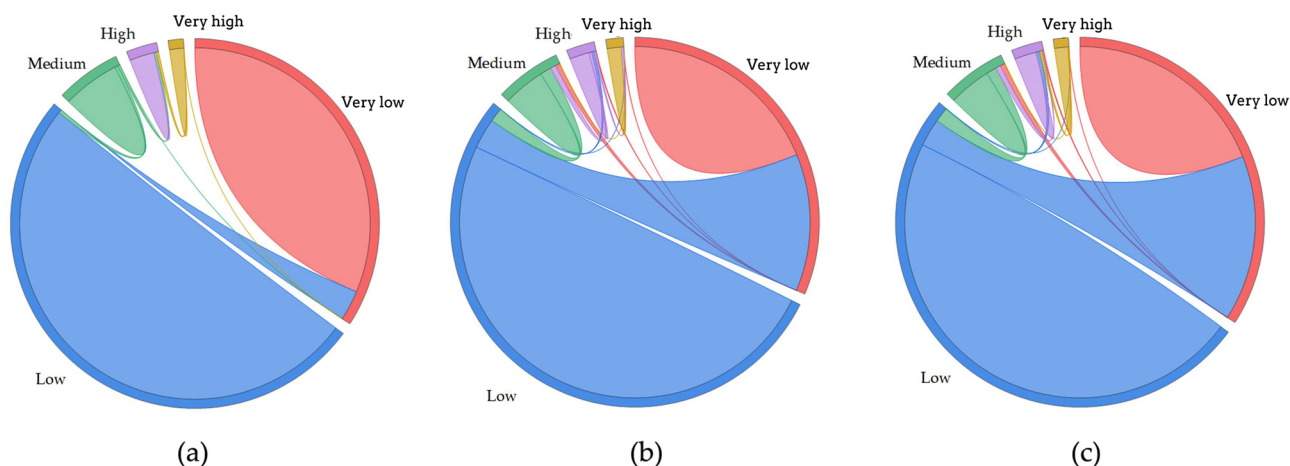
and soil loss. On the other hand, human activities including urban development, mining, deforestation, and land clearing led to the damage of forests and grasslands, exacerbating landscape fragmentation and reducing ecological resilience. Areas with Medium and Very low ERI were primarily spread in the middle and southern plains, notably in Shenyang's metropolitan regions and grain-producing areas, demonstrating a concentrated and continuous distribution pattern.

The structural alterations in ERI levels in the studied region were substantial. The area with Low ERI has experienced the largest increase, reaching 13.21%. Conversely, the area with Very low ERI has seen the most significant decrease, reaching 12.78%. The areas with Medium and High ERI have slightly decreased, while the area with Very high ERI has experienced a slight increase. Overall, there is a trend of increasing ERI in the urban area (Fig. 7, Table 7).

### Analysis of drivers of ERI change

In the single-driver probe analysis, X1 (DEM) had the greatest driving force on ERI change at 0.56. The explanatory power of X4(PRE), X2(EVP), and X6(TEM) for changes in ERI was 0.17, 0.15, and 0.11, respectively (Table 8).

In the factor interaction detection analysis, the interaction of each driver on ERI change was either nonlinearly enhanced or bi-factorially enhanced, and there were no independent, bi-factorially attenuated, or nonlinearly attenuated factors (e.g., Figure X). The interaction drivers with greater explanatory power are X5/X1 (0.7844), X2/X1 (0.77339), X4/X1 (0.76232), and X9/X1 (0.75762). The interactions of X5 (SSD), X2 (EVP), X4 (PRE), and X9 (POP) with X1 (DEM) are nonlinearly enhanced. This suggests that natural factors have a great influence on ERI, and artificial factors such as population distribution are also important drivers of ERI changes and spatial and temporal evolution(Fig. 8).



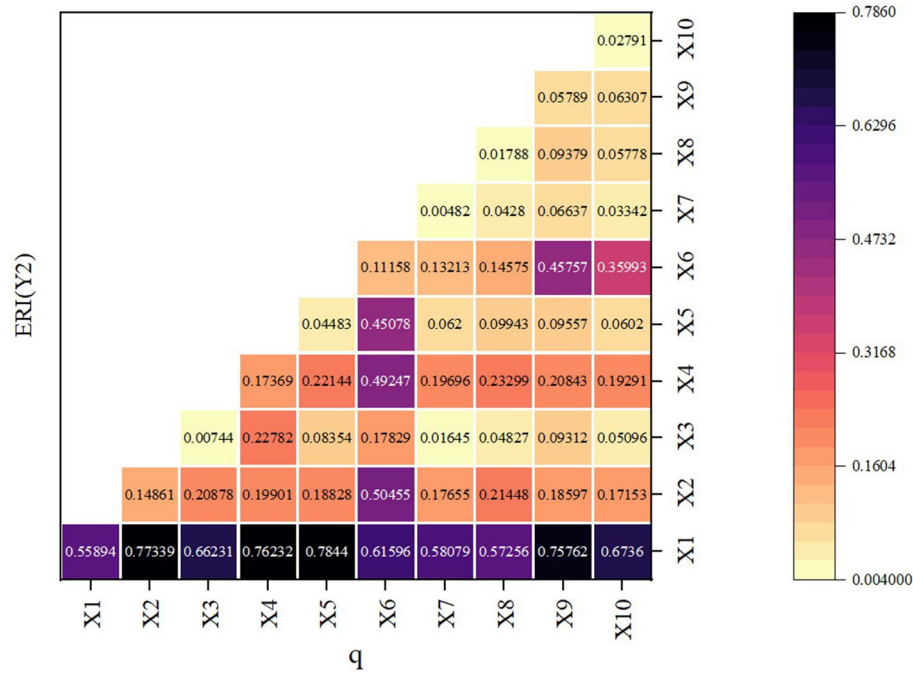
**Figure 7.** Chord diagram of ERI changes, (a) 2000–2010; (b) 2010–2020; (c) 2000–2020 (created by Oringin2022, <https://www.originlab.com/>).

	2000	2010	2020	2000–2020
Year	Ratio (%)	Ratio (%)	Ratio (%)	Ratio (%)
Very Low	35.95	33.04	23.17	– 12.78
Low	53.71	56.56	66.93	13.21
Medium	6.06	6.12	5.65	– 0.41
High	2.85	2.64	2.70	– 0.16
Very high	1.42	1.64	1.55	0.13

**Table 7.** ERI class structure 2000–2020.

	X1	X2	X3	X4	X5	X6	X7	X8	X9	X10
q statistic	0.56	0.15	0.01	0.17	0.04	0.11	0.00	0.02	0.06	0.03
p value	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00

**Table 8.** Drivers of ERI changes.



**Figure 8.** Heatmap of interaction detection results for drivers of ERI change (created by Oringin2022, <https://www.originlab.com/>).

### Spatial-temporal correlation analysis

#### Temporal correlation analysis

ESV and ERI were evaluated using data from 13,395 assessment units in the research region. Using the years 2000 and 2010 as the base period, an overlay analysis was conducted to examine the changes in ERI and ESV during the periods 2000–2010 and 2010–2020, resulting in the response of ESV changes to ERI in each period (Table 9). From 2000 to 2010, the number of assessment units with an increase in ESV exceeded those with a decrease for each risk level. During the 2010–2020 study period, the number of units with an increase in ESV at Very high ERI was less than those with a decrease, while at other risk levels, the number of units with an increase in ESV exceeded those with a decrease. Overall, from 2000 to 2020, the proportions of assessment units with a decrease in ESV for the five ecological risk levels, from high to low, were 47.37%, 49.48%, 55.17%, 56.14%, and 41.49%, respectively. The proportions of units with an increase in ESV were 48.95%, 46.86%, 44.70%, 39.49%, and 24.36%, respectively. Except for the Very high ERI, the number of assessment units with a decrease in ESV was higher than those with an increase at other risk levels. Units at Low ERI exhibited the greatest ESV variation, with 2,841 units experiencing an increase and 4,039 units experiencing a decrease.

#### Spatial correlation analysis

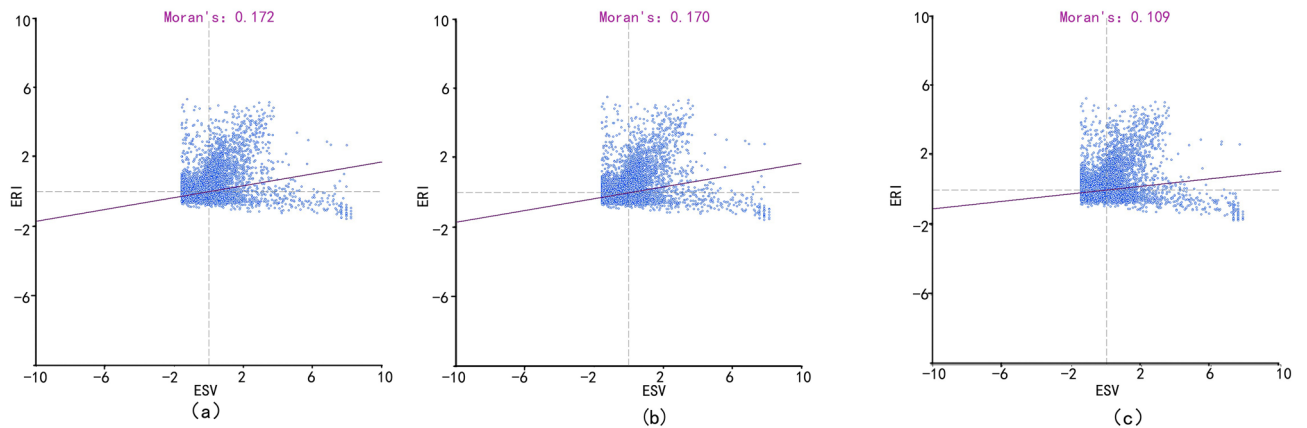
Using GeoDa1.18.0.0 to construct a spatial weight matrix, the study analyzed ESV and ERI through a bivariate correlation analysis model, resulting in a scatter plot of Moran's I index (Fig. 9). The scatter was mainly distributed in the H–H quadrant and the L–L quadrant, indicating a positive spatial correlation between ESV and ERI. The global Moran I index is 0.172, 0.170, and 0.109 for 2000, 2010, and 2020, respectively. The positive correlation between these two variables was strongest in 2000.

As shown in Fig. 8, the bivariate correlation analyses of ESV and ERI were categorized into five classes: H–H, H–L, L–H, L–L, and non-significant. The H–H areas are characterized by high ESV and high ecological risk

ERI	2000–2010			2010–2020			2000–2020		
	ESV+	ESV=	ESV–	ESV+	ESV=	ESV–	ESV+	ESV=	ESV–
Very high	107	14	69	91	8	121	93	7	90
High	247	32	103	231	29	93	179	14	189
Medium	652	10	150	654	12	154	363	1	448
Low	3670	2767	758	3813	2934	829	2841	315	4039
Very low	427	4245	144	273	4079	74	1173	1645	1998

**Table 9.** ESV response to ERI 2000–2020.



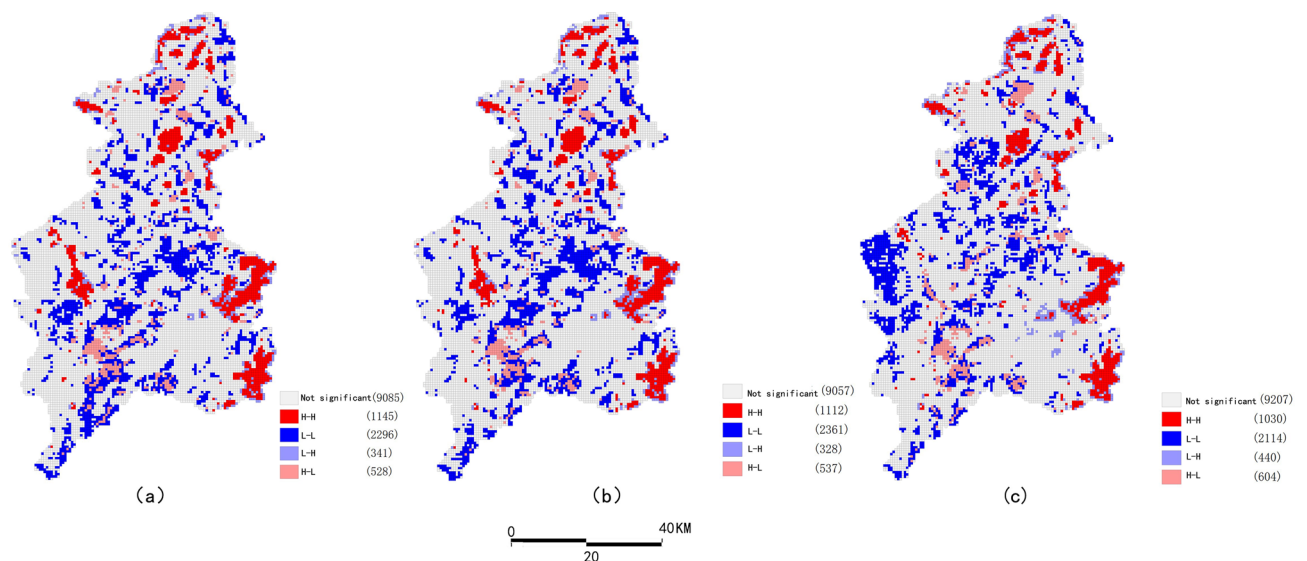


**Figure 9.** Scatter plot of Moran's I for correlation analysis between ERI and ESV (a) 2000; (b) 2010; (c) 2020 (created by Geoda1.18.0.0, <https://geodacenter.github.io/>).

levels. They are mainly found in the eastern and northern mountains of Shenyang, characterized by undulating terrain, predominantly forest and grassland, and high values for ecosystem provisioning, regulating, and landscape services. They pose a great ecological threat because of climate change and the impact on human production and living activities. The H–H areas in the western part of Shenyang have significantly decreased. The northern areas affected by the desertification of the Horqin Sandy Land have seen an increase in the H–H cluster area. The L–H areas are mainly concentrated on the periphery of the H–H areas. Under the influence of high ecological risk, the H–H areas may potentially transform into L–H areas. From 2000 to 2020, the overall H–H area decreased by 115 km<sup>2</sup>, while the L–H area increased by 99 km<sup>2</sup>. The L–L zone is scattered in the middle and south area of Shenyang, along the Liao River and Hun River alluvial plains, characterized by concentrated and contiguous arable land. ESV in this area mainly manifests as food supply, with relatively low comprehensive ecological service values. Additionally, the region has flat terrain, few geological hazards, minimal resistance to biological migration, and a low ecological risk index. The H–L zone is primarily located near plains water bodies in the central portion. Due to the restoration of the ecological wetlands of the Liao River, Pu River, and Hun River, the H–L area has increased by 76 km<sup>2</sup> over 20 years (Fig. 10).

## Discussion

It was found that the total ESV in Shenyang decreased from  $273.97 \times 10^8$  CNY to  $270.38 \times 10^8$  CNY over the past two decades, with a rate of change of  $-1.31\%$ . This further confirms the findings of Xing et al. that urbanization causes a decline in ESV<sup>67</sup>. From the data alone, the decrease in ESV in the study area is small, but this does not mean that urbanization has a small impact on ESV. Dramatic changes in land use cover during urbanization have caused great changes in the composition of ESV. Construction land is an important spatial carrier for human



**Figure 10.** Bivariate correlation analysis of ESV and ERI (a) 2000; (b) 2010; (c) 2020 (created by Geoda1.18.0.0, <https://geodacenter.github.io/>).



production and life, and is the area with the most intensive human activities and the greatest disturbance to the natural environment. With the advancement of urbanization, the urban construction land increased by 354 km<sup>2</sup> during 20 years, with a growth rate of 21.62%, and the fastest-growing area of construction land is located in the main urban area of Shenyang. Since the ESV of construction land is 0 in the assessment model, the expansion of construction land and the encroachment of other land use types with higher ESV will lead to the loss of overall ESV. Grassland and arable land are the main targets of encroachment by construction land. Along with the rapid expansion of urban construction land, the area of grassland decreased by 215.9 km<sup>2</sup>, and the area of arable land decreased by 196.6 km<sup>2</sup>. It is worth noting that the area of water bodies has increased by 51.3 km<sup>2</sup>, or 18.6%, during the past 20 years, and the ecological service functions of water bodies are relatively high, and it is precise because of the increase in the area of water bodies that the loss of ESV brought about by the increase in construction land has been compensated for, so that the total amount of ESV does not fall dramatically. Therefore, to safeguard people's ecological well-being enhancement, on the one hand, the growth of land types with low ecological service functions should be controlled. Strictly limit the growth of urban construction land, and change the "incremental development mode" to the "stock development mode". Through the implementation of the urban renewal strategy, the utilization efficiency of the stock of urban construction land will be improved, and inefficient and idle construction land will be activated to cope with the demand for urban function development. On the other hand, the protection of land with strong ecological service functions will be strengthened. The management of watersheds such as the Hun River, Po River, and Liao River should be strengthened through measures such as delineating the red line for ecological protection, dredging of rivers, management of black-smelling bodies of water, and the construction of urban wetland protection zones. The protection of forest land and grassland should be incorporated into national land spatial planning and safeguarded from encroachment by construction land, farmland, and other types of land through statutory documents on urban planning, to enable them to give full play to their ecological functions such as support, restoration, and culture.

The hilly area in northeastern Shenyang City has a high degree of landscape fragmentation, and the ecological risk continues to be at a high level. Feng<sup>68</sup> found in his study that monocentric sprawling urban land expansion has a significant ecological coercive effect. Liao et al.<sup>69</sup> showed that the encroachment of construction land into other urban land uses elevates urban ecological risk. The results of this study corroborate these views. With the advancement of urbanization and industrialization, urban construction land in Shenyang expanded from 1637.6 km<sup>2</sup> in 2000 to 1991.6 km<sup>2</sup> in 2020. The ERI is heavily transformed from Very low-risk to Low-risk areas, and the overall ecological risk level of the city has increased. It is worth noting that the expansion of urban construction land is divided into two ways: spreading development on the original basis and "enclave" development. Around the main urban areas in the central and southern parts of the city, due to strict urban planning and farmland protection regulations, the urban space is mostly expanded firstly, and although the urban scale is enlarged, the degree of landscape fragmentation is low, and the overall situation is stable and controllable, so the ecological risk assessed by the landscape pattern is low. On the contrary, in the hilly areas in the northeast, the urban planning space regulation is relatively weak, the terrain is undulating and slopes are large, and the second way of spatial expansion is mainly used. People have increased the degree of landscape fragmentation in this area through small-scale and progressive development activities, and very high-value ecological risk areas are mainly distributed here. There are three main types of these development activities, one of which is real estate development by enterprises or villagers in scenic mountainous areas, such as Zhongtian Garden, Shangmu Village, and other settlements around Qipan Mountain. The second is the predatory mining of limestone, granite, and other mineral deposits in mountainous areas. Such as Shenbei Qixing Mountain around the limestone mining caused by a large number of broken rings on the vegetation. The third is the villagers' profit-driven deforestation, resulting in a mixture of arable land and woodland grassland, which is very likely to cause environmental crises such as forest fires, soil erosion, and loss of ecological diversity as a result of agricultural production. For example, on April 17, 2019, because farmers burned straw, triggering a fire in Qipan Mountain, the forest land was affected by an area of 827 hectares, and the direct economic loss amounted to 24.605 million CNY. In summary, the study reveals that urbanization and industrialization have caused elevated ecological risks by assessing the spatial and temporal distribution of ecological risks in Shenyang. It is also found that, unlike related studies in other regions, this study finds that the area of very high ecological risk is not in the area of concentrated and contiguous growth of urban construction land, but in the area of active enclave development in the northeastern hilly area. Because of the different characteristics of the two areas, cities should formulate relevant laws and regulations to rationally deal with the conflict between "life, ecology, and production". In the new round of territorial spatial planning, urban spatial growth boundaries, the red line of basic farmland protection and the red line of ecological protection will be delineated. Urban growth will be controlled in a planned manner to prevent further disorderly expansion. Under the premise of guaranteeing that the total amount of basic farmland will not be reduced, farmers are encouraged to plant a mixture of different food crops to reduce the occurrence of pests and diseases, thereby reducing the use of pesticides and safeguarding the biodiversity of arable land, so that most of the arable land will be at a very low-risk level. In addition, for the northeastern hilly areas with the highest ecological risk level, on the one hand, it is necessary to further delineate nature reserves and forest parks in conjunction with the ecological protection red line, to protect the areas with strong ecological service functions. On the other hand, ecological restoration strategies need to be formulated for areas that have already been damaged. For example, land suitability evaluation should be carried out to vacate arable land and construction land that illegally encroach on forest and grassland. Mining land in key ecological protection areas should be closed down, and ecological restoration of mountains should be carried out to prevent further increases in ecological risks.

Cities should invest their limited ecological restoration funds in key nodes of the ecosystem. The way these critical points are identified is important. The studies of Jiang<sup>11</sup> and Zhang<sup>12</sup> assessed ESV through crop output per unit area, and the studies highlighted the use of monetized ecological service functions to measure ecological

status. Li et al.<sup>48</sup> used landscape ecological risk assessment to identify areas in urgent need of strategic ecological restoration interventions. Unlike previous studies, this study attempted to integrate the two ideas mentioned above to identify areas with high ESV and also high ERI. These areas are mainly located in the hilly areas in the northeastern part of the study area, which are more likely to cause fluctuations in the whole system if the ecological environment in the area is damaged. In future ecological restoration work in urban and rural areas, consideration should be given to prioritizing the concentration of limited resources in this region. It is recommended that ecological integrity be ensured through the following measures: (1) Incorporate the region into the red line of ecological protection as an ecological protection zone and strictly limit urban construction activities in the region. (2) Strengthening the protection of important natural resources such as forests, water sources, and soil in the region to prevent over-exploitation and pollution. (3) Establishing an ecological supervision mechanism to promptly detect pollution emissions, illegal mining, deforestation, and clearing of land, and to monitor the current status and changes in the ecological environment in real-time. (4) Improve the system of laws and regulations on ecological protection, strengthen publicity on ecological protection, and increase public participation.

At the same time, the study has some limitations. Public policies related to agricultural production, urban development, and ecological conservation can also have a significant impact on ESV and ERI. However, collecting spatial data on these factors is challenging. Subsequent research could incorporate considerations for public policy factors, expand and optimize the public policy indicator system, and strengthen the integration of qualitative and quantitative aspects to enhance the accuracy of urban ESV and ERI. China's winter cities have vast areas and significant differences among different study areas. The influencing factors selected for the ESV and ERI measurement model in this study primarily targeted the Northeast China Plain region. Subsequent research should focus on studying the ESV and ERI in ecologically sensitive areas such as plateaus and arid regions. These areas possess unique ecological environmental characteristics, and their ESV and ERI exhibit significant differences compared to other regions<sup>70–72</sup>.

## Conclusions

This study provides the first assessment of ESV and ERI in Shenyang, a representative of winter cities, over the past 20 years, and analyzes the drivers of spatial and temporal changes, and proposes a methodology for identifying critical areas for ecological restoration by combining ESV and ERI. The study draws the following conclusions:

The overall ESV of the study area has decreased by 1.31% from RMB  $273.97 \times 10^8$  to RMB  $270.38 \times 10^8$ . The ESV appears to have decreased by a relatively small amount, but the composition of the ESV has changed significantly along with the land use changes. From 2000 to 2020, land for construction has expanded significantly, increasing by 21.62%. Grassland and cropland areas decrease, by 26.24% and 2.03%, respectively. The reason why the overall ESV did not decrease significantly due to urbanization is precisely because the area of water bodies, which have the most comprehensive ecological service functions, increased by 18.60%. The factor with the strongest explanatory power for changes in ESV was DEM, and the interaction factor with the strongest explanatory power was EVP/NDVI. The overall ecological risk of the study area has increased, the area of very low ERI decreased by 12.78%, the area of low ERI increased by 13.21%, and the area of other sub-areas was relatively stable. The main urban area, where human activities are most concentrated, has a lower level of landscape fragmentation and a lower ERI level due to the spreading spatial expansion method and stricter urban planning regulation. On the contrary, the northeastern hilly area is at a very high ERI level due to the destruction of forest land and grassland by disorderly real estate development, deforestation and cultivation of fields, and mineral mining, etc. The factor with the strongest explanatory power for the ERI changes is DEM, and the interaction of SSD/DEM contributes the most to the influence of the ERI changes. The spatial and temporal correlation between ESV and ERI was observed in the study area, and the H–H areas were mainly located in the northeastern hilly areas. The H–H areas are mainly located in the northeastern hilly areas, which are facing serious ecological risks, but at the same time show strong ESV supply capacity, and are the areas that need to be prioritized for ecological restoration. Cities need to incorporate this area into national spatial planning, and strengthen the planning and control of this area through the delineation of "three zones and three lines", nature reserves, national forest parks, returning farmland to forests and grasslands, and vacating construction land. This study can provide theoretical support for the sustainable development of winter cities.

## Data availability

The original data for this study was obtained from the following public datasets: (1) The primary data source for this study is the 30-m precision vector land use data for Shenyang in the years 2000, 2010, and 2020. This data is obtained from the Global Land Cover Data Products Service website of the National Basic Geographic Information Center (<http://www.globeland30.org/>) (DOI: 10.11769). (2) The vector data for administrative boundaries is sourced from the Geographic National Conditions Monitoring Cloud Platform (<http://www.dsac.cn/>). (3) Crop Sowing Area, Agricultural Product Prices and Other Information from Shenyang Statistical Yearbook (<http://tjj.shenyang.gov.cn/>). The datasets generated by the study have been uploaded to the figshare repository. <https://doi.org/10.6084/m9.figshare.25662585.v1>.

Received: 18 April 2024; Accepted: 15 July 2024

Published online: 06 August 2024

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## Author contributions

Conceptualization, Y.L.; methodology, H.X.; software, Y.L.; validation, Y.L.; formal analysis, Y.L.; investigation, Y.L.; data curation, Y.L.; writing—original draft preparation, Y.L.; visualization, Y.L.; reviewed the manuscript, Y.L., H.X. All authors have read and agreed to the published version of the manuscript.

## Competing interests

The authors declare no competing interests.

## Additional information

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