Evaluation of industrial ecological security in industrial transformation demonstration area based on spatiotemporal differentiation

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ABSTRACT
Evaluating the state of China’s industrial transformation and its ecological protection is essential to addressing industrial ecological security. In this study, nine cities in the Wanjiang Demonstration Zone were selected for analysis using the normal cloud model and the spatial autocorrelation model. The study results showed that (1) the industrial ecological security of the Wanjiang Demonstration Zone showed an upward trend from 2012 to 2019, and the development among cities was unbalanced; (2) the industrial ecological security level in the northeast of the Wanjiang demonstration zone was higher than that in other cities; and (3) the spatial correlation within the demonstration area is positive, and the degree of agglomeration is strong initially but is subsequently attenuated. This indicates that enhancing the ecological security of the city will have a backflow effect that will attenuate connection with surrounding cities. This study elucidates ecological security in the industrial transformation demonstration area, and the following recommendations are made based on the research results: improving the strategic planning of regional industrial ecosystems, creating a new governance pattern featuring coordinated development among regions, and innovating new business forms and models for the development of inter-city linkage.

1. Introduction
Against the backdrop of increasingly severe global ecological problems, numerous international scholars are committed to studying sustainable ecological development in various forms. The weathered carbon sink of rocks significantly affects the global carbon cycle, and quantitative measurements of the weathered carbon sink aid in the accurate determination of the degree of climate change and ecological restoration (Gong et al. 2021). The establishment of a spatial map of vegetation change in the
global karst ecosystem can provide in-depth understanding of ecosystem evolution (Ran et al. 2021). Understanding the factors influencing the spatial distribution of ecosystems can aid in the development of healthy ecosystems (Ran et al. 2021). The key latitudes of river transportation of organic carbon influence the spatial redistribution of global organic carbon (Luo et al. 2022).

Industrial ecological security, an important component of global ecological concerns, is by extension derived from the concept of “industrial ecology”. Traditional industrial activities, which are ways of exploring and realizing sustainable development on the premise of continuous human development, should be transformed into an industrial ecosystem to minimize the output of industrial waste through the optimization of energy and materials. The industrial system is closely related to the surrounding environment and can be optimized for the entire material cycle (Graedel and Allenby 2003). Therefore, the concept of industrial ecological security can be summarized as follows. Within a particular range, industrial ecological security enables the resources and ecology on which the industry depends to reach equilibrium, allowing for the reasonable operation of industrial structure and sustainable development of human beings (Li 2008).

Different models with varied dimensions were established and used to study the system, efficiency, and risk status of industrial ecological security. The regional industrial security can be evaluated with early warning through the entropy weight comprehensive index method, and the factors restricting industrial ecological security can be further judged by combining it with the factor obstacle degree model (Zhang and Gong 2013). The VAR model helps to handle the dynamic role between the regional industrial structure and ecological security, and the causal relationship between the two can be determined through multivariate time-series tests (Wei and Pu 2013). When the research data include a small sample, the grey correlation method can be used to determine the correlation value and measure the regional industrial ecological security level (Du et al. 2015). For the marine industrial ecosystem, the Lotka–Volterra model can be used to describe the evolution trend of marine ecological security (Gou et al. 2017). The SBM model can measure the ecological security efficiency of the forestry industry to quantitatively explore its symbiotic relationship with forest ecology (Wu and Zhang 2019). The impact of forestry standardization on the ecology of forestry industry can be measured via data envelopment analysis. The regional industrial ecological security can be calculated via the BP neural network method to calculate the error multiple times to predict the future industrial ecological security status (Zhao et al. 2021).

In this study, the normal cloud model and spatial autocorrelation model were used to analyse the study area. The normal cloud model was proposed by academicians from the Chinese Academy of Engineering. Based on the normal distribution function and normal membership function, the expectation (Ex), entropy (En), and super-entropy (He) factors were used to address the uncertainty between quantitative and qualitative concepts through a normal cloud generator (Li and Liu 2004). The normal cloud model has been applied in many fields such as earthquake disasters, land ecological security, power supply systems, and urban security (Li et al. 2015; Liu et al. 2019; Gao et al. 2021; Guo et al. 2021). Mutual mapping between qualitative and
quantitative concepts can be achieved effectively. The first law of geography, introduced by Tobler in 1979, emphasizes the spatial relevance of adjacent areas (Zhou and Jin 2020). The spatial autocorrelation model is a data analysis model of regional spatial dependence and heterogeneity that is used to address and determine the non-independence of observation values. For example, the Moran indicator has been used as an evaluation indicator of spatial correlation based on spatial distribution (Xiong and Tang 2019; Zhu and Ali Mujiang 2019).

2. Experimental procedures

2.1. Study area

The Wanjiang Demonstration Zone, which is located along the Yangtze River Delta in China, is a national-level industrial transfer demonstration zone that encompasses nine cities in the Anhui Province and radiating surrounding areas. It is an important part of the industrial cluster in the Yangtze River Delta. Since the establishment of the Wanjiang Demonstration Zone by the State Council, its industrial structure has been significantly adjusted. During the period of industrial transformation, total energy consumption increased annually, with industrial energy consumption accounting for more than 60% of this consumption annually. However, the conventional one-way energy consumption model has strained the ecological sustainability of the Wanjiang Demonstration Zone. Therefore, the development of industrial ecological security is very urgent and of practical significance in dealing with global ecological problems (Figure 1).
2.2. Indicator system

At present, research on composite system construction index systems has been developed, and the entire optimisation can be realised through the coordination of subsystems. This study used the pressure-state-response (PSR) model as the basic framework and selected indicators from the economy-social-ecological (ESE) dimension to form the PSR-ESE model. This study emphasises that pressure, state, and response all have ecological, social, and economic factors, reflecting the interaction between the development of the industrial structure and social and economic activities in ecological security, and explaining the evolution process of industrial ecological security, as shown in Figure 2 (Zhou et al. 2009; Xiong and Tang 2019; Ye et al. 2021; Zhang et al. 2021;).

Based on the operation mechanism of the PSR-ESE industrial ecological security model, combined with the actual situation of the industrial ecology in the urban belt of Wanjiang, 18 indicators are selected from the three dimensions of economy, society, and ecology. Indicators D1-D6 reflect the challenges that expanding urbanization, rapid industrial development, and continuous population growth have brought to industrial ecological development; these factors are not conducive to the balance of supply and demand of various resources in the region. The factors are also important factors leading to the destruction of the ecological environment. Indicators D7-D12 reflect the development of an industrial layout, level of social urbanization, and the status of industrial waste treatment; these factors indicate socio-economic status and natural resource supply and demand in the region. They are related to the formation of industrial ecological layout. Indicators D13-D18 are related to the investments in scientific research by industries, control by the government over energy conservation and emission reduction, and ecological environment planning, indicating that enterprises and the government jointly implement ecological governance to achieve the sustainable development of industrial ecology. A comprehensive evaluation system of industrial ecological safety in the Wanjiang Demonstration Zone was established, and its regional industrial ecological security status was divided into five grades, as shown in Table 1: I (lower), II (low), III (general), IV (high), and V (higher).

2.3. Data sources

The research area map was based on LandSat8 images of the land use data in the Wanjiang Demonstration Area (the geo-spatial data cloud platform of the Computer
Table 1. Index system of industrial ecological security in Wanjiang Demonstration Zone.

| Goal level       | System level | Factor level                  | Index level                        | Estimation scale |
|------------------|--------------|-------------------------------|------------------------------------|------------------|
| Comprehensive     | pressure      | economic                      | GDP per capita $D_1$ (ten thousand yuan) | (0.2, 2.4, 4.6, 6.9, 9.12) |
| Evaluation        | economic      | Total profits of industrial enterprises $D_2$ (100 million yuan) | (350,600, 250,350, 150,250, 60,150, 30,60) |
| Ecological        | society       | Urban population density $D_3$ (person/km²) | (5000,6000, 4000,5000, 3000,4000, 2000,3000, 1000,200) |
| Security level    | economic      | Urbanization ratio $D_4$ (%)   | (70,80, 60,70, 50,60, 40,50, 30,40) |
|                   | ecology       | Water consumption per capita $D_5$ (m³ / person) | (900,1700, 600,900, 400,600, 200,400, 100,200) |
|                   | state         | Urban construction land $D_6$ (square kilometers) | (300,500, 150,300, 90,150, 55,90, 25,55) |
|                   | economic      | Proportion of tertiary industry in GDP $D_7$ (%) | (10,15, 15,25, 25,35, 35,45, 45,55) |
|                   | state         | Per capita industrial output value $D_8$ (Ten thousand yuan/person) | (6,9, 4,6, 3,4, 2,3, 0,2) |
|                   | society       | Gas Penetration rate $D_9$ (%) | (85,90, 90,93, 93,95, 95,98, 98,100) |
|                   | ecology       | Registered urban unemployment rate $D_{10}$ (%) | (4,4,5, 3,5, 3,5, 2,3, 2,2,5) |
|                   | state         | Comprehensive utilization rate of industrial solid waste $D_{11}$ (%) | (40,60, 60,70, 70,80, 80,90, 90,100) |
|                   | economic      | Air quality grade II $D_{12}$ (%) | (60,70, 70,80, 80,85, 85,95, 95,100) |
|                   | state         | Urban industrial power consumption $D_{13}$ (billion kwh) | (150,200, 90,150, 70,90, 45,70, 20,45) |
|                   | society       | Industrial Enterprise research and experiment fund $D_{14}$ (100 million Yuan) | (2,5, 5,15, 15,40, 40,100, 100,180) |
|                   | ecology       | Water resources per capita $D_{15}$ (m³ / person) | (300,1000, 1000,3000, 3000,5000, 5000,6000, 6000,9000) |
|                   | state         | Centralized treatment rate of urban sewage $D_{16}$ (ten thousand yuan) | (60,70, 70,80, 80,85, 80,90, 90,100) |
|                   | economic      | Green coverage rate of built-up area $D_{17}$ (%) | (35,40, 40,45, 45,50, 50,55, 55,60) |
|                   | state         | Ecological environment Water refill $D_{18}$ (100 million cubic meters) | (0,0,5, 0,5,1, 1,1,5, 1,5,2, 2,2,5) |
Network Information Centre of the Chinese Academy of Sciences), and data were obtained from the Statistical Yearbook of Anhui Province from 2013 to 2020, the statistical yearbook of various cities in the Wanjiang Demonstration Area, and the development bulletin.

3. Methods

3.1. Weight calculation

1. Dimensionless processing

The extrema method was used to compare the dimensionless processing of indicators in different units of the original data matrix (Zeng and Hu 2021). To make the data processing relevant, the dimensionless indicators were increased by 0.001 (Equations 1–3).

\[ a_{ij} \] is the actual value of an indicator before dimensionless processing; max \( a_{ij} \) and min \( a_{ij} \) are the maximum and minimum values of the sequence of this indicator, respectively; and \( b_{ij} \) is the value after dimensionless processing.

2. Weight evaluation

The entropy weight method was used to determine the weights. A mathematical model was used to obtain the weight of the indicators using Equations 4 and 5. \( i_j \) represents the \( i \)th sample and \( j \)th indicator, \( m \) represents the number of indicators, and \( p \) represents the number of evaluation samples. \( e_j \) is the information entropy, \( r_j \) is the characteristic proportion or contribution, \( W_j \) represents the indicator weight, and the weight matrix is obtained by \( W = \{ W_1, W_2, W_3 \ldots W_n \} \).

3.2. Analysis of normal cloud model

3.2.1. Cloud model

For the normal cloud model, the quantitative characteristics of cloud language values are represented by the expectation (Ex), entropy (En), and superentropy (He) factors. The uncertainty factors in the evaluation of industrial ecological security can be reduced using this model (Figure 3). In this study, a forward cloud generator was used to generate quantitative cloud droplets and membership degree with the corresponding distribution law as follows (Guo et al. 2021; Hou et al. 2020):

Set \( W = \{ x_1, x_2, x_3 \ldots X_n \} \) is the theoretical domain of the set of evaluation factors, \( T \) is the set of qualitative descriptions of the theoretical domain \( W \), and element \( X \) in the theoretical domain \( W \) is in accordance with \( \mu X \sim N \) (Ex, En²). First, a normal random \( En_i = \text{norm} (En, He²) \) was generated, and a normal random \( x_i = \text{norm} (Ex, En_i²) \) was regenerated. The membership function \( \mu(x) \) of \( T \) was calculated using Equation 6.

Therefore, \( x_i \) satisfies the normal cloud distribution in domain \( W \), and \( [x_i, \mu T(x)] \) is the cloud droplet generated therein.

3.2.2. Cloud model evaluation

1. An industrial ecological security evaluation indicator set, \( U = \{ u_1, u_2, u_3, \ldots u_n \} \), is established to determine the evaluation grade standard, \( V = \{ v_1, v_2, v_3, \ldots v_n \} \).
2. A fuzzy matrix, Q, is constructed to determine the membership degree of the evaluation indicator set, U, in evaluation grade V. According to the adopted indicator, I, the upper boundary value, C_{ij}^1, and the lower boundary value, C_{ij}^2, of evaluation grade j, the normal cloud model is used to represent the transformation between factors and grades using Equation 7.

In Equation 7, the upper and lower boundary values are critical values of different levels and should belong to two levels; the membership degrees are equal. Superentropy (He) refers to the degree of dispersion of entropy and shows the thickness of the cloud. In this study, the superentropy (He) value was selected as 0.01 according to the general law (Ye et al. 2016).

3. The membership degrees corresponding to different grades of a single factor are calculated according to Equation 5. The membership degree, mij, corresponding to grade J of factor I is obtained, and the membership degree matrix M = (mij)_{n \times M} is constructed.

4. The weight matrix W = \{w_1, w_2, w_3 \ldots W_n\}, and the fuzzy set are obtained by fuzzy transformation, H = M \times W = \{h_1, h_2, h_3, \ldots h_n\} (shown in Equation 8).

The evaluation results and corresponding grades were then determined according to the principle of the maximum membership degree.

3.3. Spatial auto-correlation analysis

3.3.1. Spatial auto-correlation model

The global Moran’s I indicator is used to evaluate the regional attribute correlation degree to determine whether the overall ecological security space in the Wanjiang Demonstration Zone is correlated.

3.3.2. Spatial auto-correlation model evaluation

Specific methods are used in Equations 9 and 10. In the above formula, n represents the number of cities, m represents the number of indicators, P_{ij} represents the spatial weight matrix, x_i represents the comprehensive indicator of the ith city, r_{ij} and W_j are the calculation results of Formulas (3) and (4) above, Global Moran’s I \in [-1,1],

Figure 3. Forward and reverse cloud generator.
where close to 0 is in random distribution, and the space is positively correlated when Global Moran’s $I > 0$. When Global Moran’s $I < 0$, the space is negatively correlated, and the absolute value is proportional to the correlation.

The Moran scatter diagram shows that each quadrant corresponds to a spatial pattern with a total of four categories. The first to fourth quadrants were HH, LH, LL, and HL aggregation areas, and the spatial aggregation and dispersion distribution of industrial ecology in the nine cities were analysed using the degree of aggregation and dispersion of points in different quadrants. To determine whether there is a significant level in the region, the Monte Carlo simulation method was used to test the significance of Moran’s $I$ statistic using Equation 11, with 999 simulations.

Where $E(I)$ represents the expected value of Moran’s $I$ autocorrelation of the observation variable, $Var(I)$ represents the variance, and $Z(I)$ represents the significance level of spatial autocorrelation.

### 4. Results and discussion

#### 4.1. Normal cloud model

According to Equation 6, the normal cloud standards at different levels of each evaluation index were obtained, and the normal cloud standards for industrial ecological safety in the Wanjiang demonstration zone were established, as shown in Table 2. For the subordinate degree of the normal cloud, the shape of the normal cloud map reflects the overall attribute of the membership degree and reveals the normal distribution law in statistics. Consider the normal cloud map of per capita industrial output and the proportion of tertiary industry in GDP as examples, as shown in Figures 4 and 5.

Based on the corresponding data of nine cities in the Wanjiang Demonstration Zone from 2012 to 2019, the results and grades of the comprehensive evaluation of the industrial ecological security of each city in the study area were determined.

| Target | Grade I          | Grade II         | Grade III        | Grade IV          | Grade V          | Attribute | Weight |
|--------|------------------|------------------|------------------|-------------------|------------------|-----------|--------|
| $D_1$  | (1,0.84,0.01)    | (3,0.84,0.01)    | (5,0.84,0.01)    | (7,5,1.27,0.01)   | (10,5,1,27,0.01) | positive  | 0.087  |
| $D_2$  | (475,106,16,0.01)| (300,42,46,0.01)| (200,42,46,0.01)| (150,38,22,0.01)  | (45,12,74,0.01)  | negative  | 0.038  |
| $D_3$  | (5500,424,63,0.01)| (4500,424,63,0.01)| (3500,424,63,0.01)| (2500,424,63,0.01)| (1500,424,63,0.01))| negative  | 0.033  |
| $D_4$  | (75,4.25,0.01)    | (65,4.25,0.01)    | (55,4.25,0.01)    | (45,4.25,0.01)    | (35,4.25,0.01)    | negative  | 0.052  |
| $D_5$  | (1300,339,70,0.01)| (750,127,39,0.01)| (500,84,93,0.01)  | (300,84,93,0.01)  | (150,42,46,0.01)  | negative  | 0.002  |
| $D_6$  | (400,84,93,0.01)  | (225,63,69,0.01)  | (120,25,48,0.01)  | (72,5,14,86,0.01) | (40,12,74,0.01)  | negative  | 0.032  |
| $D_7$  | (12.5,2,12,0.01)  | (20,4,25,0.01)    | (30,4,25,0.01)    | (40,4,25,0.01)    | (50,4,25,0.01)    | positive  | 0.058  |
| $D_8$  | (7.5,1,27,0.01)   | (5,0.85,0.01)     | (3.5,0,42,0.01)   | (2.5,0,42,0.01)   | (1,0.85,0.01)     | negative  | 0.014  |
| $D_9$  | (87.5,2,12,0.01)  | (91.5,1.27,0.01)  | (94.0,85,0.01)    | (96.5,1,27,0.01)  | (99.0,85,0.01)    | positive  | 0.016  |
| $D_{10}$ | (4.25,0.21,0.01)  | (3.75,0.21,0.01)  | (3.25,0.21,0.01)  | (2.75,0.21,0.01)  | (2.25,0.21,0.01)  | negative  | 0.043  |
| $D_{11}$ | (50.8,49,0.01)    | (65,4.25,0.01)    | (75,4,25,0.01)    | (85,4,25,0.01)    | (95,4,25,0.01)    | positive  | 0.012  |
| $D_{12}$ | (65,4.25,0.01)    | (75,4,25,0.01)    | (82.5,2,12,0.01)  | (90,4,25,0.01)    | (97.5,2,12,0.01)  | positive  | 0.062  |
| $D_{13}$ | (175,21,23,0.01)  | (120,25,48,0.01)  | (80.8,4,99,0.01)  | (57.5,10,62,0.01) | (32.5,10,62,0.01)| negative  | 0.047  |
| $D_{14}$ | (3.5,1,27,0.01)   | (10,4,25,0.01)    | (27.5,10,62,0.01)| (70,25,48,0.01)   | (140,33,97,0.01)  | positive  | 0.219  |
| $D_{15}$ | (650,297,24,0.01)| (2000,849,26,0.01)| (4000,849,26,0.01)| (5500,424,63,0.01)| (7500,1273,89,0.01)| positive  | 0.184  |
| $D_{16}$ | (65,4.25,0.01)    | (75,4,25,0.01)    | (82.5,2,12,0.01)  | (90,4,25,0.01)    | (97.5,2,12,0.01)  | positive  | 0.044  |
| $D_{17}$ | (37.5,2,12,0.01)  | (42.5,2,12,0.01)  | (47.5,2,12,0.01)  | (52.5,2,12,0.01)  | (57.5,2,12,0.01)  | positive  | 0.044  |
| $D_{18}$ | (0.25,0.21,0.01)  | (0.75,0.21,0.01)  | (1.25,0.21,0.01)  | (1.75,0.21,0.01)  | (2.25,0.21,0.01)  | positive  | 0.049  |
according to the maximum subordinate degree using the aforementioned principles and steps (Table 3 and Figure 6).

Finally, the following observations were made from this study:

1. Although the industrial ecological security in the Wanjiang Demonstration Zone has improved significantly during the research period, there is still pressure for further improvement.

   Through the time series analysis of the industrial ecological security in the Wanjiang Demonstration Zone (2012–2019), the industrial ecological security level of nine cities was significantly improved in eight years, although the safety level of each city fluctuated in those years. However, in terms of the grade of
improvement, two-thirds of the seven cities were at grade III or below, and only Hefei was above grade IV. The industrial ecological safety grades in Hefei, Wuhu, Maanshan, Chuzhou, and other cities in northern Wanjiang were significantly more optimized than those in the other five cities. Hefei and Wuhu are the two core cities in the Wanjiang urban belt. Their industrial ecological security reached grade IV in 2014, and fluctuated within a small range. They are the two core cities of economic development and industrial upgrading in Anhui Province. Significant progress was observed in the level of industrial ecological security in Chuzhou from 2017 to 2019. From 2012 to 2016, the city achieved comprehensive growth in strength from Class II to Class IV. After four years of steady

Table 3. Comprehensive evaluation results of industrial ecological security in Wanjiang Demonstration Zone.

| City      | Category | 2012 | 2013 | 2014 | 2015 | 2016 | 2017 | 2018 | 2019 |
|-----------|----------|------|------|------|------|------|------|------|------|
| Hefei     | result   | 0.359| 0.354| 0.350| 0.348| 0.251| 0.337| 0.347| 0.264|
|           | grade    | III  | III  | IV   | III  | IV   | IV   | V    | V    |
| Chuzhou   | result   | 0.417| 0.362| 0.367| 0.400| 0.565| 0.365| 0.315| 0.367|
|           | grade    | II   | II   | II   | II   | III  | III  | III  | IV   |
| Lu’an     | result   | 0.339| 0.331| 0.422| 0.495| 0.409| 0.545| 0.489| 0.383|
|           | grade    | I    | I    | II   | II   | III  | III  | III  | I    |
| Maanshan  | result   | 0.292| 0.386| 0.452| 0.326| 0.372| 0.326| 0.309| 0.289|
|           | grade    | III  | III  | III  | III  | II   | II   | II   | II   |
| Wuhu      | result   | 0.353| 0.256| 0.340| 0.359| 0.459| 0.372| 0.316| 0.306|
|           | grade    | III  | III  | IV   | IV   | IV   | IV   | IV   | IV   |
| Xuancheng | result   | 0.340| 0.477| 0.374| 0.335| 0.429| 0.499| 0.590| 0.521|
|           | grade    | II   | II   | III  | III  | IV   | IV   | IV   | IV   |
| Tongling  | result   | 0.335| 0.267| 0.358| 0.417| 0.384| 0.405| 0.378| 0.442|
|           | grade    | II   | II   | III  | III  | IV   | IV   | IV   | IV   |
| Chizhou   | result   | 0.284| 0.289| 0.263| 0.388| 0.351| 0.254| 0.358| 0.359|
|           | grade    | II   | III  | III  | III  | IV   | IV   | IV   | IV   |
| Anqing    | result   | 0.439| 0.549| 0.599| 0.576| 0.341| 0.510| 0.354| 0.406|
|           | grade    | II   | II   | II   | II   | III  | III  | III  | III  |

Figure 6. Industrial ecological security level of cities in Wanjiang Demonstration Zone.
growth and a transition decline in 2016, Maanshan’s industrial security composite level has gradually improved since 2017 and was ranked first in 2019, playing an important role in industry transfer. Owing to its failure to fully join the Wanjiajiang Demonstration Zone, Lu’an was limited with respect to the development of the nine cities and did not reach grade III until 2016. In Xuancheng, Chizhou, Tongling, and Anqing, the main axis cities in Wanjiajiang Demonstration Zone, the development of industrial ecological safety grades was grade III in 2019. The levels of these four cities in other years were mainly level II and level III. Overall, the grades fluctuated and stabilized gradually.

2. The industrial ecological security of the Wanjiajiang demonstration zone shows a remarkable trend, but the constraint relationships among the influencing factors are complex. The demonstration effect was significant for the 18 indicators. Over the past eight years, the industrial structure of the Wanjiajiang demonstration zone has been adjusted to a certain extent, which has effectively improved the industrial ecological security of the demonstration zone. In terms of the year effect of these indicators, the constraint relationships fluctuate and are complex. The overall development of cities in the northern part of the Wanjiajiang demonstration zone exceeded that in the southern part, and the four cities in the northeast were in the leading position in the study area. According to the location distribution of industrial ecological security in the Wanjiajiang demonstration zone, the development levels of adjacent areas are similar. Both Chuzhou and Maanshan are adjacent to Nanjing, and both join the Nanjing metropolitan area. In 2019, Chuzhou’s secondary industrial development took up a relatively high proportion, which was related to the policy leadership of Nanjing’s industrial transfer. In 2018, Wuhu joined the G60 Corridor of Science and Technology Innovation with relatively high urbanisation development, and the three cities have become the three potential cities around the provincial capital Hefei. Lu’an is a mountainous city located in the west of the Hefei metropolitan area and is not closely connected to surrounding cities such as Anqing. In 2018, the scatter coverage for Maanshan and Tongling was relatively high. This means that the two cities are highly correlated with industrial ecological security and belong to the industrial transformation cities.

4.2. Spatial auto-correlation model

The global Moran scatterplot of industrial ecological security in the Wanjiajiang demonstration zone from 2012 to 2019 was obtained using the adjacent spatial weight rule. To verify the significance of the data, 999 randomisation tests were performed on the results, and the corresponding P and Z values were obtained, as shown in Table 4. In Table 4, all the

| Item  | 2012  | 2013  | 2014  | 2015  | 2016  | 2017  | 2018  | 2019  |
|-------|-------|-------|-------|-------|-------|-------|-------|-------|
| Moran index | 0.123 | 0.257 | 0.265 | 0.262 | 0.193 | 0.206 | 0.131 | 0.057 |
| P value  | 0.077 | 0.025 | 0.017 | 0.022 | 0.049 | 0.029 | 0.036 | 0.067 |
| Z(I)    | 1.495 | 2.155 | 2.186 | 2.162 | 1.712 | 2.063 | 1.852 | 1.568 |
results of the Moran indicator from 2012 to 2019 were greater than 0. This means that there was a positive correlation between the levels of industrial ecological security in the Wanjiang urban belt. The P-values from 2013 to 2018 were all less than 0.05, indicating that the corresponding Z values were all higher than 1.65 through the 95% confidence test, and showing significant data correlation. The correlation between 2012 and 2019 was not statistically significant. Therefore, to accurately express the spatial pattern evolution during the study period, Moran scatterplots and 999 random displacement results from 2013 to 2018 were selected, as shown in Figures 7–12. In Figures 7–12, each scatter represents one city, and the nine cities are represented using abbreviations. HF represents Hefei, TL represents Tongling, MAS represents Maanshan, XC represents Xuancheng, WH represents Wuhu, LA represents Lu’an, AQ represents Anqing, and ChuZ and ChiZ represent Chuzhou and Chizhou, respectively.
Figure 9. Industrial ecological security in 2015.

Figure 10. Industrial ecological security in 2016.

Figure 11. Industrial ecological security in 2017.
Based on the results analysis in Figures 7–12, the following observations were made:

1. The general state of the industrial ecological security environment in the Wanjiang Demonstration Zone is severe, and there is significant demand for industrial transformation.

   From 2013 to 2018, the Moran indicator was positive and fluctuated, it increased initially and then decreased, indicating that the degree of agglomeration between the Wanjiang urban belt was initially strengthened and then attenuated. Hefei was always in the first quadrant (HH) from 2013 to 2018, which was particularly evident from 2013 to 2016. The high-value area of Hefei is surrounded by the high-value area of Wuhu. As the sub-centre of Anhui Province, Wuhu is closely connected with Hefei, and the regional linkage effect is obvious. In 2017, Chizhou entered the first quadrant, when the distribution of HH in Hefei was attenuated. In 2018, Xuancheng joined the first quadrant, which was close to the scattered point of Chizhou. As traditional tourism cities, the two cities actively develop new strategic industries based on the tertiary industry and are closely connected with each other. Wuhu was located in the third quadrant (LL) only in 2016, and in the fourth quadrant (HL) the rest of the time. The observed value of Wuhu in southern Anhui Province was relatively high. However, the adjacent city, Tongling, yielded a low observation value and has been in the third quadrant (LL) distribution during the study period. As a strong city based on industrial development, especially on the basis of the formation of four leading industries, Tongling aims to transform itself into a resource-based city in the future, but the current development level is not high.

2. The industrial spatial difference in the Wanjiang Demonstration Zone was significant, but the linkage effect of industrial ecological security between cities was weak.
There are significant differences in the level of industrial safety in different regions, and the eastern cities exhibit significantly higher development. During the study period, most cities were in the third quadrant (LL), indicating that the Wanjiang Demonstration Zone had an obvious agglomeration of cities with low levels of industrial ecological security. The Anhui Provincial Finance Department allocates at least 1 billion yuan each year for the construction of the Wanjiang District, promotes a combination of industrial transfer and technological innovation, and advocates for the same price of water and gas for the service industry in the demonstration area. However, most cities are still in an exploratory period of industrial transformation and ecological security. Lu’an is rich in ecological resources. Although the connection with the Hefei metropolitan area has been strengthened in recent years, its industrial base has been relatively weak, and its per capita GDP from 2012 to 2019 was the lowest among the nine cities. In 2019, Hefei’s tertiary industry accounted for more than 60% of its GDP, far exceeding that of other cities in the Wanjiang Demonstration Zone. This is related to Hefei’s emphasis on the development of high-tech industry. Hefei, Wuhu, Ma’anshan, Chuzhou, and the Yangtze River Delta region had higher connection strengths than the other five cities. This means that location advantages are closely related to the development of industrial ecology, and cities with insufficient regional linkages face challenges with respect to industrial upgrading and transformation.

5. Summary and conclusions

(1) Improving strategic planning for regional industrial ecosystems. According to the research results, the level of industrial ecological security in all cities has improved to varying degrees, but the aggregation and distribution level in the third quadrant of most cities is low. Among them, southern Anhui province exhibits a more optimized ecological environment, but the industrial structure is relatively single, the industrial structure lacks diversified development, and the low-level urban spatial agglomeration with industrial ecological security is obvious. Combined with other successful regional industrial development plans, the industrial system of the Wanjiang Demonstration Zone can be improved in the following three aspects (Xu 2015; Zhou et al. 2020; Yan 2020).

(1) Regional industrial bases should be developed through annual pollution prevention and control programs, industrial carbon emission control, and real-time monitoring of industrial volatile pollutants.

(2) Regional industrial ecology should incorporate the development of innovative industrial clusters and innovation systems, collect relevant innovation subjects, cultivate competitive industries, and establish a sustainable ecological system.

(3) The regional industrial ecology should focus on the construction of a high-end equipment manufacturing industry, which is weak in the current manufacturing ecosystem, and form the industrial foundation of regional
circulation and finding the breakthrough of high-quality regional development from the perspective of the supply side.

(2) A new governance pattern featuring coordinated development among regions should be developed.

According to the results, there is a positive spatial correlation within the study area, and the spatial interaction is initially strengthened and subsequently attenuated. This means that following improvement in the comprehensive strength of a city, the influence of surrounding cities is attenuated. Owing to the limited resources for urban development, this may have a backflow effect in the area. To ensure sustainable development of regional industrial transfer, the direction of regional development and overall planning should be addressed. The coordinated development among cities in the Wanjiang Demonstration Zone is inseparable from the construction of a new social governance pattern of “co-construction, co-governance, and sharing” as outlined below (Lin 2020; Gu and Zeng 2020; Rao et al. 2021).

(1) Joint construction: In-depth exchanges between regional innovation chains and industrial chains should be strengthened, in addition to building an open regional development community and promoting the coordinated development of regional industrial ecology.

(2) Co-governance: Regional governance in an open environment, the mutual penetration among government, the market, and society, and multi-level and differentiated governance to provide a platform for benign consultation among regions are crucial.

(3) Sharing: New opportunities for regional sharing reform provided by the Internet and big data are required. These can accurately display regional resources, play the linkage effect of regional sharing, and effectively promote regional resource sharing.

(3) Innovation of new business forms and models for inter-city linkage development

The results show that the industrial ecological security level of cities in the north-eastern part of the Wanjiang Demonstration Zone exceeds that of other cities. Hefei and Wuhu are the two leading core cities. In addition, Chuzhou and Ma’anshan exhibit a relatively high level of urban development, but have no significant connections, and lack interaction and cooperation in high-tech industries. Therefore, to fully understand the intercity linkage effect of the Wanjiang Demonstration Zone, it is necessary to strengthen the demonstration role of high-quality development cities in industrial transfer (Zhou and Wen 2019; Guo et al. 2021; Zeng and Hu 2021).

(1) Urban demonstration: Industries in low-carbon demonstration cities are dominated by commercial and financial services, occupying geographical and policy advantages. When implementing a carbon peak action plan, it is necessary to explore low-carbon emission reduction paths and provide many good ideas for the low-carbon transformation of other cities.

(2) Industrial demonstration: The marketization of the ecological industry should be promoted, focusing on the formulation and implementation of
industrial planning and exploring the high-quality development mode of industrial agglomeration leading the city to industrial transformation.

(3) Demonstration of scientific and technological innovation: Support for innovation capacity construction should be increased, the urban development influence of scientific and technological innovation enhanced, and the gap between high-level and low-level cities in scientific and technological innovation narrowed.

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State any potential conflicts of interest here or "The authors declare no conflict of interest".

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Data availability statement
The data used for this study could be made available on request and discussion with authors.

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