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Urban development sustainability, industrial structure adjustment, and land use efficiency in China

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ABSTRACT

It remains unclear on how industrial structure adjustment interacts with urban land use efficiency and how urbanization affects their interaction, despite its significance for urban development sustainability. We explore such interactions in China based on a panel dataset of 31 provincial administrative units from 1978 to 2018. The results show that as urbanization proceeds, the industrial structure optimization exhibits a positive linear correlation with urban land use efficiency, while the relationship between industrial structure upgrade and urban land use efficiency depends on level of urbanization, which follows an inverted U-shape. The effect of urban land use efficiency on the optimization of industrial structure is divergent across provinces. We also find that a higher level of urbanization facilitates the positive interactions between industrial structure adjustment and urban land use efficiency in the central and western regions of China, but the effect is attenuated in eastern China. We propose policy recommendations tailored to different regions with distinct levels of economic development status and industrial structure for urban development sustainability.

1. Introduction

Urbanization (URB), defined as the increase of urban areas due to human and economic activity concentration, has proven to be the economic growth engine for many countries (Ochoa, Tan, Qian, Shen, & Moreno, 2018). Urbanization, industrial structure adjustment (ISA), and urban land use efficiency (ULUE) are interrelated and can generate synergistic effect on sustained urban growth (Cobbinah, Erdiaw-Kwasie, & Amoateng, 2015; Gret-Regamey, Celio, Klein, & Hayek, 2013; Li, Zhang, Mirzaei, Zhang, & Zhao, 2018; Wang, Gao, Wang, Lin, & Li, 2022; Wang, Zhan, & Xin, 2020; Zhang et al., 2018). Over the past 40 years, China's rate of URB has exceeded the global average (Chen, Xu, Lan, & Jiang, 2020; Jiang & Meng, 2021). From 1978 to 2018, China's URB rate rose from 17.9% to 59.6%, showing a rapid development trend (Liu, 2018), and is expected to raise to 70% by 2030 (Yang, 2013). Meanwhile, China's tertiary industry output value increased from 24.6% to 53.3% in terms of total GDP from 1978 to 2018. ISA has entered relatively advanced stages of industrialization (Yi, 2013). Additionally, the development and utilization of land resources have improved the economic output of land and promoted the improvement of urban residents' living standards and well-being.

However, maintaining the long-term sustainability of URB remains a major challenge. Rapid URB has led to issues such as homogenous industrial structure across cities and low-efficiency land use (Hamidi, Ewing, Preuss, & Dodds, 2015; Liu, Li, & Du, 2018a; Qu, Gao, & Jiang, 2005; Yin, Lin, Jiang, Qiu, & Sun, 2019; Zou, Liu, Wang, & Yang, 2021), which hinders sustained urban development characterized by high density (Bryan, Gao, Ye, Sun, & Hou, 2018; Liu, Zhang, & Zhou, 2018b; Tan, Zhang, Liu, & Xu, 2021; Wu et al., 2018). Therefore, the Chinese government adopted a new development policy of 'new-type urbanization' for URB, aiming to achieve urban development sustainability by adjusting industrial structure and improving ULUE (Ning, Hu, Tang, & Zeng, 2022). Hence, it is essential to understand the interplay of these driving forces for contributing to sustained urban growth while curbing urban sprawl.

In the past decades, scholars have been striving to understand how to sustain continued URB by investigating the characteristics and mechanisms of the relationship among URB, ISA and ULUE. A large body of literature focuses on the relationship between ISA and ULUE, which mainly contain two viewpoints. One view holds that ISA can generate multiple benefits to improve ULUE. From the perspective of industrial mobility, ISA could promote elements that meet social and economic

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needs to become an important driving force to improve ULUE (Liu et al., 2021; Saavedra, Iritani, Pavan, & Ometto, 2018). From the perspective of spatial layout, the response of industrial structure in spatial relationship is land use structure (Barbier & Bergeron, 1999). ISA could strengthen technological exchange and cooperation among enterprises, improve the investment and business environment, share advanced production modes, management methods and production technologies, and promote the promotion and innovation of technologies (Wood, 2006), so as to improve the input intensity and output efficiency of urban land. From the perspective of rational industrial agglomeration, ISA could reduce the difficulty and cost of knowledge and technology transmission geographically through agglomeration effect (Krugman, 1991), and promote the horizontal or vertical sharing of information, technology and other elements through multi-level learning (Pessoa, 2014), communication and simulation (Marshall, 1981) among employees in the industry, so as to improve the economic benefits of land use. On the other hand, ISA could improve the economic efficiency of land through spatial spillover effect (Jacobs, 1999), thus attracting the agglomeration of manufacturers in the same industry, expanding spatial layout, producing scale economy, and improving ULUE (Ning, Fan, & Jian, 2016). Another view holds that the competitive effect of ISA would have a negative impact on ULUE. When the congestion effect is greater than the agglomeration effect among industries, it will hinder the sustainable development of regional economy and lead to the decrease of ULUE level (Chen, Long, Liao, Tu, & Li, 2020; Fu & Wang, 2020).

Another body of literature examines on the relationship between URB and ISA, and that between URB and ULUE. On the one hand, some scholars believe that the relationship between URB and ISA is positive. The coordinated development of URB would promote ISA towards desirable outcomes (Sulemana, Nketiah-Amponsah, Codjoe, & Andoh, 2019; Wang, 2012; Wang & Su, 2019), and ISA is the foundation of URB construction (Xiong, Zheng, & Jia, 2017). For example, developed areas with higher level of URB could promote ISA by transferring out the surplus industries, while underdeveloped areas could drive the URB development by undertaking industries from developed regions (Xu, Tian, Xie, & Zhang, 2017), and finally achieve the overall poverty alleviation goal of the region (He & Cui, 2017). On the other hand, existing research reveals that ULUE demonstrates a "U-shaped" with the development of URB (Liu, Feng, & Cao, 2014). URB is an important driving force for ULUE (Gao et al., 2019; Yang, Jiang, Zheng, Zhou, & Li, 2019). If the URB development is rational, both single-center and multi-center urban spatial structures have abilities to improve ULUE (Liu, Li, & Qin, 2017). However, only the coordinated development of URB and ULUE could promote urban development sustainability (Li et al., 2020; Luo, Zhang, & Wu, 2017).

Generally, existing research has laid a solid theoretical foundation for exploring interactions among URB, ISA, and ULUE. However, interactions between industrial structure and land use likely follow a dynamic space-time mechanism that is not only affected by changes in the land system's internal factors at a given time period, but also by the adjustment over different time periods (Zhang & Feng, 2017). Existing research primarily focuses on short-term cross-sectional assessment and single-agent analysis in a specific area of ISA and ULUE, but largely misses the spatial and temporal disparities between them, which is likely to result in biased estimation results. It is crucial to understand its reverse impact and address the resource and environmental crises (Wang, Lin, Glendinning, & Xu, 2018; Agrawal et al., 2022). However, there is a shortage of quantitative evidence on the interaction between ISA and ULUE, and the mediating effect of URB on the relationship between them.

Moreover, as the main strategy of China's new urbanization, the integration of urban agglomeration emphasizes the coordinated development among provinces and blurs the administrative boundaries between cities (Fang & Yu, 2017). Provinces are also the basic spatial unit for implementing policies such as ISA, URB development, as well as the enhancement of ULUE, which can be considered as a key governance area for realizing urban development sustainability (Wang, 2019). Therefore, we explore the relationship among URB, ISA and ULUE in China based on a panel dataset of 31 provincial administrative units from 1978 to 2018, which aims to reveal both short-term relationship among URB, ISA and ULUE, and long-term relationship between ISA and ULUE and the mediating effect of URB on their relationships. Based on the results of our analysis, we explain how to increase ULUE in China through ISA and URB. Our findings shed light on urban development strategies and the sustainable use of land resources in China and beyond.

2. Theoretical linkage

The industrial structure adjustment follows the theory of industrial structure evolution, which refers to the process of upgrading industrial structure from a preliminary to an advance level (Pipkin & Fuentes, 2017; Yang et al., 2019), as well as improving the utilization efficiency of production factors and gradually optimizing the allocation of industries (Zhou, 2014). Industrial structure upgrade refers to the process of the continuous improvement of industrial development level and industrial structure. Industrial structure optimization refers to the degree of effective utilization of resources and optimal allocation of industries. Accordingly, we use industrial structure upgrade and industrial structure optimization to represent the process of ISA. ULUE is based on the theory of factor input-output and refers to the maximization degree of land use (Li, Hu, Kuang, & Chen, 2017). Accordingly, ULUE is the result of the combined effect of land input and output.

2.1. The relationship between ISA and ULUE

Based on the above analysis and theoretical research on the relationship among URB, ISA, and ULUE (Tang, Li, Hu, & Wu, 2020; Tang, Liu, & Ma, 2017), we propose the evolutionary relationship between ISA and ULUE during the process of URB in China (Fig. 1). With the improvement of URB, the relationship curve between industrial structure upgrade and ULUE is shown as reciprocal U-shaped (solid line in Fig. 1), while the relationship curve between industrial structure optimization and ULUE generally increases and eventually tends to be stable (dotted line in Fig. 1).

2.1.1. Industrial structure upgrade and ULUE

When URB is at a preliminary stage (stage I in Fig. 1), the development of industrialization has just started, and the primary industry occupies an absolute advantage while the level of ULUE is at a low level. However, as URB continues to develop into the middle stage (stage II in Fig. 1), the improvement of ULUE mainly depends on the intensity of urban land input and output efficiency. Furthermore, when the level of

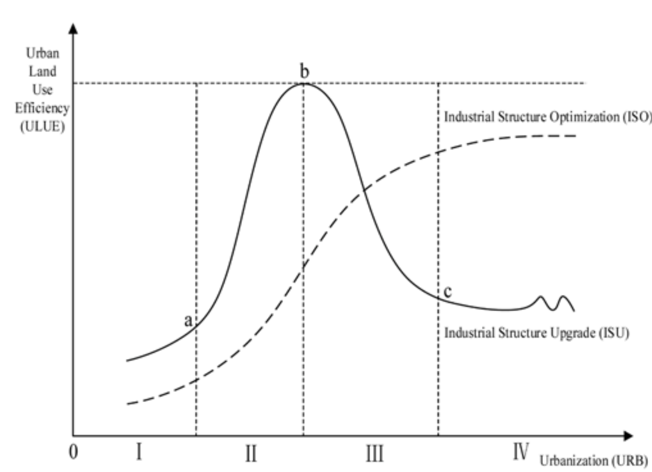

Fig. 1. The relationship between ISA and ULUE during the process of URB.

URB reaches the critical point b, it is in the advanced stage of development (stage III in Fig. 1). According to the theory of diminishing land returns (Zhao, Huang, Chen, & Chen, 2010), when the competition between industries becomes increasingly prominent, industrial structure upgrade will make the crowding effect greater than the agglomeration effect. Then land use will produce less desired output, which will gradually reduce the level of ULUE (Chen et al., 2020; Fu & Wang, 2020). However, when the level of URB reaches the critical point c, it is in the mature stage of development (stage IV in Fig. 1). After the equilibrium point c, the states of ULUE may show three trends - up, down, or balanced trend, which depends on the governance level of green technology on undesirable outputs of ULUE.

2.1.2. Industrial structure optimization and ULUE

When the level of URB is at a preliminary stage (stage I in Fig. 1), the agricultural sector is dominant, and the utilization rate of resources is low. At this stage, the optimization force of industrial structure is insufficient, and the growth rate of ULUE is slow. When the level of URB is in the middle stage of development (stage II in Fig. 1), the rural surplus labor force gradually moves to the light industry and service industry. The proportion of light and heavy industries shifts gradually while the efficiency of land use input-output is rising rapidly (Shu, Xie, Jiang, & Chen, 2018). At this stage, the growth rate of ULUE is faster than the growth rate of industrial structure optimization. When the level of URB is in the advanced stage of development (stage III in Fig. 1), and the transferable labor force has been absorbed by the secondary and tertiary industries, and the level of ULUE has reached a certain height. At this stage, the improvement of ULUE has higher requirements on production factors and environment (Xie, Chen, Lu, Wu, & Wang, 2018), and the growth rate of ULUE begins to decline. Eventually, with the level of URB reaching the mature stage (stage IV in Fig. 1), the relationship curve between industrial structure optimization and ULUE tends to stabilize.

2.2. The effect of URB on the relationship between ISA and ULUE

The relationship between ISA and ULUE follows the theory of industrial agglomeration (Marshall, 1981) and the theory of differential rent (Wang, 2007). The theory of industrial agglomeration suggests that the upgrading and agglomeration of production factors such as land, capital and labor can promote ULUE (Li et al., 2020). The theory of differential rent indicates that the higher ULUE, the higher the requirement for industrial profit, which makes the industry with strong profitability replace backward enterprises and promotes ISA in the direction of industrial structure upgrade and industrial structure optimization. Based on existing theories, we propose the relationship among URB, ISA, and ULUE below (Fig. 2).

Urbanization development is the main driving force for the interaction between ISA and ULUE. The relationship between URB and ISA follows the theory of dualistic economic structure, and the relationship between URB and ULUE follows the theory of man-land relationship. The realization path of the effect of URB on the relationship between ISA and ULUE includes social form, economic form, and ecological environment form. Social development provides talents and consumer groups for industrial development, and influences the ULUE through channels such as real estate demand, technological progress and information services (Long, Li, Liu, Woods, & Zou, 2012). Economic development is the most active part in promoting ISA and the improvement of ULUE (Long et al., 2015). Regions with a higher level of economic development can attract the agglomeration of high-tech industries by virtue of their superior resource conditions and good R&D capabilities, thereby affecting the state of regional industrial structure and the efficiency of land use (Rahman & Szabó, 2021). The development of ecological environment emphasizes the optimal allocation of resources in the limited land space and the coordination between the demand for urban land and the unexpected output of land use.

Therefore, the development of URB can lead to the transfer of labor, land, and capital, which will affect the level of industrial structure upgrade, industrial structure optimization, and ULUE in the short term (Zhao et al., 2021). And according to the above theory of industrial agglomeration and the theory of differential rent, the development of URB will influence the relationship between ISA and ULUE in the long term.

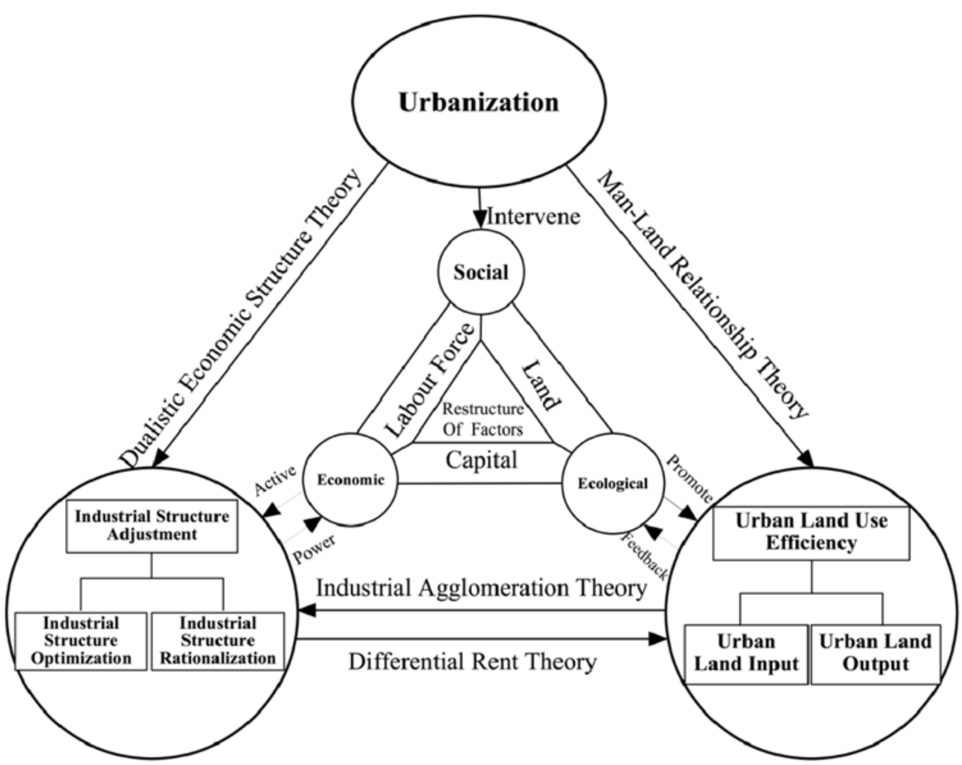

Fig. 2. The relationship among URB, ISA, and ULUE.

3. Methods

3.1. Variables

3.1.1. Measuring ISA

According to the principle that service-oriented economic structure is an important feature of industrial structure upgrade in China, industrial structure upgrade is reflected in the degree of transformation from capital-intensive industries to knowledge-intensive industries. Therefore, the study uses the ratio of the added value of the tertiary industry to that of the secondary industry to measure industrial structure upgrade. The equation is the following:

$$ISU = TI/SI \tag{1}$$

where *ISU* represents the industrial structure upgrade, *TI* represents the added value of the tertiary industry, *SI* represents the added value of the secondary industry. The higher the *ISU* value is, the higher the upgrading level of industrial structure is.

The industrial structure optimization refers to the degree of coordination between the quantity and proportion of industrial elements (labor and capital). Therefore, the study uses the reciprocal of the Theil index modified by Gan et al. (Gan, Zheng, & Yu, 2011) to measure industrial structure optimization. When the economic system is in equilibrium, all industries have the same labor productivity, that is, $Y_i/L_i=Y/L$, and TL is 0. The equation is the following:

$$ISO = 1/TL = 1/\left[\sum_{i=1}^{N}\frac{Y_i}{Y}\ln\left(\frac{Y_i}{L_i}/\frac{Y}{L}\right)\right](i=1,2,3) \tag{2}$$

where *ISO* represents the industrial structure optimization, *TL* represents the Theil index. Y is the GDP of the regional, Y_i is the added value of industry i, L is the total employment of the regional, L_i is the employment of industry i. The higher the *ISO* value is, the higher the optimization level of industrial structure is.

3.1.2. Measuring ULUE

The urban land use efficiency refers to the ratio of input system to integration of economic, social and ecological outputs. Therefore, the study uses the Slacks-Based Measure (SBM)-Undesirable model (Tone, 2001; Yu & Shen, 2020) to measure ULUE. It contains production inputs, expected outputs, and undesirable outputs (Barletti, Larson, Hewlett, & Delgado, 2020) (Table 1). Suppose there are n land use system decision-making units (DMU), each DMU contains an input variable $x \in R^m$, a desired output variable $y^e \in R^a$, and an undesirable output variable $y^u \in R^b$. The matrix X, Y^e, Y^u could be formed as follows:

Table 1
Evaluation index system of ULUE.

Index categories	Factors	Indexes
Input	Capital	Total amount of social fixed asset investment (100 million RMB)
	Land	Built-up area (km^2)
	Labor force	Employees in the secondary and tertiary industries (ten thousand people)
Expected output	Environment	Green space area (km^2)
	Economy	Added value of the secondary and tertiary industries (100 million RMB)
	Society	Average wage of employees (RMB)
Undesirable output	Environmental pollution	Total amount of waste (Ton)
		Total amount of sulfur dioxide in the exhaust gas (Ton)

$$\begin{cases} X = [x_1, x_2, \cdots, x_n] \in R^{m\times n} & X \geq 0 \\ Y^e = \left[y_1^e, y_2^e, \cdots, y_n^e\right] \in R^{a\times n} & Y^e \geq 0 \\ Y^u = \left[y_1^u, y_2^u, \cdots, y_n^u\right] \in R^{b\times n} & Y^u \geq 0 \end{cases} \tag{3}$$

where m, a and b represent production input factors, expected output factors and undesirable output factors, respectively. The production possibility set P could be formed as follows:

$$P = \left\{(x, y^e, y^u)|x \geq X\lambda, y^e \leq Y^e\lambda, y^u \geq Y^u\lambda, \lambda \geq 0 or \sum\lambda = 1\right\} \tag{4}$$

Based on the above description, SBM-Undesirable model could be formulated as follows:

$$LUE = \min\frac{1-\frac{1}{m}\sum_{i=1}^{m}\frac{Q_i^-}{x_{i0}}}{1+\frac{1}{a+b}\left(\sum_{l=1}^{a}\frac{Q_l^e}{y_{l0}^e}+\sum_{h=1}^{b}\frac{Q_h^u}{y_{h0}^u}\right)}$$

$$s.t.\begin{cases} X_0 = X\lambda + S^-; y_0^e = Y^e\lambda - S^e; y_0^u = Y^u\lambda + S^u \\ S^- \geq 0, S^e \geq 0, S^u \geq 0, \lambda \geq 0 \end{cases} \tag{5}$$

where Q^-, Q^e, Q^u represent the slack of input, expected output and undesirable output respectively, λ is the weight vector, ULUE is the value of the objective function and strictly monotonically decreasing, 0 ≤ULUE ≤ 1. The higher the value of ULUE, the higher the level of urban land use efficiency.

Land, capital, and labor force are the most basic production input factors of economic activities, which are very important to the development of urban land economy (Wang, 2019). Therefore, the input indexes of urban resources are the built-up area, the total amount of social fixed asset investment, and the number of employees in the secondary and tertiary industries. Furthermore, in the production process of urban land economy, not only expected products are produced, but also undesirable products are produced.

The expected output indexes are selected to represent the environmental, economic, and social ULUE, including the green space area, the added value of the secondary and tertiary industries, and the average wage of employees. The index of the green space area can reflect the importance of ecological land in the process of urban land use, and the higher the value of this index, the more attention paid to the protection of ecological environment in the process of urban land use, the higher the ecological environmental benefits generated by land use. The index of the added value of the secondary and tertiary industries can reflect the economic output of urban land use, and the higher the value of this index, the higher the expected economic output of urban land use. The index of the average wage of employees can reflect the impact of urban land use on people's life and social development, and the higher the value of this index, the higher the expected social output of urban land use. The total amount of sulfur dioxide in the exhaust gas and total amount of waste water, which are not conducive to the sustainable development of the city, are selected as the undesirable output indexes. From the perspective of the impact of ISA on ULUE, sulfur dioxide in the waste gas produced by secondary and tertiary industries can reflect the undesirable output of air pollution in the process of urban land use (Hu, Li, & K, 2018; Wang, Li, & Shi, 2015; Zhu, Zhang, Wei, Li, & Zhao, 2019). Combined with the Chinese government work report and the key points of water pollution control, the total amount of waste water can reflect the undesirable output of water pollution in the process of urban land use (Huang, Yang, Cheng, & Wang, 2015; Zhu et al., 2019).

3.1.3. Measuring URB

The urbanization refers to the process of spatial migration of rural population to urban areas. This study discusses the relationship between industrial structure and URB and the change of land use efficiency caused by man-land relationship from the perspective of the transfer of agricultural surplus labor force (Lewis, 1954; Ranis & Fei, 1961). Therefore, URB is measured by the proportion of the population with local residence status and the population living in cities for more than six months of the year to the total population (Qin & Zhang, 2014; Wu, He, Chu, & Yan, 2018). The equation is the following:

$$\text{URB} = \text{RP}/\text{TP} \tag{6}$$

Where URB represents the urbanization, RP represents the population with local residence status and the population living in cities for more than six months of the year, TP represents the total population.

3.2. PVAR and VAR Models

The short-term relationship at national level among industrial structure upgrade, industrial structure optimization, and ULUE were estimated by Panel data Vector Auto Regression (PVAR) model based on the panel data of 31 provinces in China from 1978 to 2018. The equation is the following:

$$y_{it} = a_{0t} + \sum_{j=1}^{k} a_{jt} y_{it-j} + f_i + d_{c,t} + \varepsilon_{it} \tag{7}$$

where, y_{it} is a column vector containing three endogenous variables, namely, industrial structure upgrade, industrial structure optimization, and ULUE. i is study area, t is year, k is the lag order, f_i is an unobservable individual fixed effect, $d_{c,t}$ is the time fixed effect vector, a_{0t} is the intercept vector, a_{jt} is a parameter matrix of lag j order. In order to ensure the accuracy of the results, Helmert method and Mean-differencing method are used to eliminate the individual fixed effect item f_i and time fixed effect item $d_{c,t}$. The lagged terms of each variable are used as instrumental variables to solve the endogenous problem.

PVAR model can only obtain the influence relationship between ISA and ULUE at national level, which cannot reflect the differences among provinces. Moreover, studying the long-term influence relationship can more accurately reflect inter-provincial differences. So, the study uses VAR to construct 31 models for each province to obtain the results of the long-term influence relationship between ISA and ULUE at provincial level based on the time series data of 31 provinces from 1978 to 2018. The equation is the following:

$$y_t = A_1 y_{t-1} + \ldots + A_k y_{t-k} + Bx_t + \varepsilon_t \tag{8}$$

where, y_t is an endogenous variable, including industrial structure upgrade, industrial structure optimization, and ULUE. x_t is exogenous variables, k is the lag order, A_1, A_2, …, A_k and B are the coefficient matrices to be estimated, ε_t is the disturbance vector.

URB is used as an exogenous variable into the PVAR and VAR models to discuss the long-term impact at provincial level and short-term response trend at national level of URB on the relationship between ISA and ULUE, respectively.

The logarithm of the variables is adopted for eliminating any potential heteroscedasticity. The Levin, Lin and Chu (LLC) (Levin, Lin, & Chu, 2002) and Augmented Dickey-Fuller (ADF) (Nelson & Plosser, 1982) methods are used to carry out the unit root test of variables. The lag order corresponding to the minimum value is selected as the optimal according to the AIC, BIC and HQIC criteria. The stability of PVAR model is tested by eigenvalue test method. The stability of PVAR model is tested by residual normal distribution test, residual sequence relationship test, eigenvalue test and Wald test for the joint significance of all order coefficients.

3.3. Data

The study explored the relationship among URB, ISA, and ULUE based on the panel data of 31 provinces in China from 1978 to 2018. Any missing data was supplemented by trend extrapolation by considering the threshold value obtained by Z standardization (Zhuo & Wang, 2018).

The indexes for measuring ISA include the GDP, the added value of primary, secondary, and tertiary industries, the total employment, and the employment of primary, secondary, and tertiary industries. The data of these indexes were collected from the Statistical Yearbook of 31 Provinces (1979–2019) and China Population and Employment Statistic Yearbook (1988–2019).

The indexes for measuring ULUE include three aspects: environment, economy, and society. The indexes of environmental ULUE include the built-up area, the green space area, the total amount of sulfur dioxide in the exhaust gas, and the total amount of waste water, and the data of these indexes were collected from the China Urban Construction Statistical Yearbook (1979–2019) and the Statistical Yearbook of 31 Provinces (1979–2019). The indexes of economic ULUE include the total amount of social fixed asset investment, and the added value of the secondary and tertiary industries, and the data of these indexes were collected from the China Statistical Yearbook (1982–2019) and the Statistical Yearbook of 31 Provinces (1979–2019). The indexes of social ULUE include the average wage of employees, and the numbers of employees in the secondary and tertiary industries, and the data of these indexes were retrieved from the China Population and Employment Statistic Yearbook (1988–2019) and the Statistical Yearbook of 31 Provinces (1979–2019).

The indexes for measuring URB include the population with local residential status, the population living in cities for more than six months of the year, and the total population, and the data of these indexes were collected from the China Population and Employment Statistic Yearbook (1988–2019) and the Compilation of statistical data for 60 years of new China (1949–2008).

4. Results

4.1. Spatial-temporal pattern

Our analysis focuses on four critical years: 1978 (the primary stage of industrialization and urbanization), 1993 (the accelerating stage of industrialization and primary stage of urbanization), 2008 (the decelerating stage of industrialization and accelerating stage of urbanization), and 2018 (the decelerating stage of industrialization and urbanization).

The temporal characteristics of industrial structure upgrade, industrial structure optimization, and ULUE during the process of URB in China from 1978 to 2018 are shown in Fig. 3. The level of industrial structure upgrade, industrial structure optimization, and ULUE were rising from 1978 to 2018. The peaks of the kernel density curves indicated that the provincial variations in industrial structure upgrade and industrial structure optimization were gradually decreasing from 1978 to 2018, while the provincial variations in ULUE in 2018 were larger than those in 1978 but showed a decreasing trend.

The spatial differentiation characteristics of industrial structure upgrade, industrial structure optimization, and ULUE during the process of URB in China from 1978 to 2018 are shown in Fig. 4. The spatial distribution of industrial structure upgrade, industrial structure optimization, and ULUE showed a relatively dispersed pattern, and most areas demonstrated a medium-low or low-level of agglomeration in 1978 and 1993 (the primary stage of URB). The spatial distribution of industrial structure upgrade, industrial structure optimization, and ULUE gradually showed a stratified clustering pattern in 2008 and 2018 (the accelerating and decelerating stage of URB). The high-level industrial structure upgrade was mainly concentrated in the east and west, while the level of industrial structure optimization and ULUE showed a gradually decreasing distribution feature from east to west in 2018.

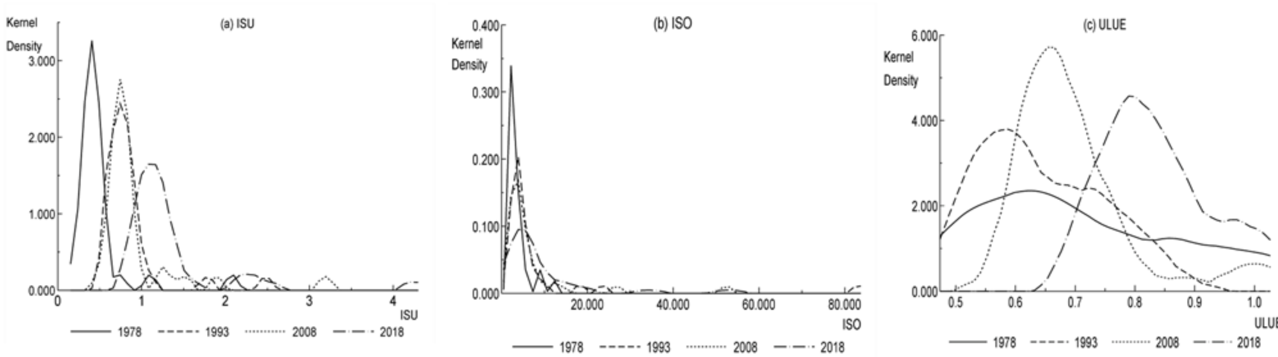

Fig. 3. The temporal evolution of industrial structure upgrade (ISU), industrial structure optimization (ISO), and ULUE in China from 1978 to 2018.

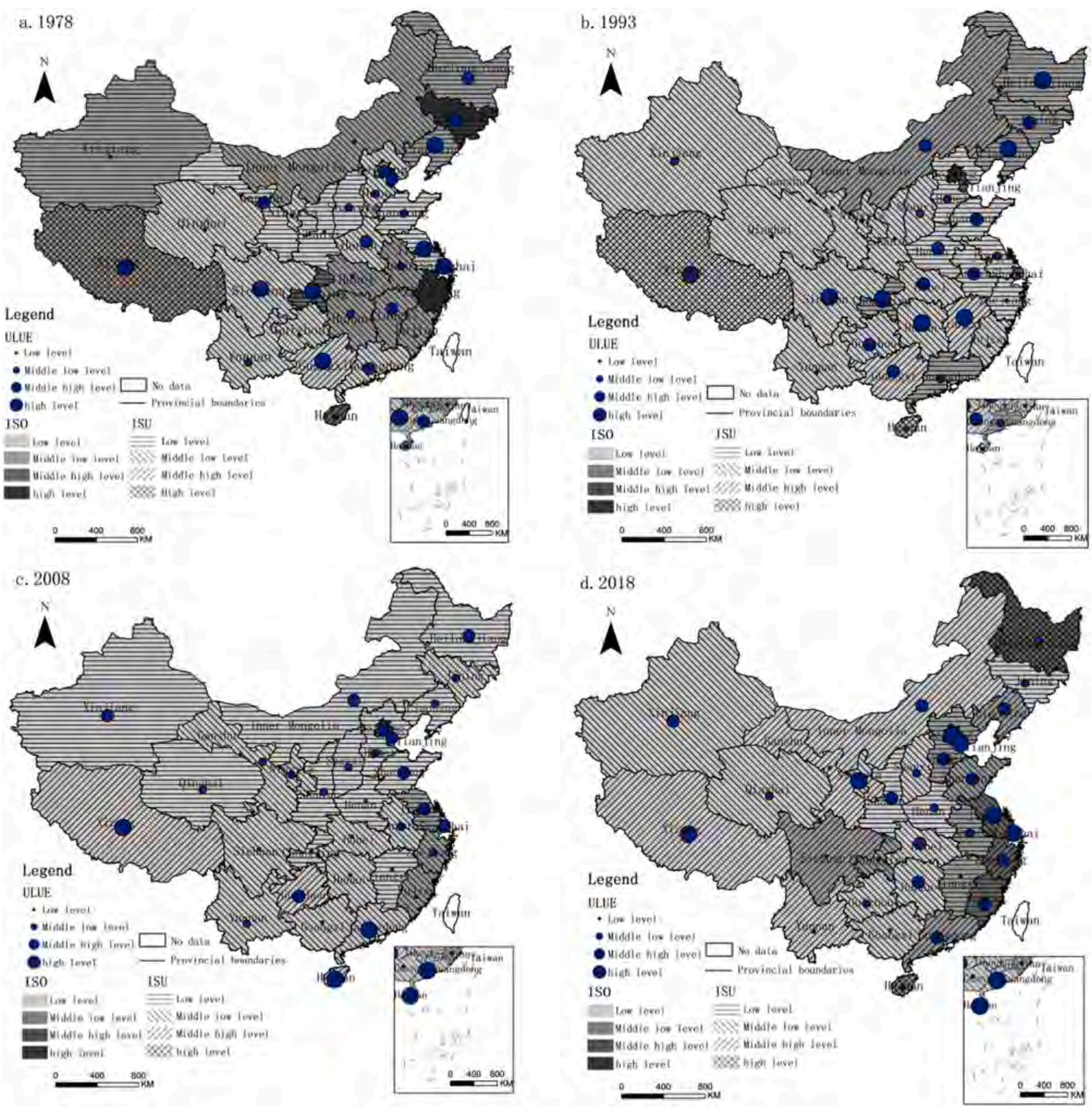

Fig. 4. Spatial differentiation of industrial structure upgrade (ISU), industrial structure optimization (ISO), and ULUE in 31 provinces of China from 1978 to 2018.

4.2. PVAR and VAR model results

The long-term and short-term of relationships between ISA and ULUE were estimated by PVAR at national level and VAR models at provincial level, respectively. The unit root test results showed that the three index sequences of industrial structure upgrade, industrial structure optimization, and ULUE all reject the null hypothesis at the significance level of 1%, that is, they are all stationary sequences, which can be used for model estimation. The optimal lag order selection results showed that the lag orders k of PVAR model and VAR models of 31 provinces are selected as 1–4. The stability test results showed that the PVAR model and VAR models were stable and could be used to analyze the relationship among variables and obtain accurate results.

4.3. Short term relationship among ISA, ULUE, and URB

4.3.1. Between ISA and ULUE

PVAR model was used to generate the impulse response function graph based on 500 Monte-Carlo simulations. Among them, the abscissa is the number of lag periods, the ordinate is the degree of impulse response, and 5% and 95% quantile lines are added on both sides of the impulse response curve.

4.3.1.1. The association between ISA and ULUE. When industrial structure upgrade and industrial structure optimization increase by a standard deviation unit, ULUE demonstrates a gradually increasing positive effect and reaches the maximum value in the first lag period, then converges to 0 (Fig. 5). It indicates that the increase in industrial structure upgrade and industrial structure optimization would promote the level of ULUE in the short term, which is consistent with the relationship between ISA and ULUE shown in Fig. 2. ISA can further optimize the allocation of urban land resources by increasing the share of high-service industries in the economic structure (He & Peng, 2017), resulting in industrial agglomeration and economic externalities, and leading to the improvement of ULUE (Gao et al., 2021). In addition, the impulse response degree of ULUE to industrial structure upgrade is higher than that of ULUE to industrial structure optimization in the first lag period (Fig. 5), indicating that the positive effect of industrial structure upgrade on ULUE is higher than that of industrial structure optimization on ULUE in the short term.

4.3.1.2. The association between ULUE and ISA. When ULUE increases by a standard deviation unit, industrial structure upgrade demonstrates a positive effect of gradually decreasing and finally approaching 0 (Fig. 6a). It indicates that the increase in ULUE would improve the industrial structure upgrade in the short term, which is consistent with the relationship between industrial structure upgrade and ULUE shown in Fig. 2. When ULUE increases by a standard deviation unit, industrial structure optimization demonstrates a gradually increasing negative effect and reaches the maximum value in the first phase, then converges to 0 (Fig. 6b). It indicates that the increase in ULUE would reduce the industrial structure optimization in the short term. The reason may be that the poorly designed land use structure hinders the optimization of industrial structure (Jian, Xu, Li, & Huang, 2020)..

4.3.2. The association between URB and ISA

When URB increases by one standard deviation unit, industrial structure upgrade and industrial structure optimization demonstrate positive effects in the first lag period (Fig. 7). It indicates that the increase in URB could improve the industrial structure upgrade and industrial structure optimization in the short term, which is consistent with the relationship between URB and ISA in stage I and II as shown in Fig. 1. The development of URB can provide relevant technologies and talents for knowledge-intensive industries, thus promoting the level of industrial structure upgrade and industrial structure optimization.

4.3.3. The association between URB and ULUE

When URB increases by one standard deviation unit, ULUE demonstrates positive effects (Fig. 8). It indicates that the increase in URB would improve the ULUE in the short term, which is consistent with the relationship between URB and ULUE in stage I and II as shown in Fig. 1. The development of URB would promote the spatial agglomeration effect of various production factors, thus promoting the level of ULUE.

4.4. Long-term relationship between ISA and ULUE

In order to further study the relationship between ISA and ULUE, this paper applies the VAR models to reveal its long-term influence relationship at provincial level.

4.4.1. The influence of ISA on ULUE

The provinces with significant positive effect of industrial structure upgrade on ULUE include Shanghai, Hebei, Jiangsu, Shandong, Guangdong in the east, Shanxi, Jilin in the central region, Guizhou, Tibet, Shaanxi, and Gansu in the west, indicating that these provinces are in stage I and II as shown in Fig. 1. The provinces with significant negative effect of industrial structure upgrade on ULUE include Beijing, Tianjin in the east, Yunnan, Qinghai in the west, indicating that these provinces are in stage III as shown in Fig. 1.

The influence of industrial structure optimization on ULUE is positive (Table 2), confirming the relationship between industrial structure optimization and ULUE in Fig. 1. And the provinces that pass the significance test are mainly concentrated in the east (accounting for 50%), suggesting that the positive effect of industrial structure optimization on ULUE is stronger in eastern China (including Beijing, Tianjin, Zhejiang,

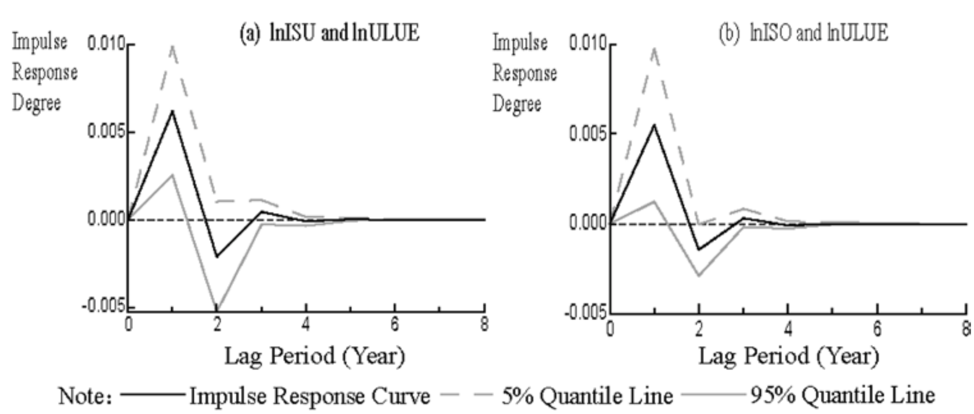

Fig. 5. The association between ISA and ULUE
Note: ISU represents the industrial structure upgrade. ISO represents the industrial structure optimization.

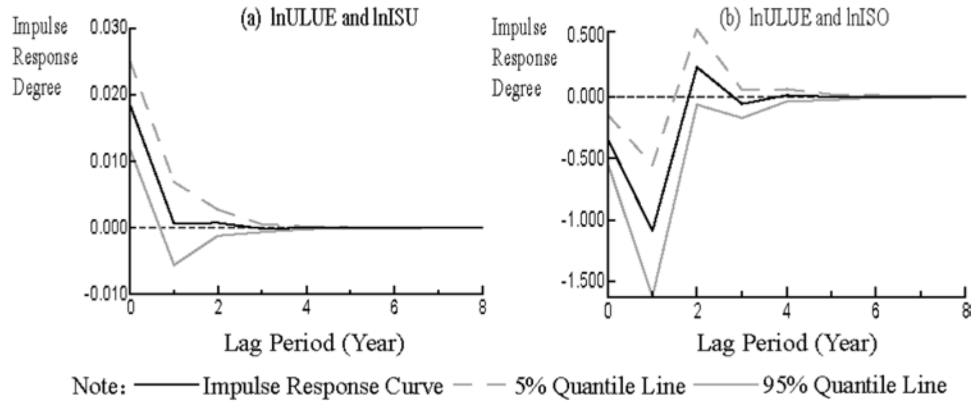

Fig. 6. The association between ULUE and ISA
Note: ISU represents the industrial structure upgrade. ISO represents the industrial structure optimization.

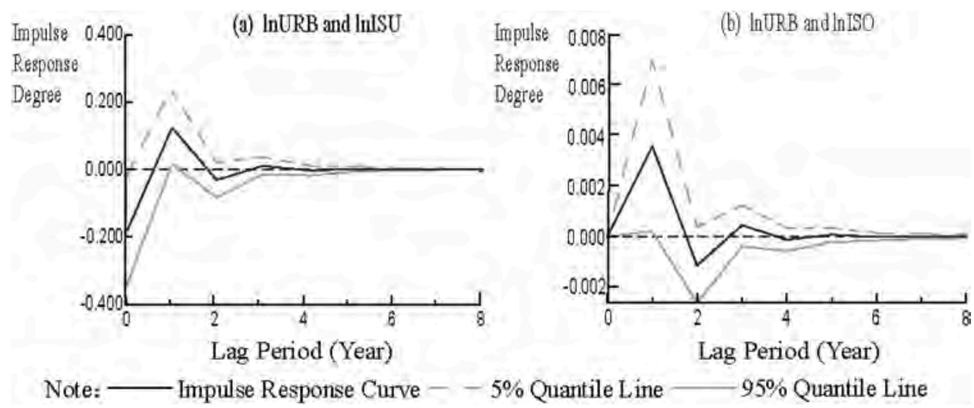

Fig. 7. The association between URB and ISA
Note: ISU represents the industrial structure upgrade. ISO represents the industrial structure optimization.

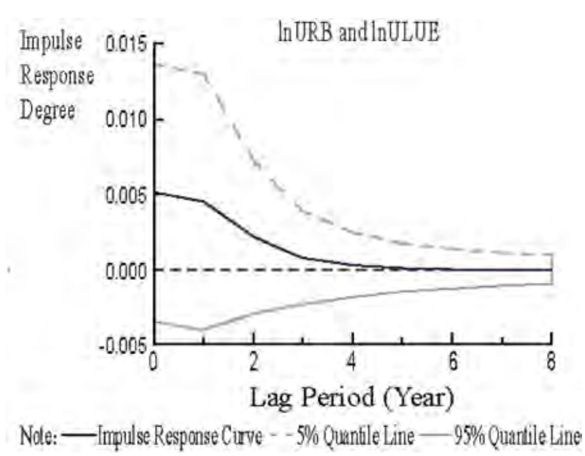

Fig. 8. The association between URB and ULUE.

Fujian and Shandong).

4.4.2. *The influence of ULUE on ISA*

The provinces with significant positive effect of ULUE on industrial structure upgrade include Jiangsu, Zhejiang, Shandong in the east, Shanxi, Jiangxi, Henan, Hubei in the central region, Gansu in the west, while the provinces with significant negative effect are Fujian, Jilin, and Heilongjiang (Table 1).

The influence of ULUE on industrial structure optimization can be either positive or negative (Table 2). The provinces with significant positive effect are mainly concentrated in the east (accounting for 50%), while the provinces with significant negative effect are mainly concentrated in the west (accounting for 70%). It also shows that the influence direction (positive or negative) of ULUE on ISA is different among provinces. In general, the positive effect is mainly concentrated in the east, while the negative effect is mainly concentrated in the central and western regions.

4.5. *The mediating effect of URB on the long-term relationship between ISA and ULUE*

4.5.1. *URB mediating the influence of ISA on ULUE*

The results of the mediating effect of URB on the long-term relationships between ISA and ULUE at provincial level by adding URB as exogenous variable into VAR models in China are shown in Table 3. Comparison between Table 2 and Table 3 suggests that the number of provinces with significant positive effect of industrial structure upgrade on ULUE has increased in the central region (+ Anhui and Jiangxi) and western region (+ Guangxi and Ningxia), and the number of provinces with significant negative effect of that increased only in the east (+ Hebei, Zhejiang, and Shandong) after adding URB as exogenous variable into VAR models.

The number of provinces with significant positive effect of industrial structure optimization on ULUE has increased in the central region (+ Hubei and Jilin) and western region (+ Chongqing, Sichuan, and Ningxia) after adding URB as exogenous variable into VAR models. Therefore, the advancement of URB has partially mediating effect on the long-term relationships between ISA and ULUE, enhancing the positive effect and accelerating the negative effect, which is consistent with the

Table 2
Estimation results of the long term relationships between ISA and ULUE by VAR models.

	LnISU → LnULUE	LnISO → LnULUE	LnULUE → LnISU	LnULUE → LnISO		LnISU → LnULUE	LnISO → LnULUE	LnULUE → LnISU	LnULUE → LnISO
Beijing	-0.453**	0.117***	-0.123	-1.150*	Hunan	0.176	0.053	0.196	0.176
Tianjin	-0.357***	0.116*	-0.085	-0.103	Inner Mongolia	0.110	-0.026	0.029	-0.671**
Shanghai	0.042*	0.002	0.026	0.117	Jilin	0.218***	0.035	-0.458**	1.853***
Hebei	0.251**	0.002	0.220	-0.671***	Heilongjiang	-0.011	0.084***	-0.869***	-0.517
Jiangsu	0.311*	0.093	0.422**	1.376***	Chongqing	0.005	0.063	0.189	0.653*
Zhejiang	0.022	0.264***	0.179*	-0.527	Guangxi	0.090	0.102	0.042	-0.770**
Fujian	-0.128	0.336***	-0.404***	0.367*	Sichuan	-0.011	-0.044	-0.208	-0.524***
Shandong	0.178*	0.154*	0.282*	0.448*	Guizhou	0.110*	-0.011	-0.043	0.546**
Guangdong	0.454**	0.030	0.031	0.327*	Yunnan	-0.219***	0.181**	0.264	0.548*
Hainan	-0.062	0.086	0.079	0.181	Xizang	0.116**	0.007	-0.336	-1.255***
Liaoning	0.022	0.075**	0.083	0.031	Shaanxi	0.523***	0.120*	0.089	-0.864**
Shanxi	0.176*	0.125**	0.143*	0.400	Gansu	0.056*	-0.044	0.521***	-0.505*
Anhui	0.363	0.309**	0.165	0.211	Qinghai	-0.068*	-0.006	0.099	0.008
Jiangxi	0.038	0.051	0.306**	0.486	Ningxia	0.034	0.042	0.270	-0.984*
Henan	0.039	0.088**	0.206*	0.153	Xinjiang	0.080	0.039	0.011	-0.964**
Hubei	0.029	0.041	0.188***	0.179					

Note: ISU represents the industrial structure upgrade. ISO represents the industrial structure optimization. A→B represents the influence of A variable on B variable. *, **, and *** indicate significant at the levels of 10%, 5%, and 1%, respectively.

Table 3
Estimation of the mediating effect of URB on the long-term relationships between ISA and ULUE by adding URB as exogenous variable into VAR models.

	LnISU → LnULUE	LnISO → LnULUE	LnULUE → LnISU	LnULUE → LnISO		LnISU → LnULUE	LnISO → LnULUE	LnULUE → LnISU	LnULUE → LnISO
Beijign	-0.545***	0.099***	-0.150	-2.091***	Hunan	0.075	0.057	0.153	0.236
Tianjin	-0.501***	0.112*	-0.102	-0.133	Inner Mongolia	0.006	-0.004	0.021	0.237
Shanghai	0.040	0.002	0.048	-0.028	Jilin	0.326***	0.048*	-0.102	1.849***
Hebei	-0.260***	0.046	0.230	-0.755***	Heilongjiang	0.005	0.088***	-0.761**	0.001
Jiangsu	0.307*	0.022	0.416**	1.343***	Chongqing	-0.121***	0.077***	0.200	0.189
Zhejiang	-0.342*	0.172***	0.124***	-1.408***	Guangxi	0.172*	0.095	0.119	-0.082
Fujian	0.020	0.349***	0.366***	0.377**	Sichuan	-0.070	0.365***	-0.191	-0.504**
Shandong	-0.427***	0.161*	0.296*	-0.812***	Guizhou	0.196*	0.012	-0.036	0.375
Guangdong	0.375**	0.186	-0.002	0.324*	Yunnan	-0.150**	0.192*	0.080	0.757***
Hainan	-0.127	0.049	0.069	0.394**	Tibet	0.119**	-0.199	-0.506	1.279***
Liaoning	0.041	0.130***	0.525**	-0.012	Shaanxi	0.757***	0.123*	0.114	-0.814*
Shanxi	0.182**	0.136	0.259*	0.400	Gansu	0.248***	0.017	0.402**	-0.454
Anhui	0.414*	0.364***	0.329*	0.571*	Qinghai	-0.110***	0.014	0.105	-0.063
Jiangxi	0.358**	0.029	0.405*	0.269	Ningxia	0.132*	0.121***	0.652**	-0.789*
Henan	-0.168*	0.167**	0.167	-0.063	Xinjiang	-0.046	0.005	0.089	0.061
Hubei	-0.225	0.413***	0.202**	0.117					

Note: ISU represents the industrial structure upgrade. ISO represents the industrial structure optimization. A→B represents the influence of A variable on B variable. *, **, and *** indicate significant at the levels of 10%, 5%, and 1%, respectively.

effect of URB on the relationship between ISA and ULUE shown in Fig. 2.

4.5.2. URB mediating the influence of ULUE on ISA

Comparing Table 2 and Table 3, the provinces with significant positive effect of ULUE on industrial structure upgrade added Fujian and Liaoning in the east, Anhui and Henan in the central region and Ningxia in the west after adding URB as exogenous variable into VAR models. The proportion of provinces with significant negative impact of ULUE on industrial structure optimization decreased to 22.58% (Inner Mongolia, Guangxi, Tibet, Gansu, and Xinjiang were eliminated) after adding the exogenous variable URB into VAR models. Such results show that although the impact of ULUE on ISA in some provinces is negative at the present stage, the mediating effect of URB could change the impact of ULUE on ISA from negative to positive. In a word, URB can strengthen the function of land and the integration and upgrading of industrial elements, so as to improve the positive impact of ULUE on ISA, which is consistent with the effect of URB on the relationship between ISA and ULUE shown in Fig. 2.

5. Discussion

The research on the relationship among URB, ISA, and ULUE has become a focus of recent academic inquiry on urban development sustainability. Our study constructs a conceptual analysis framework of the relationship among URB, ISA, and ULUE, and reveals the interaction mechanism among them using the VAR and PVAR models based on the panel data of 31 provinces in China from 1978 to 2018. Our findings shed policy implications on the choice of URB development mode, industrial structure, and land use structure across different provinces, and contribute to the realization of urban development sustainability in China.

Our study constructs the conceptual model and analysis framework of the relationship among URB, ISA, and ULUE based on the industrial agglomeration theory, differential rent theory, and diminishing land returns theory. We distinguish ISA into two dimensions: industrial structure upgrade and industrial structure optimization, which is different from the traditional definition and reflects the dynamic characteristics of ISA. The relationship between industrial structure upgrade and ULUE presents an inverted U-shaped, and the relationship between industrial structure optimization and ULUE is generally increases. On the one hand, URB development can improve ULUE by upgrading of industrial structure and integrating land resources (Wu, Wei, Huang, & Chen, 2017). On the other hand, it is considered that over-emphasizing the rapid development of URB and promoting industrial structure upgrade, while ignoring the effect of regional resource allocation and compromising the degree of industry-employment coordination, will have a negative impact on the improvement of ULUE (Zhou, Chen, Tang, & Mei, 2021). Therefore, coordinated development among URB, ISA and ULUE can better contribute to promoting urban development sustainability.

In terms of the influence of ISA on ULUE, our results concur with those from a number of past studies that ISA would lead to the improvement of ULUE (Wang et al., 2018). However, our results also show that industrial structure upgrade would lead to the inefficiency of land use in some cases. Industrial structure upgrade could previously inhibit ULUE in the early stage of URB development because of high-cost, high-consumption, and low-efficiency industries exited the market. Over-development of industrial structure upgrade would prone to crowding out effect in the advanced stage of URB development, which would ultimately not conducive to the improvement of ULUE. In terms of the influence of ULUE on ISA, it has been suggested that the improvement of ULUE would promote ISA (He & Peng, 2017; Koroso, Lengoiboni, & Zevenbergen, 2021), but this is not necessarily the case. The poor industry policy and GDP-oriented administrative assessment would inevitably lead to blind waste of investments in ULUE and unbalanced industrial structure (Liu, Yang, & Li, 2013). When the improvement of ULUE comes from the dependence on low-end industries and loses the motivation of independent research and development, it is not conducive to promote ISA.

In terms of the mediating effect of URB on the relationship between ISA and ULUE, we also find that a higher level of urbanization facilitates the positive interactions between industrial structure adjustment and urban land use efficiency in the central and western regions of China, but the effect is attenuated in eastern China. As a core driver of China's rapid economic development (Chen, Xu, Xu, & Yang, 2016), URB has gradually become an important means to influence ISA and ULUE. The increase in URB can improve the industrial structure upgrade, industrial structure optimization and ULUE in the short term, which is in line with the research result by Long et al. (2012) that economic and population size play key role in promoting structural and intensive efficiency, but not always, this impact has regional variations (Ma et al., 2016; Zhu, Xiao, & Guo, 2017). For example, in areas with a low-level of economic development such as Yunnan and Qinghai, the pursuit of industrial structure upgrade can barely meet the market demand, improvements in URB can encourage the common development of ISA and LUE to a certain extent. In contrast, in Beijing and Tianjin, where the development of advanced industrial system slows down, a high proportion of secondary industries in the industrial structure gradually emerges, consequently, further development of URB can be detrimental to urban land eco-efficiency (Jiao et al., 2020; Liu & Li, 2017; Zhou, Kong, Sha, & Wang, 2019).

We propose policy recommendations tailored to different regions with distinct levels of economic development status and industrial structure for urban development sustainability. In order to sustain continued URB, accelerate the optimization and upgrading of the industrial structure and facilitate intensive land use, we suggest that future urban development policy making should focus on the issues of the imbalance of industry-employment structure, and environmental deterioration caused by industrial structure upgrade exceeding its own value range. Land use regulation and urban-rural integration development policies should be formulated to optimize resource allocation while developing the third and secondary industries. In areas with a lower level of URB development, it is necessary to liberalize the settlement conditions, promote the talent recruitment strategy, and facilitate the industrial transformation under the premise of the coordinated development of industry and employment. However, in areas with a high proportion of secondary industry in industrial structure, the scale effect brought by URB development has minimal effect, and only through discontinuous disruptive innovations can industrial structure transformation and upgrading be realized.

However, some limitations still need to be considered for further investigation. There is still a lot of efforts to explore the mechanism of industrial agglomeration theory and differential land rent theory on the relationship among URB, ISA and ULUE. In particular, due to the complexity of industrial structure and the multi-functionality of land use, it is necessary to further improve and develop relevant theories to enrich the realization path of urban development sustainability. With the emergence of new situations and new problems of urban development sustainability in China, it is also necessary to further deepen the research on specific practical problems, so as to provide services and support for the new people-oriented urbanization construction.

6. Conclusion

Based on the panel data of 31 provinces in China from 1978 to 2018, this study applies the VAR and PVAR models to analyze the relationship among ISA, ULUE, and URB. We offered suggestions for optimizing industrial structure and improving urban land use efficiency towards urban development sustainability.

Specifically, our research has three major findings. First, the relationship between industrial structure upgrade and ULUE presents an inverted U-shaped, while the relationship between industrial structure optimization and ULUE is generally increases in the process of URB. Specifically, 35.5% of provinces are in the preliminary and middle stages of URB where industrial structure upgrade has a positive impact on ULUE, while 12.9% of provinces are in the advanced stage of URB where industrial structure upgrade has a negative effect on ULUE in China.

Second, URB has a partial mediating effect on the relationships between ISA and ULUE. In the short term, URB development would accelerate the process of ISA and promote the improvement of ULUE in China. In the long term, a higher level of URB facilitates the positive influence relationship between ISA and ULUE in the central and western regions of China, but attenuates the positive influence relationship between them in the eastern regions of China.

Finally, our findings suggest that the central and western regions can continue to promote URB, so as to improve ULUE by promoting the agglomeration of knowledge-intensive industries. The eastern region should implement the industrial structure development mode of specialization and diversification to achieve urban development sustainability.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.scs.2022.104338.

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