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The more centralized the spatial structure is, the greater the economic growth? Evidence from urban agglomerations in western China

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This research examines data from eight urban agglomerations in western China from 2003 to 2020 to investigate the impacts of spatial structure changes on economic growth. Using dynamic spatial econometrics, we find that spatial agglomeration has significant effects on the economic growth performance of urban agglomerations in western China. Moreover, the direct effects of three indicators measuring spatial structure—population, industry and land use spatial structure—on economic growth are all directly positive. Moreover, these three spatial structure indicators affect economic growth through mediating variables such as environmental pollution, technological progress, and industrial structure. Further heterogeneity tests reveal that the positive effects of spatial structure on economic growth are increasing and that the positive effects expand from the short term to both the short and long term.

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Introduction

As the world's largest developing country, China lags behind in economic growth and urbanization in its western region. Since 2000, the Chinese government has regarded urban agglomerations as an important strategy for promoting urbanization, and ten major urban agglomerations have gradually formed in western China. Additionally, since 2000, urban agglomerations in western China have undergone significant changes in terms of economic growth and the evolution of their spatial structure. From 2000 to 2020, the per capita gross domestic product (GDP) of China's western urban agglomerations grew dramatically from approximately 5616.49 yuan to 63,900.36 yuan, and the urbanization rate also increased significantly from 28.70% to 57.98%. Moreover, the population living in the urban built-up areas of China's western urban agglomerations increased from 28.70% to 57.98%, and the migration of the population to urban built-up areas was accompanied by a spatial concentration of industries and an increase in land use. Therefore, exploring the impact of the adjustment of the spatial structure of urban agglomerations on economic growth provides development ideas for economic growth in China and other parts of the world. The mechanism of the impact of urban agglomeration spatial structure on economic growth will provide an urbanization experience for many developing countries.

Since 2000, urban agglomerations in western China have developed rapidly, and great achievements have been made in terms of economic and social development. The GDP of the ten urban agglomerations in western China exceeds 50% of the total GDP of western China, making these agglomerations the core areas for economic development in the region. The GDP of the Chengdu-Chongqing, Guanzhong Plain, Qianzhong, Hubao-Eyu, Lanzhou-Xining and Dianzhong urban agglomerations has increased steadily, with an average growth rate of 26.9%, which is far greater than the overall growth rate in China. However, there are still some economic growth problems within these urban agglomerations in western China, such as an insufficient internal impetus driving economic growth, lagged industrial upgrading, and widening economic gaps between cities. Since 2000, governments at all levels in western China have formulated many policies and regional plans to regulate the spatial structure of urban agglomerations, hoping to stimulate economic growth. However, no consensus has been reached on the effect of these spatial structure changes on economic growth, and no in-depth study of their impact mechanism has been conducted.

As the economy grows and people and industries increasingly cluster in urban agglomerations, a large amount of land has also been exploited. Due to the different growth rates of different cities, the spatial structure of population, industry, and land use within urban agglomerations is also constantly changing. There is no unified conclusion in empirical research on the impact of spatial structural changes on economic growth. Some studies suggest that the impact is positive, while others suggest that it is negative or have not found significant effects (Henderson and Becker, 2000; Cervero, 2001; Lee and Gordon, 2007; Veneri and Burgalassi, 2012). One possible reason for these controversial results is that the mechanisms by which spatial structure changes affect economic growth performance are complex. Most existing studies use spatial structure indicators as explanatory variables to explore their direct impact on economic growth. However, few studies have investigated the mechanisms of the indirect effects in developing countries or regions. However, the spatial structure of urban agglomerations may also have indirect effects on economic growth through its impacts on the resource environment, production efficiency, etc. (Meijers and Burger, 2010; Fallah et al., 2011). The other possible reason is that there is little distinction between the short- and long-term impacts of these effects on economic growth. This situation has led to studies obtaining vastly different results based on different samples and observation times. Scarce research has made a distinction between the short-term and long-term effects in developing countries or regions. Moreover, current research topics in developed countries are based mainly on metropolitan areas (Meijers and Burger, 2010) or similar regional scales (Veneri and Burgalassi, 2012). However, these areas greatly differ from urban agglomerations in China in terms of spatial scale.

Moreover, most of the existing studies have ignored the spatial dependence problem. However, economic growth obviously has spatial dependence, and thus, disregarding spatial dependence can result in erroneous conclusions and suboptimal model performance. (Elhorst, 2014; Zhao et al., 2021). Compared to static spatial panel models, dynamic spatial panel models not only control spatial dependencies but also examine the dynamic impact of spatial structure changes. To our knowledge, no research has used dynamic spatial panel models to study this issue.

This paper aims to investigate the impacts of three types of spatial structure changes on economic growth performance in urban agglomerations in western China. Specifically, we use panel data from eight urban agglomerations in western China from 2003 to 2020 and an extended Cobb–Douglas production function as the basic framework. In this context, this paper makes two contributions to the literature. First, by quantitatively estimating the direct and indirect effects of the spatial structure of urban agglomerations on economic growth in western China, we find the different intermediary action paths of the impact of the population, industry and land use spatial structure of urban agglomerations on economic growth. Second, we employ both static and dynamic spatial econometric models to account for spatial dependence. We further distinguish the short- and long-term effects of spatial structure changes on the economic growth of urban agglomerations.

After the Introduction section, the rest of the paper is structured as follows. Section "Literature review" provides a literature review. Section "Method and regression model" establishes the analytical framework and constructs the spatial econometric models. The section "Data and variables" describes the data source and the variables used for the estimations. Section "Results and discussion" presents the empirical findings. Section "Conclusions and policy implications" presents the conclusions and policy recommendations.

Literature review

Impact mechanism of the population spatial structure on economic growth. Many studies have found that population agglomeration can promote economic growth through multiple pathways and has spatial spillover effects (Li et al., 2022), including labor force upgrading and other positive impacts on the labor market (Mu et al., 2018). For example, Geppert et al. (2007) analyzed German data and found that population agglomeration is an important factor in the high-level economic growth of a region. Moreover, González (2011) believed that there is a positive linear relationship between population spatial agglomeration and economic growth. Yang and Li (2019) applied provincial panel data to study the economic growth effect of population agglomeration in China and found that population agglomeration can significantly promote economic growth. Nonetheless, certain research has revealed that population clustering can have a substantial adverse effect on economic expansion. Broersma (2009) took the Netherlands as a case study and found that the crowding effect caused by population agglomeration takes precedence over the agglomeration effect, leading to a decrease in labor productivity. Additionally, Gardiner et al. (2011) found that agglomeration has a negative impact on economic growth. Futagami and Ohkusa (2003) reported that the connection between population concentration and economic growth follows a nonlinear, inverted U-shaped pattern. Furthermore, Portnov and Schwartz (2009) found that for marginal areas with small populations, population concentration is conducive to economic development, while for densely populated core areas, population agglomeration is not conducive to economic development.

With respect to the impact of population agglomeration on economic growth, studies have shown that population agglomeration is conducive to skill acquisition, information exchange and knowledge accumulation and exerts agglomeration economic effects through learning, sharing and matching, thereby improving the allocation efficiency of factor resources in urban agglomerations (Duranton and Puga, 2015). On the other hand, as the population gathers towards the city center, a crowding effect occurs, which results in external diseconomies of scale, including environmental pollution, traffic congestion, and increasing living expenses in the city center. At the same time, commuting and rent costs rapidly increase, thereby reducing the economic efficiency of the entire urban agglomeration (Maket et al., 2024). Some studies have shown that the continuous increase in population causes a crowding effect, and as the population density continues to increase, the land rent in a city will rise rapidly, leading to urban environmental degradation, a sharp reduction in the forest area, and air and noise pollution, which have serious effects on the industrialization process and cause serious economic imbalances (Kaya and Koc, 2018; Loredana et al., 2024)

The conclusions drawn from existing research on the impact of the population spatial structure in urban agglomerations on economic growth are not consistent, and useful explorations have been made on their impact mechanisms. Therefore, this paper proposes Hypothesis 1a and Hypothesis 1b.

Hypothesis 1a. The population spatial structure within urban agglomerations can directly affect economic growth.

Hypothesis 1b. Environmental pollution has a significant mediating effect on the impact of the population spatial structure of urban agglomerations on economic growth.

Impact mechanism of the industry spatial structure on economic growth. Many studies have found that industry agglomeration can promote economic growth. Ottaviano and Pinelli (2006) conducted a study on the relationship between industrial agglomeration and economic growth in Finland and showed significant positive effects. From the perspectives of agglomeration specialization and production costs, Klein (2015), Cohen (2016), and Huang et al. (2020) demonstrated that industrial clustering has a favorable effect on economic growth. However, some studies have found that industry agglomeration hinders economic growth. For example, Rappaport (2007) and Rizov et al. (2012) indicated that industrial agglomeration may have adverse effects on the regional economy due to congestion effects. Certain research has indicated that there is no substantial correlation between industrial clustering and economic growth (Combes, 2000; Bautista, 2005). It has also been found that the relationship between industry agglomeration and economic growth is nonlinear. Moreover, Futagami and Ohkusa (2003) proved that when industrial agglomeration reaches a certain level, it produces a "congestion effect", which inhibits economic growth. Brülhart and Sbergami (2008) conducted cross-country empirical studies using instrumental variable methods and found that in the early stages of economic development, industrial agglomeration has a large pulling effect on GDP, but when industrial agglomeration reaches a certain level, this effect weakens.

Regarding the influence of industrial clustering on economic growth, research has indicated that it stimulates regional economic development through the accumulation of physical capital and technological advancement (Ting and Lin, 2013). Regarding scale economies, research has shown that industrial clustering creates an environment that is conducive to corporate collaboration and innovation (Sun, 2021); therefore, it stimulates regional progress via the diffusion effects of technology (Ding et al., 2022). Some studies have focused on manufacturing and productive services and found that the agglomeration of these two industries promotes economic growth mainly by improving total factor productivity (Han and Gwang-Ho, 2020; Cheng and Xiao, 2020). Research has shown that economic growth and industrial agglomeration have self-reinforcing capabilities, and the spatial agglomeration of industries promotes economic growth by improving innovation capabilities, reducing transaction costs and industrial upgrading (Ottaviano and Martin, 2001; Yu and Zhou, 2021; Feng et al., 2022).

Based on the analysis presented above, it is clear that technological advancement acts as a crucial intermediary between industrial clustering and economic growth. Moreover, the current body of research regarding the influence of industrial spatial configurations within urban agglomerations on economic growth has not reached a consensus. Therefore, this paper proposes Hypothesis 2a and Hypothesis 2b.

Hypothesis 2a. The industrial spatial structure within urban agglomerations can directly affect economic growth.

Hypothesis 2b. Technological progress has a significant mediating effect on the relationship between the industrial spatial structure of urban agglomerations and economic growth.

Impact mechanism of the land use spatial structure on economic growth. Many studies have shown that land use agglomeration can promote economic growth. For example, Ngai (2003) studied the economic growth of Japan and Africa based on further expansion of the Solo model and suggested that land factors play an important role in economic growth. Ding and Lichtenberg (2011) showed that land factors contribute more to China's economic growth than do investments, labor, and other factors. The above authors also analyzed the impact of land on urban economic growth using land as an input factor, the results of which showed that the impact of land on economic growth was very significant and that the effect coefficient was very large. Cela (2019) demonstrated that the expansion of the construction land area has made a significant contribution to economic growth and is an important internal factor for economic growth. It has also been found that land input, as a factor, has different effects on economic growth in different stages, and the contribution of the land factor to the economy is also limited (Hansen and Prescott, 2002; Wei et al., 2024). The level of economic development will affect land demand, and similarly, differences in land supply will also affect economic development (Brock and Taylor, 2010; Wang et al., 2023).

With respect to the impact of land use agglomeration on economic growth, intensive land utilization can effectively increase the capital and labor input of unit land resources, improve the overall utilization efficiency of land resources, promote the optimization of the industrial structure and adjustment of the industrial layout, effectively transform land use methods, promote the continuous transformation of the economic growth mode, and promote the rapid and sustainable development of the economy (Gaurs, 2006; Tian et al., 2021).

It has also been found that land use agglomeration can help local governments improve capacity utilization efficiency through environmental regulation, promote exchanges between enterprises, form an agglomeration advantage of labor and capital, accelerate the flow of factor resources from low- to high-productivity sectors, and promote the continuous evolution of the industrial structure to a high level, thereby improving the economic efficiency of the entire urban agglomeration (He and Yao, 2008; Yu and Shen, 2020; Shang et al., 2022). Some scholars believe that the transmission mechanisms through which land supply affects economic growth are fiscal revenue and infrastructure investment (Cao et al., 2023). Furthermore, Sharma and Newman (2020) confirmed that land taxation and land financing can help developed countries such as the United States promote infrastructure construction and economic growth.

Based on the analysis presented above, it is evident that industrial structure upgrading serves as a significant intermediary link between land use clustering and economic growth. Current research regarding the impact of land use spatial configurations within urban agglomerations on economic growth shows inconsistent results. Accordingly, this paper proposes Hypothesis 3a and Hypothesis 3b.

Hypothesis 3a. The land use spatial structure within urban agglomerations can directly affect economic growth.

Hypothesis 3b. Industrial structure upgrading has a significant mediating effect on the impact between the land use spatial structure of urban agglomerations and economic growth.

Method and regression model

The objective of this study was to explore the mechanism and effect of spatial structure changes on economic growth from an urban agglomeration perspective.

Test model for the impact of spatial structure changes on economic growth. First, economic growth, population agglomeration, industrial agglomeration and land use agglomeration have certain spatial spillover effects; that is, there is a spatial correlation between various elements of urban agglomerations (Song et al., 2023). This paper presents a spatial econometric model to account for spatial dependence. Because the spatial autoregressive model considers only the spatial lag effect of the dependent variable and the spatial error model considers only the spatial lag effect of the residual term, the economic growth of neighboring urban agglomerations and other economic factors have an impact on local economic growth (Song et al., 2023). Therefore, this article uses the spatial Durbin model (SDM) to estimate the spatial lag terms of the explanatory and dependent variables. The specific model is defined as Eq. (1):

$$pgdp_{it} = \rho \sum_{j=1}^{n} W_{ij} pgdp_{jt} + \beta X_{it} + \theta \sum_{j=1}^{n} W_{ij} X_{jt} + \mu_i + \nu_t + \varepsilon_{it} \tag{1}$$

where $pgdp_{it}$ and $pgdp_{jt}$ represent the economic growth indices of urban agglomeration i and j, respectively, in year t; X_{it} and X_{jt} are the key explanatory variables (i.e., the spatial structure of urban agglomeration) and other control variables that may have an impact on the economic growth of urban agglomeration i or j in year t; ρ represents the spatial lag coefficient of the dependent variable of economic growth; w_{ij} denotes an element within the spatial weight matrix, which is utilized to delineate the regional spatial proximity relationship; β represents the influence coefficient of the key explanatory variable on economic growth; θ represents the spatial lag coefficient of the key explanatory variable; μ_i represents the spatial fixed effect; ν_t represents the temporal fixed effect; ε_{it} represents the random error term; i represents one of the eight urban agglomerations in western China chosen by the paper ($i = 1, 2, \cdots, 8$); and t represents the observation year.

In Eq. (1), W is the distance-based spatial weight matrix, assuming that the intensity of spatial interaction depends on the distance between regional administrative centers; that is, the interaction force decreases with increasing distance. This study employs the inverse of the distance between the central cities of two urban clusters for expression, as shown in Eq. (2):

$$W = \begin{bmatrix} 0 & \frac{1}{(d_{1,2})^2} & \cdots & \frac{1}{(d_{1,8})^2} \\ \frac{1}{(d_{2,1})^2} & 0 & \cdots & \frac{1}{(d_{2,8})^2} \\ \cdots & \cdots & \cdots & \cdots \\ \frac{1}{(d_{8,1})^2} & \frac{1}{(d_{8,2})^2} & \cdots & 0 \end{bmatrix} \tag{2}$$

In Eq. (2), d_{ij} represents the distance between the central city of the i-th urban agglomeration and that of the j-th urban agglomeration.

Second, because of continuous economic phenomena, the static spatial Durbin model may have biased estimates. On the one hand, the economic growth of urban agglomerations may be spatially dependent, while on the other hand, there may also be "time inertia" in the economic growth of urban agglomerations. That is, the current economic growth of urban agglomerations is affected not only by current factors and adjacent urban agglomerations but also by historical factors and the economic growth of historical adjacent urban agglomerations. Compared with the static spatial panel model, the dynamic model can not only consider the spatial spillover effects but also solve the endogeneity problem. Therefore, considering that changes in economic growth may depend on time (Elhorst and Paul, 2010; Debarsy et al., 2012; Gu et al., 2022; Song et al., 2023), in this study, the time lag term of economic growth is incorporated into the SDM to establish a dynamic spatial panel Durbin model. The specific model is set as Eq. (3):

$$\begin{aligned} pgdp_{it} = {} & \beta_0 + \beta_1 pgdp_{i,t-1} + \rho_1 \sum_{j=1}^{n} W_{ij} pgdp_{jt} \\ & + \rho_2 \sum_{j=1}^{n} W_{ij} pgdp_{j,t-1} + \beta_2 SSU_{it} + \rho_3 \sum_{j=1}^{n} W_{ij} SSU_{jt} \\ & + \delta X_{it} + \rho_4 \sum_{j=1}^{n} X_{ij} \mu_i \nu_t + \varepsilon_{it} \end{aligned} \tag{3}$$

where $pgdp_{it}$ and $pgdp_{jt}$ represent the economic growth indices of urban agglomeration i and j, respectively, in year t; X_{it} and X_{jt} are the key explanatory variables and other control variables (including physical capital (*cap*), human capital (*edu*), foreign direct investment (*fdi*), government intervention (*gov*), environmental pollution (*pol*), traffic accessibility (*road*), scientific and technological level (*tech*), and industrial structure upgrading (*iup*)) that may impact the economic growth of urban agglomeration i or j in year t; and $pgdp_{i,t\text{-}1}$ represents the economic growth index that lags one phase. SSU_{it} and SSU_{jt} are the spatial structural degrees of urban agglomeration i and j in year t, represented by the spatial structure of urban agglomeration population (hum_{it}), urban agglomeration industry (ind_{it}) and urban agglomeration land use ($land_{it}$) separately. w_{ij} denotes an element within the spatial weight matrix, which is utilized to delineate the regional spatial proximity relationship; μ_i represents the spatial fixed effect; ν_t represents the temporal fixed effect; ε_{it} represents the random error term; ρ_1, ρ_2, ρ_3 and ρ_4 represent the spatial autocorrelation coefficients of the dependent variable, the time lag term of the dependent variable, the main independent variable, and the control variable, respectively; β_0 is a constant term; β_1 reflects the regression coefficient of economic growth lagging one period; and β_2 reflects the influence coefficient of the spatial structure of the urban agglomeration on economic growth.

Test model for the mediating effects of environmental pollution, technological progress, and industrial structure. As mentioned earlier, the main channels through which spatial structure influences economic growth are environmental pollution, technological progress and industrial structure. To test whether environmental pollution, technological progress and the industrial structure act as mediating variables, this paper employed a standardized mediating effect model (Hayes, 2017; Wu et al., 2021; Gu et al., 2022), which uses spatial econometric models to test the indirect impact of the mediator variables on the dependent variable (Mackinnon et al., 2000; Song et al., 2023). The specific models are defined as follows:

$$Path_{it} = \eta_0 + \eta_1 Path_{i,t-1} + \theta_1 \sum_{j=1}^{n} W_{ij} Path_{jt} + \theta_2 \sum_{j=1}^{n} W_{ij} Path_{j,t-1} + \eta_2 SSU_{it} + \theta_3 \sum_{j=1}^{n} W_{ij} SSU_{jt} + \kappa \sum X_{it} + \theta_4 \sum_{j=1}^{n} W_{ij} X_{jt} + \mu_i + \nu_t + \varepsilon_{it} \tag{4}$$

$$pgdp_{it} = \alpha_0 + \alpha_1 pgdp_{i,t-1} + \lambda_1 \sum_{j=1}^{n} W_{ij} pgdp_{jt} + \lambda_2 \sum_{j=1}^{n} W_{ij} pgdp_{j,t-1} + \alpha_2 SSU_{it} + \lambda_3 \sum_{j=1}^{n} W_{ij} SSU_{jt} + \alpha_3 Path_{it} + \lambda_4 \sum_{j=1}^{n} W_{ij} Path_{jt} + \varphi \sum X_{it} + \lambda_5 \sum_{j=1}^{n} W_{ij} X_{jt} + \mu_i + \nu_t + \varepsilon_{it} \tag{5}$$

In Eq. (4) and Eq. (5), $Path_{it}$ and $Path_{jt}$ represent the environmental pollution, technological progress, and industrial structure effects of urban agglomeration i and urban agglomeration j, respectively, in year t; SSU_{it} and SSU_{jt} are the spatial structural degrees of urban agglomeration i and j in year t, represented by the spatial structure of the urban agglomeration population (hum_{it}), urban agglomeration industry (ind_{it}) and urban agglomeration land use ($land_{it}$) separately; X_{it} and X_{jt} are the key explanatory variables and other control variables that may have an impact on the economic growth of urban agglomeration i or j in year t; w_{ij} denotes an element within the spatial weight matrix, which is utilized to delineate the regional spatial proximity relationship; μ_i represents the spatial fixed effect; ν_t represents the temporal fixed effect; ε_{it} represents the random error term; *and* θ_1, θ_2, θ_3 and θ_4 represent the spatial lag coefficients.

Based on the necessary conditions for a mediating effect and the step-by-step test proposed by Baron and Kenny (1986), as well as Hayes (2017) and Song et al. (2023), first, we examined the regression coefficient β_2 in Eq. (3). If β_2 is significant, then it indicates the presence of a mediating effect. Second, we sequentially tested the regression coefficient η_2 in Eq. (4) and the regression coefficient α_3 in Eq. (5). If both coefficients are significant, then this result indicates a significant mediating effect. Finally, we examined the significance of the regression coefficient α_2 in Eq. (5). If α_2 is not significant, then it indicates that the direct effect is not significant, suggesting a full mediating effect. Conversely, if α_2 is significant, then it indicates a significant direct effect, suggesting a partial mediating effect.

Equations (3)-(5) represent the comprehensive testing procedure for the mediating effect model in this paper. Equation (4) can also be used as a test model for the existence of environmental pollution, technological progress and industrial structure upgrading effects of urban agglomeration. Specifically, when using *hum* as the *SSU* variable, we use environmental pollution as the *Path* variable to test whether environmental pollution has a significant mediating effect on the impact of the population spatial structure of urban agglomerations on economic growth. When using *ind* as the *SSU* variable, we use technological progress as the *Path* variable to test whether technological progress has a significant mediating effect on the impact of the industry spatial structure of urban agglomerations on economic growth. When employing land as the spatial structure variable, we utilize industrial structure upgrading as the mediating variable to examine whether industrial structure upgrading significantly mediates the impact of urban agglomeration spatial structure on economic growth.

In addition, prior to parameter estimation, this study examines the spatial correlation of the dependent variables to ascertain whether employing a spatial panel model is necessary (Wu et al., 2021; Gu et al., 2022; Song et al., 2023). In this study, the widely used global Moran's index and Lagrange multiplier (LM) test were employed for discrimination. To verify whether the SDM can be used, LM tests were first performed on Eqs. (3)-(5) before model estimation. This paper refers to the approach of Shao et al. (2019) and uses the generalized method of moments (GMM) to estimate the dynamic spatial Durbin model, overcoming the shortcomings of the maximum likelihood estimation method, which is prone to bias and reduces estimation errors due to endogeneity problems.

Data and variables

Referring to Fang (2019), Zhao (2020) and other studies on the spatial scope identification of urban agglomerations in China, western China includes 10 urban agglomerations: the Chengdu-Chongqing, Guanzhong Plain, Qianzhong, North and South Chinfang, Central Yunnan, Lanzhou-Xining, Hubao-Eyu, Yinchuan Plain, and Jiujiayu urban agglomerations and an urban agglomeration on the northern slope of Tianshan Mountain. In accordance with the principle of data accessibility, this study uses balanced panel data on 8 urban agglomerations (excluding those on the northern slope of Tianshan Mountain and the Jiujiayu urban agglomeration because of a lack of data on the urban construction land area and urban built-up area in these regions) from 2003 to 2020. City-level data (see Supplementary Information) are collected for various years from the "*China Urban Statistical Yearbook*", "*China Urban Construction Statistical Yearbook*", "*China Economic and Social Development Statistics Database*", the statistical yearbooks of each province, and the regional economic database—DRCNET.

Explained variable

Economic growth. There are significant differences in population size and land area among urban agglomerations in western China. Selecting the total GDP index of urban agglomerations cannot truly reflect the actual economic growth of urban agglomerations. Therefore, this paper chooses 2000 as the base year to calculate the comparable price per capita GDP of urban agglomerations to represent economic growth.

Explanatory variables

Spatial structure of an urban agglomeration (SSU). The spatial structure of an urban agglomeration studied in this paper can be defined as the sum of the spatial representations of various elements in the urban agglomeration, with this research focusing on the changing processes of population agglomeration, industrial agglomeration and land use over time and their impact on the economy. Therefore, the spatial structure of the urban agglomerations studied in this paper includes three levels of connotation: first, the population spatial structure of urban agglomerations; second, the industry spatial structure of urban agglomerations; and third, the land use spatial structure of urban agglomerations.

Most measurement studies on the spatial structure of urban agglomerations consider the agglomeration degree; referring to the research of Yang et al. (2016), the Gini coefficient is used to represent the spatial structure of the population in urban agglomerations, which reflects the spatial agglomeration characteristics of the population. The calculation formula is set as Eq. (6):

$$hum = \frac{\sum_{i=1}^{n}\sum_{j=1}^{n}|P_i - P_j|}{2(n-1)\sum_{i=1}^{n}P_i} \tag{6}$$

P_i represents the total population of city i; P_j represents the total population of city j; and n represents the number of cities in the urban agglomeration.

Based on the study of Sun et al. (2021), the Herfindahl index (H index), which reflects the characteristics of industry spatial concentration in urban agglomerations, is used to represent the industry spatial structure of urban agglomerations. The calculation formula is set as Eq. (7):

$$ind = \sum_{i=1}^{n}\left(\frac{IND_i}{IND}\right)^2 \tag{7}$$

IND represents the aggregate output value of the secondary industry of the urban agglomeration; IND_i denotes the output value of the secondary industry of city i in the urban agglomeration; and n represents the number of cities in the urban agglomeration.

Similarly, the H index is also used to represent the spatial structure of land use in urban agglomerations, which reflects the degree of agglomeration of land use spatial structure. The calculation formula is set as Eq. (8):

$$land = \sum_{i=1}^{n}\left(\frac{L_i}{L}\right)^2 \tag{8}$$

L represents the area of all construction land within the urban agglomeration; L_i represents the area of construction land in city i of the urban agglomeration; and n represents the number of cities in the urban agglomeration.

Moderating and control variables

1) Environmental pollution. Considering the characteristics of the research object and the availability of data on environmental pollution in China, we selected regional per capita sulfur dioxide (SO_2) as a proxy for measuring environmental pollution.

2) Technological progress. This variable indicates the technological level of a region, assessed by the ratio of local science expenditure to the overall local fiscal budget, in line with Li and Qi (2011).

3) Industrial structure upgrading. Based on the research of Liu and Wang (2021), the industrial structure upgrading index is used.

4) Human capital. Drawing on the practice of Zhang and Yi (2012), human capital is characterized by the proportion of the total number of students in secondary schools and colleges within the urban agglomeration to the total population within the urban agglomeration.

5) Physical capital. Taking 2003 as the base year, the perpetual inventory method is used to estimate the physical capital of urban agglomerations. The calculation formula is $K_{it} = K_{i(t-1)}(1-\delta_{it}) + I_{it}$. According to Shan (2008), the depreciation rate δ_{it} is set to 10.96%. For the estimation of the capital in the base year, the method of Hall and Jones (1999) is adopted, calculated by dividing the investment data in the initial year by 10%.

6) Government intervention. Drawing on the practice of Yu and Guo (2021), government intervention is characterized by the proportion of fiscal expenditures to fiscal revenue.

7) Foreign direct investment. Foreign direct investment is characterized by the actual amount of foreign capital utilized by urban agglomerations.

8) Traffic accessibility. The traffic accessibility of an urban agglomeration is characterized by the highway mileage per unit area of the urban agglomeration.

To satisfy the assumption of normal distribution, this paper takes the natural logarithms of all stock data. Hypothesis testing of the normal distribution of data is shown in Table 1.

Based on the test results, it can be concluded that only *edu* has a p-value of $0.2 > 0.05$, which supports the original hypothesis that the *edu* data are normally distributed. The p-values of the other variables are all less than 0.05, so with a 95% probability guaranteed, it is considered that the original data of these variables do not follow a normal distribution. Comparing the results of Table 1, it can be found that taking the logarithm changes the distribution of more explanatory variables from nonnormal to normal.

In summary, Table 2 provides the descriptive statistics of the variables employed in the empirical analysis using panel data at the urban agglomeration level.

Table 1 Hypothesis test of normal distribution results for the data.

	Normality test of the raw data				Normality test of the logarithmic raw data		
	Statistics	Degree of freedom	Significance		Statistics	Degree of freedom	Significance
pol	0.240	143	0.000	*lnpol*	0.074	143	0.050
pgdp	0.219	143	0.000	*lnpgdp*	0.078	143	0.033
hum	0.094	143	0.004	*lnhum*	0.153	143	0.000
ind	0.140	143	0.000	*lnind*	0.203	143	0.000
land	0.131	143	0.000	*lnland*	0.178	143	0.000
road	0.141	143	0.000	*lnroad*	0.060	143	0.200*
tech	0.118	143	0.000	*lntech*	0.214	143	0.000
cap	0.264	143	0.000	*lncap*	0.057	143	0.200*
edu	0.067	143	0.200*	*lnedu*	0.062	143	0.200*
fdi	0.308	143	0.000	*lnfdi*	0.064	143	0.200*
gov	0.081	143	0.024	*lngov*	0.063	143	0.200*
iup	0.238	143	0.000	*lniup*	0.476	143	0.000

The asterisk (*) indicates that it did not pass the significance level of 1%.

Table 2 Descriptive statistics of the panel urban agglomeration-level data.

Variable	Variable description	Indicator selection	Unit	Average	Max	Min	Std. dev.	Obs.
pgdp	Economic growth	GDP per capita	Yuan/person	26,091.20	134,519.93	5338.12	23,916.28	144
hum	Population spatial structure of urban agglomerations	Population Gini coefficient	—	0.139	0.262	0.014	0.071	144
ind	Industry spatial structure of urban agglomerations	Secondary industry "H" index	—	0.343	0.482	0.158	0.078	144
land	Land use spatial structure of urban agglomerations	Land use "H" index	—	0.408	0.714	0.157	0.115	144
pol	Environmental pollution	Sulfur dioxide emissions	Tons	350,124.23	1,691,764	14,275.63	354,914.32	144
tech	Technological progress	The ratio of local scientific expenditures in the general local finance budget	%	1.016	2.629	0.156	0.563	144
iup	Industrial structure upgrading	Industrial structure upgrading index	—	2.363	2.807	0.002	0.225	144
cap	Physical capital	Capital stock measured by the constant price index in the base year	Hundred million yuan	7000.06	61,763.26	297.62	10,545.27	144
edu	Human capital	The proportion of the total number of students in secondary schools and colleges to the total population within the urban agglomeration	%	8.583	11.887	3.841	1.510	144
fdi	Foreign direct investment	Actual amount of foreign capital utilized	Ten thousand dollars	280,363	2,775,614	3238	549,699	144
gov	Government intervention	The proportion of fiscal expenditures to fiscal revenue	—	2.132	3.705	1.183	0.558	144
road	Traffic accessibility	Highway mileage per unit area of each urban agglomeration	km/km^2	0.691	1.959	0.119	0.383	144

The unit "—" indicates the coefficient obtained by abstracting the cardinality of the contrast to 1.

Table 3 Global Moran's *I* values of the per capita GDP of urban agglomerations in western China.

Year	2003	2004	2005	2006	2007	2008
Moran's *I* value	0.378***	0.345***	0.450***	0.453***	0.371***	0.312***
	(3.058)	(2.851)	(3.542)	(3.985)	(3.517)	(3.401)
Year	2009	2010	2011	2012	2013	2014
Moran's *I* value	0.287***	0.235***	0.203**	0.207**	0.091**	0.160**
	(3.201)	(2.669)	(2.291)	(2.097)	(2.124)	(1.845)
Year	2015	2016	2017	2018	2019	2020
Moran's *I* value	0.116**	0.140**	0.238**	0.348***	0.360***	0.367***
	(1.324)	(1.684)	(2.384)	(3.041)	(3.337)	(3.572)

For the estimated coefficients, the *z*-values are in parentheses. ***, **, and * indicate significance at the 1%, 5%, and 10% levels, respectively.

Results and discussion

Spatial dependence test. The premise of using a spatial panel model is that there is spatial correlation between economic growth performance in each urban agglomeration of western China. Therefore, drawing on the research of Moran (1950), Zhao et al. (2021) and Wang and Long (2024), the global Moran's index (Moran's *I*) is used to test whether the spatial distribution of economic growth in urban agglomerations is clustered. Moran's *I* ranges from −1 to 1, with positive and negative signs indicating the direction of spatial correlation (Zhao et al., 2021). The definition of Moran's *I* is as follows:

$$Moran's\, I = \frac{n\sum_{i=1}^{n}\sum_{j=1}^{n} w_{ij}(X_i - \overline{X})(X_j - \overline{X})}{\sum_{i=1}^{n}(X_i - \overline{X})^2 \sum_{i=1}^{n}\sum_{j=1}^{n} w_{ij}} \tag{9}$$

where X_i is the observed value of the *i*th region, $\bar{X}$ is the mean of X, n is the number of spatial units indexed by i and j, and w_{ij} is the element in the *i*th row and *j*th column of the distance-based spatial weight matrix W, as shown in Eq. (2).

The results of the global Moran's *I* are shown in Table 3, which demonstrate that the global Moran's *I* values of the economic growth indicators from 2003 to 2020 are positive and that they all passed at least the 5% significance test.

This finding suggests that the economic growth of urban agglomerations in western China features a substantial positive spatial correlation, demonstrating clear spatial clustering. Consequently, when examining the impact of alterations in the spatial structure of urban agglomerations on economic growth, it is advisable to employ suitable spatial panel models to account for the spatial interdependence of economic growth.

Impact effect test. This paper uses the dynamic spatial panel model test, Eq. (2), to estimate the comprehensive impact of changes in the three spatial structure types on the economic growth of urban agglomerations. According to the principle of spatial econometric model judgment proposed by Anselin et al. (1996), by testing the two Lagrange multipliers (LM-sar and LM-error) and their robust forms (Robust LM-sar and Robust LM-error), it is found that both statistics pass the significance test; thus, the dynamic spatial Durbin model is finally selected as the test model to examine the influence mechanism, and the estimated results are shown in Table 4. Models (1), (2) and (3) in Table 4 show the estimated results of the population, industry and land use spatial structure of urban agglomerations as explanatory variables.

These three indicators (*hum*, *ind* and *land*) slowly increased during the survey period for most of the eight urban agglomerations. According to Table 4, changes in the population, industry and land use spatial structure of urban agglomerations in western China significantly promoted economic growth during the survey period. These combined results demonstrate that the population, industry, and land use spatial structures within urban agglomerations significantly promote the economic growth of urban agglomerations. The coefficients of the time lag term (lnpgdpt-1) of economic growth in Table 4 are significantly positive, suggesting a significant circular cumulative effect on the economic growth of urban agglomerations; that is, the economic growth of urban agglomerations in the previous period promoted economic growth in the current period. Moreover, the spatial lag term ($W\ln pgdp_{t-1}$) coefficient of economic growth is significantly positive, which indicates that there is also a positive spatial correlation effect on the economic growth of urban agglomerations and that there is a benign interaction and catch-up promotion relationship between urban agglomerations in western China. At the same time, the spatial autocorrelation coefficients in Table 4 are significantly positive, which proves that there is a spatial spillover effect on the economic growth of urban agglomerations in western China and that the economic growth of urban agglomerations will promote the economic growth of neighboring urban agglomerations.

However, in the dynamic SDM, the parameter estimation results of the explanatory variables do not represent their marginal effect. Therefore, this paper further calculated the direct and indirect impacts of urban agglomeration spatial structure on economic growth and estimated their respective long-term and short-term effects. The results are shown in Table 5.

According to Table 5, the short-term effects of the spatial structure of urban agglomerations in western China on economic growth are significant, but the long-term effects are not significant, which indicates that the population, industry and land use spatial structure adjustments of urban agglomerations are more suitable as a short-term policy tool than as a long-term policy tool. Specifically, first, the short-term direct effects are significantly positive, indicating that short-term changes in the spatial structure of the three dimensions in urban agglomerations can significantly promote economic growth. Second, the short-term indirect effects are significant, but there are also positive and negative effects. The short-term indirect effects of population and industry spatial structure adjustments on economic growth in urban agglomerations are significantly positive, and the short-term indirect effects of land use spatial structure adjustments on economic growth in urban agglomerations are significantly negative, indicating that in the short term, alterations in the population and industrial spatial structure within urban agglomerations exhibit pronounced spatial spillover effects, which enhance the economic growth of neighboring urban clusters. However, changes in the degree of land use spatial structure in urban agglomerations inhibit the economic growth of adjacent urban agglomerations. Third, the short-term direct effects are greater than the short-term indirect effects, indicating that the spatial structure adjustments of urban agglomerations have a greater contribution to the economic growth of urban agglomerations.

Table 4 The impact of spatial structure changes on the economic growth of urban agglomerations in western China.

	Population spatial structure Model (1)	Industry spatial structure Model (2)	Land use spatial structure Model (3)
$\ln pgdp_{t-1}$	2.871***	0.377***	0.458***
	(12.83)	(4.92)	(4.50)
$W\ln pgdp_{t-1}$	7.439***	5.128***	1.606***
	(10.85)	(16.34)	(4.46)
ln*hum*	2.950***		
	(11.02)		
ln*ind*		14.952***	
		(28.12)	
ln*land*			5.075***
			(5.075)
lncap	−0.888***	−1.023***	1.072***
	(−7.58)	(−10.11)	(15.02)
lnedu	4.625***	4.941***	2.356***
	(16.27)	(28.39)	(9.62)
lnfdi	0.409***	1.075***	−0.264***
	(8.72)	(41.86)	(−15.17)
lngov	−0.085	−4.546***	1.431***
	(−0.73)	(−42.08)	(8.73)
lnroad	−0.125	−0.229**	0.061
	(−1.43)	(−2.31)	(0.60)
lnpol	0.332***	0.935***	0.393***
	(6.56)	(12.25)	(3.69)
lntech	0.227***	0.336***	−0.233***
	(3.25)	(5.97)	(−5.42)
lniup	0.127***	0.373***	−0.021
	(13.78)	(17.63)	(−0.81)
*W**ln*hum*	10.812***		
	(7.23)		
*W**ln*ind*		147.298***	
		(113.78)	
*W**ln*land*			42.485***
			(32.96)
*W*Control*	YES	YES	YES
ρ	0.728***	0.400***	0.736***
	(6.16)	(4.37)	(7.05)
R-sq	0.622	0.625	0.899

For the estimated coefficients, the *z*-values are in parentheses. ***, **, and * indicate significance at the 1%, 5%, and 10% levels, respectively.

When comparing Tables 3 and 4, the influence of some control variables is worth considering. First, most of the direct effects of physical capital on the economic growth of urban agglomerations are significantly negative, which indicates that investment is no longer the main driving force for the economic growth of urban agglomerations in western China during the period under review. Second, most of the direct effects of human capital on the economic growth of urban agglomerations are significantly positive, which indicates that the growth of human capital stock during the inspection period can significantly promote the economic growth of urban agglomerations in western China; thus, the western region should improve not only the stock and quality of human capital from education, health and other areas but also the labor productivity losses caused by the excessive accumulation of low-end labor. Third, the short-term direct effects of FDI, government intervention, and traffic accessibility on economic growth are significantly positive, while the long-term effects are not significant, indicating that FDI has a positive impact on economic growth in the short term from the aspects of capital injection, industrial correlation and technology spillover, but the long-term effect is no longer significant. Government intervention in the economy may have a short-term beneficial impact on economic growth from the perspective of straightening out the functional division and industrial cooperation within urban agglomerations; however, such intervention may also lead to the distortion of resource allocation and low efficiency of financial use, which will lower the market operation efficiency and economic efficiency of urban agglomerations in the long run. The rapid development of transportation infrastructure effectively reduces transaction costs and promotes resource circulation, which boosts the economic growth of urban agglomerations in the short term; however, the long-term impact is no longer significant.

Heterogeneity analysis. Due to the different levels of policy planning in different periods, the effect of spatial structure changes in urban agglomerations on economic growth may be different in different periods. At the beginning of 2016, China's 13th Five-Year Plan for National Economic and Social Development clearly proposed that China would build 19 urban agglomerations and stressed the need to "optimize the layout and form of urbanization". Since then, the development plans of urban agglomerations in the western region have been approved, and these plans all contain the requirements of "reasonably determining the city size, population density and spatial structure" and "promoting the formation of a spatial pattern of urbanization with balanced density, division of labor and cooperation and complete functions". Therefore, this paper divides the sample into two periods, 2003-2015 and 2016-2020, and uses the dynamic spatial panel model to further explore the differences in the impacts of spatial structure changes in urban agglomerations on economic growth in western China under temporal heterogeneity, the estimated results of which are shown in Table 6.

Table 6 indicates that from 2003 to 2015, the short-term direct impacts stemming from the population, industrial, and land use spatial configurations within urban agglomerations in western China significantly promoted economic growth, with the statistical significance of this effect reaching the 1% level. However, the short-term, long-term direct and long-term indirect effects of the spatial structure of the three types of urban agglomerations did not pass the significance test during this period, which is basically consistent with the results in Table 5. From 2016 to 2020, the short-term direct effects of the population, industry and land use spatial structure of urban agglomerations in western China also promoted economic growth at the 1% significance level, and the short-term direct effect parameter estimates in this period were greater than those in 2003-2015. At the same time, from 2016 to 2020, the long-term direct effects of the population and land use spatial structure of urban agglomerations in western China promoted economic growth at the 5% significance level. These changes show that with the formulation and continuous advancement of the development plan of urban agglomerations, the short-term promotion effects of population, industry and land use spatial structure adjustments in urban agglomerations in the western region is constantly increasing, and the original short-term promotion role has gradually expanded to include the joint impact of short- and long-term promotion.

In conclusion, the robustness test results based on altered methodologies and sample intervals largely concur with past research findings, suggesting that the effects of spatial structure adjustments on the economic growth of urban agglomerations in western China are both credible and robust.

Robustness test. To validate the reliability of the research findings, this research employs diverse estimation methodologies for empirical analysis to further examine the influence of spatial

Table 5 The direct and indirect effects of spatial structure on the economic growth of urban agglomerations in western China.

	Population spatial structure				**Industry spatial structure**				**Land use spatial structure**			
	Short-term direct effect	**Short-term indirect effect**	**Long-term direct effect**	**Long-term indirect effect**	**Short-term direct effect**	**Short-term indirect effect**	**Long-term direct effect**	**Long-term indirect effect**	**Short-term direct effect**	**Short-term indirect effect**	**Long-term direct effect**	**Long-term indirect effect**
ln*hum*	0.607***	0.119***	4.997	−5.562								
	(6.97)	(2.67)	(0.06)	(-0.06)								
ln*ind*					7.873***	2.344***	127.014	62.414				
					(24.61)	(3.63)	(0.07)	(0.02)				
ln*land*									3.573***	−0.638***	−67.716	24.617
									(20.25)	(−3.71)	(−0.91)	(0.05)
ln*cap*	-0.826***	−0.165**	−7.491	8.256	−0.620***	−0.186***	−9.396	−5.280	−0.433***	0.077***	8.238	−3.416
	(−11.52)	(−2.45)	(−0.08)	(0.08)	(−10.86)	(−3.14)	(−0.06)	(−0.02)	(−6.26)	(3.20)	(0.79)	(−0.05)
ln*edu*	2.110***	0.431**	18.190	−20.140	2.874***	0.872***	42.573	15.036	1.945***	−0.341***	−37.716	13.464
	(8.66)	(2.20)	(0.08)	(−0.09)	(11.75)	(2.90)	(0.06)	(0.01)	(8.83)	(−4.28)	(−0.93)	(0.06)
ln*fdi*	0.210***	0.041***	2.029	−2.225	0.375***	0.110***	6.849	2.634	0.121***	−0.022**	−2.139	0.870
	(5.48)	(2.70)	(0.09)	(−0.10)	(8.32)	(4.23)	(0.10)	(0.02)	(3.51)	(−2.07)	(−0.71)	(0.04)
ln*gov*	1.363***	0.271***	12.195	−13.461	2.247***	0.672***	33.113	21.507	1.059***	−0.189***	−20.021	7.670
	(11.17)	(2.59)	(0.08)	(−0.08)	(18.53)	(3.41)	(0.06)	(0.02)	(7.97)	(−3.38)	(−0.89)	(0.06)
ln*road*	0.443***	0.086***	3.686	−4.099	0.642***	0.189***	11.053	3.091	0.480***	−0.087***	−8.974	3.288
	(7.52)	(2.72)	(0.06)	(−0.07)	(9.26)	(3.95)	(0.09)	(0.01)	(6.93)	(−2.87)	(−0.79)	(0.04)
ln*pol*	0.111	0.016	1.113	−1.221	−0.028	−0.014	0.606	1.782	0.199**	−0.039	−3.291	1.028
	(1.23)	(1.08)	(0.05)	(−0.05)	(−0.33)	(−0.48)	(0.02)	(0.06)	(2.24)	(−1.60)	(−0.60)	(0.03)
ln*tech*	−0.044	−0.010	−0.221	0.261	−0.255***	−0.078**	−2.862	−3.240	−0.074*	0.012	1.574	−0.519
	(−1.46)	(−1.11)	(−0.05)	(0.06)	(−6.50)	(−2.51)	(−0.03)	(−0.03)	(−1.81)	(1.91)	(0.74)	(−0.08)
ln*iup*	0.023	0.003	0.361	−0.385	−0.052*	−0.017	-0.952	0.977	−0.032	0.005	0.741	−0.283
	(0.74)	(0.52)	(0.07)	(−0.07)	(−1.86)	(−1.39)	(−0.11)	(0.08)	(−0.83)	(0.72)	(0.56)	(−0.08)

For the estimated coefficients, the *z*-values are in parentheses. ***, **, and * indicate significance at the 1%, 5%, and 10% levels, respectively.

structure evolution on urban agglomeration economic growth. The empirical test results are shown in Table 7.

In this paper, pooled ordinary least squares (POLS), the SSDM and the dynamic spatial lagged model (DSLM) are used to further test the robustness of the core conclusions. In the test, the spatial structures of population, industry and land use are still used to measure the spatial structure of urban agglomerations. The results in Table 7 show that most of the spatial structure adjustments of urban agglomerations still significantly promoted economic growth, and the estimated results are basically consistent with those in Table 4 in terms of the coefficient symbols and significance, thus proving the reliability of the above estimates.

It should be pointed out that the spatial spillover coefficient in the SSDM in Table 7 is significantly greater than that in the DSLM and the dynamic spatial Durbin model in Table 4. Especially after considering the first-order lag variable of economic growth, the lag periods of urban agglomeration economic growth ($\ln pgdp_{t-1}$) and urban agglomeration economic growth ($\ln pgdp$) pass the significance test at the 1% level in all models and are positive. This finding shows that lagged urban agglomeration economic growth ($\ln pgdp_{t-1}$) will strip the potential factors (such as the environment and institutions) that affect economic growth from the impact of the spatial structure. Hence, this adjustment rectifies the overestimation of the economic growth impact attributed to the spatial structure of urban agglomerations, as calculated by the static spatial econometric model. It also highlights the substantial cumulative temporal effect on the economic growth of urban clusters in China's western region. Therefore, it is reasonable to choose a more explanatory dynamic space panel model as the final model for empirical research.

Further discussion on the impact mechanism. This paper further uses the dynamic spatial panel model test, Eqs. (3)–(5), to estimate the impact of the spatial structure of three urban agglomerations on economic growth. According to the judgment principle proposed by Anselin and Smirnov (1996), the dynamic spatial Durbin model is finally selected as the test model. Concurrently, the determination of the outcomes presented in the reported fixed effects model adheres to the findings of the Hausman test. The estimation results are presented in Table 8.

First, the agglomeration of the population spatial structure of urban agglomerations in the western region directly promotes economic growth while also inhibiting it through environmental pollution. The results of column (1) in Table 8 show that the coefficient for the direct effect of the population spatial structure on the economic growth of urban agglomerations is 2.174 and significant at the 1% level, indicating that the population spatial agglomeration of urban agglomerations in western China provides the necessary human capital and consumer markets for economic development and directly promotes economic growth. At the same time, the results of column (2) in Table 8 show that the spatial agglomeration of the population aggravates environmental pollution, thereby inhibiting economic growth, and the mediating effect can be calculated as −0.104 according to the results of columns (2) and (3). This finding shows that the population agglomeration of urban agglomerations in western China during the investigation period also aggravated environmental pollution and environmental costs, which in turn inhibited economic growth, but the indirect inhibition effect of this population agglomeration was significantly weaker than its direct promotion effect.

Second, the agglomeration of the industry spatial structure of urban agglomerations in western China directly promotes economic growth through technological progress. The results of column (4) in Table 8 show that the coefficient for the direct effect of industry spatial structure on economic growth is 19.673 and significant at the 1% level, which indicates that the industrial

Table 6 The impact of spatial structure changes on the economic growth of urban agglomerations in western China based on different time samples.

Core explanatory variable	Effect	2003–2015		2016–2020		Control variable
		Parameter estimation	*z*-test value	Parameter estimation	*z*-test value	
Population spatial structure (*hum*)	Short-term direct effect	0.211***	2.82	0.507***	2.85	control
	Short-term indirect effect	0.012	0.97	0.036	0.19	control
	Long-term direct effect	−0.763	−0.13	0.488**	2.11	control
	Long-term indirect effect	3.037	0.08	−0.153*	−1.77	control
Industry spatial structure (*ind*)	Short-term direct effect	0.114***	2.70	0.456***	1.08	control
	Short-term indirect effect	−0.006	−0.79	0.292	0.26	control
	Long-term direct effect	−11.762	−0.03	0.426	1.08	control
	Long-term indirect effect	17.006	0.04	−0.113	−0.72	control
Land use spatial structure (*land*)	Short-term direct effect	0.194***	4.95	1.375**	2.03	control
	Short-term indirect effect	0.009	0.88	0.161	0.35	control
	Long-term direct effect	−17.147	−0.12	1.307**	2.06	control
	Long-term indirect effect	14.313	0.10	−0.348	−1.57	control

For the estimated coefficients, the *z*-values are in parentheses. ***, **, and * indicate significance at the 1%, 5%, and 10% levels, respectively.

Table 7 Robustness testing of the impact of spatial structure changes on the economic growth of urban agglomerations in western China based on different estimation methods.

	Population spatial structure			Industry spatial structure			Land use spatial structure		
	(1) POLS	(2) DSLM	(3) SSDM	(4) POLS	(5) DSLM	(6) SSDM	(7) POLS	(8) DSLM	(9) SSDM
$lnpgdp_{t-1}$		1.133***			0.955***			1.059***	
		(19.25)			(15.18)			(17.52)	
$Wlnpgdp_{t-1}$		0.773***			0.153			0.232	
		(3.47)			(0.86)			(1.29)	
lnhum	0.560***	0.603***	-0.174						
	(3.42)	(6.71)	(-0.98)						
lnind				2.069***	7.772***	1.629**			
				(2.65)	(22.64)	(2.01)			
lnland							1.560***	3.532***	1.285**
							(5.06)	(19.93)	(2.05)
lncap	0.401***	−0.822***	0.188	0.344**	−0.614***	0.012	0.378***	−0.433	0.173
	(2.60)	(−11.59)	(0.65)	(2.19)	(−11.35)	(0.04)	(2.70)	(−6.49)	(0.55)
lnedu	−0.724	2.084***	−1.029**	-0.427	2.813***	−1.025*	0.403	1.914	−1.109*
	(−1.56)	(8.39)	(−2.39)	(-0.89)	(11.47)	(−1.74)	(1.22)	(8.19)	(−1.97)
lnfdi	−0.113	0.209***	−0.164	-0.011	0.371***	−0.010	0.006	0.122	−0.127
	(−1.05)	(7.17)	(−1.57)	(-0.11)	(9.86)	(−0.20)	(0.07)	(3.76)	(−1.57)
lngov	0.448	1.349***	0.200	0.653*	2.216***	0.389	0.345	1.048	0.325
	(1.15)	(10.59)	(0.31)	(1.58)	(17.20)	(0.67)	(1.13)	(7.60)	(0.40)
lnroad	0.180	0.440***	−0.051	0.134	0.635***	0.171	−0.929***	0.482	0.142
	(0.60)	(7.10)	(−0.16)	(0.44)	(8.89)	(0.42)	(−6.35)	(6.89)	(0.30)
lnpol	0.544***	0.108	0.345**	0.387***	-0.025	0.525*	0.349***	0.199	0.651**
	(4.54)	(1.23)	(2.13)	(3.31)	(-0.31)	(1.77)	(4.18)	(2.37)	(2.47)
lntech	0.010	−0.045*	−0.073	-0.028	-0.253***	0.003	0.228*	−0.070	0.045
	(0.08)	(−1.66)	(−0.34)	(-0.21)	(-11.13)	(0.01)	(1.92)	(−3.01)	(0.19)
lniup	0.064	0.022	0.021	0.041	-0.049**	0.056	−0.001	−0.032	0.033
	(0.77)	(0.87)	(0.85)	(0.49)	(-2.14)	(1.47)	(−0.01)	(−1.26)	(0.71)
W*lnhum			−2.853***						
			(-3.84)						
W*lnind2						3.902			
						(1.51)			
W*lnland									5.626***
									(2.65)
W*Control			YES			YES			YES
ρ		0.167***	−1.081***		0.233***	−0.979***		−0.214***	−1.106***
		(3.12)	(−6.97)		(4.16))	(−5.47)		(−3.56)	(−5.27)
R-sq	0.495	0.422	0.519	0.695	0.501	0.591	0.985	0.592	0.443

For the estimated coefficients, the z-values are in parentheses. ***, **, and * indicate significance at the 1%, 5%, and 10% levels, respectively.

agglomeration of urban agglomerations in western China and the regional specialization brought about by it directly promote economic growth. At the same time, the results of column (5) in Table 8 show that industry spatial agglomeration promotes technological progress, which in turn promotes economic growth, the mediating effect of which can be calculated as 1.782 according to the results of columns (5) and (6). This finding shows that the industrial agglomeration of urban agglomerations in western China during the inspection period promoted technological progress, reduced production costs, and indirectly promoted economic growth through knowledge spillover.

Third, the agglomeration of the land use spatial structure of urban agglomerations in western China directly promoted economic growth through industrial structure upgrading. The results of column (7) in Table 8 show that the coefficient for the direct effect of the land use spatial structure on economic growth is 8.357 and significant at the 1% level, which indicates that the land use agglomeration of urban agglomerations in western China promotes intensive land utilization, increases the investment intensity per unit of land area, and directly promotes economic growth. At the same time, the results of column (8) in Table 8 show that land use space agglomeration promotes industrial structure upgrading, thereby promoting economic growth, and the mediating effect can be calculated as 0.053 according to the results of columns (8) and (9). This finding shows that changes in the land use spatial agglomeration of urban agglomerations in western China during the inspection period promoted continuous changes in the industrial structure to more advanced levels, thereby indirectly promoting economic growth.

In summary, the effect of the spatial structure on the economic growth of urban agglomerations in western China varies according to the dimensions selected by the spatial structure, but there are direct and intermediary effects, and the specific impact mechanism is shown in Fig. 1.

Conclusions and policy implications

This study examines the mechanism and the impact of the spatial structure on economic growth within urban agglomerations in western China.

First, the economic growth of urban agglomerations in western China exhibits positive spatial correlation; that is, urban agglomerations with faster economic growth have a positive driving effect on the economic growth of their neighboring urban agglomerations. Moreover, the economic growth of each urban

Table 8 Test results of the influence mechanism of spatial structure on the economic growth of urban agglomerations in western China.

	(1) lnpgdp	(2) *Path* (lnpol)	(3) lnpgdp	(4) lnpgdp	(5) *Path* (lntech)	(6) lnpgdp	(7) lnpgdp	(8) *Path* (lniup)	(9) lnpgdp
$lnpgdp_{t-1}$	2.819***		2.862***	0.794***		0.825***	0.161***		0.170***
	(14.43)		(12.76)	(25.59)		(26.44)	(3.86)		(4.12)
$Wlnpgdp_{t-1}$	6.323***		7.416***	-6.128***		−6.236***	−2.419***		−2.393***
	(10.99)		(10.70)	(-39.23)		(−40.21)	(−14.03)		(−13.90)
$Path_{t-1}$		0.848***			0.553***			−0.108***	
		(9.92)			(7.21)			(−2.04)	
$WPath_{t-1}$		0.583***			0.348***			−0.089***	
		(3.24)			(3.56)			(−1.38)	
lnhum	2.174***	0.312***	2.966***						
	(14.43)	(10.57)	(10.88)						
ln*ind*				19.673***	5.587***	20.859***			
				(44.71)	(18.78)	(47.61)			
ln*land*							8.357***	1.318***	8.191***
							(35.13)	(2.64)	(32.99)
Path			−0.334***			0.319***			0.040
			(−6.61)			(11.08)			(1.55)
ln*cap*	−0.743***	-0.407***	−0.791***	−1.600***	−0.184	−1.752***	1.601***	0.106	1.569***
	(−7.36)	(−8.12)	(−6.38)	(−19.44)	(−1.38)	(−21.69)	(29.84)	(0.55)	(30.94)
lnedu	5.323***	0.620***	4.659***	9.117***	2.170***	9.330***	4.950***	1.192	4.842***
	(14.22)	(3.13)	(16.82)	(36.21)	(10.13)	(37.14)	(17.88)	(1.42)	(16.69)
lnfdi	0.370***	0.083***	0.411***	1.462***	0.491***	1.499***	-0.438***	−0.176***	−0.421***
	(15.83)	(2.77)	(8.43)	(54.60)	(12.40)	(62.55)	(-13.13)	(−9.76)	(−11.67)
ln*gov*	−0.403***	0.388***	−0.009	−5.081***	−1.700***	−5.499***	2.199***	0.034	2.240***
	(−2.86)	(2.69)	(−0.07)	(-49.78)	(−6.53)	(−58.12)	(27.30)	(0.14)	(32.79)
lnroad	−0.125*	−0.066	−0.208**	−0.602***	−0.383***	−0.818***	−0.361***	−0.594	−0.331***
	(−1.92)	(−0.51)	(−2.24)	(−11.25)	(−2.84)	(−15.57)	(−9.14)	(−0.94)	(−8.18)
*W**lnhum	8.210***	0.978***	10.731***						
	(8.92)	(5.81)	(7.18)						
*W**ln*ind*				179.908***	52.565***	189.044***			
				(96.37)	(29.85)	(104.56)			
*W**ln*land*							74.541***	−0.818*	73.811***
							(101.58)	(−1.63)	(96.70)
*W***Path*			−1.180***			1.342***			−0.226***
			(−2.64)			(45.09)			(−5.22)
*W***Control*	YES	YES	YES	YES	YES	YES	YES	YES	YES
ρ	2.010***	0.558***	0.736	1.209***	1.031***	1.066***	1.104***	0.096	1.088***
	(8.69)	(6.38)	(6.28)	(19.24)	(23.60)	(17.02)	(18.47)	(2.31)	(17.82)
R-sq	0.531	0.755	0.761	0.591	0.430	0.632	0.531	0.587	0.631

For the estimated coefficients, the *z*-values are in parentheses. ***, **, and * indicate significance at the 1%, 5%, and 10% levels, respectively.

agglomeration in western China has a cyclic accumulation time effect, and early economic growth promotes current economic growth.

Second, alterations in the population, industry, and land use spatial structure within urban agglomerations in western China have significantly boosted the economic growth of these urban agglomerations; not only is the degree of promotion increasing, but the degree of short-term promotion has also expanded to short- and long-term promotion. In addition, the increase in the physical capital of urban agglomerations in western China has not significantly promoted the economic growth of urban agglomerations, while changes in human capital, foreign investment, government intervention and transportation accessibility have significantly promoted the economic growth of urban agglomerations.

Third, the population, industry, and land use spatial agglomeration within urban agglomerations has directly promoted the economic growth of urban agglomerations. Moreover, there are different mediating effects: the population spatial agglomeration in urban agglomerations inhibits economic growth by aggravating environmental pollution, the secondary industry spatial agglomeration in urban agglomerations promotes economic growth by promoting technological progress, and the construction land utilization spatial agglomeration in urban agglomerations promotes economic growth by accelerating the upgrading of the industrial structure.

Based on these key findings, we propose several policy recommendations.

First, the population carrying capacity of the central cities of the urban agglomerations in western China should be improved, the threshold of the registered residence system in central cities should continue to be reduced, and the population should be guided to flow to central cities with higher levels of spatial efficiency. At the same time, the quality of the population and environmental awareness should be improved, the green transformation of urban production and lifestyles should be promoted, and the relationship between population concentration and environmental pollution should be coordinated.

Second, based on the current situation of industrial development in urban agglomerations in western China, targeted measures should be taken to improve the spatial agglomeration of the secondary industries within urban agglomerations and fully

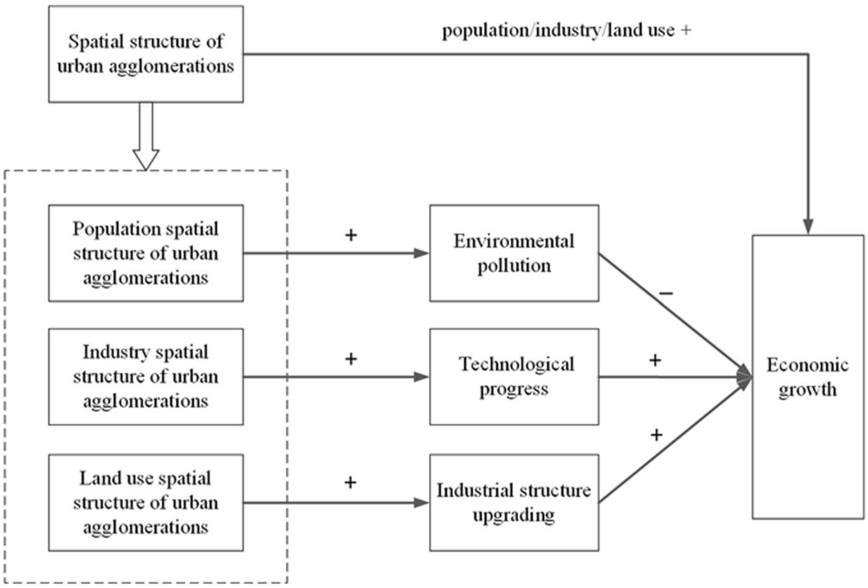

Fig. 1 Mechanism of the impact of spatial structure changes on the economic growth of urban agglomerations in western China. Note: "+" indicates enhancement, and "-" indicates weakening.

leverage the role of industrial agglomeration in promoting technological progress. Moreover, the manufacturing industry, especially the intelligent manufacturing industry, should be encouraged to gather in central cities in western China, and the cultivation of advanced manufacturing industry clusters should be accelerated. At the same time, an innovation platform for advanced manufacturing clusters should be built, a public service system serving the entire industrial chain should be formed, and the efficiency of technology transformation and technological innovation in western China should be improved.

Finally, the distribution of the construction land in the central cities of urban agglomerations in western China should be increased, the spatial concentration of the construction land should be improved, the dynamic supervision system of land use in western China should be optimized by using big data, and the overall land use efficiency of urban agglomeration should be improved. Moreover, the relationships among urban land use, socioeconomic resources and environmental benefits should be coordinated; the spatial distribution of different types of land allocation should be adjusted; and the upgrading and rationalization of the urban agglomeration industrial structure in western China should be promoted.

Data availability

The authors confirm that all data underlying the findings are fully available without restriction. All relevant data are within the paper and its Supplementary Information files.

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Author contributions
Jing Zhao designed the study. Jing Zhao and Na Chen wrote the manuscript. Zhen Jin provided scientific comments on the manuscript and proofread the manuscript. All authors have read and agreed to the published version of the manuscript.

Competing interests
The authors declare no competing interests.

Ethical approval
This article does not contain any studies with human participants performed by any of the authors.

Informed consent
This article does not contain any studies with human participants performed by any of the authors.

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