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Digital development and the improvement of urban economic resilience: Evidence from China

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A R T I C L E I N F O

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A B S T R A C T

Digital technologies are empowering economic and social development, which attracts scholars' attention to the relationship between digitalization and economic resilience, However, the empirical analysis for different countries and stages of development are inconsistent, and the influencing mechanism need to be further explored. Using panel data for 284 prefecture-level cities in China from 2007 to 2020, this study examines the impact of urban digital development on economic resilience. The findings are as follows: (1) The increased digitalization significantly enhances the urban economic resilience, and this effect was more pronounced in eastern regions and large-scale cities. (2) The relationship between digitalization and economic resilience follows an inverted U-shape as population density increases. (3) The spatial effects show that increased digitalization has a significant positive effect on local economic resilience, but weakens the resilience of the surrounding areas. (4) The analysis of mechanism reveals that the positive impact of digitalization on the urban economic resilience is mainly achieved by improving the quality of the regional labor force and total factor productivity. The study provides theoretical and empirical evidence for accelerating the digital construction, fully releasing the digital dividend in order to strengthen economic resilience.

1. Introduction

China has experienced impressive economic growth in recent decades. Despite increasing global economic stagnation and tension in international relations, China's economy has demonstrated strong resilience. Even amid contractions in demand, supply shocks, and weaker expectations, China's GDP reached 121 trillion yuan in 2022, marking an increase of approximately 3 % year-on-year. This growth illustrates the robust resilience of the Chinese economy, even in challenging environments. Nonetheless, "scarring effect" from shocks caused by risky events cannot be completely eliminated in the short term. The 2008 global financial crisis continued to have a negative impact on approximately 85 % of economies until 2017 [1]. Therefore, the key to the long-term stability and improvement of an economy lies in its capacity to resist and recover from shocks, readjusting to a stable state of development thereafter.

Although regional development is steadily improving at the city level, it faces internal risks and external uncertainties. Strengthening urban ability to cope with external shocks and resist uncertain risks with strong resilience is the key to promoting urban development. In other words, the strength of economic resilience is not only a strong guarantee for the region to continue to achieve sustainable development but also a focus for high-quality development [2]. Currently, the wave of information technology promotes the transformation of a traditional economy to a digital economy [3], with digitalization, artificial intelligence, and other new

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technologies reshaping production and lifestyle, and have a positive impact on personal convenience, enterprise digital transformation, industrial upgrading and regional development, which has aroused the academic community's attention to the relationship between digitalization and economic development. For example, relevant studies have confirmed that broadband internet access has a positive impact on the labor market in the US [4], and that internet technology can promote productivity improvement in the UK [5]. In particular, the release of digital potential in rural areas plays an important role in rural development and growth of the entire economy [6]. In a study of developing countries, scholars found that the accessibility of financial services brought about by digitalization can stimulate the economic growth and development of developing countries [7]. Relevant studies have affirmed the positive role of digitalization in regional development, laying the foundation for the improvement of regional economic resilience. However, most studies have demonstrated the relationship between digital economy and regional economic resilience, mainly through theoretical analyses, and empirical studies need to be supplemented. Although China's digital economy continues to develop and plays an important role in the international community, there has been uneven development among different regions in China, which may lead to a digital divide [8]. In the context of the rapid development of digitalization, overcoming the adverse impact of the digital divide, with data as the core production factor and digital technology as the core driving force, to enhance the resilience of Chinese cities' economic development needs urgent attention.

Therefore, by constructing a two-sector model of the traditional sector and the sector introducing digital technology, combined with the analysis of existing studies and relevant theories, this study proposes a hypothesis of the correlation between urban digital development and the improvement of economic resilience at the theoretical level. On this basis, the influence mechanism between the two and possible nonlinear and spatial effects were analyzed, and relevant research hypotheses were proposed. Besides, based on panel data of 284 prefecture-level cities in China, we empirically tested to explore the role of the digital development of Chinese cities in enhancing economic resilience.

This paper has some contributions to existing literatures. First, by introducing digitalization into the production function from the perspective of production inputs, we construct a theoretical model to analyze the impact of digital development on the rate of change in regional GDP, which provides a theoretical basis for empirically analyzing the impact of digital development on economic resilience. Second, we empirically analyze the nonlinear and spatial effects, clarifying that the impact of digitalization on urban economic resilience may be constrained by external factors and suggesting potential regional boundaries for this impact. This provides a reference for relevant sectors to use digital technology to strengthen economic resilience. Third, this study interprets the path of digital development in enhancing the economic resilience in terms of total factor productivity improvement and quality of labor force. It enriches and expands the empirical research on the relationship between digitalization and urban development. The findings of this study provide a theoretical basis for improving the level of regional digitization and enhancing economic resilience based on the rapid development of the digital economy, thus contributing to high-quality economic development.

2. Literature review and research hypotheses

2.1. Literature review

2.1.1. Definition and measurement of economic resilience

Originally a physical concept, "resilience" refers to the ability of a material to absorb energy during plastic deformation or fracture, and is also widely addressed in engineering and ecology. Ref. [9] were the first to introduce resilience to spatial economics in their study. Ref. [10] distinguished between engineering, ecological, and evolutionary resilience in their studies. Although there is no consistent definition or measurement method for resilience in academia, relevant studies have emphasized the important role of economic resilience in the stable development of the regional economy. For instance, economic resilience was defined as the ability of an economic system to recover to a stable equilibrium process after a certain shock [11], whereas some scholars consider economic resilience as a dynamic and complex process in which a region continuously adjusts after facing shocks [12]. Quantitative research on economic resilience primarily includes single indicator and indicator-system construction methods. The construction of multidimensional indicators commonly includes measurements from three perspectives: risk resilience, adaptation, and transformation [13]. Similarly, corresponding indicators from three dimensions was eslected, including resistance and resilience, adaptation and adjustment, and innovation and transformation [14]. A single indicator usually measures economic resilience in terms of the fluctuation of an economic indicator after a region is hit by a shock, mainly the level of economic development or the number of people empolyed [15,16].

2.1.2. The influencing factors of economic resilience and the role of digitalization

Wolff's law posits that human skeleton density and stiffness enhance with prolonged exposure to external stress [17], which suggests that continuous exposure to stress does not always have a negative impact, and resistance to vulnerability may be more conducive to benefiting from stress. Similarly, in terms of the long-term development of the economic system, the vulnerability of the economy may increase when it is exposed to volatility owing to the occurrence of unexpected events or risks. At this time, individuals with strong economic resilience are better positioned to face uncertainty proactively and stably, enabling them to recover themselves from short-term fluctuations. Marx's theory of economic crisis also points out that, although an economic crisis has a great negative impact, it is also a process of eliminating backward production modes [18], thereby adjusting and upgrading the industrial structure. Thus, by correctly understanding the crisis, changing the risk opening, and positioning oneself in a position to benefit from anti-vulnerability [19], one can make changes and achieve better development.

Consequently, to promote high-quality regional economic development, it is imperative to enhance the ability of a region to cope with uncertain shocks and increase the speed and effectiveness of regional recovery from shocks. Studies on the factors affecting economic resilience have identified macroeconomic policies as an important external source of a country's economic resilience [20]. Through the empirical analysis of Bangladesh's time series data, it found that the shock on financial progress can promote economic growth [21]. The significance of industrial structure in regional development, has received much attention. Some researches have pointed out the positive effect of diverse industrial structures on economic resilience. For example, Ref. [12] measured the degree of regional industrial agglomeration and empirical analysised that diversified industrial structures enable cities to disperse risks and have stronger economic resilience when the region is hit by shocks. In contrast, other studies have demostrated that industrial agglomeration improves urban economic resilience [22]. Similarly, population agglomeration also got some attention, and related research pointed out that population agglomeration can enhance economic resilience by improving urban productivity [23]. From the perspective of the government's role, improving government debt tolerance effectively inhibits liquidity risk brought by external shocks to the financial environment, thus enhancing economic resilience [24]. In the Yellow River region of China, the implementation of active support measures by the government can help cities resist shocks [25]. Besides, Ref. [26] conducted a study using US county-level data on employment, with COVID-19 as the background, this study suggested that countries with a large proportion of small banks have a lower volatility in employment rate.

The impact of factors related to digital technology on economic resilience has attracted scholars' attention. Based on the panel data from Chinese provinces, it was found that digital finance promotes economic resilience by narrowing the income gap between urban and rural areas, improving capital allocation efficiency, and leading to consumption upgrading [27]. Another study illustrated the positive role of digital economy in boosting urban economic resilience through a panel fixed effects model, using multidimensional indicators to measure urban economic resilience [28]. Ref. [29] conducted research on European countries, and found that countries with higher Internet connectivity experienced relatively low output loss during the COVID-19 pandemic, using the difference-difference method and propensity matching score method. These studies highlight the important role of information technology or digital construction in stabilizing regional economic development and enhancing urban enonomic resilience.

Through reviewing and organizing existing literature, several key points emerge. First, scholars have different focuses on the definition of economic resilience from different perspectives. However, relying solely on the calculation of the index system or the measurement of a single index may not effectively reflect fluctuations and specific response to impacts. Second, while there is existing literature on the relationship between regional digital development and economic resilience, the transmission mechanism, nonlinear relationship, and spillover effect of the relationship require further clarification. This clarification is essential to provide support for improving regional economic resilience by relying on digital technology. Therefore, this study aims to address this gap using panel data from Chinese cities. Economic resilience of cities will be calculated using a counterfactual method and the impacts of digitalization on the improvement of urban economic resilience will be explored through theoretical analysis and empirical testing.

2.2. Research hypotheses

2.2.1. Impact of digital development on urban economic resilience

The theoretical model in this study is based on the analytical approach of [30], which considers both export and traditional two-sector models, and based on this model, we construct a two-sector model of traditional economic sector and digital economic sector by referring to Ref. [31]. Drawing on existing studies, we introduce digitalization in production, that is, assuming that economy as a whole, which is composed of two sectors: the traditional economic sector and the digitalized economic sector, and the output of the digitalized sector affects the output of the traditional economic sector. The production functions of the two sectors are assumed as follows:

$$T = T(K_T, L_T, D) \tag{1}$$

$$D = D(K_D, L_D) \tag{2}$$

Where: T denotes the traditional economic sector without the introduction of digital technology, D denotes the economic sector with the introduction of digital technology, and the total output of the whole economy Y is composed of the above two parts. K_T and K_D represent the capital invested by the traditional economic sector and the economic sector with the introduction of digital technology, respectively. L_T and L_D represent the labor input of traditional and digitalized sectors of the economy, respectively. Suppose that there is the following relationship between the marginal productivity brought by the capital and labor factors of the two sectors of the economy:

$$\frac{\partial D/\partial K_D}{\partial T/\partial K_T} = 1 + \alpha \tag{3}$$

$$\frac{\partial D/\partial L_D}{\partial T/\partial L_T} = 1 + \beta \tag{4}$$

$\partial T/\partial K_T$、 $\partial T/\partial L_T$ represent the marginal output of capital and labor inputs in traditional sectors of economy, respectively; $\partial D/\partial K_D$、 $\partial D/\partial L_D$ represent, respectively, the marginal output of capital and labor inputs in sectors of the economy where digital technologies are introduced. Since the production activities introduced into digitalization tend to be more innovative and have a relatively higher production efficiency than traditional sectors of economy, the marginal output of the factors should be greater than that of the traditional sectors, which means that α and β are greater than 0. To simplify the analysis, α = β is assumed, that is, the two factors of production are assumed to have the same marginal productivity in each sector. Take the time derivative of equations (1) and (2) respectively:

$$\frac{dT}{dt}=\frac{\partial T}{\partial K_T}\frac{dK_T}{dt}+\frac{\partial T}{\partial L_T}\frac{dL_T}{dt}+\frac{\partial T}{\partial D}\frac{dD}{dt} \tag{5}$$

$$\frac{dD}{dt}=\frac{\partial D}{\partial K_D}\frac{dK_D}{dt}+\frac{\partial D}{\partial L_D}\frac{dL_D}{dt} \tag{6}$$

The total output of the whole economy Y is composed of T and D, therefore, by adding equations (5) and (6), the time derivation of total output can be expressed as:

$$\frac{dY}{dt}=\frac{dT}{dt}+\frac{dD}{dt}=\frac{\partial T}{\partial K_T}\frac{dK_T}{dt}+\frac{\partial T}{\partial L_T}\frac{dL_T}{dt}+\frac{\partial T}{\partial D}\frac{dD}{dt}+\frac{\partial D}{\partial K_D}\frac{dK_D}{dt}+\frac{\partial D}{\partial L_D}\frac{dL_D}{dt} \tag{7}$$

dK_T/dt、 dK_D/dt、 dL_T/dt *and* dL_D/dt are the increases in capital and labor in the two sectors of the economy respectively. Since the increase in capital can be expressed as the increase in investment I in the current period, and the increase in the total labor force of the entire economy is the sum of the changes in labor force in the two sectors, that is:

$$I=\frac{dK_T}{dt}+\frac{dK_D}{dt} \tag{8}$$

$$\dot{L}=\frac{dL}{dt}=\frac{dL_T}{dt}+\frac{dL_D}{dt} \tag{9}$$

Then we substituted equations (3), (4), (8) and (9) into equation (7), and sort them out, equation (10) can be obtained:

$$\frac{dY}{dt}=\frac{\partial T}{\partial K_T}I+\frac{\partial T}{\partial L_T}\frac{dL}{dt}+\left(\frac{\alpha}{1+\alpha}+\frac{\partial T}{\partial D}\right)\frac{dD}{dt} \tag{10}$$

Denoting the marginal productivity of capital in the traditional sector $\partial T/\partial K_T=\rho$, and assuming that there is a linear relationship between the actual labor productivity of the sector and the average output of labor in the entire economy, expressed as $\partial T/\partial L_T=\sigma Y/L$. Then, dividing equation (10) through by Y, it can show:

$$\frac{\dot{Y}}{Y}=\rho\frac{I}{Y}+\sigma\frac{\dot{L}}{L}+\left(\frac{\alpha}{1+\alpha}+\frac{\partial T}{\partial D}\right)\frac{\dot{D}}{D}\frac{D}{Y} \tag{11}$$

From equation (11), it can be found that the left side of the equation represents the growth rate of output, and the right side is mainly composed of three parts. Specifically, the first two parts indicate that the growth of capital input and labor input can drive the growth of output, and the third part indicates that the increase in the proportion of digitalized economic sectors in the entire economy can drive the improvement of productivity. It implies that the shift of production factors from traditional economic sectors to digitalized economic sectors is the key to the improvement of regional output growth rate. And according to the analysis, the steady improvement of regional GDP growth rate is an important consideration in a region's resilience when dealing with external shocks. An economy with a relatively high and stable growth rate tends to have stronger economic resilience.

Existing research affirms the positive impact of digital technology. In traditional development modes, factors such as flow barriers, low output efficiency, and mismatches between output and factors hinder the process of high-quality economic development, leading to relatively fragile regional economy. However, in the context of digitalization, the Internet, artificial intelligence, and big data have entered production and life has brough positive changes. From a household perspective, the use of digital technology, including the construction of rural broadband, plays a positive role in improving urban economy resilience [32]. At the enterprise level, access to rich data resources allows for efficient supply-demand matching and low-cost resource allocation [33], which is crucial for innovation, development and optimization of the industrial chain. This enables cities' ability to cope with risk shocks. At the macro level, Internet access can reduce the cost of information and knowledge collection and promotes innovation of the US [34], leading to a positive impact on regional economic growth. Therefore, digital development plays an important role in promoting the optimization and transformation of industrial structure and stimulating economic growth, and these factors contribute to stabilizing regional economic development and enhancing economic resilience. Therefore, we propose the following hypothesis:

Hypothesis 1. Digital development enhances the economic resilience of cities.

2.2.2. Analysis of the mechanism of digital development affecting urban economic resilience

As noted above, we confirmed the positive role of regional digital development in improving economic resilience through model construction and theoretical analysis. So, what is the transmission mechanism between them? In this section, we will analyze the mechanism by which digitalization affects regional economic resilience from two aspects: the increase of total factor productivity and the improvement of regional labor quality.

Data are regarded as a production factor, and they participate in the distribution according to their contribution. This indicates that the digital economy plays an important role in the improvement of total factor productivity. Specifically, technological breakthrough is the key to sustainable development [35], especially digital technology, which can break the barriers of information asymmetry and increases the information access channels for all types of market players, which not only helps improve the decision-making efficiency of enterprises [36], but also makes digital technology penetrate all walks of life in a region, thus accelerating enterprise upgrading [37] and improving total factor productivity. Furthermore, digital technology breaks regional boundaries, and by breaking down factor flow barriers and reducing transaction costs, resources can be reorganized across regions. This helps change the low output efficiency and misallocation of factors under the traditional development model and reshapes the allocation form of factors based on the information technology industry [38], thus improving allocation efficiency. In addition, the deep integration of digitalization and traditional industries has promoted the high-quality development of related industries, which is conducive to the efficient production of upstream and downstream enterprises. The improvement of regional total factor productivity has increased the operation efficiency of the entire regional economic system and driven high-quality economic development, which is the premise of regional economic resilience; that is, regions with a higher output growth rate have a more solid foundation to cope with shocks. Moreover, regions with higher production efficiency can promptly adjust the allocation of factors and ensure relatively higher output through the transfer of production factors when an impact comes, so that cities can form new growth points during the impact. Therefore, we propose the following hypothesis:

Hypothesis 2. Increased digitalization enhances economic resilience by increasing regional total factor productivity.

It is obvious that digitalization breaks the shackles of geographical distance and not only promotes the borderless flow of information, capital, and other resources, but also has a positive impact on the flow of talents. On the one hand, enhancing the digital level plays a significant role in promoting regional economic and social development. Although intelligent development will replace much low-skilled labor, the increased degree of automation will contribute to the development of enterprises to a large extent, thus increasing their job demand [39]. This implies that the improvement of digitalization can create a large number of new jobs, thus attracting more high-quality talent to flow into the region and optimizing the supply structure of the regional labor force. On the other hand, the progress of digital technology has optimized the employment environment [40], and inevitably increased the demand for highly skilled talents in digitalization, artificial intelligence and other related fields, prompting workers to constantly improve their own quality [41]. In this way, the traditional low-value labor force will be relatively reduced, and the employment structure will be optimized. Based on the supply and demand matching of the labor market, the quality of human capital in a region can be improved. In turn, the optimization of regional labor quality will have a positive impact on the upgrading of the regional industrial structure and the economic development [42], and the region will be more able to withstand economic fluctuations. Therefore, we propose the following hypothesis:

Hypothesis 3. Increased digitalization can enhance economic resilience by improving the quality of labor force in a region.

2.2.3. The nonlinear effect of digitalization on urban economic resilience

Although the positive correlation between digitalization and economic resilience has been analyzed and demonstrated, the effect may also be non-linear due to several factors, such as the urban-rural income gap weakening the positive impact of digital finance on urban economic resilience [43]. In the regional development, populations of city play a pivotal role in economic development. The characteristics such as the breaking of geographical boundaries and the strengthening of factor flow brought about by the development of digitalization have reshaped the regional population pattern, and it accelerated the population agglomeration in regions with higher digital level. Population aggregation is conducive to the development of innovation activities and the supply of labor factors. In the digital age in particular, large-scale Internet usage reduce the marginal cost of digitalization, increases marginal revenue, and exponentially increases the value of digitalization. This helps digitalization exert its enhancing effect on the resilience of the urban economy. However, excessive population density may inhibit urban economic development because of the "crowding effect"; that is, when the population density of a city is too large, the number of per capita resources will be greatly reduced in terms of resource allocation, and a certain negative externality will be generated. Not only is this not conducive to the development of various economic activities, but it also leads to talent spillover, increases the uncertainty of local development, and weakens the urban ability to resist risks. Consequently, digitalization and economic resilience may show an inverted U-shaped relationship as population density increases. To this end, this study proposes the following hypothesis:

Hypothesis 4. The positive effect of digitization levels on economic resilience is constrained by high population density.

2.2.4. The spatial effect of digitalization on regional economic resilience

A salient feature of digital technology's rapid advancement is its substantial reduction of spatial and temporal distance [44]. This phenomenon disrupts traditional physical boundaries, encouraging information flow and enhancing the exchange of human capital and technology across regions. As a result, it lowers information search costs for individuals and enterprises, reinforces inter-regional connections, and aids the economic and social development of cities, thereby boosting the urban capacity to weather shocks. However, As the level of digitization in the different regions of China varies greatly, this spatial disequilibrium will also bring about a "siphon effect" or "polarization effect" [45]. This is because in the development model of the digital economy, the fluidity of factors is enhanced and the production factors naturally seek high returns. In this case, the production factors will choose to flow from regions with backward output to the developed regions [46], resulting in high-quality factors more concentrated in regions with a higher digital level. This will create a "Matthew effect," where the strong get stronger, thereby inadvertently inhibiting the development of surrounding cities with a low initial level of digital development. Thus, in turn, can exacerbate the economic development gap between regions. As a result, neighboring regions may face many unstable factors. Once a region is hit by a shock, it is difficult to quickly respond and withdraw from it. However, they are vulnerable to certain impacts. China's digital technology is now in a stage where the rapidly developing areas find it easier to absorb the inflow of resources, and with further development of digitalization in the future, digital dividends will be gradually released. Therefore, the improvement in urban digitization can significantly enhance local economic resilience, but it may also have a siphoning effect on surrounding areas. Therefore, we propose the following hypothesis:

Hypothesis 5. Digital development increases local economic resilience, but has a "siphon effect" on surrounding areas.

3. Research methodology

3.1. Data sources

Natural disasters, such as earthquakes, floods, and fires, also have a significant negative impact on regional economic and social development. However, when taking all the cities in a country as a research sample, the effect of a crisis in one region on others is minimal, making it challenging to analyze the economic resilience of various regions comprehensively. Historical events such as the Asian financial crisis in 1997, the global financial crisis in 2008, and the COVID-19 outbreak in early 2020 had profound impacts on the entire country. Considering the timing of the events and the continuity and availability of data before and after the event, this study focuses on the 2008 financial crisis as an impact event. Notably, 2005 marked the advent of the Internet, and its rapid development laid an important foundation for enhancing the digital level in all aspects. Therefore, this study uses 2006 as the benchmark and examines urban data from 2007 to 2020. The data comes from two main sources. First, economic statistical indicators at the city level were sourced from the China Statistical Yearbook, China Urban Statistical Yearbook, Statistical Yearbook of Some Cities, and the Statistical Bulletin of National Economic and Social Development. An interpolation method was used to interpolate the missing values. Second, to measure the urban digital level, we collected and sorted government work reports of prefecture-level cities from 2007 to 2020 through textual analysis.

3.2. Model construction

According to the theoretical analysis above, the digital level of a city has a positive impact on the improvement of regional economic resilience. As the sample data selected in this paper is panel data, which include cities and years, so we constructed the panel data model. In addition, considering that there may be some variables excluded from the model, which change with the city changes and time changes, we adopt the model of dual fixed effects of year and city for empirical analysis. The Hausman test in the empirical analysis of Section 4 also proves that the fixed-effect model is more appropriate. More importantly, it assumes that there is a defined linear relationship between the independent and dependent variables, which is the same across all observations. Furthermore, this model also assumes that each individual has a unique intercept and slope, and the parameters are independent and uncorrelated between different individuals. In this paper, the individual means each city. In addition, dual fixed effects model of year and city is suitable for data analysis where individual and time characteristics need to be controlled, and it can also alleviate the endogeneity caused by missing variables to some extent. Therefore, the baseline regression model is as follows:

$$Resilience_{it} = \alpha_0 + \alpha_1 Digital_{it} + \alpha_2 Controls_{it} + \theta_i + \varphi_t + \varepsilon_{it} \tag{12}$$

In equation (12), the dependent variable $Resilience_{it}$ refers to the economic resilience of city i in year t, $Digital_{it}$ refers to the digitalization level of city i in year t, and $Controls_{it}$ refers to other control variables that may affect the urban economic resilience of city. θ_i、φ_t represent fixed effect of cities i and the time fixed effect in year t, respectively, and ε_{it} is a random error term.

In the theoretical analysis, we proposed that the digital development of cities can enhance economic resilience by facilitating the regional total factor productivity and the quality of regional labor force. In order to further test the existence of the machanisms empirically, we will constract the mediator effect model with total factor productivity and labor quality as the mediator variables, and it follows a three-step procedure, which is usually adopted in empirical analysis of the transmission mechanism between variables [47]. Specifically, on the premise that the coefficient α_1 of the baseline regression model (12) is significant, a regression model of digitalization's impact on total factor productivity and labor quality is constructed as equations (13) and (15). The regression equation of the combined impact of digitalization and mediator variables on economic resilience is shown in equations (14) and (16):

$$tfp_{it} = \beta_0 + \beta_1 Digital_{it} + \beta_2 Controls_{it} + \mu_i + \varphi_t + \varepsilon_{it} \tag{13}$$

$$Resilience_{it} = \gamma_0 + \gamma_1 Digital_{it} + \gamma_2 tfp_{it} + \gamma_3 Controls_{it} + \mu_i + \varphi_t + \varepsilon_{it} \tag{14}$$

$$labor_{it} = \theta_0 + \theta_1 Digital_{it} + \theta_2 Controls_{it} + \mu_i + \varphi_t + \varepsilon_{it} \tag{15}$$

$$Resilience_{it} = \rho_0 + \rho_1 Digital_{it} + \rho_2 labor_{it} + \rho_3 Controls_{it} + \mu_i + \varphi_t + \varepsilon_{it} \tag{16}$$

In addition, the impact of digitalization on economic resilience may be differentiated due to the difference in urban population density. For this reason, we will set the regional population density is taken as the threshold variable, and consrtuct a panel threshold model

[48], which can reflect the different effects of independent variable on dependent variable at different threshold of a variable [49]. This model is shown in equation (17), where I (·) is the indicator function, the value of which can be 0 or 1. When the threshold variable meets the conditions shown in brackets, indicates that the function takes a value of 1, otherwise 0. The regression model will be divided into several intervals according to the threshold values, thus we can analysis the different coefficients in each intervals based on the regression results [50].

$$Resilience_{it} = \tau_0 + \tau_1 Digital_{it} \cdot I(density_{it} \leq \pi) + \tau_2 Digital_{it} \cdot I(density_{it} > \pi) + \tau_3 Controls_{it} + \mu_i + \varphi_t + \varepsilon_{it} \tag{17}$$

According to our analysis, the impact of urban digitalization on economic resilience may also have spatial effects, therefore we further introduced the spatial interaction terms of dependent variable and independent variable into the model, expanded the model into a spatial econometric model. Taking the spatial lag operators of both dependent and independent variables into consideration, we constructed a Spatial Durbin Model (SDM) to test the spatial spillover effects of digital development on regional economic resilience, which is set as follows:

$$Resilience_{it} = \delta_0 + \rho W * Resilience_{it} + \delta_1 Digital_{it} + \delta_2 W * Digital_{it} + \delta_3 Controls_{it} + \delta_4 W * Controls_{it} + \mu_i + \varphi_t + \varepsilon_{it} \tag{18}$$

In this equation, ρ denotes the spatial autoregressive coefficient, W is the spatial weight matrix, and W* is the spatial lag term of each variable. To make the regression conclusion more robust, this study adopts the economic distance weight matrix and the economic geography nested matrix respectively, in which the economic distance weight matrix is measured as $W_1 = \frac{1}{|pgdp_i - pgdp_j|}$, and the *pgdp* is calculated based on the average per capita GDP of each city from 2007 to 2020. The nested matrix of economic geography is obtained by combining the geographical distance based on the latitude and longitude of the city and the economic distance based on the average per capita GDP, that is to say, it is measured as $W_2 = \left(\frac{1}{|pgdp_i - pgdp_j|}\right) \times e^{-d_{ij}}$.

3.3. Variable selection and descriptive statitics

3.3.1. Dependent variable: economic resilience

Given the relative stability of employment numbers and rates in China, and the more pronounced variance in GDP and GDP growth rates across years and regions—especially when the regional economy faces shocks—we use the per capita GDP index to gauge urban economic resilience in this study. That is to say, we define the economic resilience as the ability of urban resilience and recovery capacity to withstand shocks. Following the counterfactual methods used by Ref. [10], we compare the expected change in per capita GDP with the real changes. This is based on the real per capita GDP of each city in China from 2007 to 2020 and corresponds to the calculation of resilience and recovery capacity of each city in response to external shocks.

While previous studies generally measured resilience using statistical analyses or causal inference counterfactual methods, they often relied on national indicators for comparison. However, significant development differences exist between cities, particularly those with high levels of development or those lagging behind the national average. Thus, in this study, we use the per capita GDP of each province in the corresponding year as a reference and calculate the change in the urban per capita GDP and the expected change based on the change rate of the province's per capita GDP. This approach enhances the comparability of the variables and the relevance of the results.

The expected change in per capita GDP of a city during resilience and recovery periods is defined as follows, using the calculation method proposed by Ref. [51]:

$$(\Delta R_{i,t+k})^e = R_{i,t} \times GR_{j,t+k} \tag{19}$$

In equation (19), $R_{i,t}$ is the real per capita GDP of city i in year t, $GR_{j,t+k}$ is the real change in per capita GDP growth rate of the province j where city i is located in the period $t+k$. $(\Delta R_{i,t+k})^e$ is the expected change in per capita GDP of city i in the period $t+k$. Since the financial crisis was chosen as the impact event in this study, which began in 2007, the expected change in per capita GDP from 2007 to 2020 was calculated based on the real per capita GDP of each city in 2006.

According to the calculation result of equation (19), the resilience (Res), and recovery (Rec) after the shock for city i are calculated as:

$$Res_i = \frac{\Delta R_i^{res} - (\Delta R_i^{res})^e}{|(\Delta R_i^{res})^e|} \tag{20}$$

$$Rec_i = \frac{\Delta R_i^{rec} - (\Delta R_i^{rec})^e}{|(\Delta R_i^{rec})^e|} \tag{21}$$

In equations (20) and (21), ΔR_i^{res} and ΔR_i^{rec} represent the change in real per capita GDP of city i respectively. The values calculated based on equations (20) and (21) were used as proxy variable for the urban economic resilience, and all values were standardized.

3.3.2. Independent variable: digitization level

Based on the different research objectives, scholars in existing studies mostly measure the level of digitalization from different dimensions. For example, according to construct an index system to measure digitalization from four dimensions, including production digitalization, cunsumption digitalization, circulation digitalization and government digilization [52]. It can be seen that related study is conducted from the application level of the Internet, which means that the level of regional digitalization is usually quantified in terms of Internet or digitalization usage. According to the previous anaysis, urban digital development we discussed mainly refers to the use of digital technology and information system to promote the development and transformation of various aspects of social economy. What is more, the development of urban digitalization is intrinsically tied to various forms of governmental policy support. In this context, the frequency of words related to digitalization and digital technology in a city's annual governmental work conference report—where the municipal government summarizes the work of the previous year—serves as an indicator of the government's focus on the urban digital development. A higher frequency of these terms suggests better digital development. Besides, variables derived from keyword frequency in reports can be notably exogenous. Therefore, we manually collected annual government work reports from prefecture-level cities and utilized Python to tally frequencies of digitalization-related keywords. Following the methodology of [53], we identified 18 key words: digitalization, Internet, big data, artificial intelligence, cloud computing, digital technology, digital economy, digital industry, information technology, 5G, Internet of Things, network, blockchain, intelligent, e-commerce, cloud platform, cloud architecture, and robots. A higher occurrence of these words indicates a higher level of digital development in the region, in order to eliminate the heteroscedasticity and ensure the stationarity of the variable [54], we used the logarithmic value of the frequency of digitization-related words to measure the core independent variable, and we divided this indicator by 10, resulting in the variable *lndig*.

3.3.3. Mediator variables

In this study, we measure the urban total factor productivity (*tfp*) based on the input and output through the Malmquist index method, where the input indicators include labor and capital, specifically the number of employees and the value of fixed assets calculated based on the perpetual inventory method, and the output indicator is the real GNP of the city in that year.

Ref. [55] define the labor force with university degree or above as advanced human capital. This study draws on the practice of established scholars to measure the amount of advanced human capital as a proportion of the total regional population aged six years and above. However, as the number of people with each level of education in the city is difficult to obtain, provincial data are used as a benchmark to calculate the labor quality in the province, and on this basis, the quality of the labor force is treated as a proxy variable for the quality of human capital in the city by using the ratio of urban GDP per capita to its province's per capita GDP in that year (*lab*).

3.3.4. Control variables

In order to avoid the deviation of the estimation results caused by missing variables, and based on the existing research and the requirements of this research, we selected control variables to optimize the model of digitalization affecting urban economic resilience [2,12,56]. The control variables mainly include: financial development level (*dev*), which is measured by the proportion of the sum of deposits and loans of urban financial institutions to GDP at the end of the year, and the ratio is divided by 100 for each of analysis. Fixed asset investment (*lninv*), it is measured by the logarithm of fixed asset investment of the city. Financial self-sufficiency rate (*fin*), the ratio between local general public budget revenues and general public budget expenditures is used as the proxy variable. Urbanization rate (*urb*), expressed as the proportion of urban population to the permanent resident population of the city. Economic density (*lneco*), calculated by the ratio of an urban gross national product to its area, and we take the logarithm of the value. Disposable income (*lninc*), we use the logarithm of urban resident' per capital disposable income.

Table 1 reports the descriptive statistical results of all variables. As is shown in it, the mean of *res* is 0.2133, implying a low-resilience across the sample cities over the recent years, that is to say, enhancing urban economic resilience is necessary and significant. The mean and standard of *lndig* is 2.5577 and 0.7941, respectively, which indicates the unbalance digilization among cities. Similarly, the results of other variables also demonstrated that although the development of cities has improved in recent years, there is still an unevenness among cities.

4. Empirical analysis

4.1. Baseline regression analysis

Based on the analysis above, we tested equation (12) using both the fixed effects model and the random effects model. The

Table 1
Descriptive statistics.

variables	N	Min	Max	Mean	Std.
res	3976	0	1	0.2133	0.0539
lndig	3976	0	4.7958	2.5577	0.7941
dev	3976	0.5600	14668.2400	5.9893	232.5905
lninve	3976	12.9102	19.1433	16.0239	1.0349
lnfin	3976	0.0544	1.5413	0.4628	0.2281
urban	3976	0.1641	1	0.5277	15.8837
lneco	3976	0.3426	11.8391	7.0256	1.3144
lninc	3976	8.7131	11.2442	10.0488	0.4240

Hausman test result, with a *P*-value less than 0.01, suggests selecting the fixed effects model for further analysis. Thus, we developed subsequent models using the fixed effects model. Columns (1) and (2) of Table 2 show the impact of various factors on urban economic resilience after considering only the level of digitization and adding control variables to the model. The results show that after controlling for city and time fixed effects, the regression coefficients of the influence of the regional digitization level on economic resilience are significantly positive. The model's goodness of fit notably improves when control variables are added, underscoring the appropriateness of the control variables selected. Specifically, the coefficience in Column (2) is 0.022, indicating that when the urban digital level increases by one unit, the economic resilience index increases by 2.2 %, which confirms that the development of digitalization can play a significant and positive role in improving urban economic resilience, this result is consistent with the studies of some scholars [14,28], this reason is that the improvement of digital enables city to rely on the information technology to improve the development level of digital economy, thus driving the high-quality development of urban economy [31,56], which provides strong ability to resist risks and cope with uncertain events for cities. Therefore, city with higher digital level also has a stronger economic resilience, indicating that Hypothesis 1 is confirmed.

The regression results of the control variables show that improvements in financial development level, financial self-sufficiency rate, and economic density positively affect the urban economic resilience. This finding highlights the importance of bolstering urban economic strength, enhancing the level of financial development, and strengthening government financial capacity for stabilizing urban development and improving the economy's risk resistance of cities. More importantly, a study based on Aferican demonstrated that the financial development have positive effect on economic growth, especially with a higher degree of economic growth [57], which is similar to ours, whereas provides additional evidence of the improtance to higher levels of economic development. However, fixed asset investment negatively impacts economic resilience, suggesting that an increase in current period investment may not effectively enhance urban resilience, this might be due to the lag in economic benefits generated by investments, which do not necessarily have a positive effect in the current period.

4.2. Endogeneity problem

Our findings indicate that digital development positively impacts urban economic resilience. However, regions with stronger economic resilience also develop relatively faster economic and social terms, thereby laying the foundation for increased digitalization. In addition, regions with higher resilience may be more inclined to consolidate their own development trends through diversified elements, and favorably focus on digitalization. Thus, there may be a reverse causality between the level of regional digital development and the strength of economic resilience. In addition, although this study controlled for potential variables that may affect urban economic resilience, it still cannot cover all the variables, therefore, there may still be the problem of missing variables. To assess the impact of regional digitalization on economic resilience more accurately, possible endogenous issues in the model must be addressed.

To comply with instrumental variables requirements and the specific needs of this study, we primarily selected two instrumental variables. One is the independent variable with a two-period lag, which helps mitigate possible reverse causality in the model. The other is a historically index for studies on digitalization and the digital economy—specifically, the per capita postal and telecommunications business volume in each city from 1984 [44,58]. Historically, this volume reflected a regional postal and communications development level, which subsequently laid the groundwork for future digital services. Therefore, it is highly correlated with the digitalization level of independent variables. This historical indicator is unlikely to be negatively affected by the urban current development situation, hence meeting the instrumental variables selection criteria. However, as the data employed in this study consist of panel data, and the variable is a static cross-sectional index, we utilize the method proposed by Ref. [59] to incorporate time-varying variables for instrumental variable construction. We use the mean value of the digitalization level of other cities in the same province—with a one-period lag and excluding the city itself—interacted with the per capita postal and telecommunications business volume of the city in 1984, as the instrumental variable for the urban digital level in the current year. We use the two stage least squares method for estimation. In the first stage, instrument variables are used to predict endogenous variable, and the regression equation of the first stage is obtained. The predicted value is put into the regression model as the independent variable, and the fixed

Table 2
Baseline regression results.

	FE (1)	FE (2)	RE (3)	RE (4)
lndig	0.025* (1.78)	0.022* (1.71)	0.015 (1.06)	0.009 (0.71)
dev		0.005*** (12.48)		0.001** (2.45)
lninve		−0.006* (−1.66)		0.012*** (4.23)
lnfin		0.027** (2.45)		0.016 (1.62)
urban		0.019 (0.71)		−0.029 (−1.33)
lneco		0.100*** (12.26)		0.009** (2.16)
lninc		−0.004 (−0.21)		−0.032*** (−4.86)
constant	0.213*** (50.40)	−0.307* (−1.87)	0.215*** (50.82)	0.280*** (6.85)
i.year	YES	YES		
N	3976	3976	3976	3976
R^2	0.013	0.179	0.053	0.012
Hausman test	chi2 (2) = 48.68 Prob > chi2 = 0.0000			

Notes: Significance levels: ***p < 0.01; **p < 0.05; *p < 0.1. The t value is in the parentheses.

model is analyzed to get the estimated value, which is the second stage. As is shown in Table 3, Columns (1) and (2) report the results of taking the lag time of the explanatory variable as the instrumental variable, whereas Columns (3) and (4) report the regression results of the instrumental variable based on the historical per capita postal and telecommunications traffic in the city. The first stage test results affirm the coefficient of $L2.lndig$ and $post * dig$ is 0.061 and 0.036, respectively, and both pass the significance level of 1 %, illustrating that the strong correlation between the instrumental variables and the independent variables. The second stage results show that the coefficients of *lndig* is 0.713 and 0.163, respectively, which align with the benchmark regression in coefficient direction and pass the significance test, revealing that regional digitalization continues to significantly positively impact economic resilience enhancement even when excluding endogenous influences. This supports the main conclusions' robustness of this study. In addition, the KP-LM test and weak instrumental variable test of instrumental variables indicate that the instrumental variables do not exhibit weak instrumental variable problems or unidentifiable problems, confirming the appropriateness of the instrumental variables selected.

4.3. Robustness test

To further test the robustness and validity of the baseline model, we construct robustness tests from the following aspects.

4.3.1. Alternative variables

4.3.1.1. Independent variable. The urban digitalization level is highly correlated with the development level of digital economy, therefore, with reference to the research of [44,58], and combined with the research object of this paper and the data availability at the city level, we select four indicators at the city level to measure the level of digital economy instead of the independent variable *lndig*: per capita Internet users, per capita mobile phone users, per capita telecom business income, and the ratio of information transmission computer services and software industry employees to build an indicator system of urban digital development level, and adopts the entropy weight method for comprehensive evaluation. A comprehensive index (dig_1) reflecting the level of regional digital development was calculated. Column (1) of Table 4 reports the regression results using dig_1 as independent variable. It can be found that the positive impact of the digital composite index on economic resilience passes the test at the significance level of 5 %, and the coefficient of dig_1 is 0.083, which shows that each increase of one unit of dig_1 will increase urban economic resilience by 8.3 %, indicating that the core conclusion of positive effect of digitalization on economic resilience is robust.

4.3.1.2. Alternative the dependent variable. In this part, we change the measurement of economic resilience to test the robustness of our baseline model. Based on the median of the economic resilience index calculated above, we assign a value of 1 to the sample above the median and 0 to samples below the median, which is represented by Res_1. Considering that the dependent variable is a binary discrete variable, we choose the panel logit model to analyze. The regression results are shown in column (2) of Table 4, the coefficient of independent is still positive and significant, signifying that digitalization has a positive effect on improving urban economic resilience, the baseline results is robust.

4.3.2. Reduce the sample period

The global financial crisis that broke out from 2007 to 2008 and the COVID-19 that broke out from the end of 2019 to the beginning of 2020 had major impacts on the economic and social development of the country and the world. However, due to the relatively short resistance period and the different degree of impact suffered by different parts of the country when the incident occurred, so related samples may skew the results. Therefore, we exculded the years of the two shocks. The regression results of the reduced sample period are shown in column (3) of Table 4. The regression coefficient of digital development is significantly positive, indicating that the

Table 3
Regression results for instrumental variables.

	2SLS Second Stage (1)	2SLS First Stage (2)	2SLS Second Stage (3)	2SLS First Stage (4)
	res	*lndig*	*res*	*lndig*
lndig	0.713** (2.38)		0.163* (1.79)	
L2 lndig		0.061*** (3.32)		
*post*dig*				0.036*** (7.87)
dev	0.005*** (14.38)	−0.001 (−0.31)	−0.146 (−1.13)	3.887** (2.01)
lninve	−0.003 (−0.85)	−0.044 (−1.36)	−0.009*** (−3.37)	0.049 (1.36)
lnfin	0.006 (0.36)	0.273** (2.35)	0.042*** (4.01)	−0.041 (−0.35)
urban	0.018 (0.73)	0.415* (1.80)	0.005 (0.22)	0.913*** (3.54)
lneco	0.095*** (14.34)	−0.016 (−0.24)	0.083*** (12.94)	−0.148* (−1.95)
lninc	0.006 (0.36)	0.113 (0.79)	−0.104*** (−6.78)	1.233*** (13.76)
i.year	YES	YES	YES	YES
N	3692	3692	2996	2996
Kleibergen - Paaprk LM	11.04 (*P*-value = 0.0009)		64.96 (*P*-value = 0.0000)	
Cragg - Donald Wald F	13.271 (above the 15 % critical value of 8.96)		61.179 (above the 10 % critical value of 16.38)	

Notes: Significance levels: ***p < 0.01; **p < 0.05; *p < 0.1. The t value is in the parentheses.

Table 4
Results of the robust test.

	Alternative the independent variable (1)	Alternative the dependent variable (2)	2009–2018 (3)	Broadband China = 0 (4)	Broadband China = 1 (5)
	res	*res₁*	*res*	*res*	*res*
dig1	0.083** (1.99)				
lndig		3.192** (2.53)	0.025** (2.24)	0.017 (1.27)	0.058* (1.99)
dev	0.006*** (14.92)	34.725*** (3.07)	0.006*** (10.63)	0.006*** (12.59)	0.328 (0.65)
lninve	−0.004* (−1.72)	−0.453 (−1.60)	−0.003 (−1.00)	−0.008** (−2.02)	−0.015 (−1.67)
lnfin	0.029*** (3.18)	1.692** (2.08)	0.027* (1.76)	0.021* (1.80)	0.017 (0.64)
urban	−0.007 (−0.34)	3.169 (1.64)	0.021 (0.68)	−0.009 (−0.31)	0.068 (0.70)
lneco	0.102*** (19.01)	11.021*** (14.76)	0.102*** (10.53)	0.108*** (12.41)	0.086*** (3.51)
lninc	−0.006 (−0.59)	−3.647*** (−3.70)	0.031 (1.46)	−0.005 (−0.29)	−0.187** (−2.22)
constant	−0.318*** (−3.43)		−0.720*** (−3.47)	−0.292* (−1.71)	1.563** (2.08)
i.year	YES	YES	YES	YES	YES
N	3692	2996	2840	3772	204
R^2	0.166		0.150	0.176	0.459

Notes: Significance levels: ***p < 0.01; **p < 0.05; *p < 0.1. The t value is in the parentheses, but the z value is in the parentheses of Column (2).

conclusion is robust after reducing the sample period.

4.3.3. Subsample regression based on "Broadband China"

The development of digitalization is closely bound up with the construction of network infrastructure [44]. Broadband, as an important support for the development of high-tech industries, plays a key role in the new wave of informatization. To promote the development of China's network infrastructure, the State Council issued the "Broadband China" strategy and implementation Plan on August 17, 2013. A total of 120 cities (city clusters) in three batches in 2014, 2015 and 2016 served as "Broadband China" demonstration cities. The pilot of "Broadband China" coincides with the goals of urban digital construction and digital economy development. Therefore, a sub-sample discussion is conducted based on whether cities have been included in the pilot in that year, which was used to judge whether the pilot could intensify the role of digitalization in boosting urban economic resilience, thus verifing the robustness of the baseline result. Since the list of pilot cities is announced around October every year, the value assigned to cities included in the pilot is 1 from the second year of inclusion, the value is 0 for the rest of the years, and cities that were never included in the pilot were assigned a value of 0 for all years. Accordingly, the sample is divided into two sub-samples. Columns (4) and (5) of Table 4 show the regression results of sub-samples. It can be found that for cities included in the "Broadband China" pilot, the increase of digitization index by one unit can increase the urban economic resilience by 5.8 %, while the regression results of sub-samples not included in the pilot cities are not significant. In addition, the absolute regression coefficient of the subsample included in the pilot cities is larger than that of the regions not included, reflecting the important role of digital construction in enhancing the urban economic resilience, which is consistent with the core conclusions.

4.4. Heterogeneity test

Due to the differences in geographical location, the speed of development and resources among cities in China, there are significant heterogeneity in terms of the digital development and their resilience to risk shocks. As a result, the impact of urban digital development level on economic resilience may also show different effects across different locations and different city sizes. So, we divide the

Table 5
Results of the regional heterogeneity test.

	Eastern Region (1)	Central Region (2)	Western Region (3)	Northeastern region (4)	Large-sized city (5)	Small and medium-sized city (6)
	res	*res*	*res*	*res*	*res*	*res*
lndig	0.073** (2.40)	0.007 (0.35)	0.030 (1.53)	0.015 (0.86)	0.022* (1.77)	0.025 (0.34)
dev	0.005*** (4.69)	0.158 (0.82)	0.613* (1.67)	0.110 (1.17)	0.005*** (12.25)	−0.665 (−0.43)
lninve	0.020 (1.64)	0.013 (1.50)	−0.007 (−1.04)	−0.002 (−0.48)	−0.005 (−1.39)	−0.024 (−1.16)
lnfin	0.070** (2.22)	0.012 (1.02)	0.013 (0.60)	0.022 (0.95)	0.022** (2.00)	0.077 (0.87)
urban	0.138** (2.26)	0.004 (0.07)	−0.004 (−0.07)	0.035 (1.30)	0.022 (0.78)	−0.083 (−0.47)
lneco	0.082*** (4.59)	0.114*** (8.16)	0.126*** (8.20)	0.200*** (10.51)	0.097*** (12.07)	0.118** (2.38)
lninc	0.051 (1.23)	−0.061* (−1.81)	−0.028 (−1.41)	0.075*** (3.80)	−0.006 (−0.31)	0.105 (1.70)
constant	−1.328*** (−3.15)	−0.123 (−0.41)	−0.123 (−0.67)	−1.605*** (−7.42)	−0.282* (−1.67)	−1.109* (−1.88)
i.year	YES	YES	YES	YES	YES	YES
N	1204	1120	1176	476	3833	143
R^2	0.137	0.354	0.353	0.719	0.160	0.556

Notes: Significance levels: ***p < 0.01; **p < 0.05; *p < 0.1. The t value is in the parentheses.

sample into eastern, central, western and northeastern based on the geographical administrative division of China. What is more, according to the Notice on Adjusting the Classification Standards of City Size issued in 2014, we classify the cities based on their permanent population in urban areas. The cities of large city size and above are classified as large cities (with a permanent population of more than 1 million people). Medium-sized cities and small cities are uniformly classified as small and medium-sized city sub-samples (with a permanent population of less than 1 million). Therefore, we explore the heterogeneous effect of the digital development on economic resilience based on the sub-samples of regions and city sizes.

Columns (1) to (4) of Table 5 present the sub-sample regression results based on regional heterogeneity. It can be seen that there is significant heterogeneity among different regions in the enhancement effect of digital development on economic resilience. The regression coefficient of the eastern region is much higher than that of the other regions. Moreover, only the regression results in the eastern region pass the test at the significance level of 5 %, and every increase of 1 unit in the digital index of the city in eastern region will increase the economic resilience by 7.3 %. The regression results of the heterogeneity based on city size are shown in columns (5) and (6) of Table 5, indicating that the regression coefficient of large-sized cities is significantly positive, while the regression results of small and medium-sized cities fail the significance test, affirming that among cities in the eastern part of the region and large-scale cities, digital development has a stronger positive effect on enhancing the economic resilience. The result may be explained by the fact that the economic and digital development of eastern cities and large-scaled cities is relatively faster, and therefore these regions are able to release the digital dividends, which plays a beneficial role in stabilizing regional development and enhancing the resistance and recovery from shocks. The heterogeneous results further validate the necessity of regional digital development.

5. Further analysis

5.1. Nonlinear effect analysis

Based on the analysis above, this section empirically analyzes whether the relationship between the level of regional digital development and economic resilience is nonlinear due to the impact of population density. The existence of a panel threshold was tested following [48]. The results in Table 6 show that, after 300 repeated samplings using the bootstrap method, the results passed the test of a single threshold at a significance level of 5 %. Therefore, a threshold number is set to perform the panel threshold model regression according to equation (17). Table 7 reports the regression results of the threshold effect based on urban population density, indicating that, with an increase in population density, the impact of digital development on urban economic resilience presents an inverted U-shape, which first increases and then decreases. In other words, when population density is on the left side of the threshold, rapid digital development has a significant promoting effect on urban economic resilience. When urban population density crosses the threshold, the impact of digitization on economic resilience shifts from positive to negative. Therefore, hypothesis 4 is valid.

5.2. Spatial spillover effect analysis

As is discussed above, there may be a spatial effect between digitalization and economic resilience. Using the Moran'I index method, we conduct spatial autocorrelation tests on the digitization level and economic resilience index of the cities based on the economic distance matrix and the geographic economy nested matrix respectively. Table 8 shows that in most years from 2007 to 2020, digitalization level and economic resilience have significant Moran'I index based on different spatial matrices, indicating that during the sample observation period, the urban digital development level and economic resilience present a clustering feature in spatial distribution, and have significant spatial autocorrelation.

According to equation (18), the regression results based on the dual fixed Spatial Durbin Model (SDM) is reported in Table 9. It can be seen that the coefficient of spatial lag term is positive at the significance level of 1 %, indicating that the spatial effect is positive, and the urban economic resilience has a significant spatial dependence feature, which means that the improvement of regional economic resilience has a spatial spillover effect, and it is conducive to strengthening the economic resilience of the surrounding areas. According to the regression results of the impact of digitalization on economic resilience, when we adopted the economic distance weight matrix, the coeffiecient of *lndig* and $W * lndig$ is 0.021 and −0.058, respectively, illustrating that when the digital level increases 1 %, the economic resilience of this city will improve 2.1 %, while the economic resilience of surrounding area will decrease 5.8 %. When we adopted the economic geography nested matrix, the coeffiecient of *lndig* and $W * lndig$ also indicated that there is a positive effect of digitalization on urban economic resilience, while a negative effect on surrounding areas, suggesting that the digital development in a region has a certain "siphon effect", Hypothesis 5 is verified.

Table 6
Threshold existence test for variables.

Threshold	F value	P value	Threshold value	BS	critical value 10 %	critical value 5 %	critical value 1 %
Single	30.24**	0.0167	774.3668	300	17.2293	20.3098	31.6068
Double	8.18	0.4567	1034.1109	300	18.7038	25.1273	34.5940
Triple	7.80	0.4233	755.7917	300	15.6329	23.2342	36.9810

Table 7
Regression results of threshold effect model.

	FE
lndig_1	0.0197* (1.70)
lndig_2	−0.039 (−1.50)
dev	0.005*** (11.38)
lninve	−0.008** (−2.23)
lnfin	0.042*** (3.72)
urban	0.018 (0.69)
lneco	0.088*** (11.19)
lninc	−0.089*** (−10.50)
constant	0.579*** (11.03)
N	3976
R^2	0.147

Notes: Significance levels: ***p < 0.01; **p < 0.05; *p < 0.1. The t value is in the parentheses.

Table 8
Global Moran's I of urban digitalization and economic resilience from 2007 to 2020.

	economic distance matrix		geographic economy nested matrix		economic distance matrix		geographic economy nested matrix	
	lndig		lndig		res		res	
	Moran'I	Z value	Moran'I	Z value	Moran'I	Z value	Moran'I	Z value
2007	0.115***	4.070	0.012***	2.708	−0.002	0.065	0.002	0.930
2008	0.044**	1.653	0.031***	6.130	−0.029	−0.887	0.005*	1.555
2009	0.119***	4.232	0.042***	8.161	−0.016	−0.427	0.008**	2.081
2010	0.043*	1.608	0.074***	13.761	−0.003	0.003	0.022***	4.531
2011	0.107***	3.823	0.075***	13.911	0.037*	1.391	0.018***	3.865
2012	0.016	0.669	0.069***	12.974	0.036*	1.364	0.015***	3.344
2013	0.072***	2.615	0.048***	9.211	0.072***	2.824	0.172***	33.476
2014	0.009	0.443	0.037***	7.201	0.043*	1.619	0.015***	3.228
2015	0.007	0.361	0.021***	4.309	0.051**	1.881	0.016***	3.466
2016	0.034*	1.285	0.025***	5.067	0.062**	2.258	0.016***	3.459
2017	0.055**	2.004	0.029***	5.746	0.048**	1.787	0.022***	4.596
2018	0.065***	2.382	0.024***	4.946	0.055**	2.002	0.017***	3.702
2019	0.064**	2.320	0.036***	7.090	0.083***	3.015	0.016***	3.521
2020	0.004	0.273	0.033***	6.499	0.132***	4.688	0.018***	3.806

Notes: Significance levels: ***p < 0.01; **p < 0.05; *p < 0.1.

Table 9
The regression results of Spatial Durbin model.

	economic distance matrix (1)	geographic economy nested matrix (2)
	res	*res*
lndig	0.021* (1.84)	0.020* (1.81)
dev	0.005*** (16.41)	0.008*** (22.54)
lninve	−0.006*** (−2.88)	0.007*** (3.20)
lnfin	0.026*** (3.24)	0.017** (2.08)
urban	0.015 (1.02)	0.012 (0.76)
lneco	0.099*** (22.36)	0.138*** (28.65)
lninc	−0.003 (−0.28)	0.006 (0.60)
*W*lndig*	−0.058* (−1.79)	−0.227* (−1.81)
*W*dev*	−0.001* (−1.85)	−0.016*** (−3.27)
*W*lninve*	0.002 (0.35)	0.007 (0.32)
*W*lnfin*	0.083*** (3.32)	−0.066 (−1.01)
*W*urban*	0.042 (0.96)	−0.068 (−0.68)
*W*lneco*	−0.037*** (−2.94)	−0.338*** (−8.14)
*W*lninc*	−0.064** (−2.56)	−0.026 (−0.38)
Spatial rho	0.293*** (9.91)	0.737*** (15.53)
Variance sigma2_e	0.001*** (44.33)	0.001*** (43.96)
N	3976	3976

Notes: Significance levels: ***p < 0.01; **p < 0.05; *p < 0.1. The t value is in the parentheses.

5.3. Mechanism analysis

5.3.1. Mechanism test based on TFP

According to the analysis above, the improvement of digitization level may enhance the urban economic resilience through its effect on regional total factor productivity. Therefore, model (13) and (14) are tested successively according to the three-step method of mediation effect test by Ref. [60]. The first step is shown in the benchmark regression, and the second step examines the impact of digitalization on regional TFP, which is shown in column (1) of Table 10, showing that digitalization development can significantly improve regional TFP, this result is consistent with [61], and each unit of digitalization level increases TFP by 17.3 %. Furthermore, digitalization and TFP were added to the model at the same time to test their impact on economic resilience. The regression results in column (2) show the coefficients of *lndig* and *tfp* are 0.021 and 0.003, respectively, illustrating that digitalization and the improvement of TFP have significant positive effects on enhancing economic resilience. In other words, it can be found that the urban digital development can lead to an increase in total factor productivity, thereby enhancing the conomic resilience, which indicates that the mediation effect path of *tfp* is established and hypothesis 2 is confirmed.

5.3.2. Mechanism test based on labor quality

To verify whether the improvement of labor quality is a transmission mechanism of digital development influencing economic resilience, we adopt the three-step method to conduct the mediation effect test based on model (15) and model (16). Column (3) in Table 10 reports a positive impact of the digital development on the labor quality, but this result did not pass the test of statistical significance. Column (4) in Table 10 shows the coefficients of *lndig* and *lncap* are 0.021 and 0.686, respectively, and both are significant, indicating that the labor quality of city also has positive effect on economic resilience. Furthermore, sobel test should be adopted caused by the insignificant of the independent variable in the second step of the mediation effect test. The Z statistic of Sobel test was 2.999, and the P value was 0.0027, indicating that the labor quality is also an effective mediator variable for the effect of digitalization on economic resilience. Similarly, the digital economy's role in enhacing the quality of employment has been proven [62]. That is, the digitalization of cities can effectively improve the quality of regional labor force, thus empowering urban development and enhancing the ability of cities to withstand risks, the hypothesis 3 is confirmed.

6. Conclusion and policy implications

6.1. Conclusion

This study investigates the relationship between digital development and economic resilience in 284 prefecture-level cities in China. Through the construction and theoretical analysis of a model, using digital index and economic resilience index, we utilized a fixed effect model for empirical analysis. The main conclusions are drawn as follows: First, digitalization significantly enhances urban economic resilience, and this result remains significant after considering endogeneity, replacing dependent and independent variables separately, reducing the sample period, and sub-sample tests based on "Broadband China" demonstration cities. But the effect varied across regions and cities of different sizes. It not only indicates the necessity of accelerating the development of urban digital construction, and it is of great significance to fully release digital dividends and boost the urban economy resilience to achieve high-quality development by relying on digital techonology, but also implies that the balanced development of digitalization should be taken into account. Second, the positive impact of digitalization on urban economic resilience is achieved mainly through the improvement of regional labor quality and total factor productivity. Third, The impact of digitalization on economic resilience shows an inverted U-shape under the difference in population density, that is, on the left of the threshold value of population density, digitalization significantly promotes economic resilience as population density increases, whereas the crowding effect is not conducive to economic resilience once the threshold is crossed. Fourth, the results based on the spatial panel model show that the improvement of digitalization has a significant positive impact on the resilience of the local economy, while there is a "siphon effect", meaning that the urban digital development can weaken the resilience of the surrounding regions.

6.2. Policy recommendations

The policy implications of our findings are obvious, it is significant to pay attention to the coordination between regions when accelerating China's digital construction. That is, to promote the coordinated development of digital construction, fully release the digital dividend, so as to enhance the core competitiveness of urban development and improve the ability to resist risks. To achieve this goal, we propose the following policy recommendations.

First, it is necessary to promote the construction of regional digital infrastructure and accelerate the practical application of digital technologies, such as artificial intelligence and big data, so as to give full play to the positive role of regional digital development and strengthen the urban capacity to handle various shocks. Second, cities should introduce policies based on their unique development conditions and needs. Policies that attract population inflow, expand population size, and encourage population agglomeration can aid in digital enhancement and economic resilience. Actively guiding the transfer of surplus rural labor to cities, on the other hand, encourage the relaxation of household registration policies for cities with better economic development. However, the differences in the development of different regions should be consideration, indicating that it is important to prevent the crowding effect caused by excessive population density while introducing population inflow. Third, it is essential to upgrade the quality of the human capital. Local government should introduce policies and measures for talent introduction to facilitate the introduction of highly skilled labor,

Table 10
The regression results of the mechanism test.

	tfp (1)	*res* (2)	*lncap* (3)	*res* (4)
lndig	0.173* (1.65)	0.021* (1.67)	0.002 (0.23)	0.021* (1.80)
tfp		0.003* (1.92)		
lncap				0.686*** (24.92)
dev	−0.003 (−1.38)	0.005*** (12.49)	0.002*** (10.88)	0.004*** (12.34)
lninve	−0.032* (−1.75)	−0.006 (−1.62)	−0.006*** (−5.13)	−0.002 (−0.75)
lnfin	0.106 (1.56)	0.027** (2.39)	0.008 (1.62)	0.022*** (2.78)
urban	−0.139 (−1.10)	0.020 (0.74)	0.007 (0.78)	0.015 (0.99)
lneco	−0.004 (−0.10)	0.099*** (12.23)	0.039*** (14.90)	0.073*** (16.20)
lninc	−0.039 (−0.58)	−0.004 (−0.19)	0.004 (0.82)	−0.007 (−0.77)
constant	2.036*** (3.22)	−0.314* (−1.90)	−0.133*** (−2.72)	−0.216*** (−2.65)
i.year	YES	YES	YES	YES
N	3976	3976	3976	3976
R^2	0.895	0.179	0.658	0.297

Notes: Significance levels: ***p < 0.01; **p < 0.05; *p < 0.1. The t value is in the parentheses.

implement human capital investment policies according to local conditions, and improve the level of regional human capital. In addition, relevant departments can carry out digital-related knowledge training and skills training, improve the digital literacy of farmers and some backward urban residents, accelerate the transformation of the labor force from the traditional mode to adapt to the digital development, and better meet the talent demand in the market. Therefore, cities can take full advantage of digitalization's ability to break down spatial boundaries and enhance cross-regional connectivity of high-level talents, and use digital development to invigorate regional entrepreneurship and employment, while attracting and retaining highly skilled talent. Fourth, government should strengthen the digital construction of developed cities, and formulate relevant policies to favor cities with low digital level, particularly emphasizing the digitalization in central and western regions and northeast China. Strengthen digital infrastructure in underdeveloped regions and promote coordinated development among regions. Meanwhile, the flow of production factors among regions through policy incentives and other measures can improve regional production efficiency and promote inter-regional coordinated development, so as to prevent cities with rapid digital development from absorbing high-quality resources from surrounding areas owing to the siphon effect, which could stifle the development potential of neighboring areas.

6.3. Limitations of the study and future research

This study has some limitations. First, there has been no unified conclusion on the quantification of resilience, and various measurement methods have their strengths and weaknesses. Although we adopted economic resilience calculated on the basis of regional GDP, it still cannot fully fit the degree of urban economic resilience. Second, the influence of digitalization on economic resilience is not limited to factors at the macro level. For example, the development of regional digitalization can impact the development of various economic and financial activities of residents, while the occurrence of individual behaviors will lead to the accumulation of risks under circumstances of lack of cognition and preference for risks, to transmit micro risks to the macro level. Additionally, the digital development of a city impacts innovation and various business activities of enterprises, and the development of enterprises will, in turn, affect the economic resilience of the region. Therefore, future studies should combine macro and micro levels, try to follow the change in micro-subject behavior from the perspective of regional development, and focus on the change in regional resilience from the change in behavior to enhance the realistic value of the research.

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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.

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