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Spatiotemporal patterns and influencing factors of human migration networks in China during COVID-19

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HIGHLIGHTS
1 COVID-19 has affected human migration.
2 The human migration network shows an obvious “center-periphery” structure.
3 Income level is an important factor affecting large-scale human migration.

ABSTRACT
The social lockdowns and strict control measures initiated to combat the COVID-19 pandemic have had an impact on human migration. In this study, big data was used to analyze spatial patterns of population migration in 369 Chinese cities during the COVID-19 outbreak and to identify determinants of population migration. We found that the overall migration intensity decreased by 39.87% compared to the same period in 2019 prior to the COVID-19 outbreak. COVID-19 severely affected human migration. The public holidays and weekends have impacted human migration from the perspective of time scale. The spatial pattern of China's population distribution presents a diamond structure that is dense in the east and sparse in the west, which is bounded by the Hu line and the cities such as Beijing, Shanghai, Guangzhou, and Chengdu as nodes to connect. There is a strong consistency between the population distribution center and the level of urban development. The urban human migration network is centered on provincial capitals or municipalities at the regional scale, showing a prominent “center-periphery” structure. COVID-19 dispersed the forces of human migration in time and changed the direction of human migration in space. But it did not change the pattern of national migration. The most critical factors influencing mass migration are income levels and traditional culture. This study reveals the impacts of major public health emergencies on conventional migration patterns and provides a scientific theoretical reference for COVID-19 prevention and control.

1. Introduction
COVID-19 has swept the world and disrupted people's everyday life (Huang et al., 2020; You et al., 2020; Zhang et al., 2020). COVID-19 is highly contagious and can be transmitted from person to person (Chinai et al., 2020). When it broke out in China just before the Spring Festival, China underwent a large-scale and long-distance population movement. Fortunately, the measures of the "lockdown" were adopted under the scientific decision-making of the government and strong popular support. By the end of March 2020, the domestic pandemic had been stopped in Wuhan, effectively curbing the spread of COVID-19 (Tian et al., 2020; Sulaymon et al., 2021). Critical phased results were
achieved in preventing and controlling the pandemic (Huang, 2020; Li et al., 2020). However, the current international pandemic is still undergoing rapid evolution, and there are also some small-scale outbreaks domestically. Therefore, analyzing the direction and proportion of population movement before and after COVID-19 outbreaks and studying migration after the human intervention are of great value to the pandemic prevention and control.

Throughout the past, various plagues such as smallpox (Brown, 1965), measles (Dörig et al., 1993), black plague (Herlihy, 1997), cholera (Chin et al., 2011) and malaria (Murray et al., 2012) have occurred. In recent years, the Ebola virus (Feldmann and Klenk, 1996), SARS (Severe Acute Respiratory Syndrome) (Rota et al., 2003) and H7N9 influenza (Zhou et al., 2013) have also emerged. However, the large-scale COVID-19 outbreak superimposed on the Chinese Spring Festival is rare. Human migration may cause the virus to spread geographically (Jia et al., 2020; Xu et al., 2020) and become a flashpoint to further spread the pandemic (Shi, 2020). Because the traditional measurement of the floating population is based on small sample surveys and the coverage is small, it is difficult to track the population (Wei et al., 2018; Pan and Lai, 2019). In addition, it is difficult to identify the proportion and direction of population movement. Thus there is little research on human migration under major public safety incidents like COVID-19. The relationship between human migration and COVID-19 remains unknown, especially the daily proportion and direction of human migration.

In recent years, the rapid development of geographic information systems (GIS), remote sensing (RS) and global positioning system (GPS) technology, mobile internet, internet of things (IoT) and other technologies, has made the integration and continuous observation of human spatiotemporal behavior data, including geographic location, social attributes, movement trajectory, migration process and interaction mode possible (Ke et al., 2015; Liu and Shi, 2016). High-spatiotemporal-resolution of human migration data represented by Baidu, Tencent and Gaode migration data have complemented conventional survey methods and are being applied to research on the regularity of human migration (Cui et al., 2020; Zhang et al., 2020). Furthermore, the "flow space" has been successfully identified by interweaving physical infrastructure and virtual networks (Castells, 2015; Liu and Shi, 2016), revealing the interaction of human migration between cities such as the population migration related to the Chinese Spring Festival. Before the Spring Festival, people go to their hometowns and return to the city after the Spring Festival and Lantern Festival. The human migration data collected by big data methods can be superimposed with COVID-19 pandemic data to get a time and space perspective. Due to the large-scale COVID-19 outbreak, the human migration patterns had significantly different characteristics. Understanding the trajectory of population movement has a fundamental role in judging the distribution area of the pandemic and blocking transmission channels for pandemic control. It also provides other countries with human migration patterns under the interference of COVID-19 to facilitate the control of COVID-19.

To reveal the characteristics of the short-term impact of COVID-19 on population migration in China, Baidu migration data were applied to construct a network of human migration between cities, and time series methods were employed to measure the scale and regularity of human migration.

2. Materials and methods

2.1. Data source and processing

2.1.1. Baidu migration data

Location Based Service (LBS) Open Platform of Baidu Maps (http://lbsyun.baidu.com/) is a technical service platform with the broadest LBS data in China. It provides high-quality positioning services for 500,000 mobile apps with average daily location service requests exceeding 120 billion. Baidu Tianyan and Maps are used to provide location services for third-party apps. GPS, IP addresses, mobile base stations, WiFi and hybrid positioning methods are used to collect the user location at different points in time and to determine whether users have migrated. Moreover, the data are input into the Baidu cloud computing platform for statistical data processing to obtain comprehensive, real-time patterns of human migration. The results of this analysis are displayed on the Baidu migration website (https://qianxi.baidu.com/2020/). This web page shows the migration scale index at the city level that reflects the scale of immigration or emigration, horizontal comparison between cities and the top 100 cities, and the relative proportions of the immigration or emigration. The webpage contents are acquired and analyzed through Python programming to obtain a daily migration and migration intensity index for 369 Chinese cities from 1 January 2020 to 31 March 2020. According to statistics, most cities cover more than 95%, and a small number of cities cover more than 85%. This helps to guarantee the validity and representativeness of the data. However, since the proportion of urban immigration or emigration is relative, it is impossible to compare cities directly. Therefore, it is necessary to multiply the comparable migration intensity index by the relative proportion of the immigration or emigration intensity to obtain a comparable rate between cities.

2.1.2. COVID-19 and statistical yearbook data

In order to reveal the dynamic mechanism of population migration, the influencing factors of human migration reflect city size, income and the economic development level, including the number of COVID-19 infections, GDP (Ten thousand yuan), primary industry accounts for the proportion of GDP (%), the second industry accounts for the proportion of GDP (%), the third industry accounts for the proportion of GDP (%), population, the number of industrial enterprises above a designated size, average wages of employees in urban areas (Yuan), and urban area (km²). The COVID-19 data was downloaded from China Data Lab Dataset of Harvard University (https://dataverse.harvard.edu/dataverse/2019ncov), and the statistics on the number of COVID-19 infections were consistent with the research period. The statistical yearbook data are freely downloaded from China City Statistical Yearbook (2019) (https://data.cnki.net/trade/yearbook/Single/N20200502297z-2006), Due to the lack of statistical data for some western Chinese cities, we collected data for 274 cities. For the stability of the results, the logarithm of all indicators was used.

2.2. Methodology

2.2.1. Construction of population flow networks

Baidu migration reflects the ratio of population inflow and outflow between cities (Liu and Shi, 2016). We set the number of people who emigrated from the city i to j on a certain day as \( p_{ij}^{\text{out}} \), the number of people who immigrated from the city i to j as \( p_{j,i}^{\text{in}} \) and the sums of emigrated and immigrated population are \( \sum p_{i,j}^{\text{out}} \) and \( \sum p_{j,i}^{\text{in}} \), respectively, so the emigration and immigration data provided by Baidu migration are \( S_{ij}^{\text{out}} = p_{ij}^{\text{out}} / \sum p_{i,j}^{\text{out}} \) and \( S_{ij}^{\text{in}} = p_{j,i}^{\text{in}} / \sum p_{j,i}^{\text{in}} \). Through the directed weighted asymmetric matrix (Chen, 2015; Zhao et al., 2017; Yang et al., 2020), we constructed 96 daily 369×369 bidirectional matrices \( S_{ij} \) during the research period.

\[
S_{ij} = \begin{bmatrix}
0 & S_{12} & \cdots & S_{1(i-1)} & S_{1j} \\
S_{21} & 0 & \cdots & S_{2(i-1)} & S_{2j} \\
\cdots & \cdots & \cdots & \cdots & \cdots \\
S_{(i-1)1} & S_{(i-1)2} & \cdots & 0 & S_{(i-1)j} \\
S_{i1} & S_{i2} & \cdots & S_{ij-1} & 0
\end{bmatrix}
\]  

(1)

The proportion of net population inflow to the city i and j on a certain day is:

\[
C = S_{ij}^{\text{in}} - S_{ij}^{\text{out}}
\]  

(2)
Where \( C > 0 \) indicates the direction of population inflow and conversely \( C < 0 \) indicates the direction of population outflow. The labor import and export cities can be judged according to the net population inflow in different periods before and after the holidays.

2.2.2. Decomposition of time series

Migration changes over time and time series methods can be used to reveal these changes (Taylor and Letham, 2018). The time series of human migration are recorded as \( y_t \) (\( t = 1, 2, \ldots, n \)), and \( y_t \) is constituted of a trend term \( (y_t) \), seasonal term \( (s_t) \), holiday effect \( (h_t) \) and residual term \( (e_t) \). We use a multiplicative combination model. If \( t > 0 \):

\[
y_t = g_t \times s_t \times h_t \times e_t
\]

Here the trend model is

\[
g_t = (k + a(t)\delta) \cdot t + (m + a(t)^T \cdot y)
\]

where:
- \( k \) is the growth rate;
- \( \delta \) is the rate adjustments;
- \( m \) is the offset parameter; and
- \( y \) is set to \(-s, \delta, \) to make the function continuous.

We can approximate arbitrary smooth seasonal effects with

\[
s_t = \sum_{n=1}^{N} a_n \cos \left( \frac{2\pi nt}{P} \right) + h_n \sin \left( \frac{2\pi nt}{P} \right)
\]

For the series with the year as the period \( (P = 365.25) \), \( N = 10 \); for the series with the week as the period \( (P = 7) \), \( N = 3 \).

Here the holiday model is

\[
h_t = \sum_{i=1}^{L} k_i \cdot 1_{(t \in D)}
\]

where:
- \( L \) represents the number of holidays;
- \( D \) represents a period before and after holidays; and
- \( k \sim \) Normal \( (0, \sigma^2) \)

3. Results

3.1. Temporal characteristics of population flows

3.1.1. Overall characteristics of net population inflow

The COVID-19 pandemic coincided with the traditional Chinese "Spring Festival", making human migration more complicated. Combined with the holiday time (the statutory holiday for the Spring Festival in 2020 was January 24–29), people's travel habits and characteristics (the majority choose to spend the Lantern Festival at home before going to work) are shown in Fig. 1. The structure of the population flows is divided into three periods, i.e., 'Pre-Lockdown' (January 1–23 2020), 'During-Lockdown' (January 24 to February 9 2020), and 'Post-Lockdown' (February 10 to March 31 2020) when Covid-19 control policy began to allow migration to some cities.

The overall national migration proportion during the study period (from January 1 to March 30) decreased by 39.89% compared with the same period in 2019 due to the influence of the COVID-19 pandemic. Taking the national migration proportion as the demarcation point on January 23, the rapid growth from the Pre-Lockdown turned to a cliff-like decline during the strict pandemic control period. The decline was 58.23% in the same period last year. During the orderly resumption period, migration trend gradually increased after a week of wandering, and was close to the same period on March 31, 2019. The proportion of net inflow in cities during Pre-Lockdown period was 67.75% and the proportion of net outflow was 32.25%. During-Lockdown, the proportion of net inflow was 30.08% and the proportion of net outflow was 69.92%. The proportion of net inflow and outflow in the cities during the Post-Lockdown period was 30.89% and 60.11%, respectively.

Fig. 2 shows the top ten cities in terms of net population inflow in the three periods. Cities that showed a net outflow during the Pre-lockdown, and then changed to net inflow during the pandemic control period and the orderly resumption period included "labor import" cities were Shenzhen, Dongguan, Guangzhou, Shanghai and Beijing. On the contrary, cities with net inflows during the Pre-lockdown, and then changed to net outflows during the COVID-19 pandemic control period and orderly resumption period included "labor export" cities were Zhoukou, Chongqing, Fuyang, Shangrao and Ganzhou. Generally, the population agglomeration effects of megacities such as Beijing, Shanghai and Guangzhou show an obvious employment-driven pattern, while the population agglomeration failed in third-and-fourth tier cities that had population outflows (Shi, 2020).

Affected by the COVID-19 pandemic, the policy of immobilization measures was used leading to traffic control and factory shutdowns. The post-holiday population movement was different from the 2019 Spring Festival with only a small peak flow on the sixth day of the lunar month. The proportion was much lower, reaching only 20% of the same period of the 2019 lunar calendar. Overall, the proportion of migration was low during Lockdown and Post-Lockdown periods. Resumption of work, school and business travel was hindered, and there were slow population inflows in a few provincial capital cities. The population inflows from megacities such as Beijing, Shanghai and Guangzhou come from other cities across the country, while inflows to provincial capital cities, especially in central and western regions, come from surrounding cities in the province.

3.1.2. Trends in net population flows

The most active period of population flows in China is during the Spring Festival. Generally, people return home before New Year’s Eve. When the sixth day of the New Year and Lantern Festival ends, people began to return to their workplaces. After the Lantern Festival, most migration has subsided (Wei et al., 2018). To reveal the impact of holidays and weekends on migration during the pandemic, time series methods were used to analyze labor import and export. The results are shown in Fig. 3.

As Fig. 3 shows, migration is affected by holidays and weekends. After the net outflow of labor import cities reached its lowest value on New Year’s Eve, it began to recover gradually. After reaching its peak on the sixth day of the New Year, it began to show weekly fluctuations. Population flows were low during working days and peaked on weekends. The overall net inflows was on the rise. On the contrary, the net inflow of labor export cities began to decline after reaching the highest value on New Year’s Eve, and began to show weekly fluctuations after reaching the lowest point on the sixth day of the New Year. Overall, the net inflow showed a downward trend. Affected by the COVID-19 pandemic this year, the short-distance travel caused by visiting relatives, friends, and travel during the Spring Festival has not risen significantly. The fluctuation of human migration was mainly caused by returning to work.

3.2. Spatial patterns and hierarchy of population flow networks

3.2.1. Spatial patterns of net population flow intensity

The total proportion of human immigration and emigration is balanced, with strong spatial heterogeneity ranging from dense in the east to sparse in the west. As can be seen from Fig. 4, some cities in China showed a net inflow of population, while others showed a net outflow, and the direction of human migration was opposite before and after the holidays. Therefore, from the perspective of individual cities, almost all capital cities in the Pre-Lockdown showed a net population outflow, except for Chongqing and Harbin. At the regional level, from the Beijing-Tianjin-Hebei to the east of Hu line, Yangtze River Delta, and Pearl River Delta were the population gathering places for net population outflow.
The Yangtze River Delta covered a larger area. A very small number of non-provincial capital cities exhibited net population outflows, such as Dongying, Zibo, Qingdao in Shandong, Ningbo in Zhejiang and Lianzhou in Guangxi. Affected by the COVID-19 pandemic, the population size of Wuhan, Wenzhou and other cities with a high incidence of COVID-19 showed a net outflow before the holidays, but the human migration during the Lockdown did not recover like other cities until the Post-Lockdown. It can be said that the population flowed from the labor-intensive export areas in the Pre-Lockdown, while the population flowed into those areas during the Lockdown and Post-Lockdown. Obviously, the cities that showed a net population inflow before the holidays were the main inflow cities where people resumed work after the holiday. Overall, the Hu line still controlled the distribution and migration pattern of China’s population (Liu et al., 2016; Jiang and Wang, 2017; Zhao et al., 2017).

3.2.2. Spatial patterns of the Top 1 population flow networks
The route of the Top 1 flow in the geographic network represents a dominant relationship in the network. The significant spatial structure characteristics of the entire network are revealed at the expense of the amount of data, reflecting the network status of a city on a macro scale. Statistics of the first flow routes of population migration in all cities are shown in Fig. 5. The overall migration direction of the urban population has obvious “centripetal” characteristics in the Pre-Lockdown, During-Lockdown and Post-Lockdown. The provincial scale is based on the municipality or provincial capital cities and other key cities as the center, showing a state of “convergence” and thus a vertical correlation between cities of different levels is formed, showing characteristics of a "center-periphery" spatial pattern.

This "center-periphery" spatial model can be divided into two types. The first is the hierarchical structure dominated by the urban hierarchy. The megacities (Beijing, Shanghai, Guangzhou, and Chengdu) control regional population migration. Their radiation intensity and breadth of connections have broken through administrative boundaries. Those are the core cities in the province (city) and are connected to the population in a trans-provincial region. It has a strong appeal to the population of distant cities.

The second is the proximity effect dominated by the geographical location. The population flow is controlled in non-core cities and provincial capitals, which affects the inflow of urban population in or around the province. Compared with Beijing, Shanghai, Guangzhou and Chengdu, the influence of other provincial capitals is relatively weak. Overall, key cities in the country (provincial capitals or municipalities) are the main nodes of population migration, with important functions of agglomeration, diffusion and transit, and they are in a key position in urban population migration (Zhang et al., 2020). With changes in urban economic linkage activities and the improvement of traffic conditions, the attractiveness to population and radiation range of core cities will become wider and the spatial friction of economic linkages will become smaller and smaller (Pan et al., 2019).

Wuhan City is where China’s first COVID-19 case was discovered. It had population migration during the Pre-Lockdown, however the number of people moving in and out was very small during Lockdown and Post-Lockdown. There was no obvious “center-periphery” spatial structure feature caused by traffic control or the lockdown policy. On the contrary, although the intensity of population migration in the Pearl River Delta and the Yangtze River Delta declined compared with the same period in 2019, they still showed a trend of concentrated and contiguous net population inflows and presented an obvious employment-driven pattern.

3.2.3. Spatial patterns of population flow networks
The density of the population migration between cities in a region often determines the city’s economic development. As can be seen from Fig. 6, China’s population migration network presents a spatial structure with Beijing, Shanghai, Guangzhou and Chengdu as the apex, Wuhan as the center of two axes running north and south. It is shown as a “diamond” structure that is supported by a cross-shaped skeleton formed by connecting the east-west axis. In addition, there are two migration routes that have broken through the "diamond" structure. One is the northwest route from Lanzhou to Urumqi and the other is the northeast route from Beijing to Shenyang and from Changchun to Harbin (Pan et al., 2019; Shi, 2020).

Flow and direction are the basic attributes of population migration. Statistics show that the top ten cities carry about 30% of the total migration which means that nearly one-third of China’s population movement occurs in only ten cities. These cities represent the future of China’s economic development. These cities include most municipalities, provincial capital cities and other cities in the Pearl River and Yangtze River Delta. In summary, there are two urban migration directions. One is the diversification of outflow destinations. Henan Province is a typical representative with the population mainly flowing to Beijing, Shanghai, Hangzhou, Guangzhou and Xi’an. The other one is the centralization of outflow destinations. For example, the population of Anhui Province flowing to the Yangtze River Delta urban agglomeration, the population of Hunan Province flowing to the Pearl River Delta, the population
Fig. 2. Net population flows during COVID-19.
of Hebei Province flowing to Beijing and Tianjin and the population of Sichuan Province flowing to Chongqing.

The urban population aggregation is still very prominent in the eastern provinces and megacities with developed economies and abundant employment opportunities (Shi, 2020). With the vigorous development of high-speed rail, airports and other facilities, distance is no longer a significant factor hindering population mobility. The floating population in the two major central and eastern regions is frequent and increasing. The labor market has been integrated to form a national market (Development Research Centre of the State Council, 2019). Many migrants from central and western cities go to eastern cities with higher average income levels. However, northeastern and western border cities are less attractive with smaller and more confined migration. The proportion of the population outflow in these provinces is also low.

Fig. 3. Characteristics of population inflows for selected Chinese cities.
3.3. Analysis of the factors affecting population flow networks

Urban populations in or around the provinces migrate to provincial capital cities or regional cities. Large cities have a strong gravitational force and a large range of influence, affecting regional urban population migration. Fig. 7 shows the relationship between the net population flows and nine influencing factors during Pre-Lockdown, Lockdown and Post-lockdown. Population migration was negatively correlated to: COVID-19 infections in cities; GDP; the third industry accounts for the proportion of GDP; population; the number of industrial enterprises above designated size; and the average wages of employees in urban areas in Pre-Lockdown. However, migration was positively correlated to the primary industry accounts for the proportion of GDP. Before the Chinese New Year, the population migrated from large cities with high economic development to small and medium-sized cities with high agriculture ratios and relatively low incomes.

During Lockdown, population migration was positively correlated with: the number of COVID-19 infections; GDP; the proportion of the tertiary industry in GDP; the registered population at the end of the year; the number of industrial enterprises above a designated size; the average wages of urban workers; and was negatively correlated with the proportion of the primary industry in GDP. Population flowed from economically backward cities to developed big cities after the Chinese New Year. During Lockdown, the government strictly controlled population movement, but the demand for employment and for the return of people who travelled before the Spring Festival was urgent, and the migration of urban populations where the pandemic was not serious was still active.

In Post-Lockdown, migration was affected by the number of COVID-19 infections. In cities with severe COVID-19 numbers, control measures were more strict, the resumption rates lower, and the corresponding population migration was lower. In addition, population migration in small cities dispersed over time, while the immigration and emigration of the population between large cities offset each other, and urban population inflows were relatively low.

Overall, COVID-19 delayed population migration, dispersed the proportion of population migration in time, and interfered with the direction of population migration spatially. However, income levels and the demand for employment were the main driving mechanisms of population migration after the Spring Festival. Income levels were an important mechanism for stimulating the population flows from third and fourth-tier central and western cities to first-tier eastern cities. In addition, people often return home for the New Year due to the traditional culture (Wei et al., 2018).

4. Discussion

The population migration network is bounded by the Hu line, which is dense in the east and sparse in the west, with Beijing, Shanghai, Guangzhou, Chengdu and Wuhan as nodes. It shows a rhombus structure as the basic spatial feature of population migration at a national scale (Liu and Shi, 2016; Zhao et al., 2017; Jiang and Wang, 2017; Pan et al., 2019; Zhang et al., 2020).

Due to the outbreak of COVID-19, large-scale social intercourse has been confined, which is unprecedented. This analysis provides a case study of migration patterns of China’s urban population during COIVD-
We found that COVID-19, as a public safety emergency, greatly reduced the strength of population migration. Compared with the same period in 2019, it disrupted the timing and direction of population migration. It changed the intensity and pattern of local migration, but it did not change its general trend with population migration being affected by holidays and weekends. Urban industrial structures, urban areas and incomes had an important impact on population migration during the Covid-19 pandemic period and the Spring Festival. The income gap is an important driving mechanism for stimulating population flows from China’s central and western third and fourth-tier cities to first-tier eastern cities.

Although Baidu’s migration data had advantages that traditional data cannot match, it also has limitations related to data acquisition (Liu and Shi, 2016). Baidu migration has many users, but there are unconnected. The time for two positioning requests is fixed at eight hours and staying in the destination city for four hours is recorded as migration. However, this may result in: missing long-distance migration; repeated calculation errors; disassembled travel routes; and problem with fully identifying user travel. In addition, to protect user privacy, it is difficult to obtain social attributes such as occupation, gender, age, travel purpose and duration times (Pan et al., 2019). Furthermore it is impossible to distinguish migrant workers, visiting relatives and students trav-
Fig. 6. Spatial patterns of population flow networks.

elling home for their holidays. However, as a source of daily population flows between cities, it is unmatched by any other data source. In the future, multi-source geographic big data should be integrated to explore the social attributes of population migration.

5. Conclusion

Baidu migration applies LBS technology to record the daily dynamic and real-time population flows between cities, becoming important for characterizing geographic behavior. Baidu’s daily migration data from 1 January to 31 March 2020 were used in this manuscript. These data were divided into the Pre-Lockdown, During-Lockdown and Post-Lockdown periods. Time series and geographic network methods were adopted to study migration and its influencing factors under a major public safety incident.

The 2020 national migration strength decreased by 39.87% compared with the same period in 2019. The pandemic severely affected population migration. After the Lockdown in Wuhan, population flows were disrupted with outflows effectively controlled. In terms of timing, population migration was affected by holidays and weekends. The national population migration network is bounded by the Hu line which is dense in the east and sparse in the west, showing a diamond structure.
with Beijing, Shanghai, Guangzhou, Chengdu and Wuhan as the nodes. The urban population migration network is centered on the provincial capital or municipality, showing an obvious "center-periphery" structure. Generally, the attractiveness of provincial capital cities is weak, which affects the population migration to provinces. The attractiveness of large cities is strong and affects regional urban population migration. Income is the most important factor affecting large-scale population migration. COVID-19 dispersed the intensity of migration over time and changed the spatial direction of migration. The study helps to support a balanced national and regional economic development pattern for the control of COVID-19.
Declaration of Competing Interest

The authors declare that no known financial interests or personal relationships influenced the research reported in this paper.

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