Population movement, city closure in Wuhan and geographical expansion of the 2019-nCoV pneumonia infection in China in January 2020

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Summary

Population outflow from Wuhan might be one important trigger for the transmission of 2019-nCoV pneumonia in China, and early implementation of the closure measures may be more effective.

Abstract

Background The unprecedented outbreak of 2019-nCoV pneumonia infection in Wuhan City caused global concern, the outflowing population from Wuhan was believed to be a main reason for the rapid and large-scale spread of the disease, so the government implemented a city closure measure to prevent its transmission considering the large amount of travelling before the Chinese New Year.

Methods Based on the daily reported new cases and the population movement data between January 1 and 31, we examined the effects of population outflow from Wuhan on the geographical expansion of the infection in other provinces and cities of China, as well as the impacts of the city closure in Wuhan in different scenarios of closing dates.

Results We observed a significantly positive association between population movement and the number of the 2019-nCoV cases. The spatial distribution of cases per unit outflow population indicated that some areas with large outflow population might have been underestimated for the infection, such as Henan and Hunan provinces. Further analysis revealed that if the city closure policy was implemented two days earlier, 1420 (95% CI: 1059, 1833) cases could have been prevented, and if two days later, 1462 (95% CI: 1090, 1886) more cases would be possible.

Conclusions Our findings suggest that population movement might be one important trigger for the transmission of 2019-nCoV infection in China, and the policy of city closure is effective to control the epidemic.

Keywords: 2019-nCoV infection; Wuhan; Population movement; Infection transmission

Introduction

In December 2019, an unprecedented pneumonia outbreak caused by a novel coronavirus, namely 2019-nCoV, emerged in Wuhan, the capital city of Hubei Province in China [1]. Similar with severe acute respiratory syndrome (SARS), the outbreak was highly suspected to be linked to the wild animals in the seafood market, although the definitive source was not clear yet [2] .

As of January 31, 2020, the infection has been transmitted to all the provinces in China and a few other countries. Epidemiology evidence showed that most of the cases outside Wuhan had a history of living or travelling to Wuhan, and human-to-human transmission route was possible [3], which might be the reason for a rapid increasing rate of infection across the country and globally [4].

Considering the person-to-person transmission and the large travel volume during the traditional Chinese New Year (the largest annual population movement in the world), it is expected that the population movement would lead to further expansion of the infection, so the government imposed a lockdown on Wuhan City at 10:00 am on January 23, as well as some other cities later on [5]. However, an estimated 5 million individuals had already left Wuhan for the holiday or travelling, some of which rushed out after the lockdown announcement [6]. In addition, the novel coronavirus is infectious during the incubation period and when the symptoms are not obvious, which is likely to make the huge floating population potential sources of infection [7]. Therefore, it is reasonable to hypothesize that the population transported from Wuhan may have a significant impact on the potential outbreaks in other parts of China.

Recent studies on the novel coronavirus pneumonia focused more on its etiology [8, 9], transmission route [10, 11], and epidemiological characteristics [12, 13], there is still a lack of investigating the relationship between the migrating population and the outbreak, which is of great importance for making intervention policies. Thus, we conducted this study with the following objectives: 1) to evaluate the impacts of the population movement on the spatial transmission of the 2019-nCoV cases at the provincial and city levels in China; 2) to estimate the potential outbreak risk at areas with the population outflowed from Wuhan; 3) to evaluate the effectiveness of the city closure measures on the epidemic control.

Methods

Data collection

The data on the daily number of 2019-nCoV pneumonia cases from January 1 to 31 were derived from the real-time update of the China Health Commission (http://www.nhc.gov.cn/), 2019-nCoV epidemic report on the websites of Phoenix and Dingxiangyuan. The diagnosis and definition of the case have been described elsewhere [2, 3]. In brief, a confirmed case was defined as a pneumonia case that was laboratory confirmed 2019-nCoV infection with related respiratory symptoms and a travel history to Wuhan or direct contact with patients from Wuhan.

The floating population

As the city closure took place at 10:00 am on January 23, 2020, and the incubation period of the infection was considered to be about 3-7 days [14], we obtained the daily index of population outflow from Wuhan and the proportion of the daily index from Wuhan to other provinces and top 50 cities, from January 1 to 31 in 2020, the information was retrieved through the Spring Festival travel information of China released by Baidu Qianxi. The data came from Baidu Location Based Services (LBS) and Baidu Tianyan based on location and traffic information systems, which could provide real-time dynamic information on regional population outflow. Data of Baidu Qianxi was freely available to the public (http://qianxi.baidu.com).

Statistical analysis

Number of 2019-nCoV cases per unit outflow population

The daily index of population outflow from Wuhan to other provinces and top 50 cities was obtained by multiplying the daily index of population outflow within Wuhan by the corresponding proportion for each province. To evaluate the effect of prevention and control measures of the local government, we calculated the number of 2019-nCoV cases per unit outflow population, the formula can be specified as follows, among them, A refers to the total index of outflow population from Wuhan from January 1 to 31, j refers to 31 provinces in China, and D is the total index of population inflow from Wuhan to other provinces:

$A = \{a_i\} (i = 1,2\ldots,31)$

B is the daily proportion of the daily index from Wuhan to other provinces from January 1 to 31:

$B = \{b_{ij}\} \ (i = 1,2\ldots,31; j = 1,2\ldots,31)$

C is the cumulative 2019-nCoV cases in each province from January 1 to 31:

$C = \{c_j\} (j = 1,2\ldots,31)$

D is the total index of population inflow from Wuhan to other provinces:

$D = \{d_j\} (j = 1,2\ldots,31)$

We finally calculated the average number of cases per unit outflow population for each province in China:

$$\sum_{j=1}^{31} c_j \Big/ \sum_{j=1}^{31} d_j$$

Evaluation of the effects of earlier city closure dates

After the city closure of Wuhan was taken in force on January 23, some population still outflowed from Wuhan. We subtracted the outflow index on January 23 from the average outflow index from January 24 to 31, to obtain the index of outflow population within Wuhan reduced by the advanced city closure on January 21 and 22 (the advanced outflow index). And then we calculated the average proportion of the outflow index from January 24 to 31 for each province (the average proportion). The number of cases reduced by the advanced city closure in each province was estimated by multiplied the advanced outflow index by the average proportion and one corresponding unit. The formula can be specified as:

The reduced index of outflow population:

$$\sum_{i=1}^{p} a_{n+1-i}$$

Here, n was the date that government announced city closure; p was the advanced days of city closure.

The increased index of outflow population:

$$\frac{\sum_{i=n+1}^{m} a_i}{m-n}, \quad n=23, m=31$$

The net loss of index of outflow population:

$$\sum_{i=1}^{p} a_{n+1-i} - p\frac{\sum_{i=n+1}^{m} a_i}{m-n}, \quad n=23, m=31$$

The average proportion of the outflow index from Wuhan into each province during the city closure:

$$\frac{\sum_{i=n+1}^{m} b_{ij}}{m-n}, \quad n=23, m=31$$

The net loss index of outflow population caused by advanced Wuhan city closure for each province:

$$\left(\sum_{i=1}^{p} a_{n+1-i} - p\frac{\sum_{i=n+1}^{m} a_i}{m-n}\right)\frac{\sum_{i=n+1}^{m} b_{ij}}{m-n}, \quad n=23, m=31$$

As of January 31, 2020, the total reduced number of 2019-nCoV cases in China:

$$\sum_{j=1}^{31}\left\{\left(\sum_{i=1}^{p} a_{n+1-i} - p\frac{\sum_{i=n+1}^{m} a_i}{m-n}\right)\frac{\sum_{i=n+1}^{m} b_{ij}}{m-n}\cdot\frac{\sum_{j=1}^{31} c_j}{\sum_{j=1}^{31} d_j}\right\}, \quad n=23, m=31$$

Similarly, we evaluated the impacts of one-day and two-day delayed city closure. We took the average index of the population outflow between January 21 and 23 as the daily index of population outflow before the city closure, and used the same calculation method to estimate the index of population outflow within Wuhan increased by the delayed city closure on January 24 and January 25 (the delayed outflow index). We multiplied the delayed outflow index by the average proportion and one corresponding unit to estimate the increased number of cases caused by one-day and two-day delayed city closure of Wuhan for each province in China.

Results

As of January 31, 2020, a total of 11791 confirmed cases and 259 deaths due to the 2019-nCoV infection were reported in China, which were widely dispersed in all of 31 provincial administrative areas. In general, the number of 2019-nCoV pneumonia cases are still on the rise. During the period of January 11-31, 2020, the cumulative number of cities infected with 2019-nCoV cases increased rapidly (Figure.s1). A total of 313 cities in mainland China reported the occurrence of 2019-nCoV infection, of which the number of reported cases from January 20 to 29 increased rapidly from 7 to 313, an increase of nearly 44 times. Among the cities, 97 of them belong to the regions with high population exodus out of Wuhan, and 7138 cases have been reported, accounting for 83.23% of the total reported cases outside Wuhan (Figure.s1).

Outflow population of Wuhan could be divided into four periods based on the migration data of Baidu (Figure 1 and 2). In the first stage (January 1-10), migrant population flowed out of Wuhan without the influence of the epidemic situation, the mean daily index of population outflow was 58039.71 (95% CI: 48883.38-66454.00), and 2019-nCoV cases were mainly distributed in Wuhan. From beginning of Spring Festival travel rush on January 10 and announcement of 2019-nCoV infection, the mean index of population outflow rose to 66777.98 (95% CI: 61125.90-72962.78), which increased by 15.10% compared with the previous period. Meanwhile, 2019-nCoV cases gradually accumulated in Wuhan and several nearby cities. On January 20, the news that the virus could be transmitted from person to person was released, then a large number of Wuhan residents left Wuhan. The corresponding index of population outflow of this period surged to 112385.88 (95% CI: 107367.44-118403.21), which increased by 93.60% compared with the previous period. A strict city closure policy was implemented on January 23, the index reduced to 9180.29 (95% CI: 3055.35-19101.40), falling by 91.80% comparing with the third period, the 2019-nCoV cases were widely distributed in all of 31 provinces.

The scatter diagram demonstrated the association between the number of 2019-nCoV cases and index of outflow population at the scales of province and city. At the provincial level (Figure 3), outflow population from Wuhan was mainly distributed in Henan, Hunan, Guangdong, Anhui, corresponding to a higher number of 2019-nCoV cases. The index of outflow population of Henan was about 50000, and the number of cases was about 450, in contrast, the floating population index of Zhejiang was only one fifth of that of Henan, but the number of cases was as high as 600, indicating the actual epidemic situation in Henan may have been underestimated. Similar results were obtained using the number cases per unit outflow population (Figure.s2): The mean value of the number of 2019-nCoV cases per unit outflow population across the whole country was 129.72, however, the value in Zhejiang province was more than 450 and the corresponding result in Henan was lower than average.

At the city level (Figure 4), we observed that there was a large number of cases in the cities of Hubei province such as Huanggang, Xiaogan, Xiangyang, Jingzhou, etc. Similarly, the positive approximately linear association between the index of outflow population and the number of 2019-nCoV cases at the city-level was in line with that at the provincial level, and some cities (Wenzhou, Taizhou, Xuchang, Luoyang and Guiyang) were deviated from the general trend. For instance, the index of outflow population of Wenzhou (Zhejiang Province) was almost the same as that of Luoyang (Henan Province), but the number of 2019-nCoV cases in the two cities was quite different.

To evaluate the effect of the city closure on the infection transmission one and two days in advance, we used the index of population outflow of January 21-23, 2020 when the Wuhan was still open and index of population outflow of January 24-31, 2020 when the city closure policy had been implemented, and the calculations gave the reduced index of population outflow (Appendix): 102206.69 for city closure one day in advance and 211429.60 for city closure two days in advance. In addition, we obtained the reduced index of population outflow of each other province and correspondingly reduced 2019-nCoV cases. Finally, about 687 and 1420 2019-nCoV cases would be avoided with implementing city closure policy one and two days in advance (Table 1). On the contrary, if the closure measures was delayed for one to two days, the number of cases would increase by 722 and 1462, respectively.

Discussion

Understanding the driving factors of the infectious disease is of particular importance for the formulation of effective interventions. Our findings suggested a close relationship between the population outflow from Wuhan and the 2019-nCoV infection in China. We also evaluated the effect of the city closure, and the effect in regards to different implementation dates.

The dramatic decrease in index of outflowing population of Wuhan indicated that the lockdown reduced the outward movement of the population effectively. It is also suggested that a large number of populations of Wuhan had flowed out before 10:00 am January 23, 2020, since then the 2019-nCoV cases was widely dispersed nationwide.

The distribution of population outflows and cases varied across provinces. Our findings on the effects of population movement on the disease transmission was consistent with those of other coronavirus studies [15-17]. Since the virus is transmitted through the respiratory tract and close contact, the infection is greatly affected by population movements: a great number of people flowing out of Wuhan may transmit the virus to other parts of China during the Chinese Spring Festival, and the absence of detectable symptoms during the long incubation period made it difficult to identify cases in the early stage [18], which made the 2019-ncov virus be able to spread on a large scale in a short period of time. A high level of outflow population and the number of cases was observed in the surrounding cities of Wuhan, so the government should strengthen the traffic control in the surrounding cities, so as to limit the outflow of population in Wuhan, thus controlling the spread of the epidemic.

Our study provided timely evidence for the formulation of efficient strategies to prevent diseases from spreading out. On the one hand, the result could help assess the effectiveness of the prevention and control efforts. For example, the cases in Zhejiang and Guangdong are apparently more than estimated, which indicated a better health emergency response system (i.e. higher detection efficiency) or inadequate isolation, whereas the cases reported in Henan were much lower than expected. Two possible explanations should be considered: (1) strong prevention and control measures had been adopted in Henan; (2) the epidemic in Henan has been underestimated and enhanced screening efforts should be enforced. On the other hand, exploring the association was expected to help identify high-risk areas and guide health strategy formulation [19, 20]. Take Henan as an example, great difference between estimated and reported data may imply a great increase of cases in the future, which required enhancement of the surveillance system and rational allocation of resources [17]. The medicine supply, personal protective equipment, hospital supplies, and the human resources necessary to respond to an outbreak should be always ensured [21]. In addition, this study could be used to guide the assessment of the risk of disease transmission and help raise public awareness. As a large number of infected people had transported to all of 31 provinces, epidemics across the country may be inevitable. To halt the spread of the epidemic, harsh measures including quarantine and isolation of exposed persons, cancellation of mass gatherings, school closures, and travel restriction were needed to reduce transmission in affected areas. Furthermore, screening of people who have been to Wuhan recently was of crucial importance, especially cities with close ties to Wuhan.

Considering the impact of population movements on the outbreak, the Wuhan government announced the suspension of public transportation on January 23, 2020, with a closure of airports, railway stations, and highways, to prevent further disease transmission [22]. Despite inconsistent reports on the role of the lockdown in halting the disease transmission across China [11, 20, 21], the unprecedented measure might play an important role in slowing the epidemic spread, especially when an effective vaccine was developed [23, 24]. In addition, to explore the impact of date selection, we estimated the changes of cases when the measure was implemented on different date. The results varied significantly, 1420 cases could be prevented with the measure implemented two days earlier, and the number of cases will increase by 1462 with the lockdown implemented two days later, suggesting that the effect of the lockdown depending on the choice of date greatly, which could provide a reference for the future outbreaks. Since the political and economic effects were not considered, further studies on secondary impacts of the measure, like socioeconomic impacts, were also warranted. Though we estimated that some cases would possibly be prevented if the policy was implemented earlier, it was actually hard to make such a huge decision given the whole picture of the infection was not clear at that stage. The authors believe that the current policy was appropriate at this complex situation.

There were a few limitations of our study. Firstly, we used the index of population outflow to reflect the general real-time magnitude of population movements, so it was not an accurate representation of the actual population flow data. Secondly, some possible influencing factors, such as socio-economic factors and demographic characteristics, were not included in the analysis because of data inaccessibility. Thirdly, it is assumed that the infected travelers in the population were randomly distributed [25] and that there was no significant difference in the surveillance capability between cities [17], which would result in some difference between the estimated value and the actual situation. In addition, daily data used in this study was reported infection data, rather than the actual number of incident cases.

In summary, our study indicates that the population outflow from Wuhan might be one important trigger for the transmission of 2019-nCoV pneumonia in China, and early implementation of the closure measures may be more effective. The magnitude of epidemic in some places, such as Henan and Hunan, may have been under-estimated and should be taken seriously.

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Disclaimer

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Declaration of interests

The authors declare they have no conflict of interest.

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***Table* 1. The impact of different city closure dates on the number of 2019-nCoV infections in China**

Alternative implementing dates	Reduced or increased 2019-nCoV	95% CI*
Two days earlier: 2020-01-21	-1420	-1833,
One day earlier: 2020-01-22	-687	-886, -512
One day later: 2020-01-24	722	539, 932
Two days later: 2020-01-25	1462	1090, 1886

*Table footnotes: 2019-nCoV=2019 novel coronavirus. CI=confidence interval.

Figure legends

Figure 1. The spatial distribution of 2019-nCoV cases in China during period of January 1-31, 2020.

Figure 2. Index of population outflow of Wuhan City during period of January 1-31, 2020.

Figure 3. The association between the number of 2019-nCoV cases and the total index of population outflow at the provincial scale from January 1 to 31, 2020.

Figure 4. The association between the number of cases and the total index of population outflow at the city scale.

Figure s1. Number and cumulative number of cities reported 2019-nCoV case in mainland China during period of January 11-31, 2020.

Figure s2. The number of 2019-nCoV cases per unit outflow population across 31 provincial administrative areas in mainland China.

Figure 1

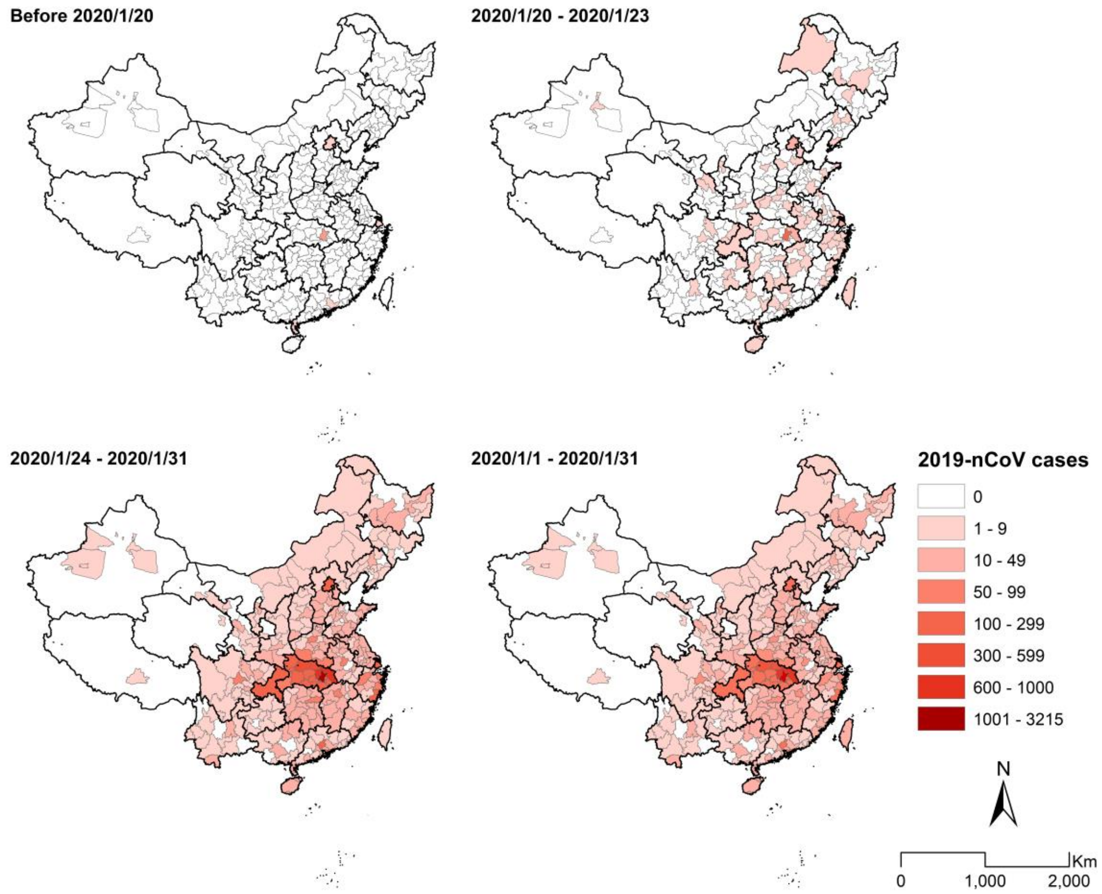

Before 2020/1/20
2020/1/20 - 2020/1/23
2020/1/24 - 2020/1/31
2020/1/1 - 2020/1/31
2019-nCoV cases
0
1 - 9
10 - 49
50 - 99
100 - 299
300 - 599
600 - 1000
1001 - 3215
N
Km
0
1,000
2,000

Figure 2

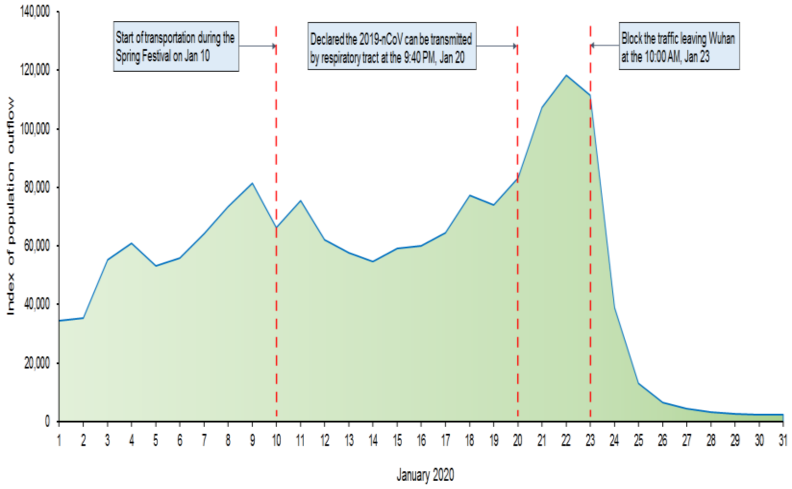

Start of transportation during the Spring Festival on Jan 10
Declared the 2019-nCoV can be transmitted by respiratory tract at the 9:40 PM, Jan 20
Block the traffic leaving Wuhan at the 10:00 AM, Jan 23
Index of population outflow
140,000
120,000
100,000
80,000
60,000
40,000
20,000
0
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 26 27 28 29 30 31
January 2020

Figure 3

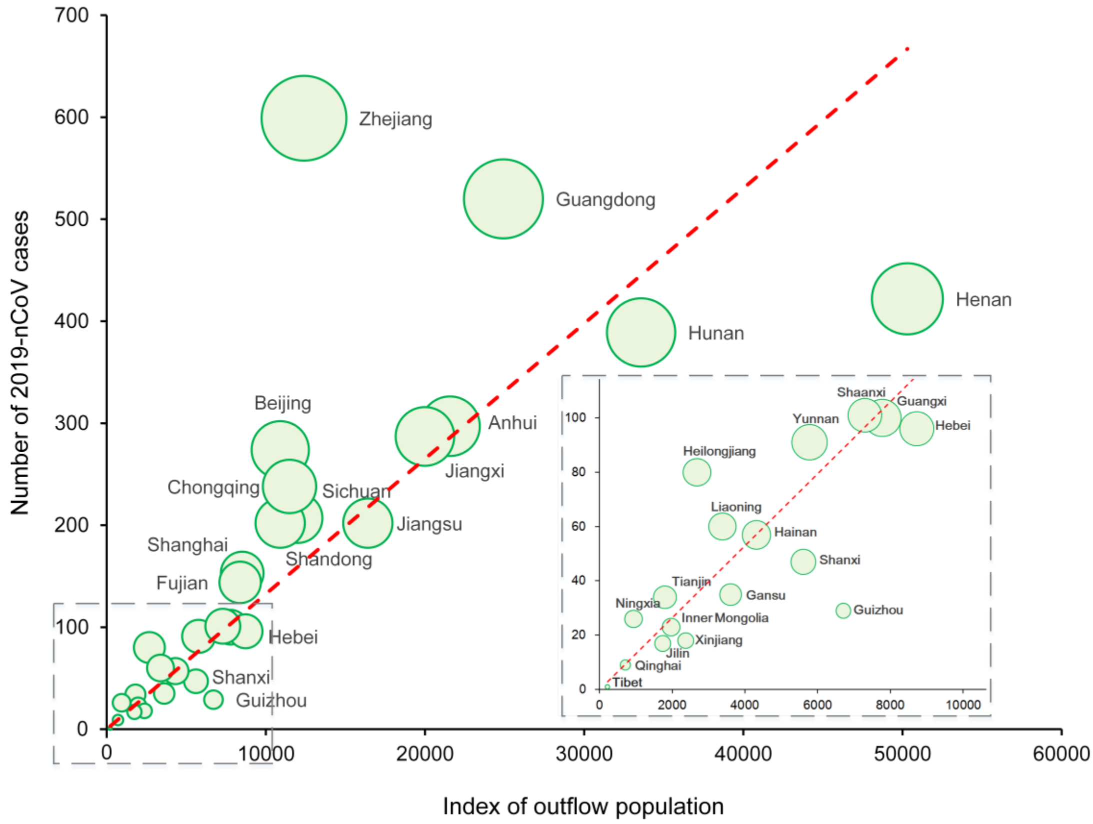
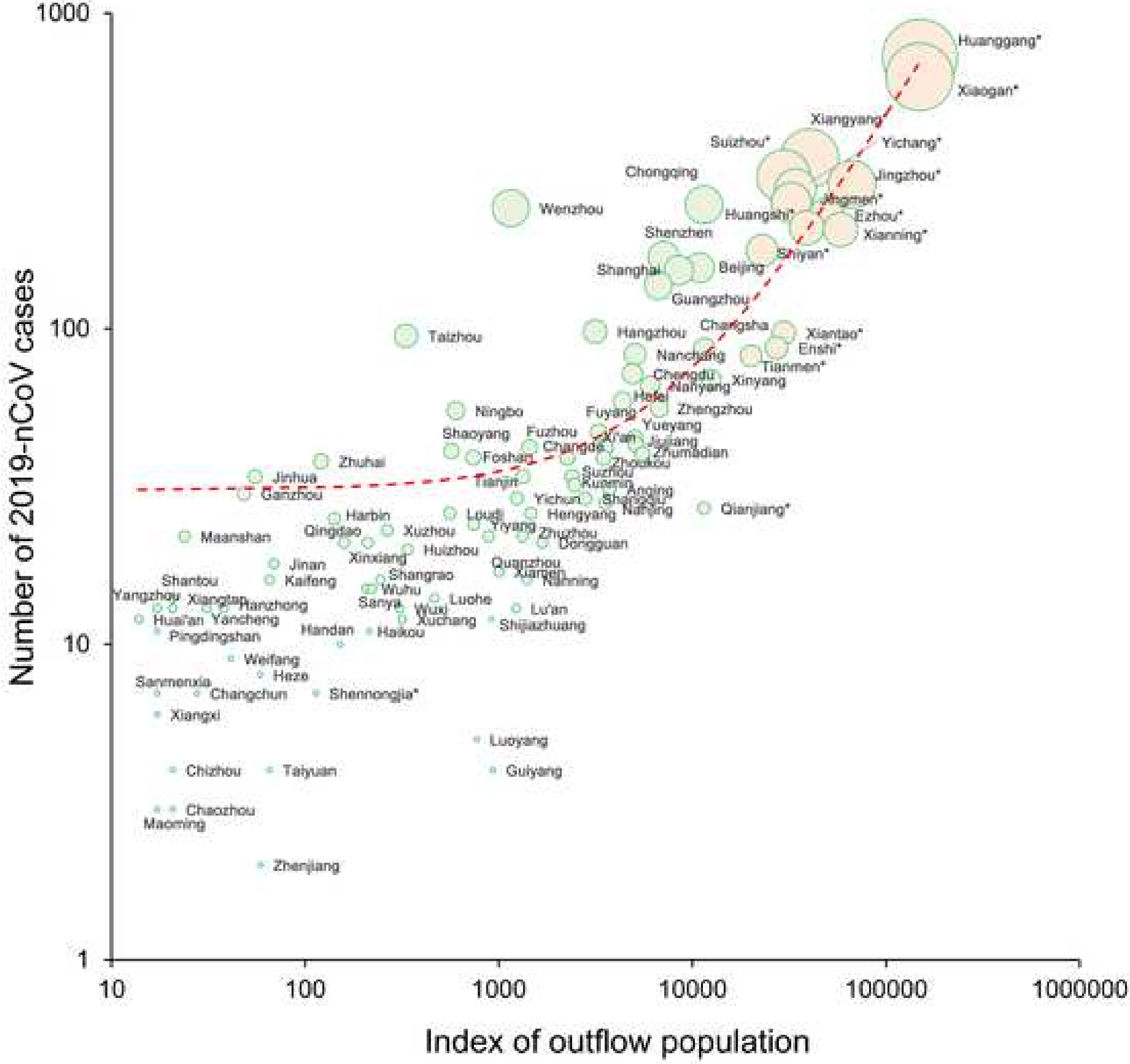

Number of 2019-nCoV cases
Index of outflow population
Zhejiang
Guangdong
Henan
Hunan
Beijing
Anhui
Jiangxi
Chongqing
Sichuan
Jiangsu
Shanghai
Shandong
Fujian
Hebei
Shanxi
Guizhou
Shaanxi
Guangxi
Yunnan
Heilongjiang
Liaoning
Hainan
Tianjin
Gansu
Ningxia
Inner Mongolia
Xinjiang
Jilin
Qinghai
Tibet

Figure 4



Number of 2019-nCoV cases
Index of outflow population
1000
100
10
1
10
100
1000
10000
100000
1000000
Huanggang*
Xiaogan*
Xiangyang
Suizhou*
Yichang*
Chongqing
Jingzhou*
Jingmen*
Wenzhou
Huangshi*
Ezhou*
Shenzhen
Xianning*
Shiyan*
Shanghai
Beijing
Guangzhou
Taizhou
Hangzhou
Changsha
Xiantao*
Enshi*
Nanchang
Tianmen*
Chengdu
Nanyang
Xinyang
Hefei
Ningbo
Fuyang
Zhengzhou
Yueyang
Shaoyang
Fuzhou
Xi'an
Jiujiang
Changde
Zhumadian
Foshan
Zhuhai
Zhoukou
Suzhou
Jinhua
Tianjin
Kunming
Anqing
Ganzhou
Yichun
Shangqiu
Nanjing
Qianjiang*
Harbin
Loudi
Hengyang
Qingdao
Yiyang
Xuzhou
Zhuzhou
Maanshan
Dongguan
Huizhou
Xinxiang
Jinan
Quanzhou
Xiamen
Shangrao
Kaifeng
Nanning
Shantou
Wuhu
Luohe
Yangzhou
Xiangtan
Hanzhong
Sanya
Wuxi
Lu'an
Huai'an
Yancheng
Xuchang
Shijiazhuang
Handan
Haikou
Pingdingshan
Weifang
Heze
Sanmenxia
Changchun
Shennongjia*
Xiangxi
Luoyang
Chizhou
Taiyuan
Guiyang
Chaozhou
Maoming
Zhenjiang