Summary of the COVID-19 epidemic in China: When and how to launch an emergency response

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Research Article

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Abstract

In December 2019, Coronavirus Disease 2019 (COVID-19) was first detected in Hubei Province and spread rapidly around the world. Summarizing the development of COVID-19 and assessing the effect of control measures are very critical to China and other countries. A heatmap was used to find the highest concentration of the COVID-19 outbreak and the areas with initial imported cases. A logistic growth curve model was employed to compare the development of COVID-19 before and after the emergency response took effect. We found that the number of confirmed cases peaked 9-14 days after the first detection of an imported case, but there was a peak lag in the province where the outbreak was concentrated. The average growth rate of cumulative confirmed cases decreased by approximately 50% after the emergency response began. Areas with frequent population migration have a high risk of outbreak. The emergency response taken by the Chinese government was able to effectively control the COVID-19 outbreak. Our study provides references for other countries and regions to control the COVID-19 outbreak.

Introduction

On December 31, 2019, China notified the World Health Organization of unknown pneumonia cases in Wuhan, Hubei Province [1]. This pneumonia came with persistent fever, cough, and dyspnea [2] and was then named Coronavirus Disease 2019 (COVID-19). The disease spread rapidly from Hubei Province to other provinces in China within two weeks [3,4]. Beginning January 15, 2020, the Chinese government launched an emergency response at all levels. On the one hand, in the outbreak area, Hubei Province implemented traffic control. On the other hand, the whole nation was required to wear masks and to avoid going out and having close contact with other people in order to reduce the exposure to susceptible people. By March 20, 2020, a total of 81,416 confirmed cases and 3,261 deaths had been reported in China, of which less than seventeen percent of the cases and less than four percent of the deaths occurred outside Hubei Province. Since January 13, 2020, first Thailand [5], then more than 200 countries, including Japan, Korea [6], the United States [7] and the United Kingdom [8], have reported imported COVID-19 cases. Due to the speed and scale of transmission, the WHO described COVID-19 as a pandemic on March 12, 2020, officially declaring that COVID-19 entered the global epidemic phase.

By March 31, the total number of confirmed COVID-19 cases and deaths outside China reached 776,506 and 38,841, respectively, and were increasing. There have been concentrated outbreaks in Europe [9] and America [10]. Many imported cases have been reported in the Middle East [11] and in African countries [12]. These countries are currently in different stages of COVID-19 development. However, there is no relevant research or evidence on how to assess the development of COVID-19 [13]. As the earliest occurrence area, Hubei Province, China has been through the process of case accumulation – outbreak detection – isolation and control. The rest of China has been through a complete process of case imports – detected transmission – isolation and control. Therefore, summarizing COVID-19 development in Hubei Province and other regions of China can help us to explore the epidemic characteristics of COVID-19 and provide a reference for other countries to assess the stages of the COVID-19 epidemic.

The course of COVID-19 includes incubation, disease, and recovery or death [2,14]. This course is characterized at the population level, as the number of cumulative confirmed cases experience a period of delay before exponential growth, then present a period of maximum increasing density, and finally enter a stable stage. The entire process presents an S-shaped development trend. A logistic growth curve model [15] is often used to describe such ecological processes [16,17]. Both the average growth rate and the maximum value of the growth curve have clear epidemiological significance and are of great reference value in the field of public health. Therefore, this study intends to use the logistic growth curve model to fit the development of COVID-19 into two periods and then summarize the development of a concentrated COVID-19 outbreak in Hubei Province and in high-risk areas with imported cases. In addition, this study will extract historical data to simulate a short-term dynamic prediction and discuss the application of the growth curve model in the assessment of COVID-19 in order to provide a reference for other countries.

Methods

Data sources

Confirmed COVID-19 case data were obtained from the *Chinese Center for Disease Control and Prevention* [18]. All cases were confirmed by laboratory and clinical diagnosis and met the definition of confirmed cases according to *the National Health Commission of China* [19]. Baidu is the most widely used search engine in China, and we extracted population migration data from the *Baidu Qianxi* to find areas with early imported cases [20]. Considering that in the early stages of the COVID-19 outbreak, the situation reports may have underreported cases, we used confirmed cases from January 22 to March 4, 2020 to ensure the reliability of the data.

Statistical analysis

This study conducted a spatiotemporal distribution analysis of cumulative confirmed COVID-19 cases in China on a provincial level. We selected Hubei Province as the concentrated outbreak area for analysis, and we selected other provinces with early reported cases as representative provinces facing the risk of outbreak.

We fitted the growth curve model for the cumulative confirmed cases in Hubei and other provinces facing the risk of outbreak. The formula for the model is as follows:

$$N_t = \frac{N_0 K}{N_0 + (K - N_0)e^{-rt}}$$

where N_t represents the cumulative confirmed COVID-19 cases at time t, N_0 represents the cumulative confirmed cases at the initial time, K represents the maximum cumulative confirmed cases within the analysis period, and r is the average increase rate of the cumulative confirmed cases.

After the outbreak of COVID-19, the first level of the Chinese public health emergency response [21] (later referred to as “emergency response”) was gradually implemented in each province. To assess the impact of the emergency response implemented in each province, we fitted the growth curves at two different periods, using an average incubation period of seven days [14,19] after the emergency response time as the cut-off point (for details of the time period, see Supplementary Table S1). The first time period was used to assess the situation before the emergency response was implemented. The second time period, from the end of period one to March 4, 2020, was used to assess the situation after the emergency response had taken effect. The coefficient of determination (R^2) was used to evaluate the goodness of fit. The average growth rates of periods one and two in each province were compared to assess the impact of the prevention and control measures.

To evaluate the prediction capacity of the logistic growth curve model, we used the cumulative confirmed cases from January 22 to February 4, 2020 to simulate the short-term dynamic prediction. The step lengths of the dynamic predictions were set as one, three and seven days, referred to as the 1, 3, or 7 out-of-sample prediction. In the 1 out-of-sample prediction, the cumulative confirmed cases from January 22 to February 4 were selected as the training set, and one day after, February 5, was selected as the test set. Then, the model was updated with actual observations from February 5, and the cumulative confirmed cases on February 6 were predicted by the updated model until all the predicted cumulative confirmed cases from February 5 to March 4 were obtained. The average absolute error (MAE) and average absolute percentage error (MAPE) were then calculated for each dynamic prediction with different step lengths to measure the model prediction accuracy.

All statistical analyses were performed in R 3.6.3 using packages such as “growthcurver,” “rgdal” and “ggplot2.”

Results

General characteristics of COVID-19 in China

Wuhan, Hubei Province shut down outward traffic beginning January 23, 2020, followed by the rest of Hubei Province. To find high-risk areas caused by imported cases, we drew a heatmap of the migration out of Hubei on January 22, 2020 (Fig. 1a), which indicated that people mainly migrated to Henan, Hunan, Chongqing, Jiangxi, Guangdong, Anhui, Sichuan, Jiangsu, Zhejiang, Beijing and Shanghai. A heatmap of the cumulative confirmed cases in Chinese provinces from January 22 to March 4, 2020 highlights similar provinces (Fig. 1b). Hubei Province was the location of the concentrated COVID-19 outbreak, followed by its neighbors (Henan, Anhui, Jiangxi, Hunan and Chongqing) and some economically developed and densely populated provinces (Guangdong, Zhejiang, Jiangsu, Shandong, Sichuan, Shanghai and Beijing). Thus, Sichuan, Guangdong, Beijing, Shandong, Chongqing, Zhejiang, Jiangxi, Anhui, Jiangsu, Hunan, Shanghai and Henan were selected as high-risk areas with imported cases for further analysis. In addition, since Hubei Province had the most severe epidemic, we also analyzed national data excluding Hubei Province to present the average epidemic in other provinces.

Table 1 shows the peak number of confirmed COVID-19 cases, the corresponding peak date and the cumulative number of confirmed cases in China. Fig. 2 shows a time series of confirmed COVID-19 cases in the identified provinces. The confirmed COVID-19 cases in Hubei Province and nationwide showed a rapid increase before February 4, followed by a decline, and gradually stabilized after February 18, 2020. In high-risk provinces with imported cases, the peak of confirmed cases was around January 30, 2020 in Sichuan, Guangdong, Zhejiang and Shanghai, and around February 2, 2020 in Beijing, Chongqing, Jiangxi, Anhui, Jiangsu, Hunan and Henan.

Table 1 Peak number of confirmed COVID-19 cases, corresponding peak date and cumulative confirmed cases in Hubei Province, China and twelve high-risk provinces from January 22 to March 4, 2020.

Area	Peak confirmed cases	Peak date	Cumulative cases
China	3893	2/4/2020	81047
Hubei	3156	2/4/2020	67990
China except Hubei	890	2/3/2020	13057
Sichuan	36	1/30/2020	538
Guangdong	127	1/31/2020	1325
Beijing	32	2/2/2020	411
Shandong	45	2/5/2020	757
Chongqing	38	2/2/2020	571
Zhejiang	132	1/29/2020	1209
Jiangxi	85	2/3/2020	937
Anhui	72	2/3/2020	991
Jiangsu	37	2/3/2020	631
Hunan	74	2/1/2020	1017
Shanghai	27	1/30/2020	329
Henan	109	2/3/2020	1273

Two outliers occurred in China and Hubei Province on February 12 and 13, as the National Health Commission of the PRC revised the definition of COVID-19 confirmed cases in Hubei Province on February 12, adding “clinical case” to “confirmed case,” and left the other provinces unchanged [22]. Another outlier was found in Shandong Province on February 20, corresponding to an outbreak at a prison with 200 confirmed cases [23]. The overall trend of confirmed cases in the other provinces increased first and then decreased.

Impact evaluation of emergency response

We fitted the growth curves at two different periods to assess the impact of the emergency response implemented in each province. Fig. 3 shows the growth curves of each area. The coefficients of the logistic growth curve models in two periods are referred in Supplementary Table S2 and S3. The fitted cumulative confirmed cases were close to the actual observed cases, and the R^2 of all models was above 0.95.

The average growth rates of the two periods in Hubei Province, China and twelve high-risk provinces are presented in Table 2 and Fig. 4. The average growth rate decreased by 44.42% nationally and by 32.5% outside Hubei Province. The average growth rate in each province decreased significantly after the emergency response. The average growth rate in the twelve high-risk areas decreased by 29.8%, which was lower than that outside Hubei Province. Before the emergency response, the provinces with the highest average growth rates were ranked from highest to lowest as follows: Hunan, Hubei, Zhejiang, Shandong, Jiangxi, Jiangsu, Guangdong, Sichuan, Anhui, Henan, Chongqing, Beijing and Shanghai. Hubei, Shandong, Zhejiang, Jiangxi and Hunan had growth rates higher than the national average. After the emergency response, the average growth rate of each province from highest to lowest was Zhejiang, Hunan, Anhui, Shanghai, Jiangxi, Jiangsu, Hunan, Guangdong, Hubei, Chongqing, Beijing, Sichuan and Shandong. The growth rates of Guangdong, Zhejiang, Jiangxi, Anhui, Jiangsu, Hunan, Shanghai and Henan were higher than the national average.

Table 2 Comparison of the average growth rates before and after the emergency response in China, Hubei Province and twelve high-risk provinces.

Area	r_1[a]	r_2[b]	Percentage decrease
China	0.565	0.314	0.444
Hubei	0.614	0.328	0.466
China except Hubei	0.508	0.343	0.325
Sichuan	0.475	0.279	0.413
Guangdong	0.498	0.370	0.257
Beijing	0.443	0.308	0.305
Shandong	0.584	0.179	0.693
Chongqing	0.450	0.313	0.304
Zhejiang	0.603	0.435	0.279
Jiangxi	0.576	0.397	0.311
Anhui	0.469	0.417	0.111
Jiangsu	0.509	0.393	0.228
Hunan	0.625	0.418	0.331
Shanghai	0.440	0.402	0.086
Henan	0.468	0.393	0.160
Average of 12 high-risk areas	0.512	0.359	0.298

a r_1: Average growth rate before the emergency response.

b r_2: Average growth rate after the emergency response.

Prediction capacity evaluation of logistic growth curve models

We used cumulative confirmed case data, from January 22 to February 4, 2020, to simulate a short-term dynamic prediction. Table 3 shows the MAE and MAPE of the logistic growth curve model in each province. Fig. 5 shows the 1-step dynamic prediction of the logistic growth curve model in Hubei Province, China and twelve high-risk provinces. The 1-step dynamic prediction outperformed the rest, with a MAPE of 1.16%-5.45% in different areas. Except for the models for China, Hubei and Shandong provinces, which were affected by the three outliers mentioned above, the models showed predictions close to the observations.

Table 3 MAE and MAPE of the logistic growth curve model in Hubei Province, China and twelve high-risk provinces.

Area	MAE			MAPE（%）		
	1 out-of-sample	3 out-of-sample	7 out-of-sample	1 out-of-sample	3 out-of-sample	7 out-of-sample
China	1322.3	2170.57	2285.19	3.54	5.02	13
Hubei	1392.29	2472.08	2290.85	4.05	6.28	14.04
China except Hubei	1780.99	1781.32	1805.11	3	3.97	6.55
Sichuan	2.83	7.7	11.1	4.58	5.88	8.77
Guangdong	4.81	9.62	16.37	2.64	3.3	4.99
Beijing	2.41	3.39	3.77	3.43	3.97	5.78
Shandong	17.6	23.49	27.35	5.45	7.71	12.95
Chongqing	2.17	4.03	6.04	2.7	3.33	4.73
Zhejiang	5.24	13.98	17.22	3.4	4.27	6.52
Jiangxi	3.92	9.04	13.7	1.72	2.57	4.83
Anhui	3.59	9.33	15.49	1.16	1.82	4.3
Jiangsu	2.78	9.69	13.33	2.71	3.94	7.2
Hunan	4.15	10.34	14.66	2.03	2.86	5.07
Shanghai	1.75	3.13	4.28	4.48	5.28	7.5
Henan	4.69	8.73	14.2	1.68	2.35	4.28

Discussion

On January 30, 2020, the WHO declared COVID-19 to be a public health emergency of international concern (PHEIC), and later, it was described as a pandemic. COVID-19 is threatening the public health security of every country [24,25]. As the country with the initial COVID-19 outbreak, China issued a series of policies and regulations to control the outbreak [26,27], including cross-regional traffic control and suspending the operations of restaurants, entertainment, and cultural tourism areas. The government encouraged citizens to stay at home, stop gathering, wear masks and wash hands frequently. Summarizing the development of COVID-19 in China and assessing the effect of control measures can provide a reference for other countries to deal with the outbreak. In this paper, we summarized the development of COVID-19 in Hubei Province, China and twelve other provinces with a high incidence of COVID-19. We also compared the characteristics of the epidemic before and after the emergency response to assess the impact of the prevention and control measures.

Before the traffic leaving Wuhan, Hubei was shut down, and people from Hubei Province mainly migrated to Henan, Hunan, Chongqing, Jiangxi, Guangdong, Anhui, Sichuan, Jiangsu, Zhejiang, Beijing and Shanghai, which was consistent with provinces later had high incidences of COVID-19. Other studies have shown that population density can directly affect the spread of such diseases [28]. It has been suggested that blocking migration from severe outbreak areas would be of great importance to prevent the disease from spreading to other areas, especially during early stages. Tian H et al. showed that this suggestion worked [29].

The peak outbreak occurred from February 1 to February 4, 2020, which could be related to the population migration and the incubation of COVID-19. As January 25th was the traditional Chinese New Year, most people were returning to their hometowns to reunite with their families. Therefore, the densified migration in the week before the traditional Chinese New Year led to the rapid spread of COVID-19. The incubation of COVID-19 is estimated to be 3-7 days. Each province experienced 9-14 days from the first detection of imported cases to the peak of confirmed cases, which was consistent with the sum of the migration peak and the incubation period. However, in the region with the most severe outbreak, Hubei Province, the peak of confirmed cases was delayed due to the long accumulation of confirmed cases and inadequate testing capacity, which is consistent with the findings of Kaiyuan Sun et al. [30]. Therefore, 9-14 days after the detection of imported cases is the critical period for preventing further transmission. In this period, screening tests and the quarantine of COVID-19 patients should be carried out to identify the infection source and protect susceptible populations.

We fitted the logistic growth curves of cumulative COVID-19 cases before and after the implementation of an emergency response in each study province and found an approximate 50% reduction in the average growth rate after the emergency response. As all the emergency responses were launched within one week after the first confirmed case, the reduction in the average growth rate suggested that rapid growth of the epidemic can be slowed by a timely emergency response after the early detection of imported cases within the critical period of 9-14 days.

The average growth rate in Zhejiang, Jiangsu, Anhui, Jiangxi, Hunan, Shanghai, and Henan provinces remained higher than the national average growth rate after the implementation of the emergency response. Among them, the economically developed provinces and labor-exporting provinces with frequent population migration, such as Zhejiang, Hunan and Anhui provinces, had the highest growth rates, indicating a high outbreak risk. Therefore, the control measures should be particularly strengthened to prevent COVID-19 outbreaks in these regions. Although the emergency response reduced the average growth rate, in the outbreak center, Hubei Province, the peak in confirmed cases was delayed. This suggests that if the outbreak was not detected in time, the critical control period would be missed. This would lead to a lag in the implementation of prevention and control measures in response to the outbreak. Therefore, for concentrated COVID-19 outbreak areas, the growth of the epidemic would not be easily controlled within the standard critical period of 9-14 days. The lagged peak of confirmed cases should be fully considered, and the duration of control measures should be extended for further development of the epidemic.

In the 1-step dynamic prediction of the cumulative confirmed COVID-19 cases in the early stage of the epidemic, the MAPE between the predicted and actual cumulative cases was 1.16%-5.45%. Despite the increase due to the change in diagnostic criteria on February 13th in Hubei Province, the values predicted by the logistic growth curve model were very close to the actual observed values. Thus, the logistic growth curve model can be used to assess the short-term development of COVID-19 and aid in the short-term adjustment of prevention and control measures.

In conclusion, the logistic growth curve model can accurately assess and predict the short-term development of the COVID-19 epidemic. Timely detection of imported cases and blocking migration from the epidemic area are important for controlling the spread of COVID-19. Nine to 14 days after the first detection of imported cases is the critical period for epidemic prevention and control. In areas where the epidemic is severe, we need to consider the peak lag and extend prevention measures. Areas with frequent migration have a high risk of COVID-19 outbreak, so the prevention and control measures should be strengthened. The emergency responses launched in China efficiently reduced the spread and further development of the epidemic, which provides a reference for other countries and regions.

This study is based on the existing surveillance data, and the detection capacity of COVID-19 varies between different regions and countries. Insufficient detection capacity will lead to an underestimated occurrence, and the outbreak reflected by the surveillance data may be delayed. Each region should consider local detection capacity when formulating prevention and control measures.

Declarations

Data availability

Chinese Center for Disease Control and Prevention has published the COVID-19 situation since Jan 16th. Everyone can obtain the daily confirmed COVID-19 cases from http://2019ncov.chinacdc.cn/2019-nCoV/. This research has been conducted using the confirmed COVID-19 cases from 22th January 2020 to 4th March.

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Author contributions

F.Y. and Y.M. designed the study, collected data, and contributed to data analysis. J. T. contributed to the literature search, data analysis, data interpretation, figures, and writing. C.L., J.H., and T.Z. contributed to data interpretation. All authors contributed to writing the manuscript and revising the final version.

Competing interests

The authors declare that they have no conflict of interest.

Supplementary Information

See “Supplementary Appendix” file.

Equipment and Settings

All statistical analysis and figures was performed in R 3.6.3 using packages such as "growthcurver", "rgdal" and "ggplot2".

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Figures

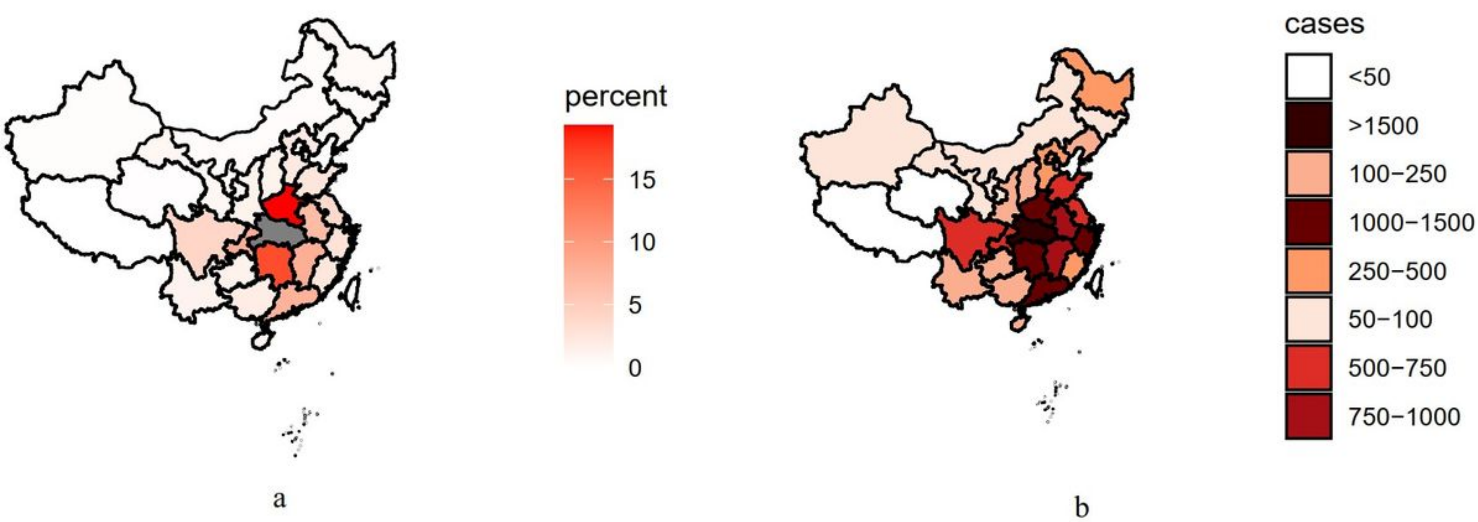

Figure 1

a Percentage of the migration population moving from Hubei province to other provinces on January 22, 2020. b The cumulative confirmed COVID-19 cases in Chinese provinces from January 22 to March 4, 2020. Note: The designations employed and the presentation of the material on this map do not imply the expression of any opinion whatsoever on the part of Research Square concerning the legal status of any country, territory, city or area or of its authorities, or concerning the delimitation of its frontiers or boundaries. This map has been provided by the authors.

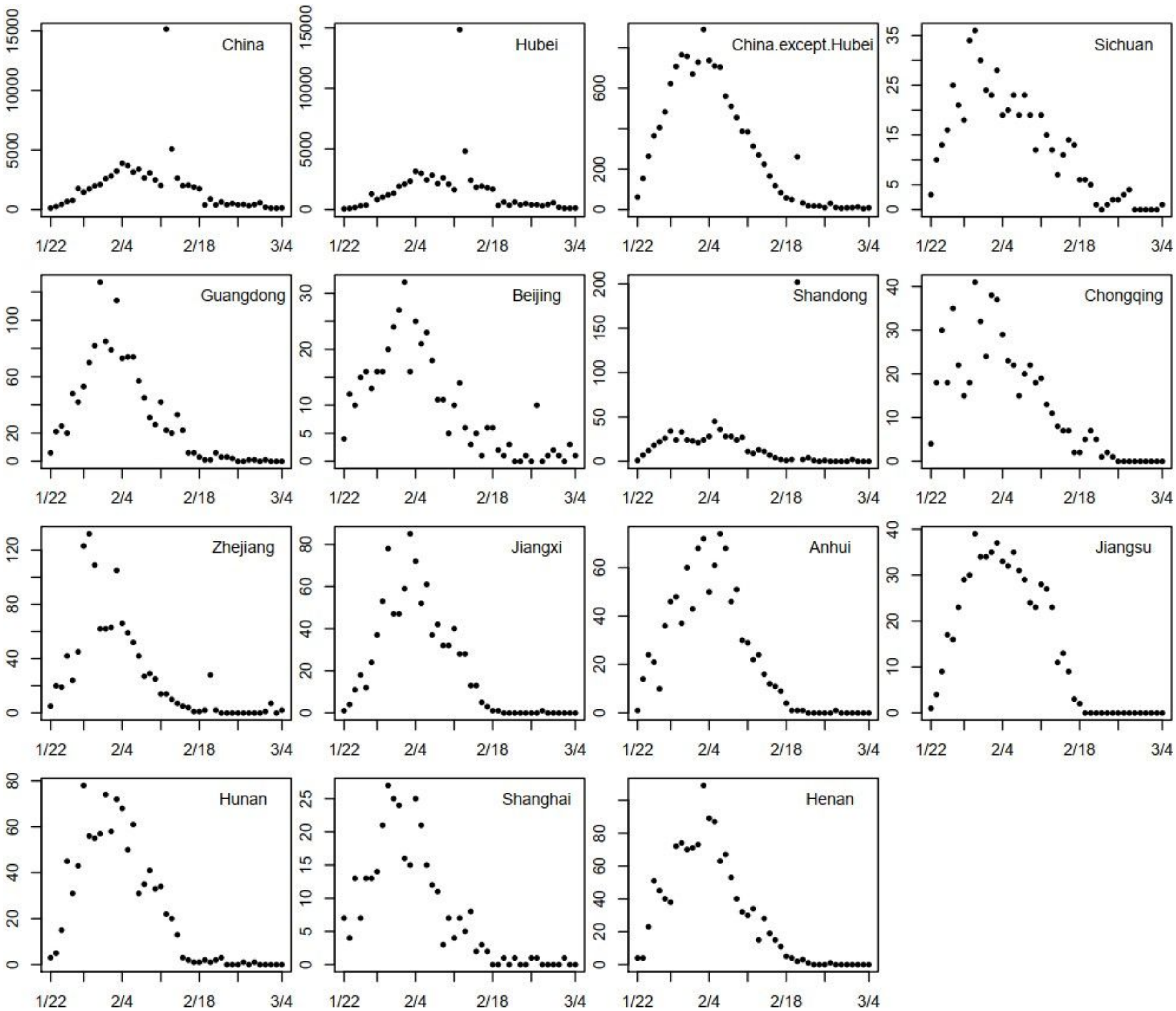

Figure 2

The time series of confirmed COVID-19 cases in China, Hubei province and twelve high-risk provinces from January 22 to March 4, 2020.

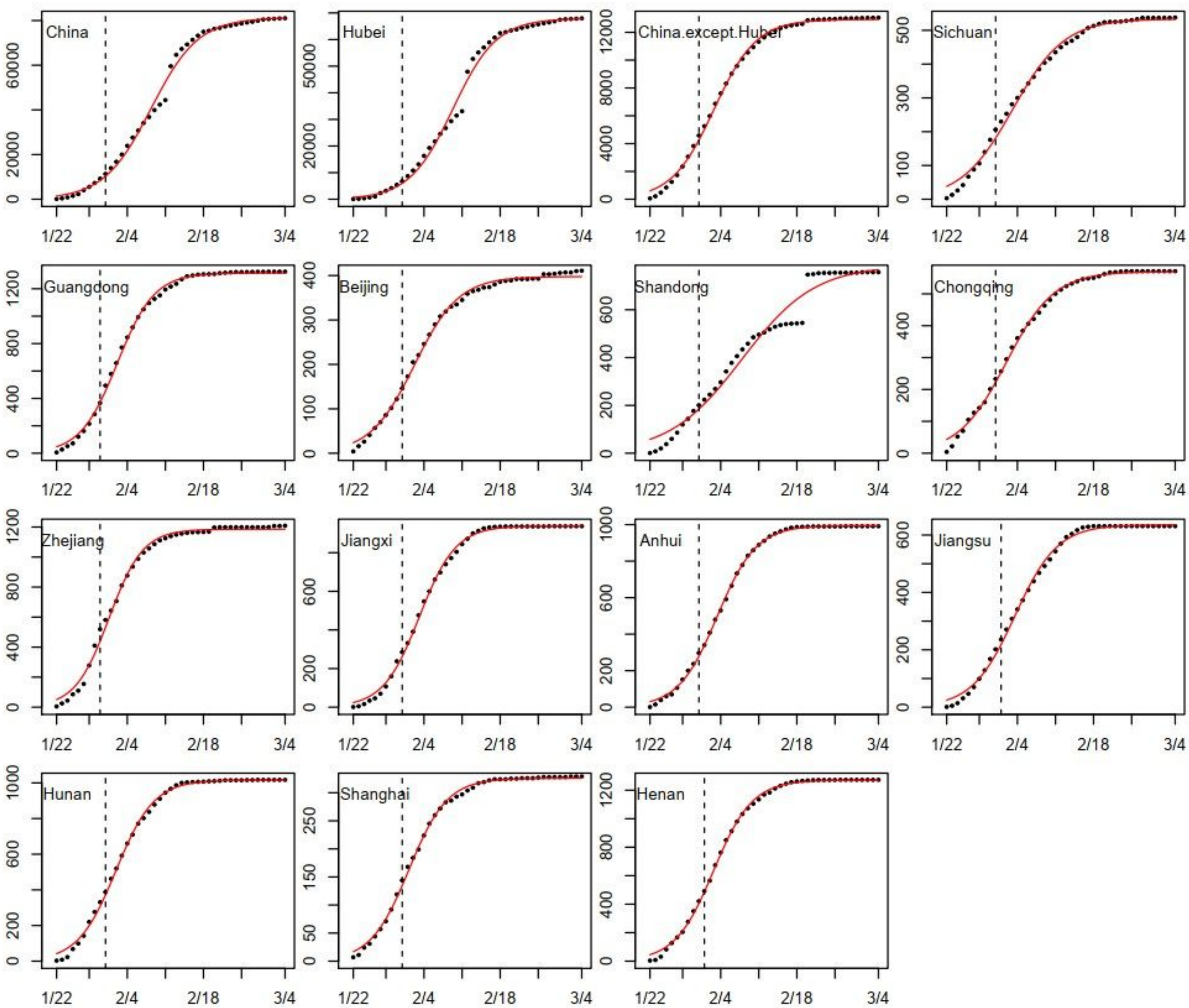

Figure 3

The Logistic growth curves of China, Hubei province and twelve high-risk provinces before and after emergency response. Note. Black points representing observed values, red lines representing fitted growth curves and black dash lines representing two different periods cut-off point.

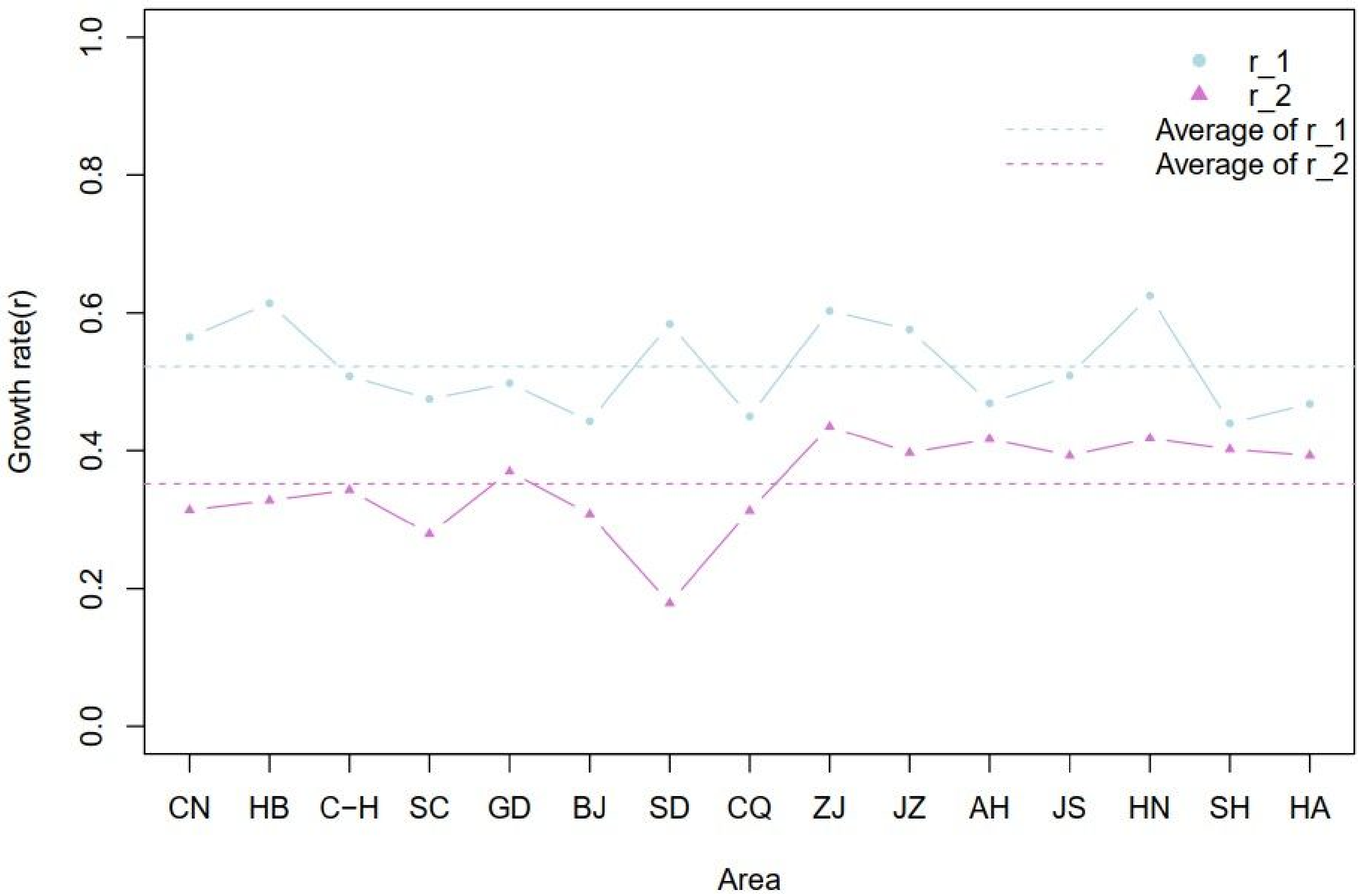

Figure 4

The comparison of the average growth rates before and after emergency response in China, Hubei province and twelve high-risk provinces.

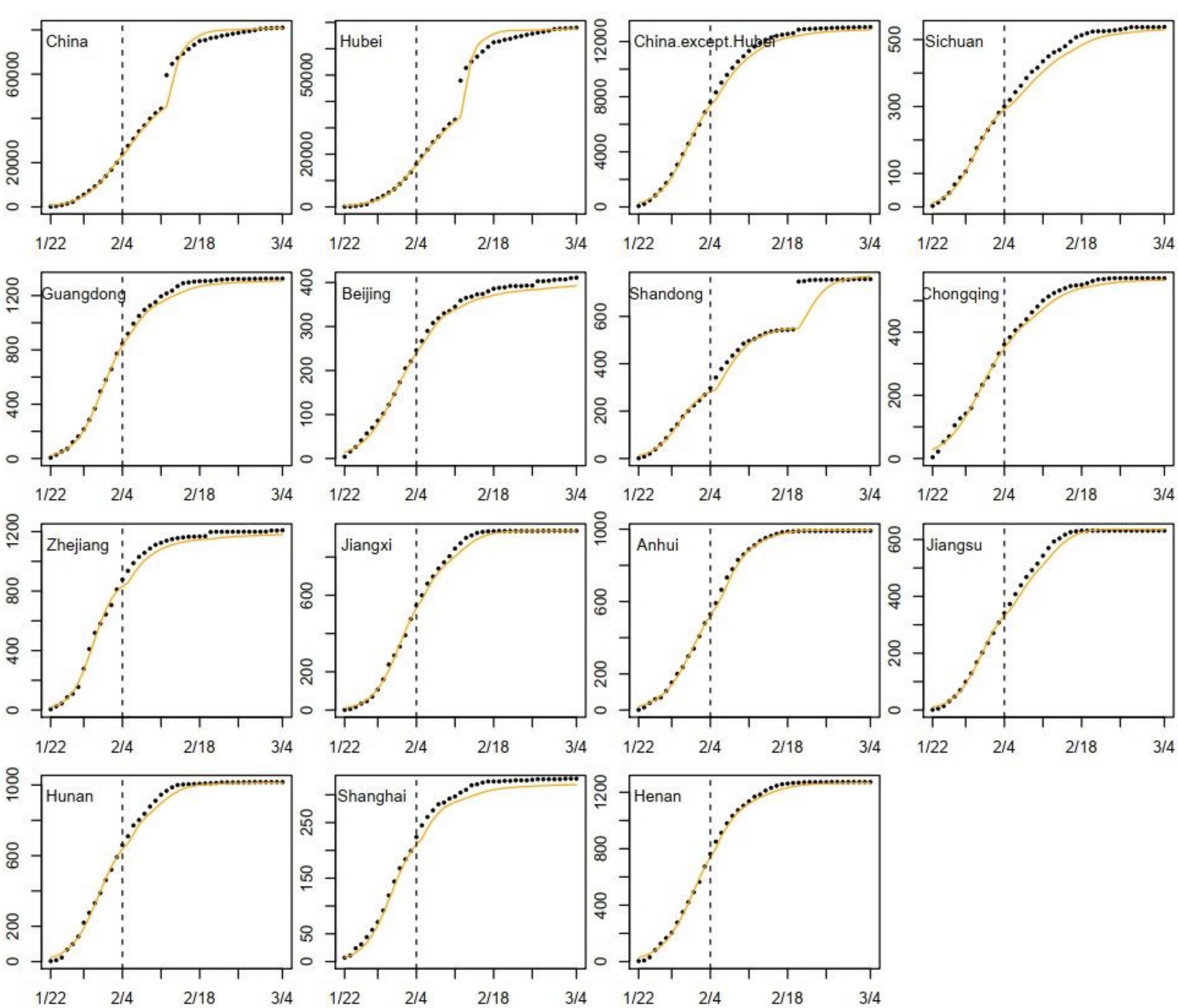

Figure 5

The 1-step dynamic prediction of Logistic growth curve model in China, Hubei province and twelve high-risk provinces. Note. Black points representing observed values, orange lines representing fitted growth curves.

Supplementary Files

This is a list of supplementary files associated with this preprint. Click to download.

- SupplementaryAppendix.pdf