Effect evaluation of non-pharmaceutical interventions taken in China to contain the COVID-19 epidemic based on the susceptible-exposed-infected-recovered model

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Research Article

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Abstract: The spread of the coronavirus disease 2019 (COVID-19) had resulted in 16 million infected individuals and 640000 deaths across the world as of July 27, 2020. Unfortunately, there is still no sign that the epidemic spread is slowing down. China, as the first country suffering from the widespread outbreak of the epidemic, has effectively contained the spread of the epidemic since March, 2020. Therefore, confirmed cases of COVID-19 from January 20 to March 18, 2020 were taken as the sample set to establish the susceptible-exposed-infected-recovered (SEIR) model. The model was used to analyze changes in the numbers of individuals becoming infected, exposed (latently infected), susceptible, and recovered in the experimental groups taking different non-pharmaceutical interventions (NPIs) and in the control group not taking any NPIs, so as to evaluate effects of different NPIs. By doing so, the research expects to provide references to other countries for formulating corresponding policies. The results show that type-A NPIs for reducing daily contacts with infected and exposed cases and type-B NPIs for decreasing the probability of post-exposure infections both can delay the timing of large-scale infections of the susceptible population, timing of the number of exposed individuals to peak, and timing of peaking of the number of infected cases, as well as decrease the peak number of exposed cases. Moreover, type-B NPIs have more significant effects on susceptible and exposed populations. Type-C NPIs for improving the recovery rate of patients are able to effectively reduce the peak number of patients, greatly decrease the slope of the curve for the number of infected cases, substantially improve the recovery rate, and lower the mortality rate; however, these NPIs do not greatly delay the timing of the number of infected cases to peak. In addition to these, considering effects of different NPIs on the susceptible and exposed populations and in delaying the timing for the number of infected cases to peak, it is found that the government's organization of medical supply related companies to resume production exerts the best effect. As for reducing the epidemic number of patients in the core epidemic area (CEA, Hubei Province), delivery and putting-into-operation of Leishenshan hospital shows the best effect, followed by dispatching of medical staff to support Wuhan, delivery and putting-into-operation of Huoshenshan hospital, and construction of mobile cabin hospitals.

Keywords: coronavirus disease 2019, Chinese experience, susceptible-exposed-infected-recovered model

Introduction

Human beings have experienced a serious public health event, the novel coronavirus disease (COVID-19), caused by the severe acute respiratory syndrome coronavirus[1,2]. On February 11, 2020, the World Health Organization (WHO) renamed the virus causing COVID-19 as severe acute respiratory syndrome coronavirus 2 (SARS-CoV-2)[3,4]. Some of the COVID-19 cases in the early period were found to be associated with a seafood market in Wuhan city, Hubei Province, China, and now COVID-19 has spread to more than 100 countries outside of China. The SARS-CoV-2 on the one hand exerts harmful effects on organs, such as heart [6] and liver [7] of human beings and to some extent increases the incidence of Measles [8]; on the other hand it also influences the weather forecast and climatic record [9].

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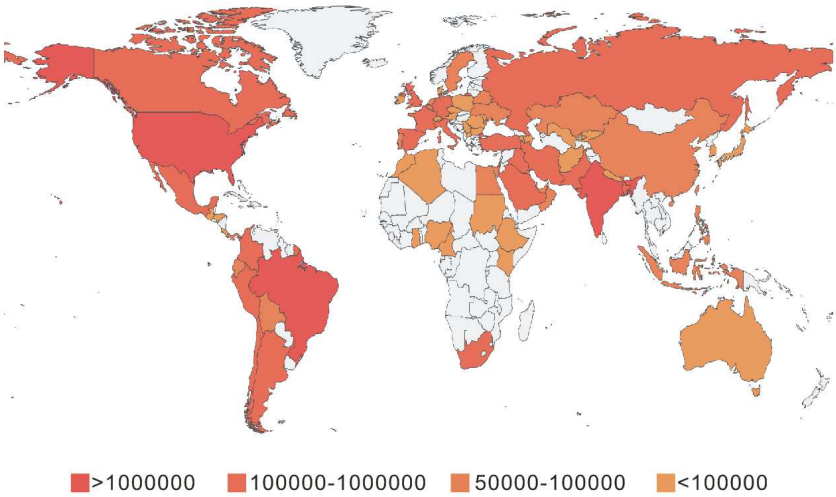

Figure 1 Global epidemic map (up to July 27, 2020)

As of July 27, 2020, the cumulative number of infected cases of COVID-19 in colored regions of the map had exceeded 10000. As shown in Figure 1, although all countries have come up with various policies successively to contain spread of the epidemic, the situation is still very grim. The pneumonia caused by the SARS-CoV-2 virus has become an international infectious disease and has been reported in six continents including the Asia and Europe, and the number of confirmed cases in the United States has been well above 4 million. Because specific medicines or vaccines for the COVID-19 have not been developed, the number of countries with confirmed cases is still rising and the number of patients is also ascending. Up to July 27, 2020, the global cumulative death toll from COVID-19 had reached 640000.

Due to the rapid increase in the number of infected cases in other countries, the WHO declared that the COVID-19 epidemic in China has become a public health emergency of international concern (PHEIC) on January 30, 2020. Despite being a country of the largest population in the world, China has effectively contained spread of the epidemic attributed to a series of NPIs taken by the government since the outbreak of COVID-19, including requirement of wearing masks (in public places), travel restrictions, and isolation of confirmed cases. According to the latest data released by the National Health Commission of the People's Republic of China (http://www.nhc.gov.cn/), the number of daily confirmed cases has declined significantly after climbing to the peak on February 4, 2020 (Figure 2).

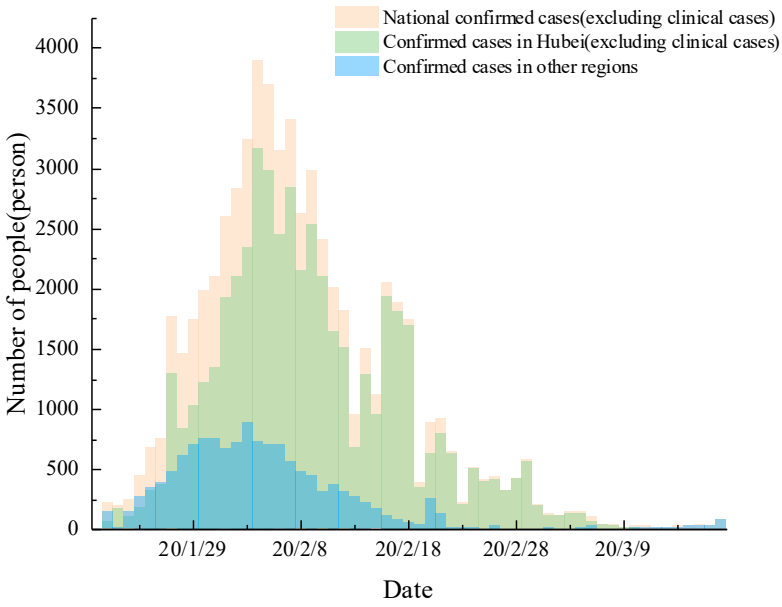

Figure 2 The number of daily confirmed cases (from January 1 to March 18, 2020)

Due to changes in the testing mechanism for the number of confirmed cases during February 2 to 15, 2020, the number of clinical cases were also included in that of the total confirmed cases, so that the number of daily confirmed cases fluctuated greatly. In the research, to guarantee consistency of data sampling standards, the addition of clinical cases was not taken into account. As shown in Figure 2, the following conclusions can be obtained: 1) the number of daily confirmed cases in Hubei Province with the most series infections was significantly larger than that in other regions; 2) as of March 10, 2020, the number of daily confirmed cases had reduced to about 0, indicative of effective control over the epidemic spread in the period; and 3) despite the slow decrease in the number of confirmed cases in Hubei Province since reaching the peak in the beginning of February, the number also increased abruptly in some days, while only small fluctuations were found in regions outside of Hubei Province.

To more effectively respond to the COVID-19 epidemic, scholars have conducted numerous studies on the origin of the virus and efficacy of preventive NPIs. For the origin of the virus, Zhou *et al.* [10] pointed out that the virus is probably related to bats. Yuan *et al.* [11] analyzed the relationship between the outbreak of SARS and the COVID-19 with wildlife diet in China and proposed that regulatory intervention is not only critical for China but also for other countries where wildlife hunting is prevalent, to prevent from novel virus exposures. In terms of the efficacy of the preventive NPIs, Zhou and Wei [12] defined the confirmed cases, suspected cases, close contact, and suspicious exposure from the clinic perspective according to epidemiological risks. On this basis, Tian *et al.* [13] studied the epidemic in Beijing and found that populations are all susceptible to infections, the fatality rate is relatively low, and the NPIs for preventing spread are effective in the early stage. Ung [14] believed that community pharmacists played a key role in preventing spread of COVID-19 by informing, advising and educating the community, maintaining a stable supply of pharmaceuticals and personal hygiene products, screening suspected cases, and making appropriate referral as required. Moreover, the development trend of the epidemic in China was also predicted [15]. Suggestions of how to respond to development of the epidemic also received much attention. However, the research objects are generally a city or a whole country, there is lack of research on the CEA and the non-core epidemic aera (NCEA).

Numerous scholars have simulated the epidemic data while failed to classify and study NPIs in different regions. One of the mathematical models in epidemic dynamics, known as the "warehouse" model, has been widely applied for a long time since it was forwarded by Kermack and McKendrick in 1927 [18]. It includes several basic and improved models, such as susceptible-infected-recovered (SIR), susceptible-infected-susceptible (SIS), SEIR, and so on, among which the SEIR model is a typical example that takes the incubation period into account [19]. The SEIR model has played a positive part in studying the transmission speed and route of infectious diseases, so as to guide the effective prevention and control over the diseases [20,21]. Many scholars have used the SEIR model in the research into the transmission risk of the COVID-19 and in the inoculation of vaccines and control of the epidemic [23]. And Figure 3 shows a series of policies formulated by the Chinese government in response to the outbreak of the epidemic.

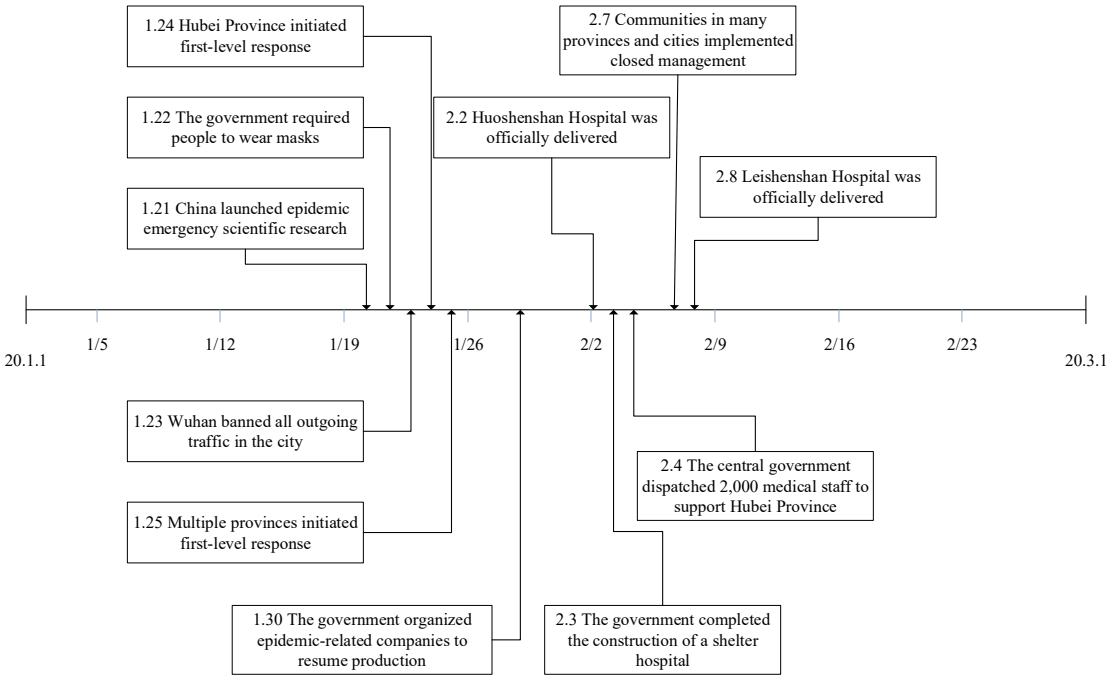

Figure 3 Timeline of policies taken in China

Classification of NPIs

Up to March 18, 2020, the NPIs taken in the CEA for containing COVID-19 mainly included lockdown of Wuhan, initiation of the first-level emergency responses of Hubei Province, official delivery and putting-into-operation of Huoshenshan hospital, and so on; those taken in the NCEA mainly involved initiation of the first-level emergency responses of various provinces, closure of communities, requirement of wearing masks, *etc*. All of these NPIs are classified into three types (A, B, and C) according to their objectives, as shown in Table 1. In the table, type-A NPIs mainly play the role in decreasing the daily contacts of infected and exposed cases; type-B NPIs are taken to effectively reduce the probability of post-exposure infections; and type-C NPIs mainly play a part in effectively improving the recovery rate.

Table 1 NPIs taken in the CEA and the NCEA

	CEA		NCEA	
	Time	NPIs	Time	NPIs
Type-A NPIs	January 22	Requirement of wearing masks	January 22	Requirement of wearing masks
	January 30	Organization of medical supply related companies to resume production	January 30	Organization of medical supply related companies to resume production
Type-B NPIs	January 23	Lockdown of Wuhan	January 25	Initiation of the first-level emergency responses of various provinces (except for Tibet Autonomous Region on January 29)
	January 24	Initiation of the first-level emergency responses of Hubei Province	February 7	Closed management of communities
Type-C NPIs	February 2	Putting-into-operation of Huoshenshan hospital	January 21	Emergency scientific research in China in challenging fields pertaining to the epidemic
	February 3	Construction of mobile cabin hospitals		
	February 4	Dispatching 2000 medical staff to support Hubei Province by the central government		
	February 8	Putting -into-operation of Leishenshan hospital		

Based on the above analysis, the changes in the number of confirmed COVID-19 cases in China from January 20 to March 18, 2020 were taken as the dataset to build the SEIR model. By analyzing influences of different NPIs on Hubei Province and other regions in China, the effects of these NPIs on the CEA and surrounding regions were revealed, so as to evaluate these NPIs taken by the Chinese government for containing COVID-19 and providing suggestions for epidemic prevention to the international community. Innovations of the research are shown as follows:

1) The research divides China into the CEA and the NCEA, to separately study corresponding NPIs taken therein.

2) NPIs taken in the CEA and the NCEA are classified and compared using the simulation results obtained by the improved SEIR model.

3) The characteristic that exposed populations in the incubation period are also infectious is introduced in the SEIR epidemic model, which is used to compare efficacy of various NPIs taken in China.

Results

As of March 18, 2020, cumulatively 80928 confirmed cases had been reported nationwide and there are 7263 confirmed cases now; a total of 67800 confirmed cases (83.778% of the total number in China) has been reported in Hubei Province, and now there remain 6992 cases, which account for 96.269%[4] of the total number in China. Therefore, Hubei Province is taken as the CEA while other regions are the NCEA. To better fight against the epidemic, the Chinese government has formulated different NPIs for the CEA and the NCEA, which have gained favorable effects [27,28]. The research evaluated the actual effects of NPIs taken in the CEA and the NCEA respectively.

Effect evaluation of NPIs taken in the CEA (Hubei Province) to respond to the epidemic

Evaluation of implementation effects of type-A NPIs

It can be seen from Table 1 that the type-A NPIs taken in Hubei Province mainly include lockdown of Wuhan and initiation of the first-level emergency responses of Hubei Province. Suppose that the daily contacts of infected and exposed cases after lockdown of Wuhan reduced to 6 and it further decreased to 4 after the province initiated the first-level emergency responses. Figure 4 is obtained by fitting the SEIR model using data released by the National Health Commission and the Wuhan Municipal Health Commission. Figures 4(a)~(d) separately describe the changes in the numbers of susceptible, exposed, infected, and recovered cases in the CEA, respectively.

As Figure 4 shows, compared with the condition of not taking any NPIs, after lockdown of Wuhan, the S curve exhibits a significant rightward shift and gradually flattens, indicating that the city lockdown can effectively inhibit the conversion of the susceptible population to exposed and infected populations; after initiating the first-level emergency response in Hubei Province, the S curve rightward shifts further and flattens, which implies that the measure is more effective in protecting the susceptible population compared with the city lockdown and has bought more time for developing targeted vaccines and therapeutic drugs and manufacturing badly-needed medical supplies. In comparison with the condition of not taking any NPIs, the peak of the E curve gradually lowers and moves rightward and the curve slope decreases after lockdown of Wuhan. It suggests that the intervention is able to effectively reduce the number of exposed individuals and delays the timing of their number to reach the peak. After initiating the first-level emergency responses in Hubei Province, the peak of the E curve reduces to one half of that when no intervention is taken and further rightward shifts, and the curve flattens. This implies that the measure can more effectively decrease the exposed population, delay the timing of their number to peak, and reduce the outbreak degree thereof, which buy time for the province to overcome shortages of medical supplies and medical effective therapies. Relative to the condition of not taking any NPIs, the I curve shifts obviously rightward after lockdown of Wuhan and the peak also reduces and moves to the right side, indicative of efficacy of the intervention in delaying the timing of the number of infected cases to peak, reducing the peak number of infected cases, and slowing down the trend of infections. All these are effective in relieving the prevention and control pressure and medical burdens in the CEA; after initiation of the first-level emergency responses in Hubei Province, the I curve rightward shifts further and the time for peaking is two times as long as that with no NPIs taken. It indicates that the intervention is more effective in delaying the timing of the number of infected cases to peak, and therefore slows down the development of the epidemic in the CEA. Compared with the condition of not taking any NPIs, the R curve also rightward shifts apparently after lockdown of Wuhan, suggesting that the intervention is effective in inhibiting increases in the number of infected cases under same medical therapies. After initiating the first-level emergency responses in the province, the R curve further rightward shifts, which indicates that the measure more effectively relieves the prevention pressure against the epidemic in the CEA.

Generally speaking, type-A NPIs can effectively reduce the number of exposed and infected cases and slow down spread of the epidemic in the CEA. Moreover, carrying out strict prevention and control in the whole CEA shows better effects than only performing strict prevention and control in key outbreak sites therein and is more conducive for fighting against the epidemic.

[4] Data source: National Health Commission of the People's Republic of China

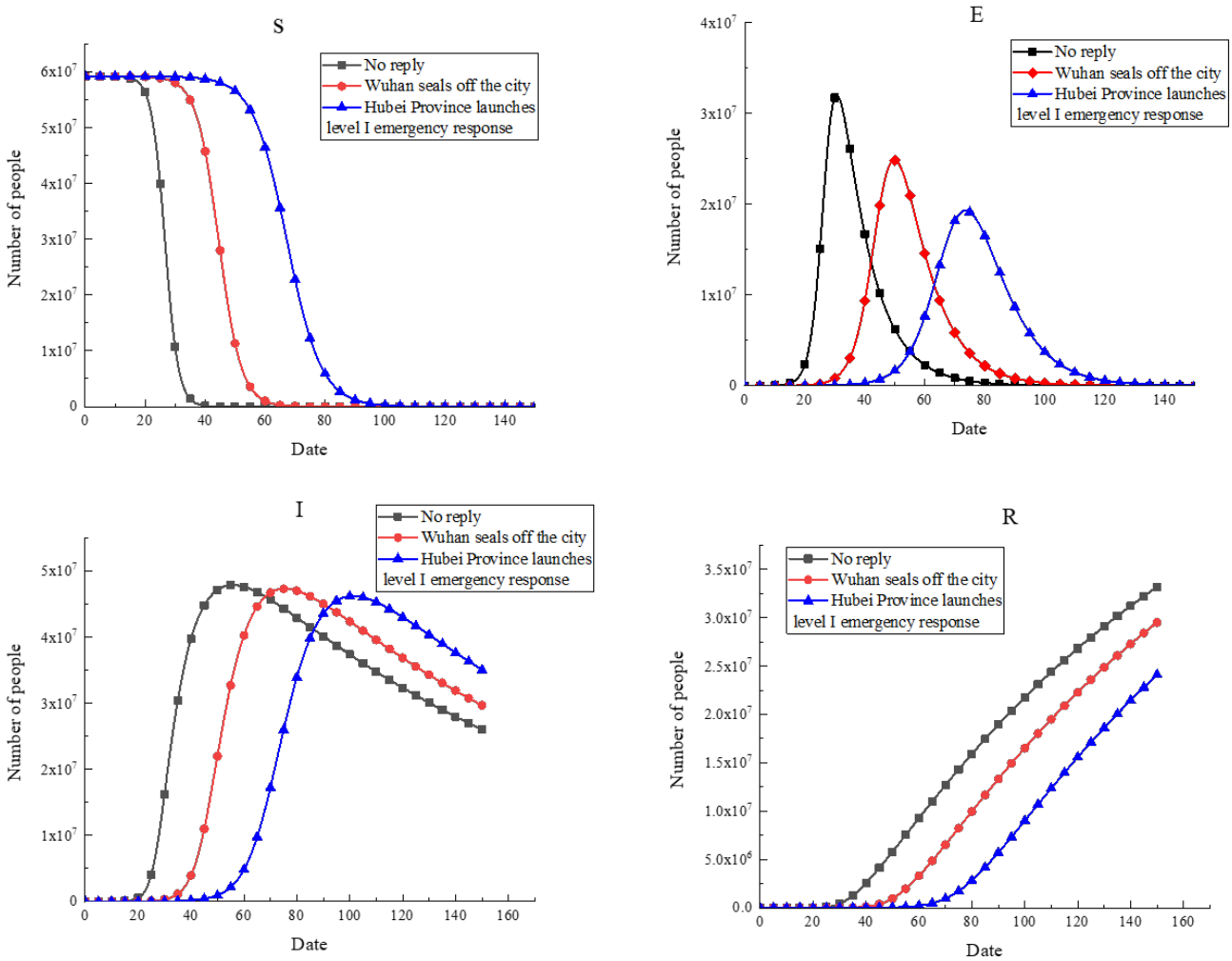

Figure 4 Fitting results of the SEIR model after taking type-A NPIs in the CEA

Evaluation of implementation effects of type-B NPIs

As shown in Table 1, type-B NPIs taken in Hubei Province mainly include requirement of wearing masks, government's organization of medical supply related companies to resume production, *etc*. After implementing the first one, the demand for masks was still far larger than the supply, so the probability of post-exposure infections was fitted to reduce to 0.03. As the government organized the medical supply related companies to resume production, the supply of materials including masks increased substantially, which effectively narrowed the demand gap. Attributed to the NPI, it was fitted that the probability of post-exposure infections decreased to 0.01. By fitting the SEIR model using the National Health Commission and Wuhan Municipal Health Commission, Figure 5 is obtained.

It can be seen from Figure 5 that the NPI of the government requiring people wearing masks in public places renders the S curve to shift rightward. It indicates that the NPI slows down the conversion speed of the susceptible to exposed or infected. After the government organizing medical supply related companies to resume production to increase supply of masks and protective clothing, the S curve rightward shifts remarkably and flattens apparently. Compared with the case of not taking any NPIs, the time period for the susceptible population to reduce remarkably is two times longer. It indicates that the NPI dramatically contains the spread of COVID-19. Moreover, compared with the condition of not taking any NPIs, the implementation of the NPI makes the E curve rightward shift and the peak decreases and shift to the right side. The result implies that the NPI can decrease the exposed population, delay the timing of peaking of the number of exposed cases, and slow down the outbreak trend thereof. After the government organizing medical supply related companies to resume production, the E curve also rightward shifts substantially, the peak number decreases dramatically, and the curve flattens. It is an indication of the high efficacy of the NPI in reducing the exposed population, slowing down the outbreak trend thereof, and delaying the timing of a substantial increase in the exposed population. Relative to the condition of not taking any NPIs, the requirement of wearing masks shifts the I and R curves rightward, suggesting that the NPI is favorable for reducing the

number of infected cases and slowing down the outbreak trend. The government's organization of medical supply related companies to resume production leads to a significant rightward shift of the I and R curves, and the I curve tends to flatten apparently. The result indicates that the NPI exerts an instant effect in reducing the number, lowering the outbreak degree, and delaying the timing of a substantial increase in the number of infected cases.

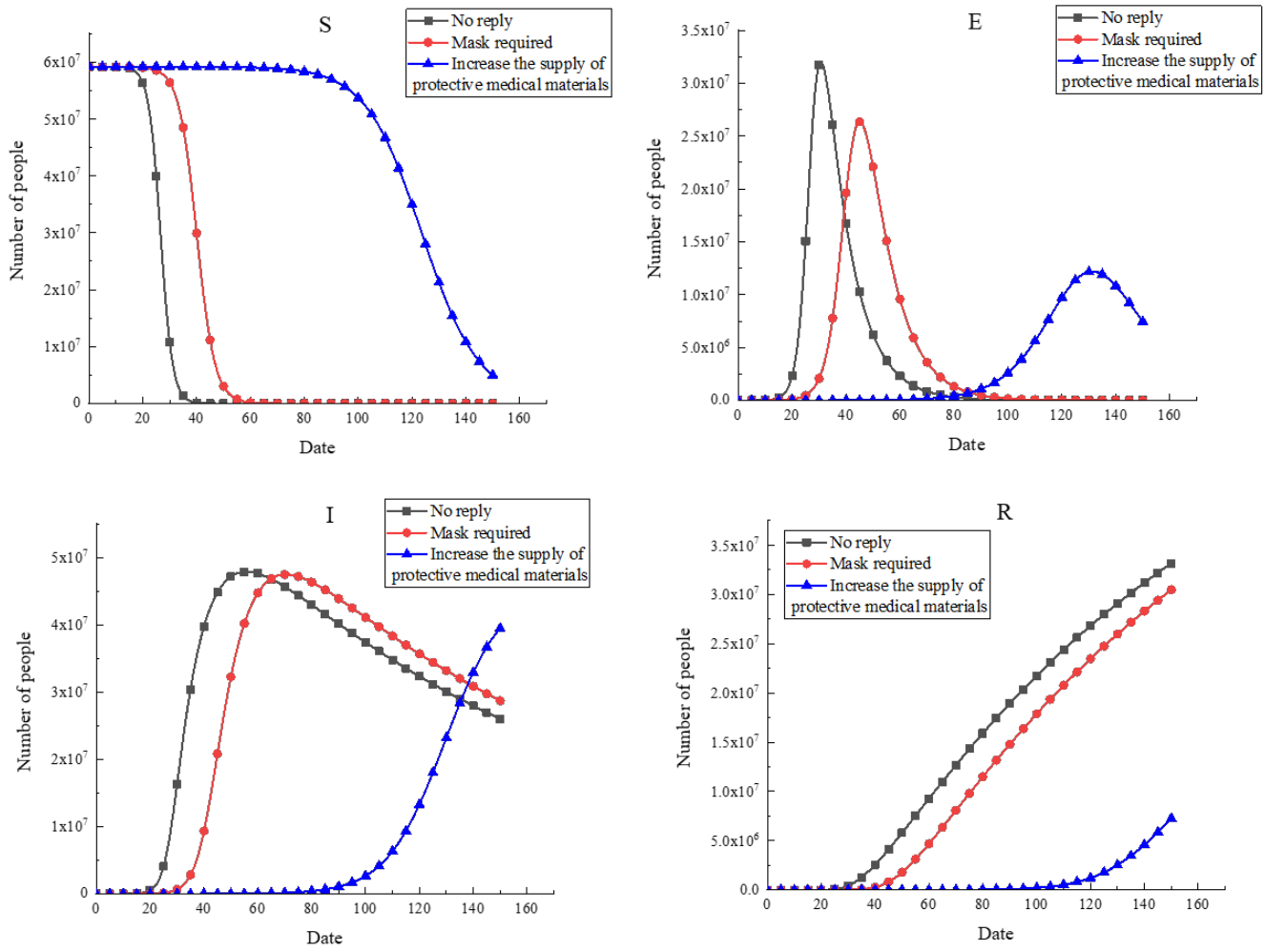

Figure 5 Fitting results of the SEIR model after taking type-B NPIs in the CEA

Generally speaking, type-B NPIs can reduce the peak number of exposed cases, delay the timing of the number of exposed cases to peak, and postpone the dates on which corresponding values appear. Particularly, the probability of infections of susceptible populations reduced remarkedly after the government organizing medical supply related companies to resume production to enlarge the supply of medical materials such as masks and protective clothing. In addition, the timing of the epidemic outbreak was greatly delayed, which bought a relatively long time for epidemic prevention and control and medical teams to develop targeted schemes.

Evaluation of implementation effects of type-C NPIs

As Table 1 displays, the putting-into-operation of Huoshenshan hospital, constructing mobile cabin hospitals, dispatching medical staff to support Wuhan, and putting-into-operation of Leishenshan hospital are main type-C NPIs taken in Hubei Province. According to data released by the National Health Commission, the average treatment duration of a patient is about 20 days in Hubei Province, so the recovery rate of patients after implementing various NPIs for 20 days were calculated using Formula 4. In this way, it is obtained that the values of γ corresponding to the above four NPIs are 0.035, 0.030, 0.045, and 0.063, respectively. By substituting them in the SEIR model, Figure 6 can be obtained.

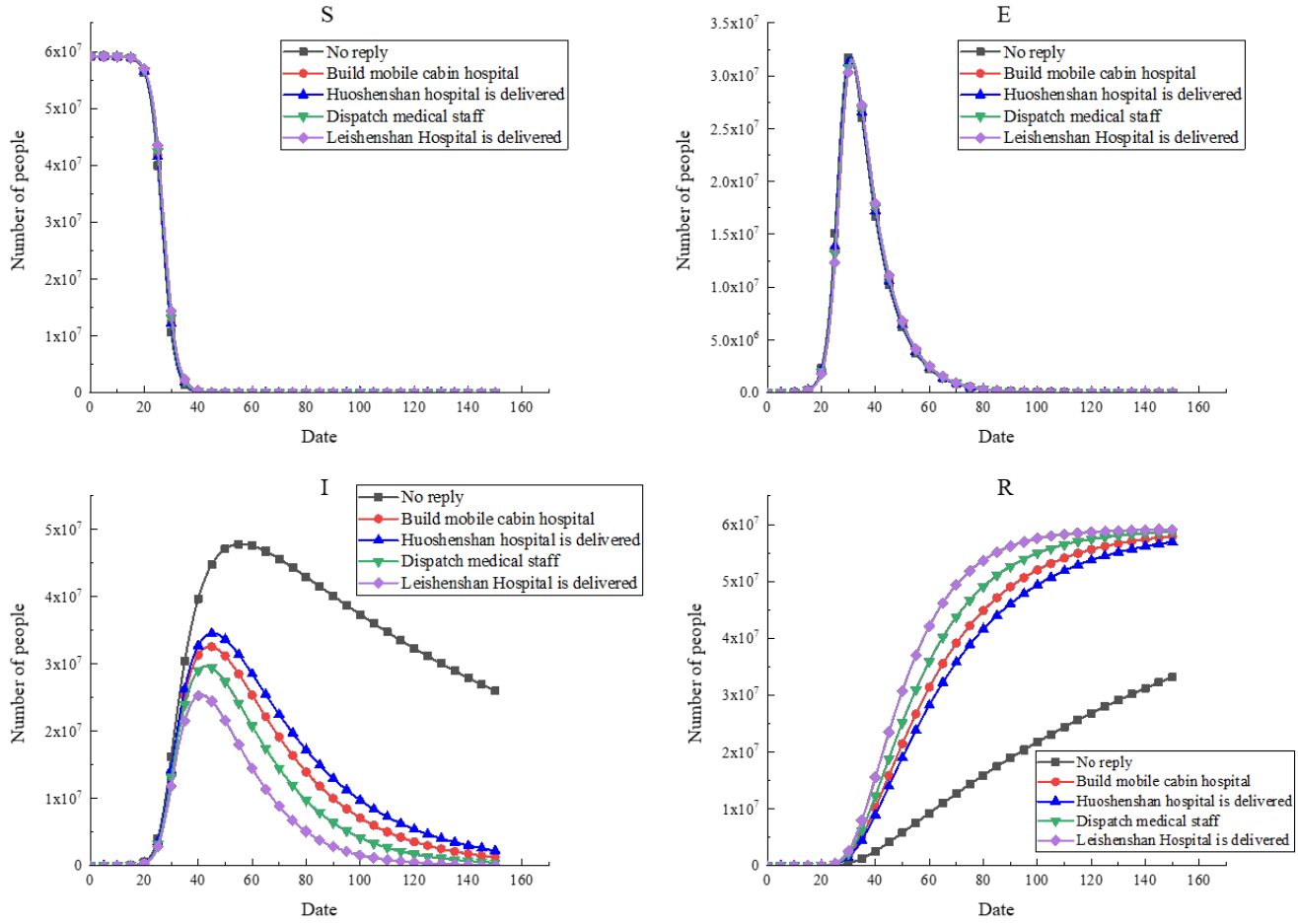

Figure 6 Fitting results of the SEIR model after taking type-C NPIs in the CEA

It can be seen from Figure 6 that compared with that not taking any NPIs, NPIs including putting-into-operation of Huoshenshan hospital, construction of mobile cabin hospitals, dispatching of medical staff to support Wuhan, and putting-into-operation of Leishenshan hospital do not apparently shift the S and E curves rightward. It indicates that the target of these NPIs is not susceptible and exposed populations. Compared with the condition of not taking any NPIs, these NPIs all can lower the peak of the I curve and flatten the curve, both to different extents. Among them, putting-into-operation of Leishenshan hospital contributes the most in lowering the peak and flattening the curve, followed in succession by dispatching medical staff to support Wuhan, putting-into-operation of Huoshenshan hospital, and constructing mobile cabin hospitals. The result suggests that this type of NPIs, particularly putting-into-operation of Leishenshan hospital, can greatly reduce the severity of COVID-19 outbreak and values at the inflection point of the epidemic. They can also relieve the medical burdens and alleviate the economic and social damages of the epidemic. In comparison with not taking any NPIs, NPIs including constructing mobile cabin hospitals increases the slope of the R curve at different degrees. Among them, putting-into-operation of Leishenshan hospital results in the most significant change in the slope of the R curve, which is successively followed by dispatching medical staff to support Wuhan, putting-into-operation of Huoshenshan hospital, and constructing mobile cabin hospitals. The result indicates that this type of NPIs, especially putting-into-operation of Leishenshan hospital, are able to substantially improve the recovery rate of patients, reduce the mortality rate, and contain the further development of the epidemic.

In summary, the type-C NPIs mainly target infected and recovered populations while have little effects on susceptible and exposed populations. They can significantly lower the outbreak degree of the epidemic and the number of infected cases at the inflection point of the epidemic, and also improve the recovery rate of patients. They, to a certain extent, allay the public's fear and decrease the socio-economic impacts of the epidemic.

Comparison of effects of the three types of NPIs

According to results of the empirical analysis on the three types of NPIs, the effects of the three types of NPIs on

different populations were compared and the following conclusions were drawn:

1) For the susceptible population, both type-A and type-B NPIs can delay the timing of massive infections of them, and type-B NPIs have better overall effects. Among all NPIs, the government's organization of medical supply related companies to resume production to enlarge supply of masks and protective clothing is found to have the best effect, followed in succession by initiation of the first-level emergency responses of Hubei Province, lockdown of Wuhan, and requirement of wearing masks. In comparison, type-C NPIs do not exert significant effects on the susceptible population.

2) For the exposed population, both type-A and type-B NPIs are able to delay the timing of peaking and lower the peak number of this group of people. On the whole, type-B NPIs have better effects than type-A ones. Likewise, the government organizing medical supply related companies to resume production to enlarge supply of masks and protective clothing is the NPI of the best effect. It is followed in succession by initiation of the first-level emergency responses of Hubei Province, lockdown of Wuhan, and requirement of wearing masks. However, type-C NPIs do not exert significant effects on the exposed population.

3) As to the infected population, type-A and type-B NPIs both can delay the timing of peaking of the number of infected cases, while slightly affect the value of the peak and the slope of the I curve. In comparison, type-C NPIs are able to effectively reduce the peak number of patients and remarkably decrease the slope of the I curve, while have less effects in delaying the timing of this group of people to peak. In terms of delaying the timing of infected cases to peak, government's organization of medical supply related companies to resume production to enlarge supply of materials including masks and protective clothing exerts the best effect, followed successively by initiation of the first-level emergency responses of Hubei Province, lockdown of Wuhan, and requirement of wearing masks. With regard to lowering the peak number of infected cases, the NPI of the best effect is putting-into-operation of Leishenshan hospital. It is followed by dispatching medical staff to support Wuhan, putting-into-operation of Huoshenshan hospital, and constructing mobile cabin hospitals.

4) Type-C NPIs are superior to type-A and type-B NPIs for the recovered population. They can substantially improve the recovery rate and lower the mortality rate of patients. Among this type of NPIs, putting-into-operation of Leishenshan hospital has the best effect, followed by dispatching medical staff to support Wuhan, putting-into-operation of Huoshenshan hospital, and constructing mobile cabin hospitals in succession.

Effect evaluation of NPIs for containing the epidemic in the NCEA (regions except for Hubei Province)

Evaluation of implementation effects of type-A NPIs

It can be seen from Table 1 that type-A NPIs taken in other regions of China except for Hubei Province mainly include initiation of the first-level emergency responses of various provinces and closed management of communities. Suppose that the daily contacts of infected and exposed cases after initiation of the first-level emergency responses in various provinces reduce to 6; after performing closed management of communities, the daily contacts of them further reduce to 4. According to relevant data released by the National Health Commission and Wuhan Municipal Health Commission, the SEIR model is fitted, thus obtaining Figure 7.

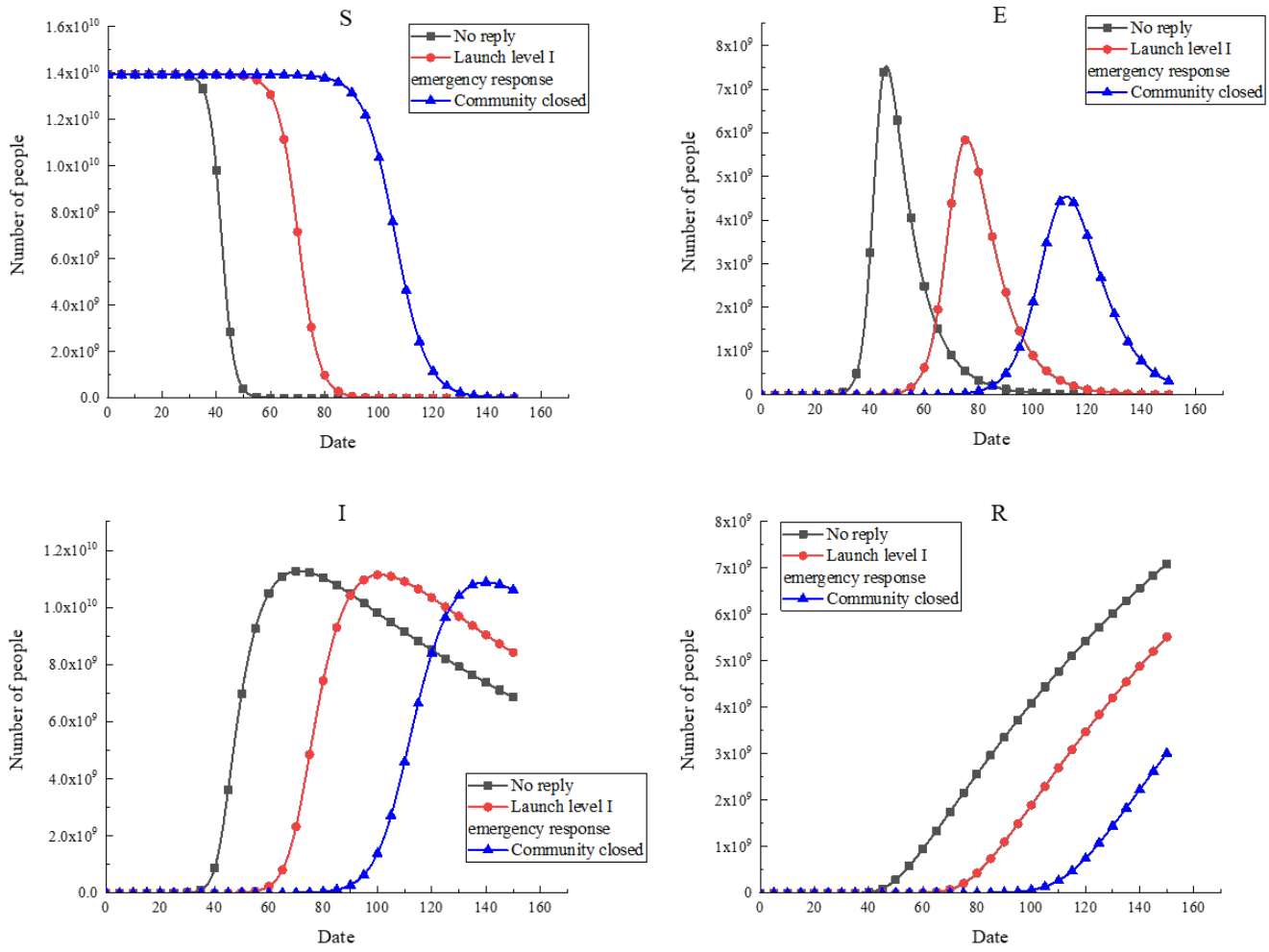

Figure 7 Fitting results of the SEIR model after taking type-A NPIs in the NCEA

It can be seen from Figure 7 that compared with conditions not taking any NPIs, the initiation of the first-level emergency responses makes the S and E curves shift rightward obviously, greatly lowers the peak of the E curve and flattens the E curve on the whole. It indicates that the NPI is able to delay the timing of the massive infections of the susceptible population, decrease the peak number of exposed cases, and slow down the outbreak trend of exposed cases. After closure of communities, S and E curves witness a more apparent rightward shift, and the peak of the E curve declines more greatly. The result suggests that the NPI is very effective in delaying the timing of conversion of the susceptible population into exposed and infected populations, delaying the timing of the number of exposed cases to peak, and reducing the number of exposed cases. In comparison with conditions not taking any NPIs, the initiation of the first-level emergency responses also rightward shifts the I and R curves apparently, indicative of efficacy of the NPIs in delaying the timing of massive outbreak of the epidemic; after closure of communities, the two curves are found to have a greater rightward shift, which indicates that the NPI is more effective in delaying the outbreak of the epidemic.

Evaluation of implementation effects of type-B NPIs

As shown in Table 1, type-B NPIs taken in the NCEA mainly include the requirement of wearing masks, government's organization of medical supply related companies to resume production, and so on. As the requirement of wearing masks was released, the demand for masks was still far larger than the supply, so it was supposed that the probability of post-exposure infections reduced to 0.03; after the government organized medical supply related companies to resume production, the supply of medical materials such as masks grew dramatically, while the demand gap was effectively narrowed, so it was supposed that the probability of post-exposure infections decreased to 0.01. Figure 8 is drawn after fitting the SEIR model based on data released by the National Health Commission.

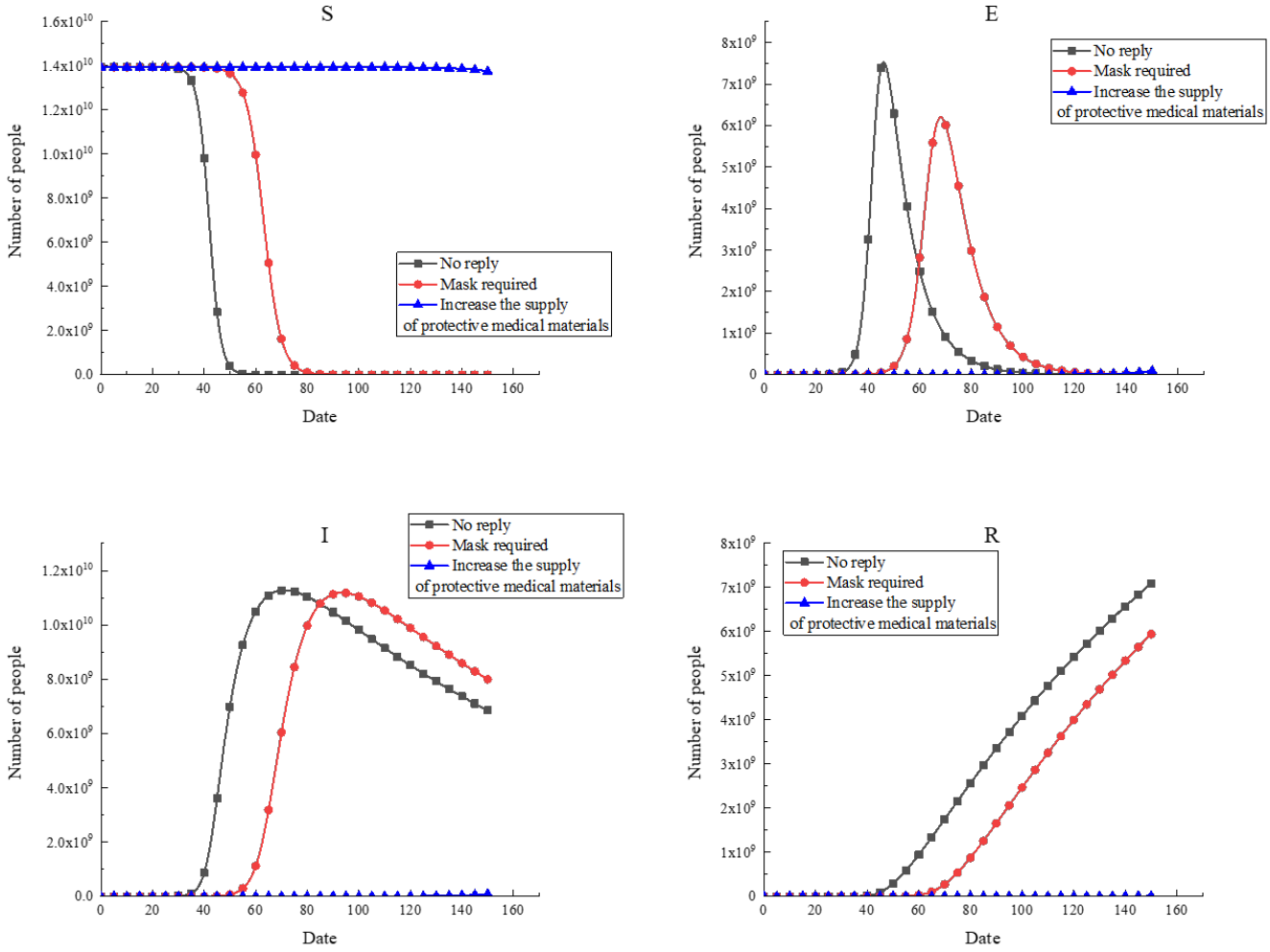

Figure 8 Fitting results of the SEIR model after taking type-B NPIs in the NCEA

As shown in Figure 8, the requirement of wearing masks makes the S and E curves undergo an apparent rightward shift; in addition, the peak of the E curve decreases and shifts rightward obviously, and the I and R curves rightward shift, compared with not taking any NPIs. These changes indicate that the NPI is very effective in delaying the outbreak of the epidemic. It also contributes to decreasing the number of exposed cases and relieving the massive outbreak of exposed cases. After the government organized medical supply related companies to resume production, the supply of materials including masks grew substantially, which effectively filled the demand gap. The figure also shows that the slopes of the four curves all decline abruptly, rendering the curves to almost straight lines. It implies that the NPI is of great significance in preventing and controlling the epidemic. So the government is suggested to vigorously encourage and subsidize relevant enterprises to resume production, so as to enlarge the supply of protective materials such as masks and protective clothing, so that the public can take effective protective measures and strengthen their self-protection awareness.

Evaluation of implementation effects of type-C NPIs

As listed in Table 1, the type-C NPIs taken in the NCEA mainly include emergency scientific research in challenging fields pertaining to the epidemic. The recovery rate of patients 20 days after taking NPIs was calculated using Formula 4. In this way, γ corresponding to implementation of the measure is attained to be 0.099. By substituting the value in the SEIR model, Figure 9 is drawn.

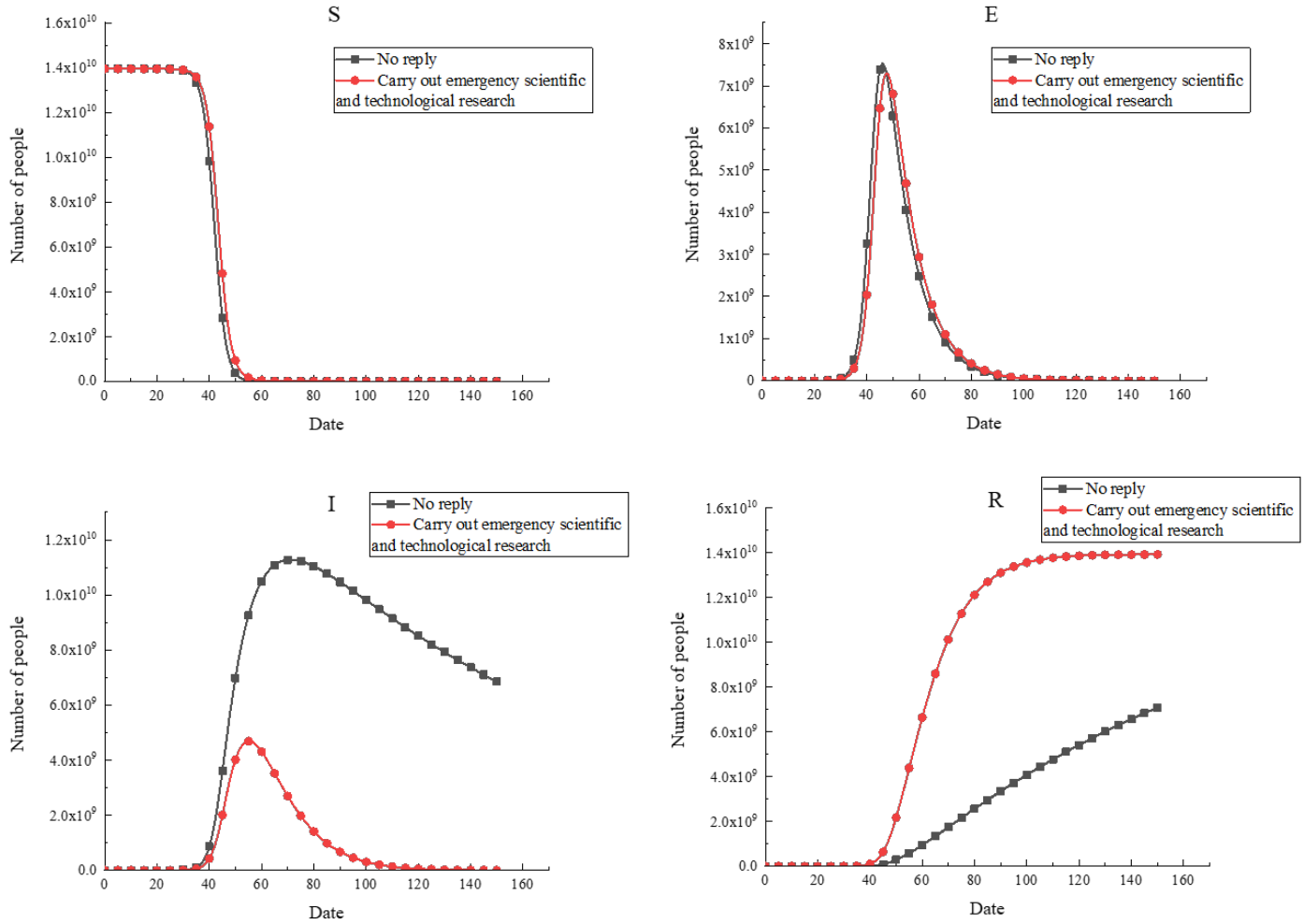

Figure 9 Fitting results of the SEIR model after taking type-C NPIs in the NCEA

It can be seen from Figure 9 that compared with conditions not taking any NPIs, the emergency scientific research in challenging fields pertaining to the epidemic fails to make significant changes in the S and E curves, while it greatly reduces the peak of the I curve which also flattens significantly and leads to an apparent increase in the slope of the R curve. It indicates that the NPI mainly targets at infected and recovered populations. It can greatly decrease the outbreak degree of the epidemic, increase the recovery rate, and decrease the mortality rate of patients, thus facilitating the development of special treatments to end the epidemic and reassure the public.

Comparison of the three types of NPIs

The above analysis elaborates that for the NCEA, the three types of NPIs generally exert consistent effects as those in the CEA, with certain differences:

1) Type-C NPIs slightly influence the susceptible population, while type-A and type-B NPIs both can delay the timing of massive infections of the susceptible population. As in the CEA, type-B NPIs exert better effects than type-A NPIs on the whole in the NCEA. Among these NPIs, the government's organization of medical supply related companies to resume production has the best effect, followed in succession by initiation of the first-level emergency responses of various provinces, closed management of communities, and requirement of wearing masks. Besides, various NPIs in the NCEA exert better effects than those in the CEA.

2) For the exposed population, type-C NPIs slightly affects its number while the other two types of NPIs both can delay the timing of their massive outbreak, effectively decrease the number of exposed cases, and lower the outbreak degree. Among the NPIs, the government organizing medical supply related companies to resume production exerts the best effect,

followed successively by initiation of the first-level emergency responses of various provinces, closed management of communities, and requirement of wearing masks.

3) Type-A and type-B NPIs can effectively delay the timing of the number of infected cases to peak. Likewise, effects of the government's organization of medical supply related companies to resume production, initiation of the first-level emergency responses of various provinces, closed management of communities, and requirement of wearing masks in succession decrease successively. This type of NPIs can effectively reduce the number and outbreak degree of infected cases, and effectively contain the spread of the epidemic.

4) For the recovered population, type-C NPIs exert better effects than type-A and type-B NPIs. This type of NPIs are effective in improving the recovery rate, shortening the recovery duration, and decreasing the mortality rate of patients, thus are of profound significance in containing the fast spread of the epidemic and fostering confidence for economic prospect.

Discussion

Due to the fast spread of the COVID-19 epidemic caused by SARS-CoV-2 across the world, the global number of confirmed cases had exceeded 16 million by the end of July, 2020. However, except for China, other countries do not have experience in fighting against the epidemic. In such context, the number of confirmed cases in China from January 20 to March 18, 2020 were taken as the sample set, which is further divided into those of Hubei Province and other regions according to whether it is the CEA or not. In this way, the SEIR model suitable for prediction under conditions that exposed populations in the incubation period are also infectious was constructed for analysis. Finally, effects of different NPIs on the epidemic were attained.

For the convenience of evaluation, the NPIs were summarized and classified into type-A, type-B, and type-C ones which are separately for reducing the daily contacts with the infected and exposed populations, decreasing the probability of post-exposure infections, and improving the recovery rate.

The research results show that

1) In either the CEA or the NCEA, both type-A and type-B NPIs can delay the timing of the susceptible population to be massively infected and the timing of the number of exposed individuals to peak, and reduce the peak number of exposed cases. Moreover, type-B NPIs more significantly affect the susceptible and exposed populations than type-A ones, while type-C NPIs do not exert significant effects on these two groups of people.

2) No matter in the CEA or the NCEA, both type-A and type-B NPIs can delay the timing of the number of infected cases to peak, while they slightly influence the value of the peak and the slope of the I curves. In comparison, application of type-C NPIs enables an effective reduction of the peak number of patients and remarkably decreases the slope of the I curve; while it plays a little role in delaying the timing of the number of infected cases to peak.

3) Considering effects of different NPIs on the susceptible and exposed populations and in delaying the timing of the number of infected cases to peak, it is found that the government's organization of medical supply related companies to resume production to increase the supply of masks and protective clothing has the best effect. In the CEA, following this are the initiation of the first-level emergency response of Hubei Province, lockdown of Wuhan, and requirement of wearing masks; while in the NCEA, initiation of first-level emergency responses of various provinces, closed management of communities, and requirement of wearing masks are effective NPIs second only to the production resumption of medical supply related companied under organization of the government. In terms of reduction of the peak number of patients in the CEA, the official delivery and putting-into-operation of Leishenshan hospital plays the most effective role, followed by dispatching medical staff to support Wuhan, official delivery and putting-into-operation of Huoshenshan hospital, and construction of mobile cabin hospitals successively.

4) Type-C NPIs are more effective than type-A and type-B NPIs for the recovered population. This type of NPIs are able to tremendously improve the recovery rate and reduce the mortality of patients. Therein, the official delivery and putting-into-operation of Leishenshan hospital exerts the best effect, followed by dispatching medical staff to support Wuhan, official delivery and putting-into-operation of Huoshenshan hospital, and construction of mobile cabin hospitals successively.

Based on the above analysis, the following suggestions are proposed:

1) City lockdown or initiation of regional first-level emergency responses can be used in the CEA, while regional control or initiation of regional first-level emergency responses in the NCEA can be taken to reduce the daily contacts of infected and exposed cases. These NPIs can finally decrease the peak number of exposed cases and postpone the timing of the number of exposed cases to peak.

2) The government is suggested to prioritize the organization of medical supply related companies to resume production in either the CEA or the NCEA and requires residents to wear masks, so as to reduce the infection probability of the susceptible population after being in contact with confirmed and exposed populations.

3) For the CEA, establishment of several isolation sites for confirmed cases most significantly affects the reduction of the peak number of confirmed cases. In addition, increasing the number of medical staff can also effectively reduce the peak number of confirmed cases.

Methods

Modeling

The COVID-19 has an incubation period as long as 14 days and infected individuals in the incubation period also can also infect the susceptible population. Considering these facts, the method proposed by Wang *et al.* [24] was used to introduce the characteristic of COVID-19 that exposed individuals in the incubation period are infectious into the SEIR model to predict the number of confirmed cases. To build the model, the whole population is divided into four classes, *i.e.* the susceptible (*S*), exposed (*E*), infected (*I*), and recovered (*R*) ones [25].

$$S_n = S_{n-1} - r\beta I_{n-1} S_{n-1} / N - r_2 \beta_2 E_{n-1} S_{n-1} / N \tag{1}$$

$$E_n = E_{n-1} + r\beta I_{n-1} S_{n-1} / N - \alpha E_{n-1} + r_2 \beta_2 E_{n-1} S_{n-1} / N \tag{2}$$

$$I_n = I_{n-1} + \alpha E_{n-1} - \gamma I_{n-1} \tag{3}$$

$$R_n = R_{n-1} + \gamma I_{n-1} \tag{4}$$

where n represents the days of spread of the SARS-CoV-2; r and r_2 separately refer to the daily contacts of the infected and exposed individuals; β and β_2 represent the infection probabilities of the susceptible population after being in contact with the infected and exposed populations; α is the probability of an exposed individual converting to the infected; γ and N denote the recovery rate and the total population, respectively.

$$N = S_n + E_n + I_n + R_n \tag{5}$$

where S_n, E_n, I_n, and R_n denote the numbers of the susceptible, exposed, infected and recovered individuals on the *n*th day.

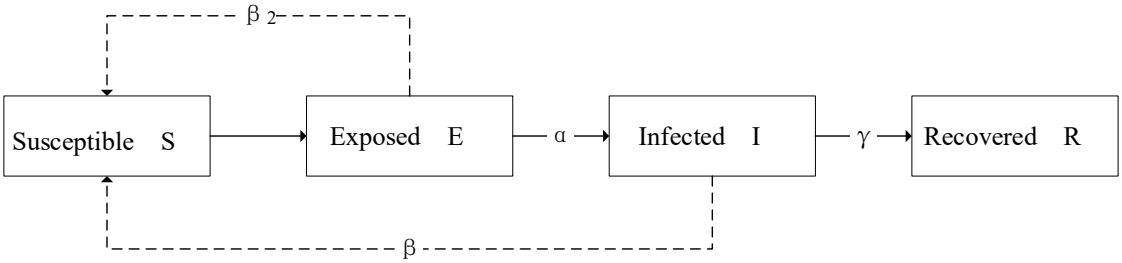

Figure 10. The SEIR model

The solid lines in Figure 10 represent conversion of the four classes of population and the dotted lines denote the influences of the exposed and infected populations on the susceptible ones.

Research assumptions

To evaluate effects of various NPIs taken in China during the epidemic on the number of finally confirmed cases, the following assumptions are made:

1) It is assumed that the pneumonia induced by the SARS-CoV-2 virus spreads only through the human-to-human

transmission, while infections caused by other transmission routes including aerosol transmission and oral-faecal transmission are not taken into account.

2) The infected individuals will develop corresponding antibodies after recovery, so the recovered individuals will not become susceptible, exposed, or infected ones again.

3) No specific medicines or vaccines for the COVID-19 are available at present.

4) For the convenience of evaluation of various NPIs on the number of finally confirmed cases, it is supposed that various NPIs do not have interactions and external environmental factors do not influence the change of the number.

5) There is no inter-regional population movement during the evaluation of these NPIs.

6) A single NPI only influences changes of a single index in the model while not affects multiple indexes.

Determining equation parameters

The total population N: According to the demographic data released by the National Bureau of Statistics of the People's Republic of China, the total population of Hubei Province and China are 59.17 million and 1.4 billion, respectively.

Calculation for the infection probabilities β and β_2 as well as the probability of exposed individuals converting to infected ones: In actual life, due to implementation of NPIs, it is supposed that the daily contacts of the infected and exposed populations are r = 10 and r1 = 10 during the outbreak of the epidemic [26], and the number of susceptible individuals is equal to the result of subtracting the number of the infected and exposed individuals from the total population. The change rate of the infected population is $dI_i / d_i = \beta I_i S_i / N - \gamma I_i \approx (\beta - \gamma) I_i$. It is estimated that $\beta = \beta_2 \approx 0.045$ by fitting based on the data released by the National Health and Family Planning Commission of the People's Republic of China during the outbreak. It is calculated that $\alpha \approx 0.10$ according to $\alpha = I_i / E_i$.

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Figures

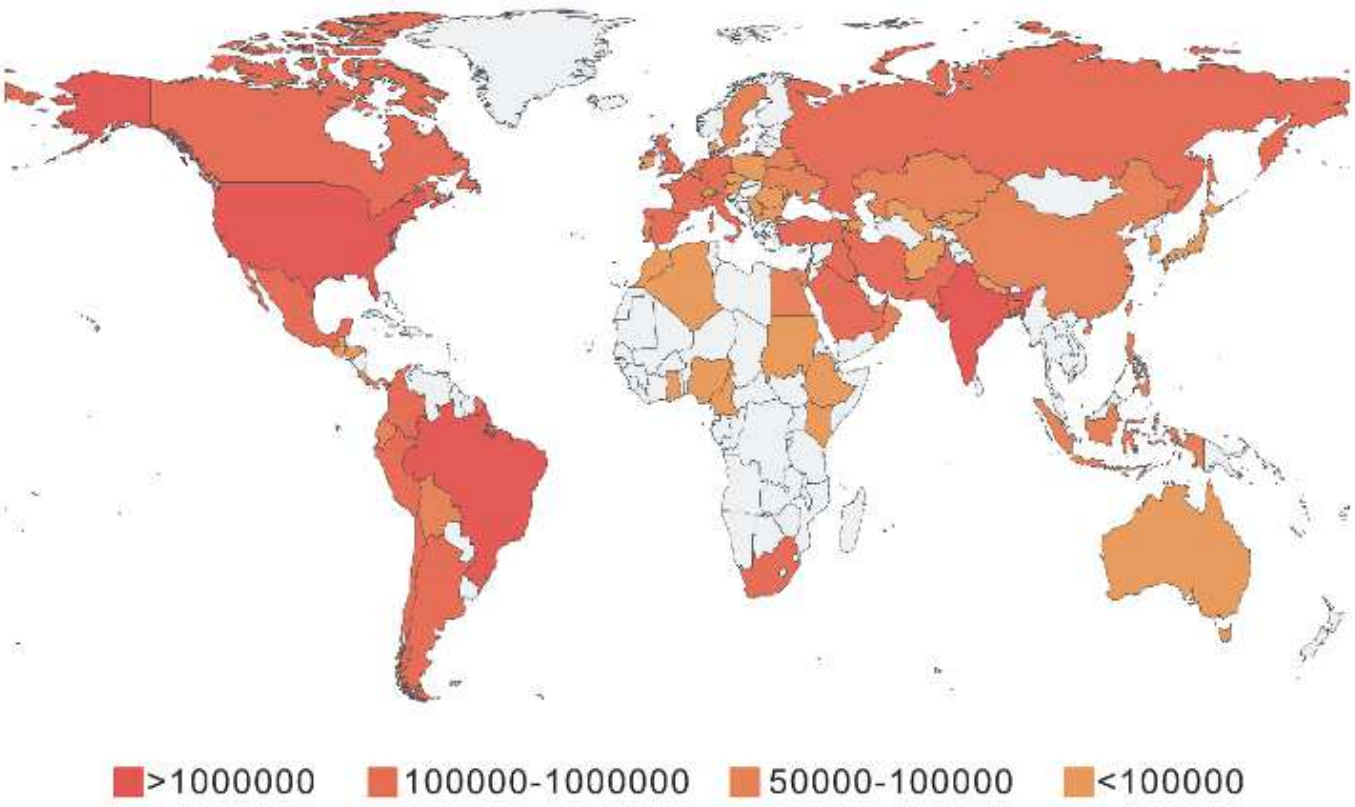

Figure 1

Global epidemic map (up to July 27, 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.

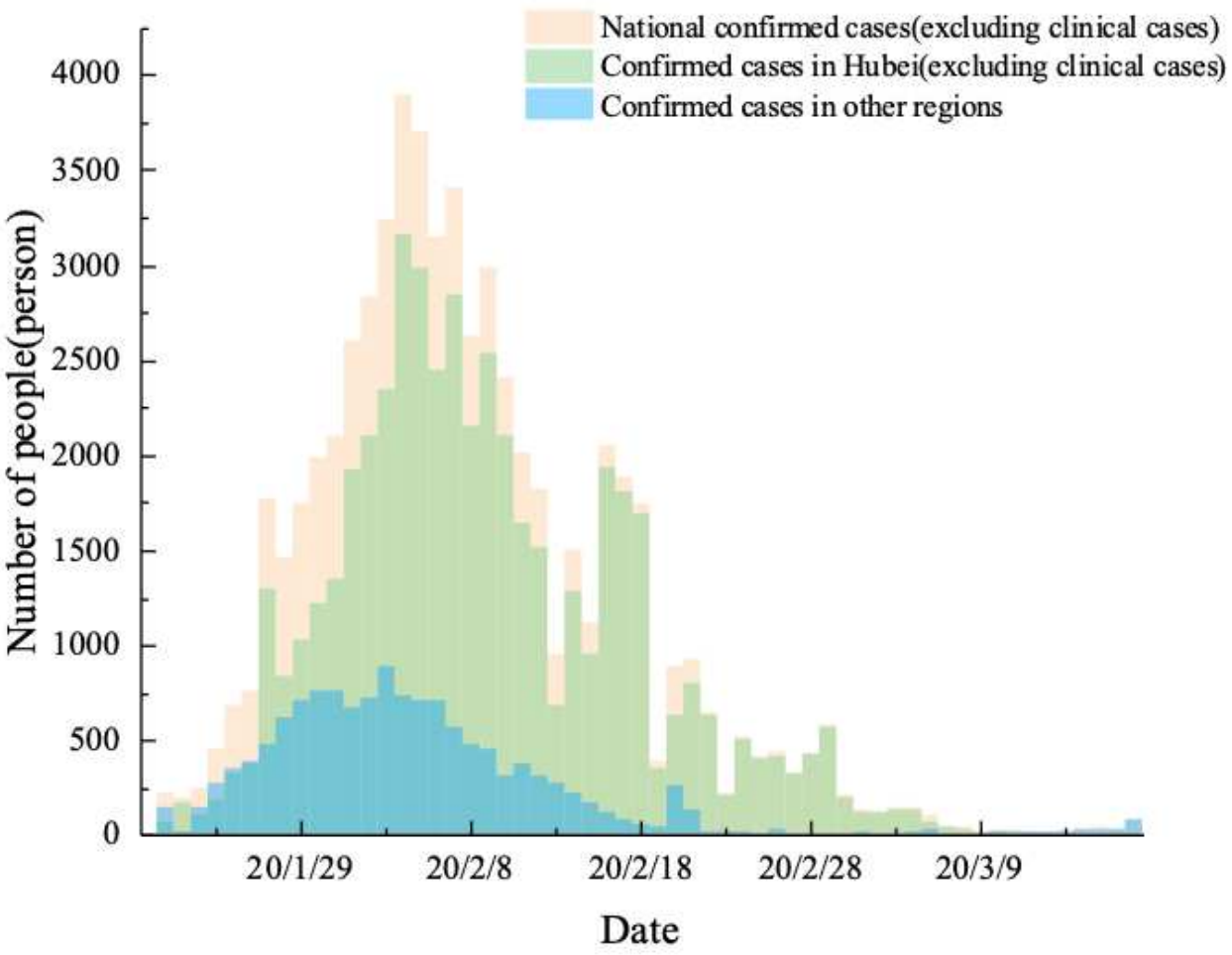

Figure 2

The number of daily confirmed cases (from January 1 to March 18, 2020)

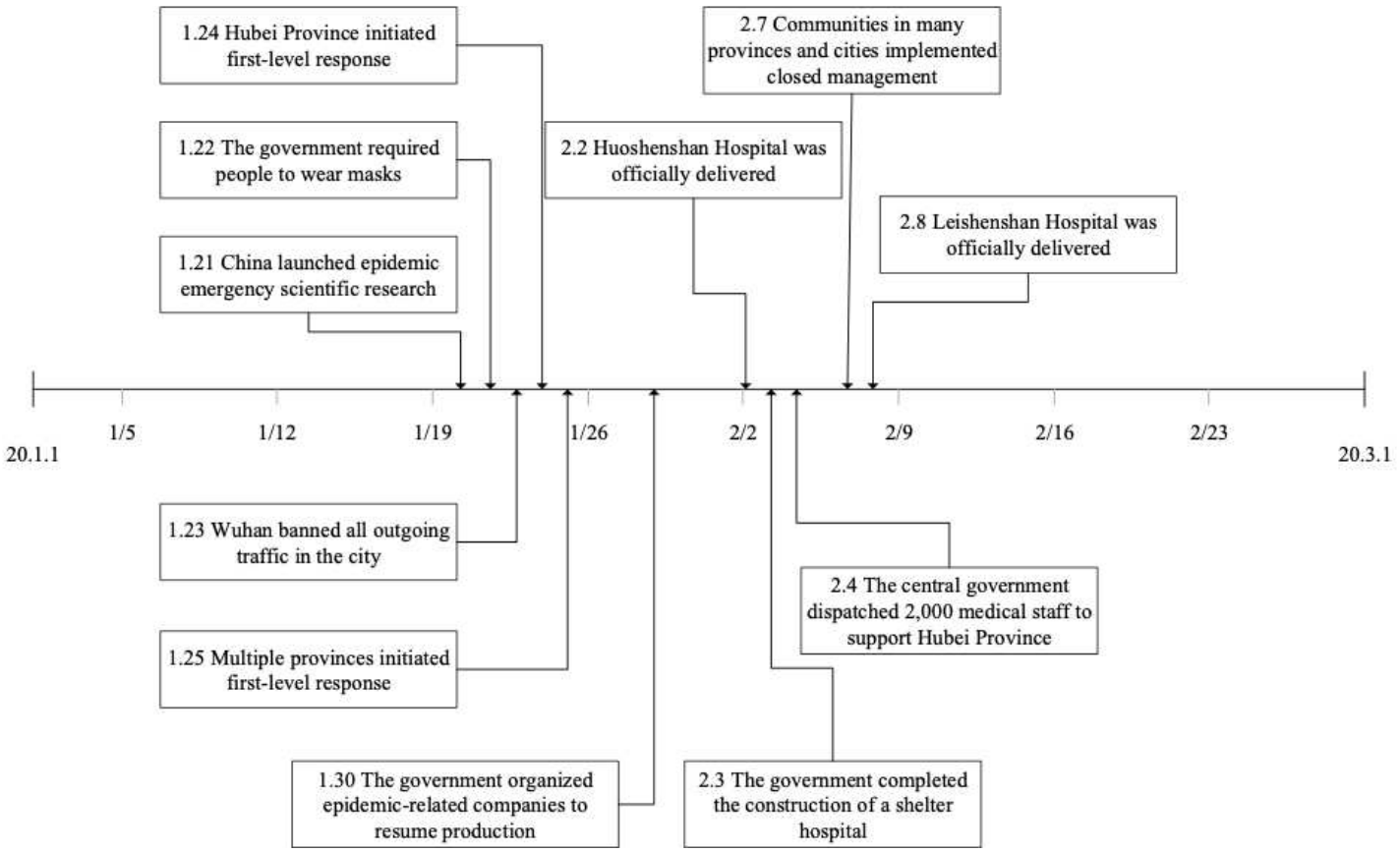

Figure 3

Timeline of policies taken in China

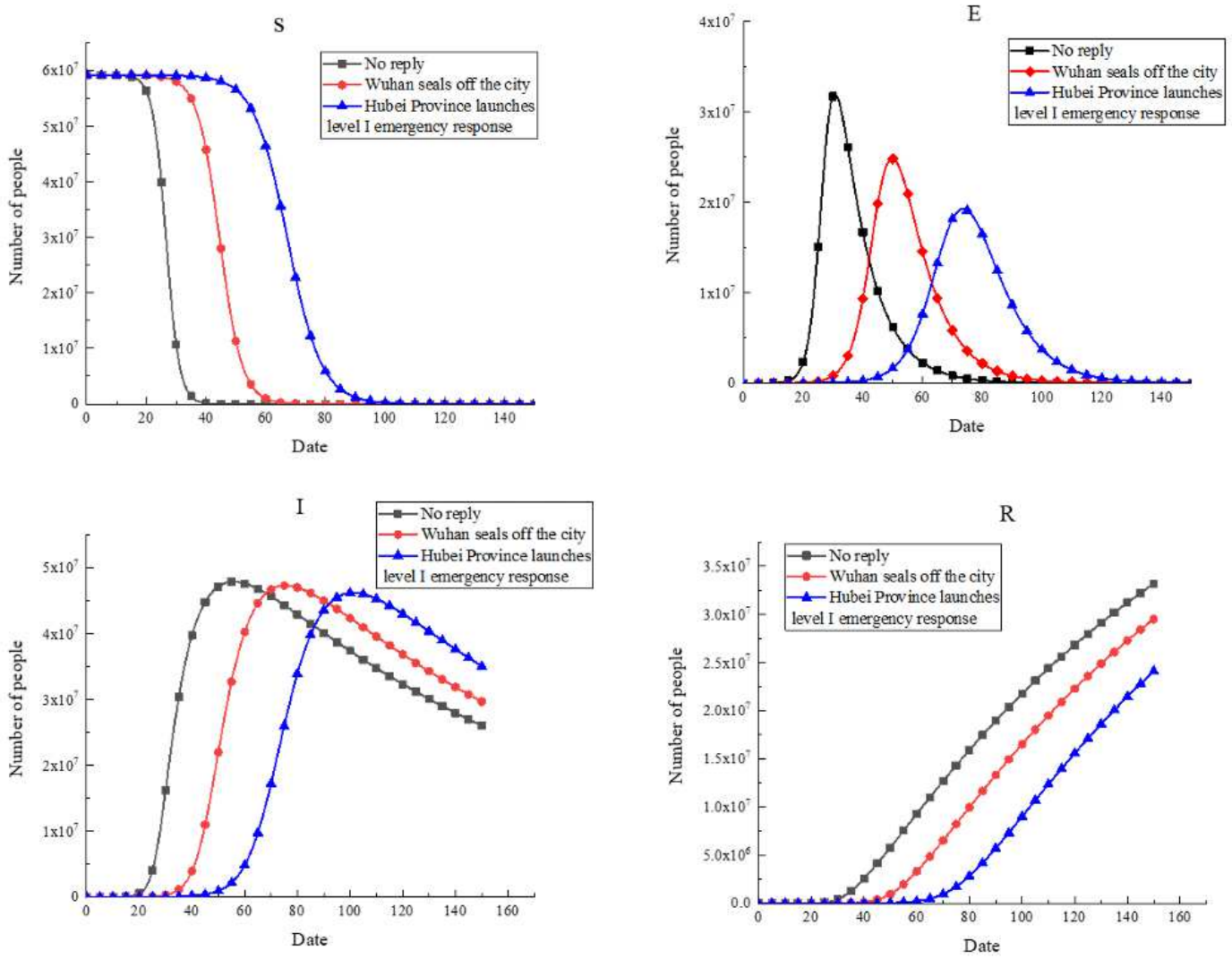

Figure 4

Fitting results of the SEIR model after taking type-A NPIs in the CEA

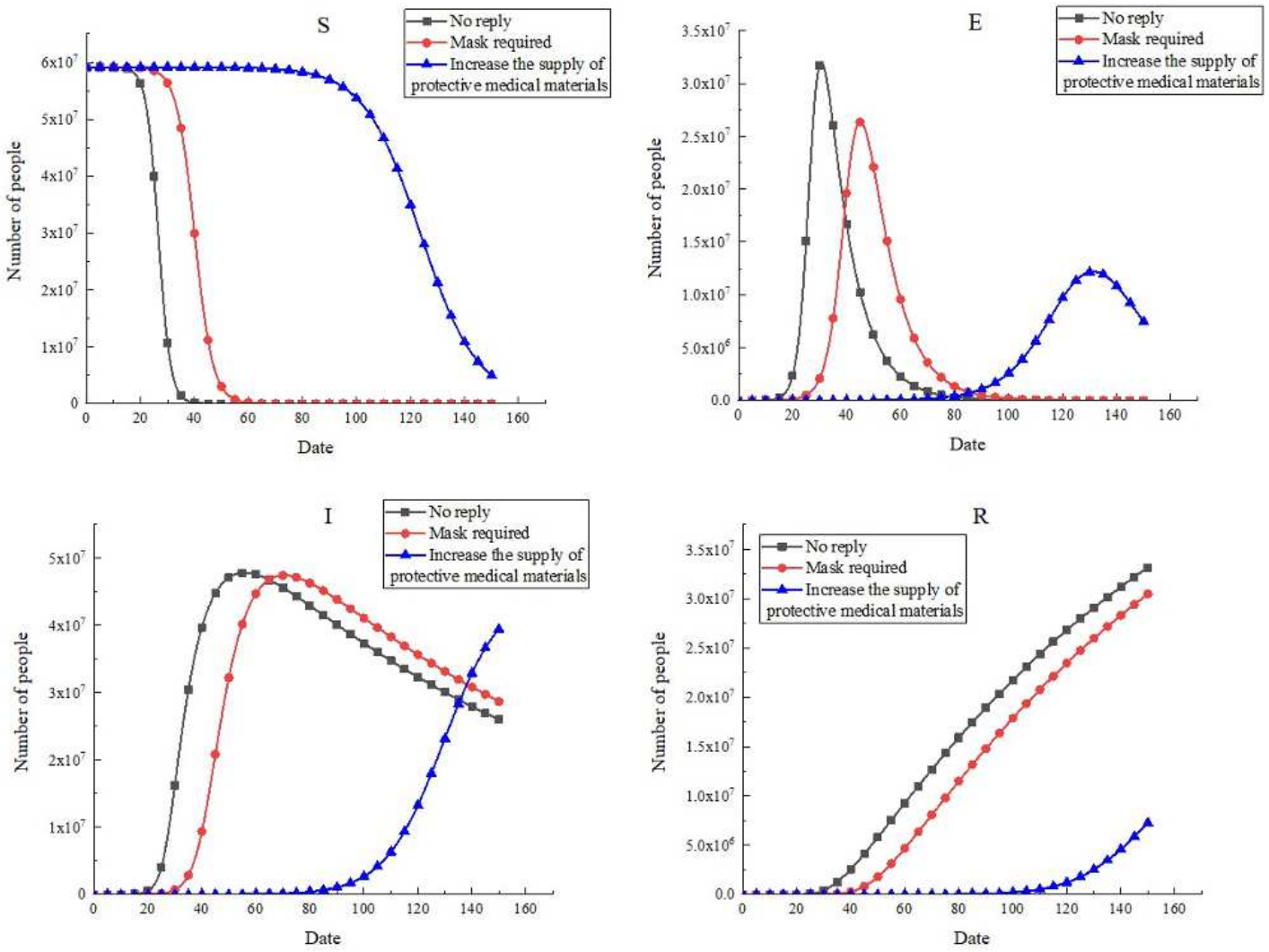

Figure 5

Fitting results of the SEIR model after taking type-B NPIs in the CEA

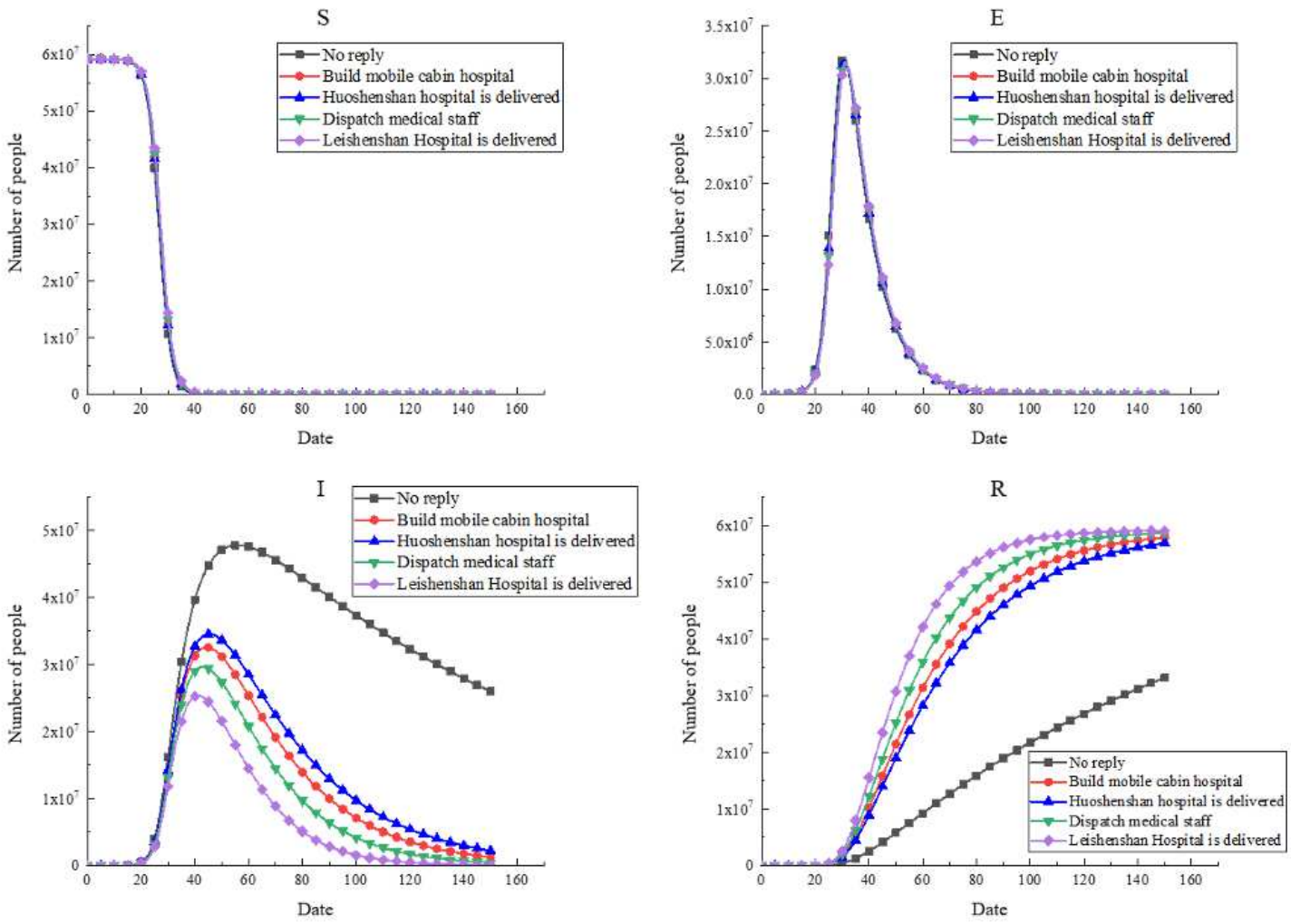

Figure 6

Fitting results of the SEIR model after taking type-C NPIs in the CEA

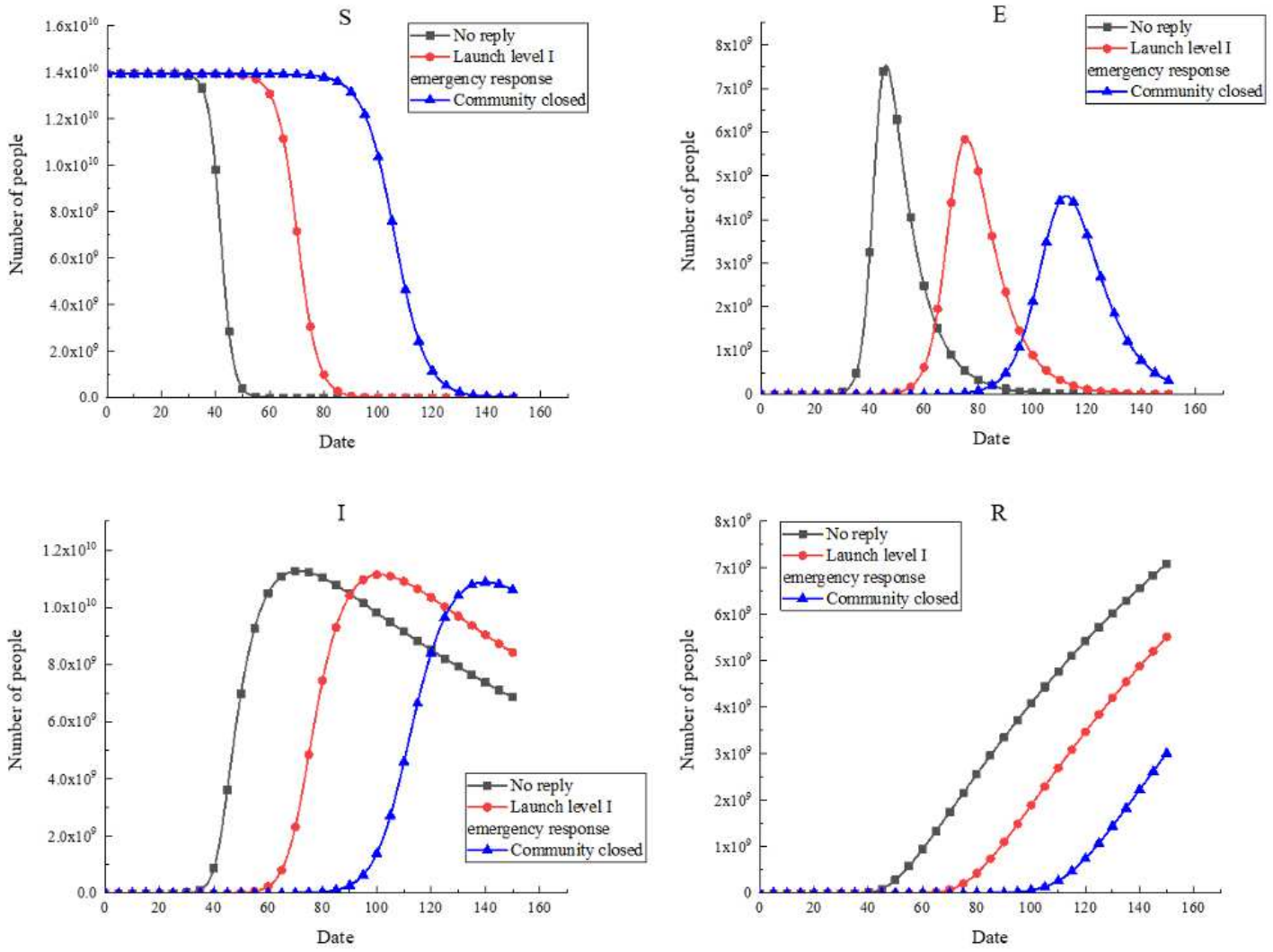

Figure 7

Fitting results of the SEIR model after taking type-A NPIs in the NCEA

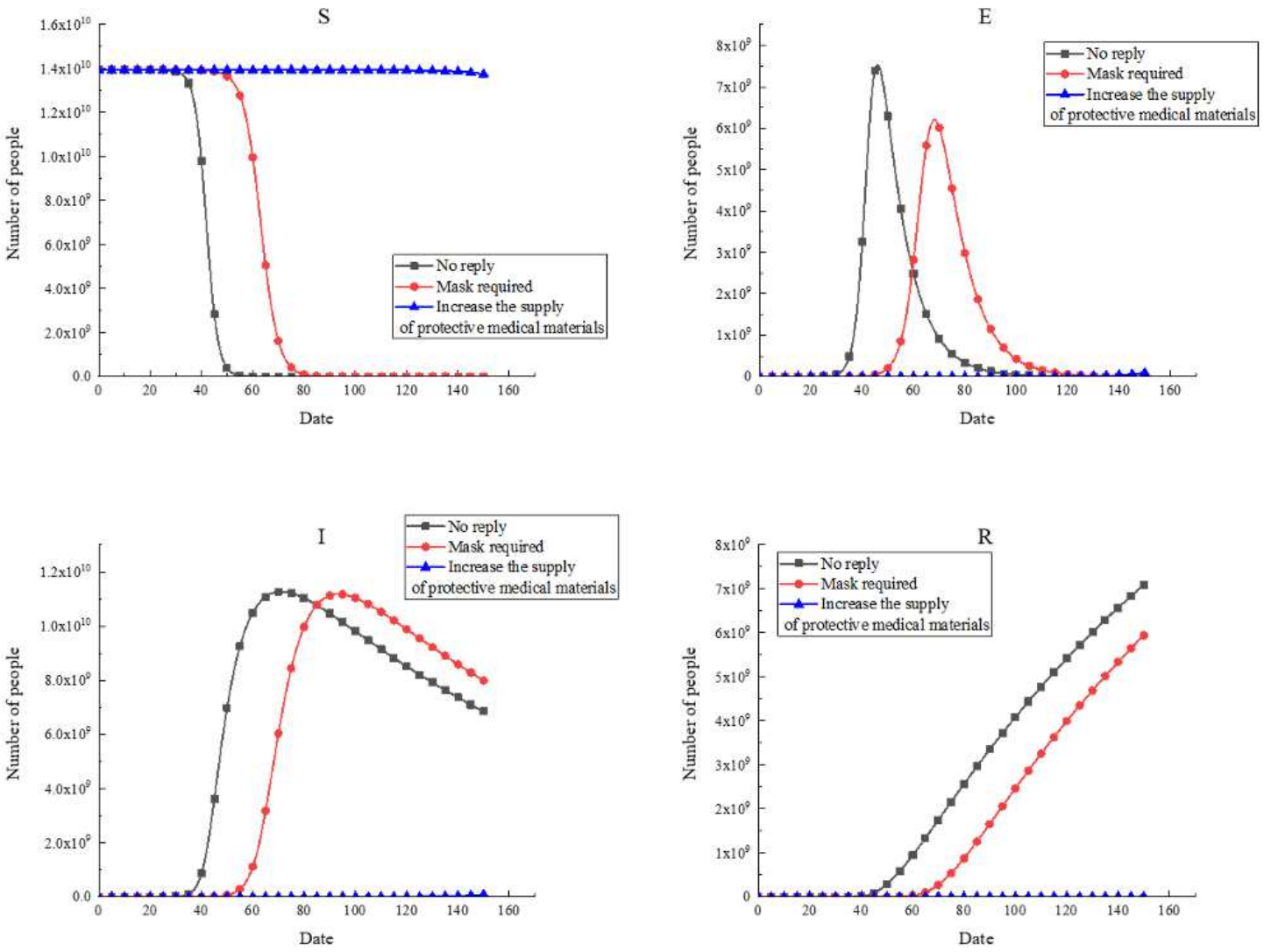

Figure 8

Fitting results of the SEIR model after taking type-B NPIs in the NCEA

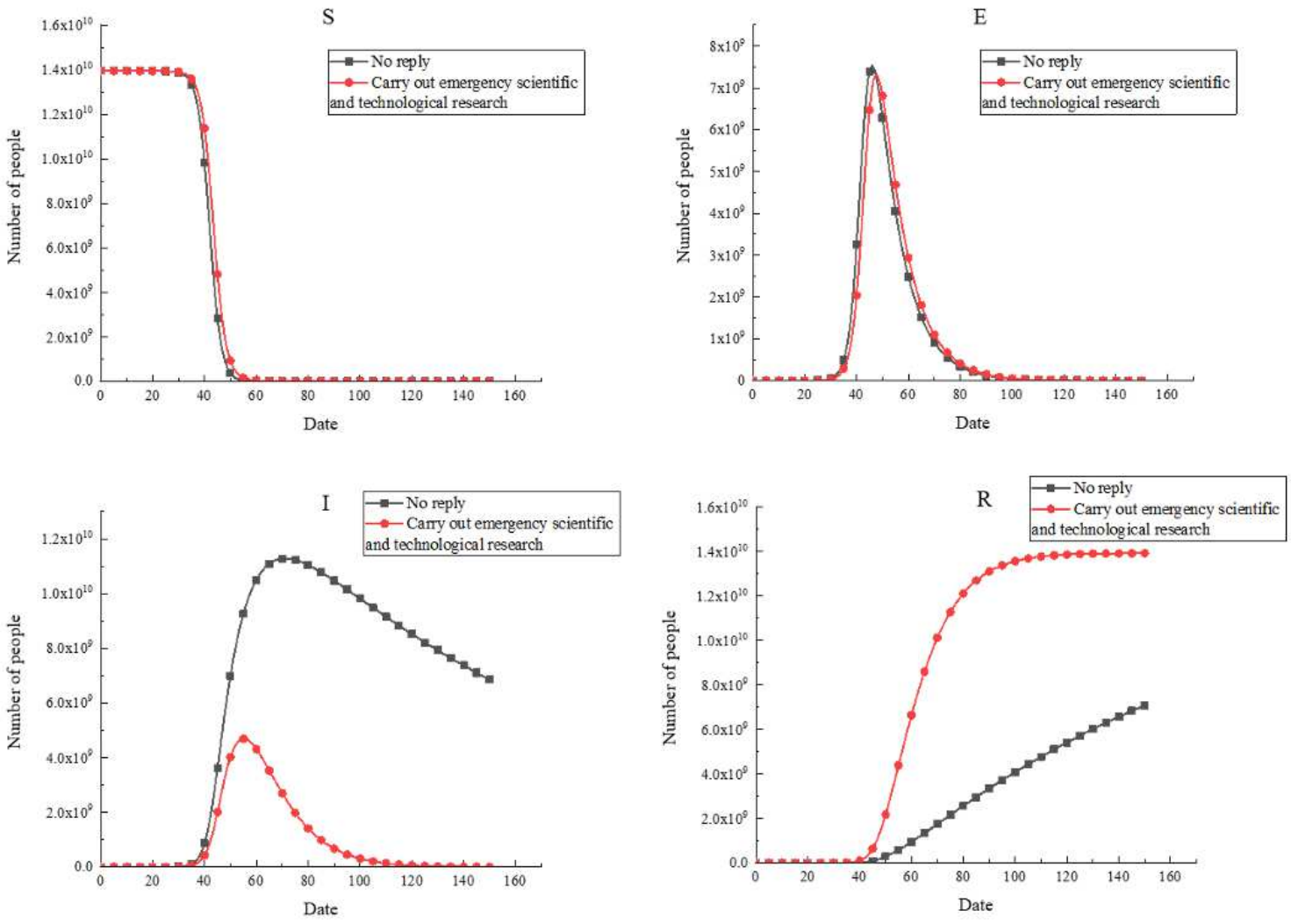

Figure 9

Fitting results of the SEIR model after taking type-C NPIs in the NCEA

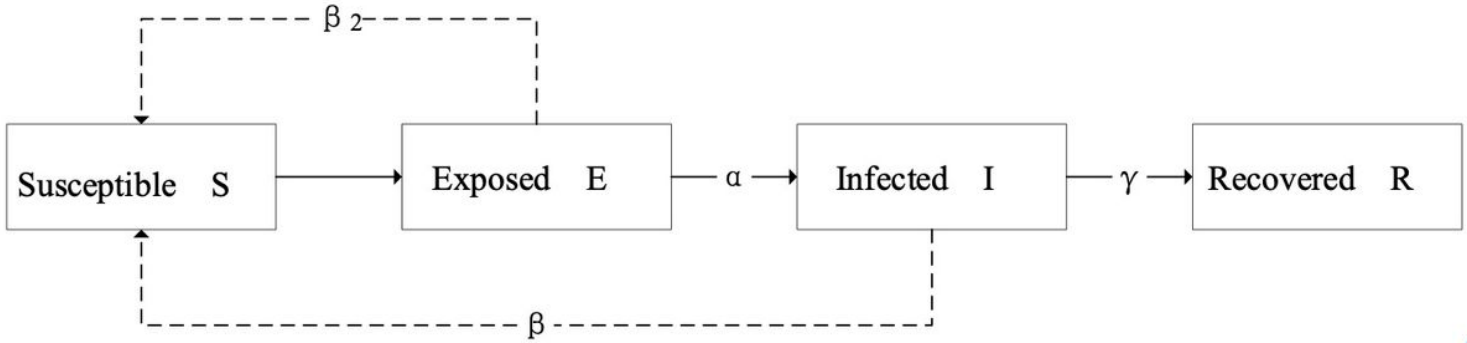

Figure 10

The SEIR model

Supplementary Files

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

- Thenumberofconfirmedcases.xlsx