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Could COVID-19 Pandemic be Stopped with Joint Efforts of Travel Restrictions and Public Health Countermeasures: a modelling study

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Could COVID-19 Pandemic be Stopped with Joint Efforts of Travel Restrictions and Public Health Countermeasures: a modelling study

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Abstract

Objective: We aim to explore and compare the effect of global travel restrictions and public health countermeasures in response to COVID-19 outbreak.

Design: A data-driven spatio-temporal modeling to simulate the spread of COVID-19 worldwide for 150 days since January 1,2020 under different scenarios.

Setting: Worldwide.

Interventions: Travel restrictions and public health countermeasures.

Main outcome: The cumulative number of COVID-19 cases.

Results: The cumulative number of COVID-19 cases could reach more than 420 million around the world without any countermeasures taken. Under timely and intensive global interventions, 99.97% of infections could be avoided comparing with non-interventions. The scenario of carrying out domestic travel restriction and public health countermeasures in China-only could contribute to a significant decrease of the cumulative number of infected cases worldwide. Without global travel restriction, 98.62% of COVID-19 cases could be avoided by public health countermeasures in China-only compared with non-interventions at all.

Conclusions: Public health countermeasures were generally more effective than travel restrictions in many countries, suggesting multi-national collaborations in the public health communities in response to this novel global health challenge.

Keywords: **COVID-19, Travel Restrictions, Countermeasures, public health**

Strengths and limitations of this study

- Under timely and intensive global interventions, 99.97% of infections could be avoided comparing with non-interventions.
- The scenario of carrying out domestic travel restriction and public health countermeasures in China-

only could contribute to a significant decrease of the cumulative number of infected cases worldwide.

- Public health countermeasures were generally more effective than travel restrictions in many countries, suggesting multi-national collaborations in the public health communities in response to this novel global health challenge.
- The analysis was limited to the study time. Our hypothetical scenarios were based on counterfactual and backtrack the results to compare with the current situations.

Introduction

Novel infectious diseases appear to be emerging faster now than ever before, possibly driven by a variety of factors, including population growth, cross-species interactions, climate change, and international travel and trade. Globally, as at October 18 2020, a total of 39,442,444 peoples have been confirmed COVID-19 cases, including 1,039,406 deaths, reported by the World Health Organization (WHO).[1] WHO declared COVID-19 a Public Health Emergency of International Concern on 30 January 2020 [2] and then a pandemic on 9 March, and called on Member States to respond to the COVID-19 pandemic by implementing nation-wide COVID-19 countermeasure strategies.

In the absence of effective drugs and vaccines, non-pharmaceutical interventions were effective in controlling the SARS-CoV-2 transmission in different populations.[3 4] A series of social distancing countermeasures including school closures and restriction on mass gathering were implemented to minimize risk of spread between humans. Travel restrictions were enforced by several countries to uphold boarder security and shut down the transmission passage from any imported infected cases. The decline of COVID-19 cases in China showed the effectiveness of non-pharmaceutical public health interventions. However, over the past eight months, the number of cases reported has increased rapidly without showing signs of decay around the world. Selection of intervention strategies seem to be associated with the variation in domestic and global responses to the COVID-19 pandemic.

In February and March, WHO did not recommend imposing travel or trade restrictions on countries experiencing COVID-19 outbreaks.[5] The International Health Regulations (2005) (IHR) formulated the global joint response to the disease in order to avoid unnecessary international traffic and trade restrictions.[6] WHO commented that travel and trade restrictions would cause harm than good.[7] More than 130 countries have implemented different forms of travel restrictions, including suspensions of flights, halting visa-on-arrival programs, discouraging travel to and from high-risk areas, and closing boarders for foreigners.[8] Recently, a few reports explored the effectiveness of travel restrictions on COVID-19 in different countries.[9, 10] To some extent, travel restrictions avoided the importation of infected cases by breaking the chains of transmission between different locations, however the containment effect on COVID-19 pandemic was unknown. Nonetheless, an Australian study showed the travel restrictions to and from China were somewhat effective on containing the COVID-19.[11]

The purpose of this study was to compare the current situations with our assumed scenarios under different intervention strategies to explore the effectiveness of different interventions in containing the COVID-19 transmission. Findings may support local decision makers to select intervention strategies particularly in relation to travel restrictions to prevent, contain, and manage COVID-19 spread in the nearer future.

Methods

Data sources

Size of population by country were obtained from Worldometer.[12] Air flights data were obtained from the OpenFlights databases,[13] which contains information of 7698 airports and 67,663 domestic and international routes and other related data. International routes were aggregated to the country level, with total numbers of seats on all the flights estimated as the proxy number of passengers travelling from country to country.

Information on travel restrictions against China was obtained from the National Immigration Administration (https://www.nia.gov.cn/), and complemented with information from the council on foreign relations (https://www.thinkglobalhealth.org/article/travel-restrictions-china-due-covid-19). Other travel restriction information was obtained from the International Air Transport Association (IATA) updated on 1 April 2020 (www.iatatravelcentre.com/international-travel-document-news).

Epidemic simulation model

We employed the SimInf R package to implement the COVID-19 spatio-temporal modelling.[14 15] The model comprised multiple nodes and each node, representing one country, contained the susceptible (S), Exposed (E), infected (I) and Removed (R) compartments. Transitions between these compartments were modelled as a continuous-time discrete state Markov chain (CTMC). Individuals' movements across different countries were processed with scheduled events, causing the change of the population in each country. We only considered the movement of individuals in one country to a destination country, irrespective of the birth or death. The scheduled movements were carried on when the simulation in continuous time reaches the pre-defined time. The individuals were randomly sampled from the compartments affected by the event. At time t, there were $a_{ij,t}$ susceptible individuals moved from node i to j, while $a_{ji,t}$ susceptible individuals moved from j to i. The number of Exposed, Infected and Removed individuals travelled from country i to j were noted by $b_{ij,t}$ $c_{ij,t}$ and $d_{ij,t}$, respectively. Transitions between compartments in one country and the movements between different countries were illustrated by Figure 1. The number of individuals' movements across countries were estimated to represent different scenarios. We implemented a classic SEIR transmission model to simulate the spread of COVID-19. For simplicity, we presented the deterministic version of the transmission model in each country, described by the following set of differential equations:

$$\frac{\mathrm{d}S}{\mathrm{d}t} = -\frac{\beta SI}{N}$$

$$\frac{\mathrm{d}E}{\mathrm{d}t} = \frac{\beta SI}{N} - \sigma E$$

$$\frac{\mathrm{d}I}{\mathrm{d}t} = \sigma E - \gamma I$$

$$\frac{\mathrm{d}R}{\mathrm{d}t} = \gamma I$$

where $1/\sigma$ is the latent period with value of 6.4 days, and $1/\gamma$ is the recovery period with value of days.[16 17] In our model, we set the reproductive number, $R_0 = 2.35$, corresponding to the effective contact rate $\beta = 0{\cdot}8103$.[17]

We assumed 10 initial infectious cases of COVID-19 emerging from Wuhan city of China. The number of susceptible individuals were set to the size of population in each country, while the number of exposed and recovered were all set to zero. We ran the models for 150 days and used the cumulative number of infections to investigate the influence of travel restrictions and public health countermeasures including social distancing, isolation of cases, quarantine of close contacts, etc., during the global spread of COVID-19. The first day of the simulation was set on 1 January, 2020.

Modelling scenarios

Seven scenarios were modelled to simulate the spread of COVID-19 around the world (Table 1). The baseline scenario for comparison was set assuming neither travel restrictions nor public health countermeasures. Additional six scenarios were then modelled assuming different combination of travel restrictions and public health countermeasures.

We separated global travel restrictions into three situations, i.e., none, travel restrictions against China, or multinational travel restrictions. After WHO declared COVID 19 a Public Health Emergency of International Concern, many countries imposed travel restrictions against China, most of which were effective on 1 February, 2020. Since March 2020, COVID-19 has spread around almost everywhere in the world. Responsive to this pandemic, country-wide travel bans were implemented strictly worldwide. We collected the information on multinational travel bans from IATA [18] (updated on 1 April, 2020), from which we assumed global travel restrictions were carried out on 20 March, 2020.

We separated the public health countermeasures into three situations, i.e., none, public health countermeasures implemented in China, or global public health countermeasures implemented worldwide. In the study, public health countermeasures represented a series of activities reducing effective contact rate between humans. These activities included isolating confirmed cases, quarantining close contacts, suspending public transports, closing schools and entertainment venues, and banning public gatherings.[19] These public health countermeasures have been put in place to stop transmission of COVID-19 since late January 2020, which demonstrated a reduced daily contact by most, during the COVID-19 social distancing period, with most human interactions restricted to be held within each household.[20] We assumed the global public health countermeasures were implemented in a less strict way than those in China. Therefore, for public health countermeasures implemented in China, we set the effective contact rate in China reducing 85% after 24 Jan, 2020, whereas for global public health countermeasures, we set the effective contact rate among other countries reducing 50% from 25 Jan, 2020.

Patient and Public Involvement statement

Patients and the public were not involved in this study.

Results

Table 2 presented the median estimates of the total cumulative number of infections worldwide for each scenario. The cumulative cases would have reached more than 420 million if no countermeasures had been taken. On 29 May, there were 5,708,365 cases reported by WHO. The numbers of cases under scenario 2 and 5 were far more than the actual reporting data, respectively, whereas that under scenario 3 were similar to the actual reporting data. The absolute number of cases in scenario 7 were far lower than the actual reporting data.

Interventions implemented in China contributed to the significant decline in the cumulative number of infections worldwide according to the scenario 3, 4, and 6 in comparison with no action taken at all. In scenario 3, 98.62% of COVID-19 cases could have be avoided compared with the no-action baseline scenario. Implementing travel restrictions against China alone (scenario 2) had little effect on the controlling of global spread of COVID-19, as no substantial reduction in cases was observed. In scenario 5, implementing international travel restrictions could have only avoided 0.65% of number of infected cases in comparison with the no-action baseline scenario. Figure 2-3 and Figure S1-5 showed the spatial distribution of the cumulative number of infected cases over 150 days in each scenario.

Discussion

Our modelling results showed that COVID-19 transmission could be contained by timely and intensive travel restrictions and public health countermeasures with multinational joint efforts, and consequently the risk of becoming pandemic could perhaps be mitigated. Reduction in cumulative infections and local transmissions of COVID-19, were somewhat attributed towards the aggregated public health countermeasures, and to a much lesser extent, international travel restrictions.

Compared with previously reported number of COVID-19 cases,[1] those predicted under scenarios of either imposing travel restrictions against China or implementing global travel restrictions were greater than the real-world observations. That is, these strategies appeared to be ineffective or somewhat exaggerated. This finding indicated the intervention strategies implemented in China have played an important role on the control of COVID-19 spread in communities. On 23 Jan, authorities in Wuhan have taken a series of unprecedented COVID-19 countermeasures with millions of local residents strictly upholding these policies, including city lockdown, traffic suspension, and quarantine.[21] Recent epidemiological studies have demonstrated that these interventions have contributed to the interruption of the spread of SARS-CoV-2 transmission,[21,22] which was consistent with our modelling analysis. The decrease of daily COVID-19 infections in China has provided another set of evidence of the field effectiveness of these public health countermeasures.[23]

Ideally, should most of the countries around the world have taken public health countermeasures including stockpiling medical resources, initiating emergency response procedures, screening high-risk population, and promoting social distancing at the beginning of the epidemic outbreak, the global spread of COVID-19 could have been restricted to a much lesser extent around the world (scenario 7). However, as of 29 May, there were 5,708,365 cases reported by WHO, greater than the simulated finding under scenario of every member state taking precautionary countermeasures as early as January when city quarantine in China has been initiated. Compared with what we assumed that the public health countermeasures should have been carried out around the world from January 25, there was a 2-month window period during which the global health communities did not effectively responded. European countries began to implement a series of intervention strategies since mid-March, 2020.[3] The stay-at-home order has been issued in the 42 states of United States in late March and early April.[24] Facing a possible reemergence of COVID-19 later this year, any countermeasures that have been proved effective in the field should have been implemented timely and strictly around the world.

The global travel restriction played a relatively modest preventive role on controlling the SARS-CoV-2 transmission in our analysis, which was consistent with previous studies.[9,25] While any global travel bans could slow the rate of importing cases, but they cannot stop the spread of COVID-19 around the world.[9] A systematic review of 23 studies has showed the travel restrictions were effective in delaying the epidemic trajectory, but ineffective in stopping it.[26] Other concerns about the global travel restriction strategy include its consequences of global economic issues as well as social dissatisfaction in relation to human rights and discrimination.[27] Furthermore, one tradeoff of the global travel restrictions would be related to a possible delay of appropriate responses in low-income countries because a large amount of medical resources via air transportation from developed countries could have been blocked down.[8] While the variation in effectiveness of partial or entire travel ban was under investigated,[11 25] our findings suggest travel restriction a somewhat robust strategy during the outbreak. Additional efforts may invest on screening and quarantining travelers from high-risk regions at the transportation interchange, and remain social distancing strategies in the communities.

Our study has some limitations. First, our analysis was limited to the study time. Our hypothetical scenarios were based on counterfactual and backtrack the results to compare with the current situations. Second, we assumed aggregated strategies which could vary across different settings, and therefore result should be interpreted with caution. Nonetheless, the rapid spread of this novel infectious diseases, demonstrated adverse impact on the entire world with harms to the global health, economy, and social governance. The COVID-19 pandemic has posed a major threat to our society, and no country could be immune to such complex issues and stay out of the multinational collaborations. In the face of this global challenge, the principle of one health and one world should be encouraged by all nations to, achieve global governance in public health.

Conclusion

Number of COVID-19 infected cases around the world could have been largely prevented by public health countermeasures in each country, and, to a lesser extent, by the global travel restriction. Rapid response to this novel public health challenge requires multi-national collaborations to carry out timely and intensive intervention strategies.

Contributors

Conception and design of the work: WD, LCK, and YH; acquisition of data: LCK and YH; statistical analysis: LCK and YH; interpretation of data: WD, LCK, and YH; drafted the manuscript and revised: WD, LCK, YH, QW, YW, TY, XDC, HJ, and LJF. All authors revised the manuscript and read and approved the final version.

Declaration of interests

We declare no competing interests.

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Data sharing

No additional data are available.

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Ethics

Not applicable.

Figure caption

Fig.1 The flowchart of transitions between compartments and movements between countries

Fig.2 Cumulative cases at days 150 in scenario 1

Fig.3 Cumulative cases at days 150 in scenario 7

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Table 1. Assumed scenarios to simulate the spread of COVID-19*

Scenarios	Descriptions	Global travel restrictions			Public health countermeasures		
		A	B	C	D	E	F
1(baseline)	None countermeasures	No	No	No	No	No	No
2	Travel restrictions imposed on China from February 1	No	Yes	No	No	No	No
3	Public health countermeasures in China from January 25	No	No	No	No	Yes	No
4	Travel restrictions imposed on China from February 1, Public health countermeasures in China from January 25	No	Yes	No	No	Yes	No
5	Travel restrictions imposed on China from February 1, global travel restrictions implemented from March 20	No	Yes	Yes	No	No	No

6	Travel restrictions imposed on China from February 1, global travel restrictions implemented from March 20 Public health countermeasures in China from January 25	No	Yes	Yes	No	Yes	No
7	Travel restrictions imposed on China from February 1, global travel restrictions implemented from March 20, Public health countermeasures in China and all around the world from January 25	No	Yes	Yes	No	Yes	Yes

* A: none, B: travel restrictions against China, C: global travel restrictions, D: none, E: public health countermeasures in China, F: global public health countermeasures

Table 2. Results for the run with median of the total cumulative number of infections.

Scenarios	**Median of cumulative infections at 150 days**	**Avoided median number of cases****	**Reducing the estimated median number of infections (%)**
1(baseline)	420,520,763	-	-
2	385,399,261	35,121,502	8.35
3	5,809,925	414,710,838	98.62
4	4,832,306	415,688,457	98.85

5	417,781,694	2,739,069	0.65
6	5,270,174	415,250,589	98.75
7	133,575	420,387,188	99.97
Actual reporting*	5,708,365	414,812,398	98.64%

*Number of confirmed cases were derived from WHO data reported on May 29, 2020 (150th day since January 1, 2020)

** Compared with infections in baseline 1

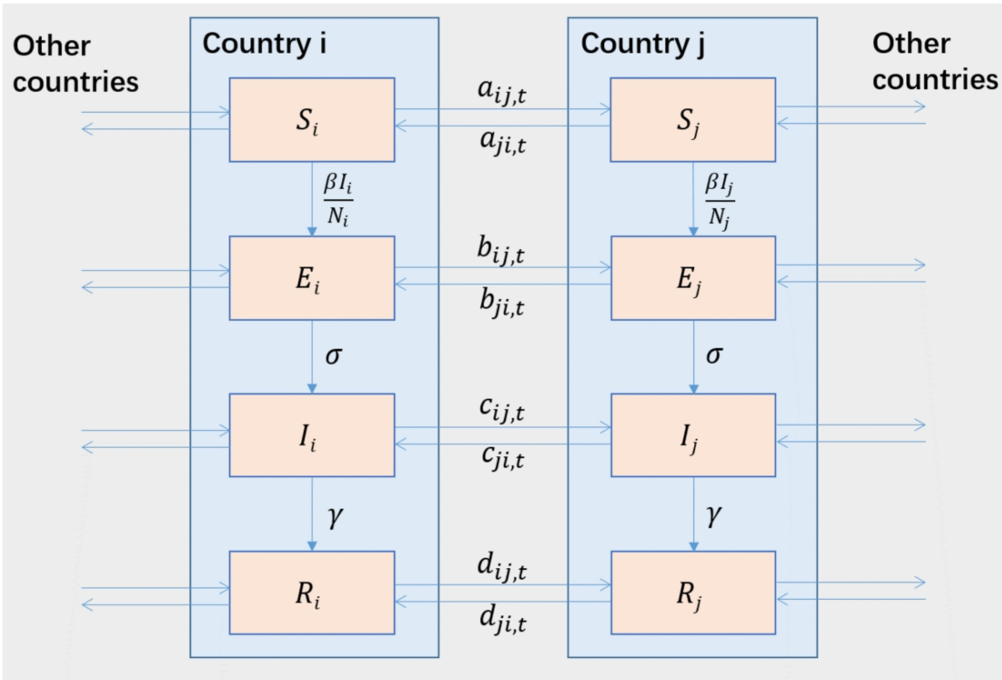

Fig.1 The flowchart of transitions between compartments and movements between countries

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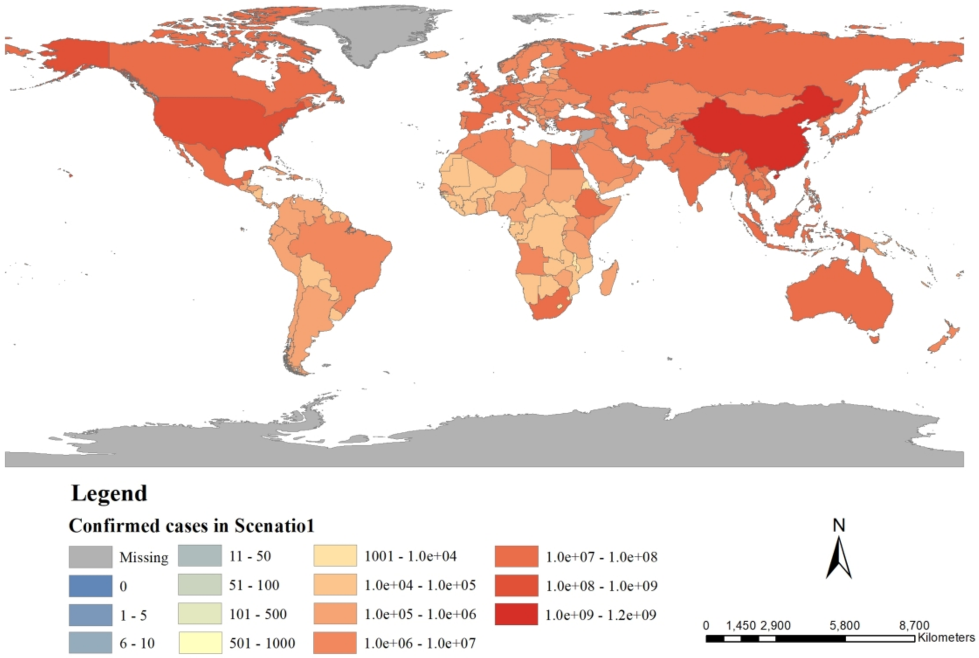

Fig.2 Cumulative cases at days 150 in scenario 1

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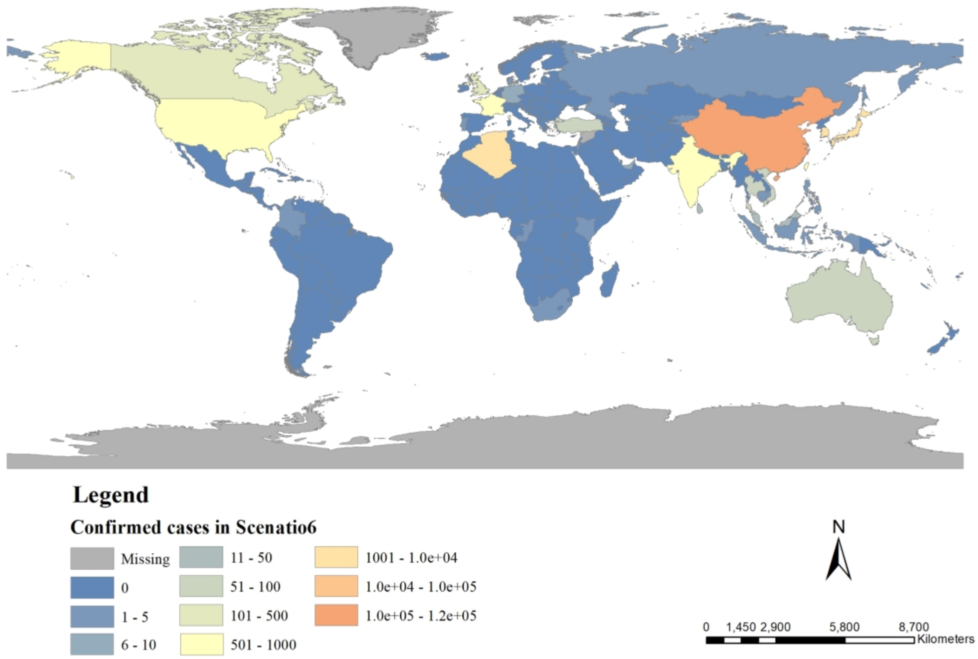

Fig.3 Cumulative cases at days 150 in scenario 7

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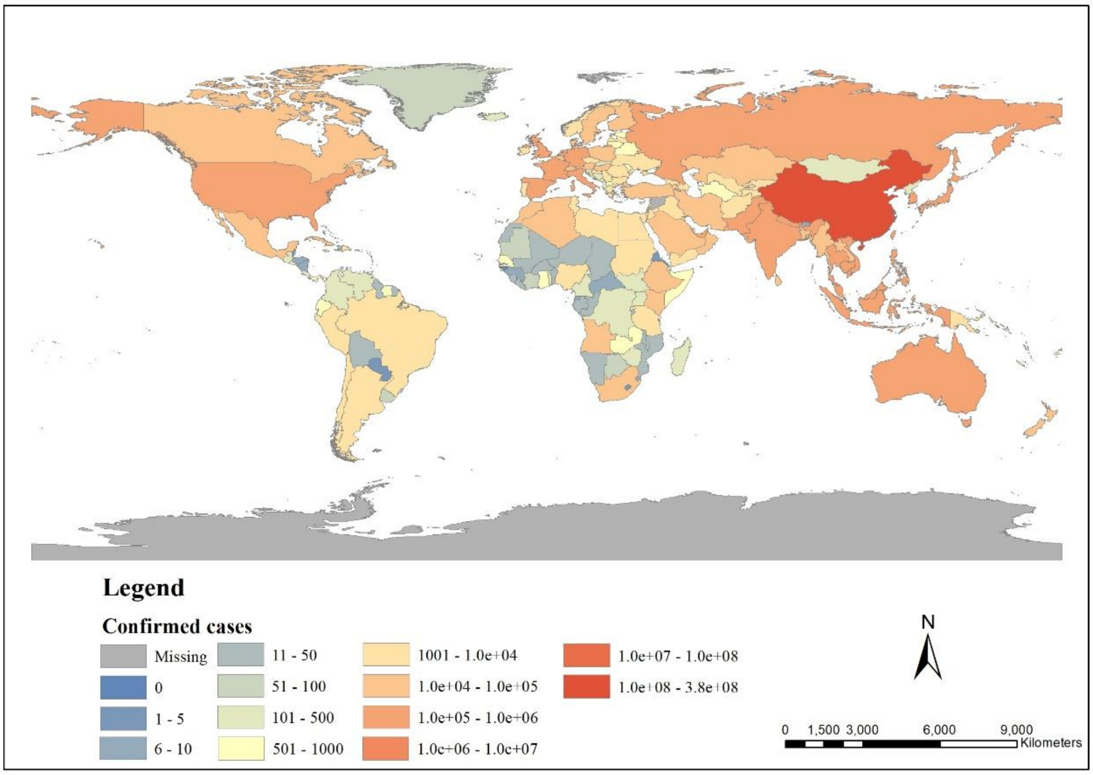

Fig.S1 Cumulative cases at days 150 in scenario 2.

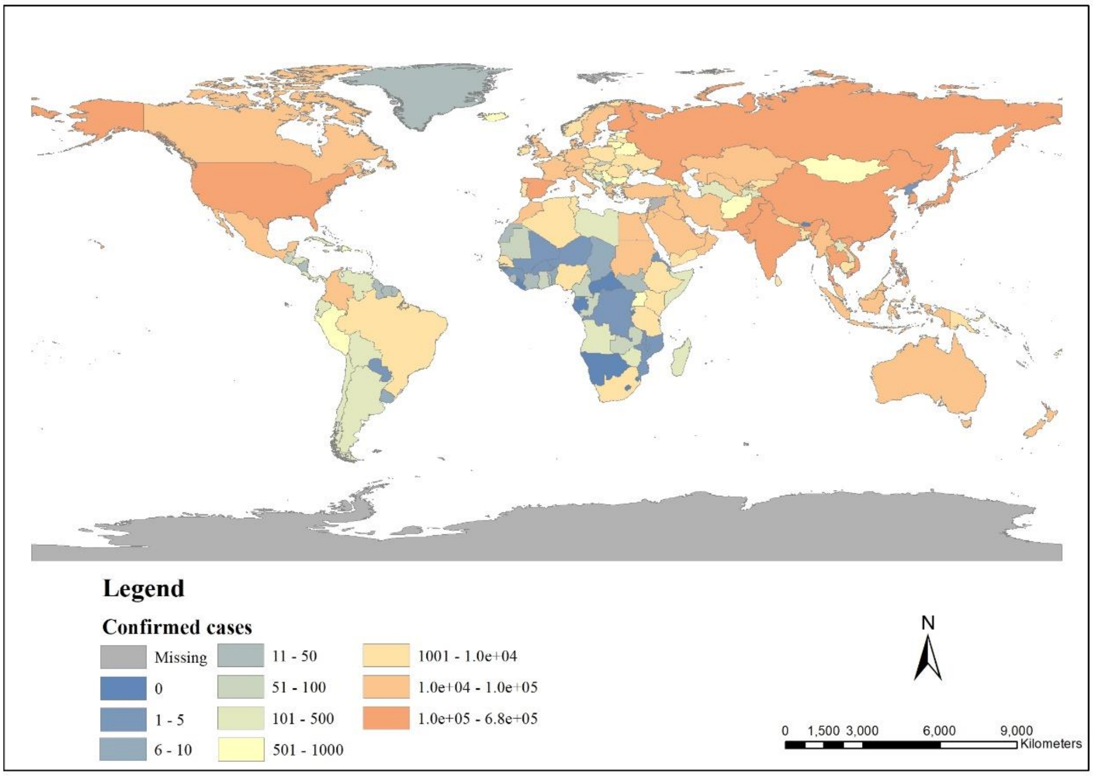

Fig.S2 Cumulative cases at days 150 in scenario 3.

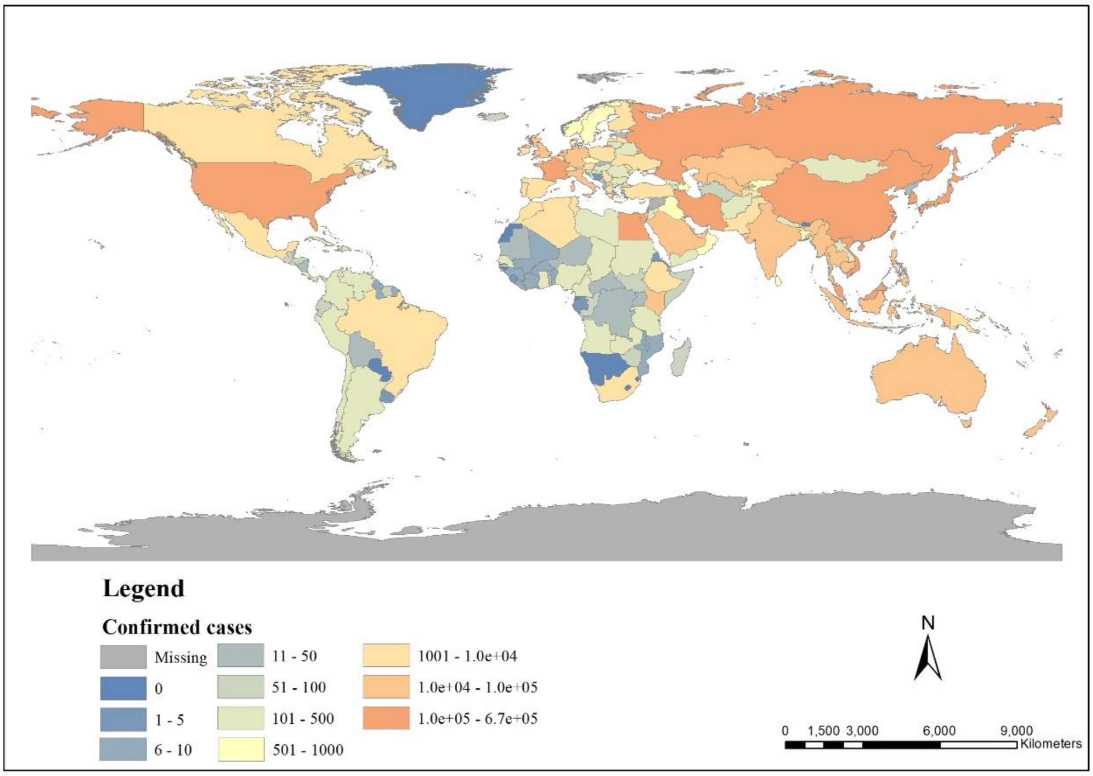

Fig.S3 Cumulative cases at days 150 in scenario 4.

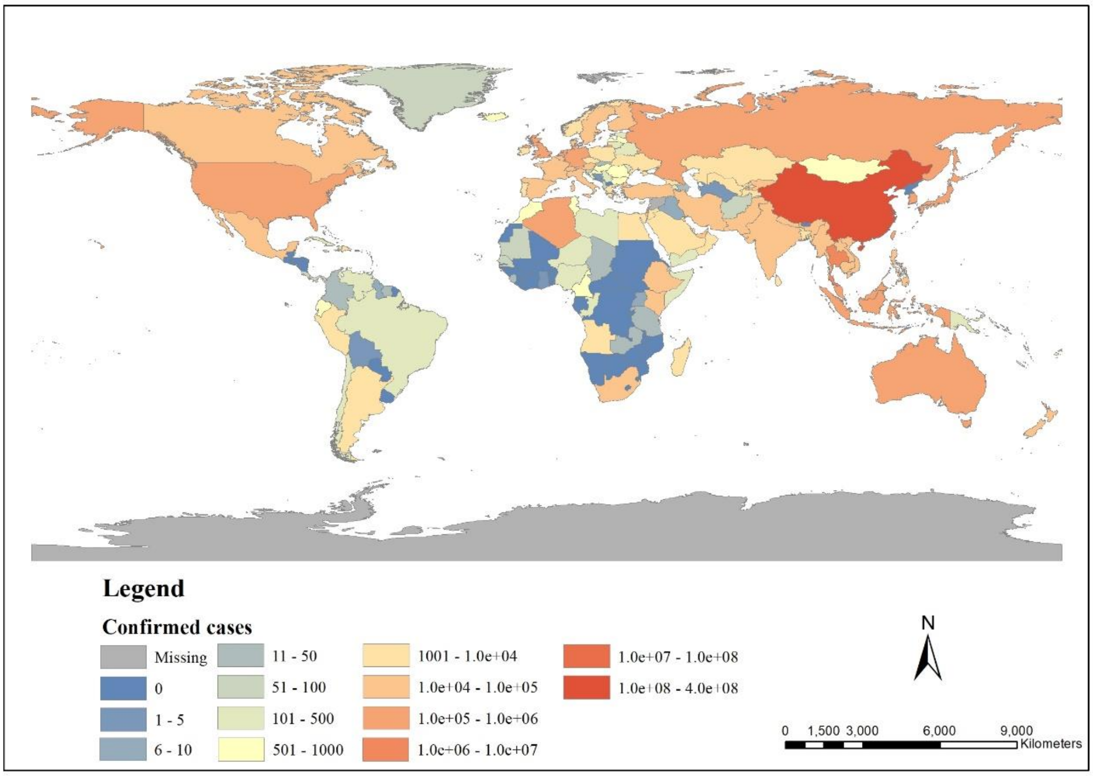

Fig.S4 Cumulative cases at days 150 in scenario 5.

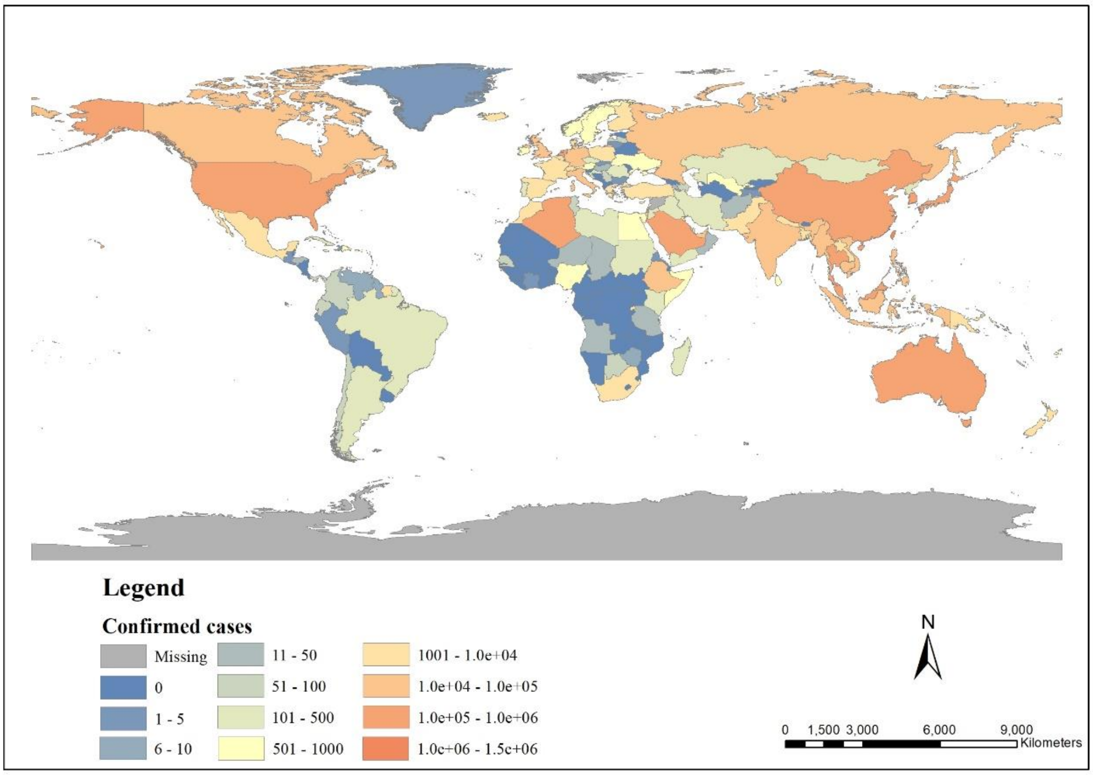

Fig.S5 Cumulative cases at days 150 in scenario 6.

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Abstract

Objective: We aim to explore and compare the effect of global travel restrictions and public health countermeasures in response to COVID-19 outbreak.

Design: A data-driven spatio-temporal modeling to simulate the spread of COVID-19 worldwide for 150 days since January 1,2020 under different scenarios.

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Main outcome: The cumulative number of COVID-19 cases.

Results: The cumulative number of COVID-19 cases could reach more than 420 million around the world without any countermeasures taken. Under timely and intensive global interventions, 99.97% of infections could be avoided comparing with non-interventions. The scenario of carrying out domestic travel restriction and public health countermeasures in China-only could contribute to a significant decrease of the cumulative number of infected cases worldwide. Without global travel restriction in the study setting, 98.62% of COVID-19 cases could be avoided by public health countermeasures in China-only compared with non-interventions at all.

Conclusions: Public health countermeasures were generally more effective than travel restrictions in many countries, suggesting multi-national collaborations in the public health communities in response to this novel global health challenge.

Keywords: **COVID-19, Travel Restrictions, Countermeasures, public health**

Strengths and limitations of this study

- Under timely and intensive global interventions in the study setting, 99.97% of infections could be avoided comparing with non-interventions.

- The scenario of carrying out domestic travel restriction and public health countermeasures in China-only could contribute to a significant decrease of the cumulative number of infected cases worldwide.
- Public health countermeasures were generally more effective than travel restrictions in many countries, suggesting multi-national collaborations in the public health communities in response to this novel global health challenge.
- The analysis was limited to the study time. Our hypothetical scenarios were based on counterfactual and backtrack the results to compare with the current situations.

Introduction

Novel infectious diseases appear to be emerging faster now than ever before, possibly driven by the systematic manipulation of nature by humans, not only through a variety of factors, including population growth, cross-species interactions, climate change, and international travel and trade, yet also through weakening of naturel barriers to disease emergence and persistence. Globally, as at October 18 2020, a total of 39,442,444 peoples have been confirmed COVID-19 cases, including 1,039,406 deaths, reported by the World Health Organization (WHO).[1] WHO declared COVID-19 a Public Health Emergency of International Concern on 30 January 2020 [2] and then a pandemic on 9 March, and called on Member States to respond to the COVID-19 pandemic by implementing nation-wide COVID-19 countermeasure strategies.

In the absence of effective drugs and vaccines, non-pharmaceutical interventions were effective in controlling the SARS-CoV-2 transmission in different populations.[3 4] A series of social distancing countermeasures including school closures and restriction on mass gathering were implemented to minimize risk of spread between humans. Travel restrictions were enforced by several countries to uphold boarder security and shut down the transmission passage from any imported infected cases. The decline of COVID-19 cases in China showed the effectiveness of non-pharmaceutical public health interventions, with their implementation exceptionally stringent as compared to most other countries.[5] However, over the past eight months, the number of cases reported has increased rapidly without showing signs of decay around the world. Selection and implementation of intervention strategies appeared to be different across countries and regions in their responses to the early sign of disease spread, which could explain in part the current COVID-19 pandemic.

In February and March, WHO did not recommend imposing travel or trade restrictions on countries experiencing COVID-19 outbreaks.[6] The International Health Regulations (2005) (IHR) formulated the global joint response to the disease in order to avoid unnecessary international traffic and trade restrictions.[7] WHO commented that travel and trade restrictions would cause more harm than good.[8] More than 130 countries have implemented different forms of travel restrictions, including suspensions of flights, halting visa-on-arrival programs, discouraging travel to and from high-risk areas, and closing boarders for foreigners.[9] Recently, a few reports explored the effectiveness of travel restrictions on COVID-19 in different countries.[10 11] To some extent, travel restrictions avoided the importation of infected cases by breaking the chains of transmission between different locations, however the containment effect on COVID-19 pandemic was unknown. Nonetheless, an Australian study showed the travel restrictions to and from China were somewhat effective on containing the COVID-19 spread.[12]

The purpose of this study was to compare the current situations with our assumed scenarios under different intervention strategies to explore the effectiveness of different interventions in containing the COVID-19 transmission. Findings may support local decision makers to select intervention strategies particularly in relation to travel restrictions to prevent, contain, and manage COVID-19 spread in the nearer future.

Methods

Data sources

Size of population by country were obtained from Worldometer.[13] Air flights data were obtained from the OpenFlights databases,[14] which contains information of 7698 airports and 67,663 domestic and international routes and other related data. International routes were aggregated to the country level. Although number of travelers would most accurately reflect the population mobility, this exact information was not available; hence, we used the aircraft seating capacity as the best available proxy measure for analysis relating to number of travelers.

Information on travel restrictions against China was obtained from the National Immigration Administration (https://www.nia.gov.cn/), and complemented with information from the council on foreign relations (https://www.thinkglobalhealth.org/article/travel-restrictions-china-due-covid-19). Other travel restriction information was obtained from the International Air Transport Association (IATA) updated on 1 April 2020 (www.iatatravelcentre.com/international-travel-document-news).

Epidemic simulation model

We employed the SimInf R package to implement the COVID-19 spatio-temporal modelling.[15 16] The model comprised multiple nodes and each node, representing one country, contained the susceptible (S), Exposed (E), infected (I) and Removed (R) compartments. Transitions between these compartments were modelled as a continuous-time discrete state Markov chain (CTMC). Individuals' movements across different countries, which were estimated by the aircraft seating capacity as the proxy for number of travelers, were processed with scheduled events, causing the change of the population in each country.

We only considered the movement of individuals in one country to a destination country, irrespective of the birth or death. The scheduled movements were carried on when the simulation in continuous time reaches the pre-defined time. The individuals were randomly sampled from the compartments affected by the event. At time t, there were $a_{ij,t}$ susceptible individuals moved from node i to j, while $a_{ji,t}$ susceptible individuals moved from j to i. The number of Exposed, Infected and Removed individuals travelled from country i to j were noted by $b_{ij,t}$ $c_{ij,t}$ and $d_{ij,t}$, respectively. Transitions between compartments in one country and the movements between different countries were illustrated by Figure 1. The number of individuals' movements across countries were estimated to represent different scenarios. We implemented a classic SEIR transmission model to simulate the spread of COVID-19. For simplicity, we presented the deterministic version of the transmission model in each country, described by the following set of differential equations:

$$\frac{\mathrm{d}S}{\mathrm{d}t} = -\frac{\beta SI}{N}$$

$$\frac{\mathrm{d}E}{\mathrm{d}t} = \frac{\beta SI}{N} - \sigma E$$

$$\frac{\mathrm{d}I}{\mathrm{d}t} = \sigma E - \gamma I$$

$$\frac{\mathrm{d}R}{\mathrm{d}t} = \gamma I$$

where $1/\sigma$ is the latent period with value of 6.4 days, and $1/\gamma$ is the recovery period with value of days.[17 18] In our model, we set the reproductive number, $R_0 = 2.35$, corresponding to the effective contact rate $\beta = 0{\cdot}8103$.[18]

We assumed 10 initial infectious cases of COVID-19 identified from Wuhan city of China. The number of susceptible individuals were set to the size of population in each country, while the number of exposed and recovered were all set to zero. We ran the models for 150 days and used the cumulative number of infections to investigate the influence of travel restrictions and public health countermeasures including social distancing, isolation of cases, quarantine of close contacts, etc., during the global spread of COVID-19. The first day of the simulation was set on 1 January, 2020.

Modelling scenarios

Seven scenarios were modelled to simulate the spread of COVID-19 around the world (Table 1). The baseline scenario for comparison was set assuming neither travel restrictions nor public health countermeasures. Additional six scenarios were then modelled assuming different combination of travel restrictions and public health countermeasures.

We separated global travel restrictions into three situations, i.e., none, travel restrictions against China, or multinational travel restrictions. After WHO declared COVID 19 a Public Health Emergency of International Concern, many countries imposed travel restrictions against China, most of which were effective on 1 February, 2020. Since March 2020, COVID-19 has spread around almost everywhere in the world. Responsive to this pandemic, country-wide travel bans were implemented strictly worldwide. We collected the information on multinational travel bans from IATA [19] (updated on 1 April, 2020), from which we assumed global travel restrictions were carried out on 20 March, 2020.

We separated the public health countermeasures into three situations, i.e., none, public health countermeasures implemented in China, or global public health countermeasures implemented worldwide. In the study, public health countermeasures represented a series of activities reducing effective contact rate between humans. These activities included isolating confirmed cases, quarantining close contacts, suspending public transports, closing schools and entertainment venues, and banning public gatherings.[20] These public health countermeasures have been put in place to stop transmission of COVID-19 since late January 2020, which demonstrated a reduced daily contact by most, during the COVID-19 social distancing period, with most human interactions restricted to be held within each household.[21] We assumed the global public health countermeasures were implemented in a less strict way than those in China. Therefore, for public health countermeasures implemented in China, we set the effective contact rate in China reducing 85% after 24 Jan, 2020, whereas for global public health countermeasures, we set the effective contact rate among other countries reducing 50% from 25 Jan, 2020.

Patient and Public Involvement statement

Patients and the public were not involved in this study.

Results

Table 2 presented the median estimates of the total cumulative number of infections worldwide for each scenario. The cumulative cases would have reached more than 420 million if no countermeasures had been taken. On 29 May, there were 5,708,365 cases reported by WHO. The numbers of cases under scenario 2 and 5 were far more than the actual reporting data, respectively, whereas that under scenario 3 were similar to the actual reporting data. The absolute number of cases in scenario 7 were far lower than the actual reporting data.

Interventions implemented in China contributed to the significant decline in the cumulative number of infections worldwide according to the scenario 3, 4, and 6 in comparison with no action taken at all. In scenario 3, 98.62% of COVID-19 cases could have be avoided compared with the no-action baseline scenario. Implementing travel restrictions against China alone (scenario 2) had little effect on the controlling of global spread of COVID-19, as no substantial reduction in cases was observed. In scenario 5, implementing international travel restrictions could have only avoided 0.65% of number of infected cases in comparison with the no-action baseline scenario. Figure 2-3 and Figure S1-5 showed the spatial distribution of the cumulative number of infected cases over 150 days in each scenario.

Discussion

Our modelling results showed that COVID-19 transmission could be contained by timely and intensive travel restrictions and public health countermeasures with multinational joint efforts at the early stage of spread, and consequently the risk of becoming pandemic could perhaps be mitigated. Haug et al. quantified the change of Rt (i.e., the effective reproduction number of COVID-19) in relation to different adoption time of non-pharmaceutical interventions, and reported that the earlier adoptions were associated with more benefits.[22] China's rapid responses to the COVID-19 spread also demonstrated a successful case in the real world.[5] While the spread of the pandemic follows an exponential pattern during the initial growth phase, it is particularly important to uptake the effective intervention strategies as early as possible, especially when facing the COVID-19 resurgence spread.

Reduction in cumulative infections and local transmissions of COVID-19, were somewhat attributed towards the aggregated public health countermeasures, and to a much lesser extent, international travel restrictions, which was consistent with previous studies using a similar analytic approach. Chinazzi et al reported impose travel restrictions on mainland China had a modest effect on the epidemic trajectory.[23] Wells et al showed that the travel restrictions as well as airport screening enforced in China and other countries were insufficient to contain the COVID-19 spread around the world.[10] Russell et al found that in general stringent travel restrictions might have little impact on the epidemic dynamics.[24] Given several factors including complex human behaviors that could determine the spread of the current pandemic, lessons learnt from China's experience could be informative to initiate multiple public heath countermeasures such as the grid-network of community-based health checkpoints,[5] when facing a COVID-19 resurgence spread at present. Our study findings emphasized again the importance of carrying out collaborative public health countermeasures rather than simply placing travel restrictions.

Compared with previously reported number of COVID-19 cases,[1] those predicted under scenarios of either imposing travel restrictions against China or implementing global travel restrictions were greater than the real-world observations. That is, these strategies appeared to be ineffective or somewhat exaggerated. This finding indicated the intervention strategies implemented in China have played an important role on the control of COVID-19 spread in communities. On 23 Jan, authorities in Wuhan have taken a series of unprecedented COVID-19 countermeasures with millions of local residents strictly upholding these policies, including city lockdown, traffic suspension, and quarantine.[25] Recent epidemiological studies have demonstrated that these interventions have contributed to the interruption of the spread of SARS-CoV-2 transmission,[25,26] which was consistent with our modelling analysis. The decrease of daily COVID-19 infections in China has provided another set of evidence of the field effectiveness of these public health countermeasures.[5]

Ideally, should most of the countries around the world have taken public health countermeasures including stockpiling medical resources, initiating emergency response procedures, screening high-risk population, and promoting social distancing at the beginning of the epidemic outbreak, the global spread of COVID-19 could have been restricted to a much lesser extent around the world (scenario 7). However, as of 29 May, there were 5,708,365 cases reported by WHO, greater than the simulated finding under scenario of every member state taking precautionary countermeasures as early as January when city quarantine in China has been initiated. Compared with what we assumed that the public health countermeasures should have been carried out around the world from January 25, there was a 2-month window period during which the global health communities did not effectively responded. European countries began to implement a series of intervention strategies since mid-March, 2020.[3] The stay-at-home order has been issued in the 42 states of United States in late March and early April.[27] Facing a possible reemergence of COVID-19 later this year, any countermeasures that have been proved effective in the field should have been implemented timely and strictly around the world.

The global travel restriction played a relatively modest preventive role on controlling the SARS-CoV-2 transmission in our analysis, which was consistent with previous studies.[10,28] While any global travel bans could slow the rate of importing cases, but they cannot stop the spread of COVID-19 around the world.[10] A systematic review of 23 studies has showed the travel restrictions were effective in delaying the epidemic trajectory, but ineffective in stopping it.[29] Other concerns about the global travel restriction strategy include its consequences of global economic issues as well as social dissatisfaction in relation to human rights and discrimination.[30] Furthermore, one tradeoff of the global travel restrictions would be related to a possible delay of appropriate responses in low-income countries because a large amount of medical resources via air transportation from developed countries could have been blocked down.[9] While the variation in effectiveness of partial or entire travel ban was under investigated,[12 28] our findings suggest travel restriction a somewhat robust strategy during the outbreak. Additional efforts may invest on screening and quarantining travelers from high-risk regions at the transportation interchange, and remain social distancing strategies in the communities.

Our study has some limitations. First, our analysis was limited to the study time at the early stage of COVID-19 spread. Our hypothetical scenarios were based on counterfactual and backtrack the results to compare with the current situations. Second, the finding of substantial variation in the geographic spread across countries reflected heterogenetic contact rates in different countries. Although the summary statistics around the world demonstrated a global benefit by means of public health interventions, each member state is encouraged to select appropriate countermeasures in its own setting to minimize the risk of COVID-19 resurgence spread becoming endemic. Third, we assumed aggregated strategies which could vary across different settings, and therefore result should be interpreted with caution. Nonetheless, the rapid spread of this novel infectious diseases, demonstrated adverse impact on the entire world with harms to the global health, economy, and social governance. The COVID-19 pandemic has posed a major threat to our society, and no country could be immune to such complex issues and stay out of the multinational collaborations. In the face of this global challenge, the principle of one health and one world should be encouraged by all nations to achieve global governance in public health.

Conclusion

Number of COVID-19 infected cases around the world could have been largely prevented by public health countermeasures in each country, and, to a lesser extent, by the global travel restriction. Rapid response to this novel public health challenge requires multi-national collaborations to carry out timely and intensive intervention strategies.

Contributors

Conception and design of the work: WD, LCK, and YH; acquisition of data: LCK and YH; statistical analysis: LCK and YH; interpretation of data: WD, LCK, and YH; drafted the manuscript and revised: WD, LCK, YH, QW, YW, TY, XDC, HJ, and LJF. All authors revised the manuscript and read and approved the final version.

Declaration of interests

We declare no competing interests.

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Data sharing

Data are available upon reasonable request. Requests for data access should be directed to the corresponding author.

Acknowledgments

We thank Prof Yilan Liao for her advice and critical comments.

Ethics

Provincial Health Commissions in mainland of China have reported municipal-level incident numbers of COVID-19 suspected, confirmedly infected, recovered, and deceased individuals, respectively on a daily basis since January 2020. These data were publically available and therefore this study was exempted for ethics approval by institutional review boards with respect to data collection, analysis and reporting.

Figure caption

Fig.1 The flowchart of transitions between compartments and movements between countries

Fig.2 Cumulative cases at days 150 in scenario 1

Fig.3 Cumulative cases at days 150 in scenario 7

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Table 1. Assumed scenarios to simulate the spread of COVID-19*

Scenarios	Travel restrictions against China (from February 1)	Global travel restrictions (from March 20)	Public health countermeasures in China (from January 25)	Global public health countermeasures (from January 25)
1(baseline)	No	No	No	No
2	Yes	No	No	No
3	No	No	Yes	No
4	Yes	No	Yes	No
5	Yes	Yes	No	No
6	Yes	Yes	Yes	No
7	Yes	Yes	Yes	Yes

Table 2. Results for the run with median of the total cumulative number of infections.

Scenarios	Median of cumulative infections at 150 days	Avoided median number of cases**	Reducing the estimated median number of infections (%)
1(baseline)	420,520,763	-	-
2	385,399,261	35,121,502	8.35
3	5,809,925	414,710,838	98.62
4	4,832,306	415,688,457	98.85
5	417,781,694	2,739,069	0.65
6	5,270,174	415,250,589	98.75
7	133,575	420,387,188	99.97
Actual reporting*	5,708,365	414,812,398	98.64%

*Number of confirmed cases were derived from WHO data reported on May 29, 2020 (150th day since January 1, 2020)

** Compared with infections in baseline 1

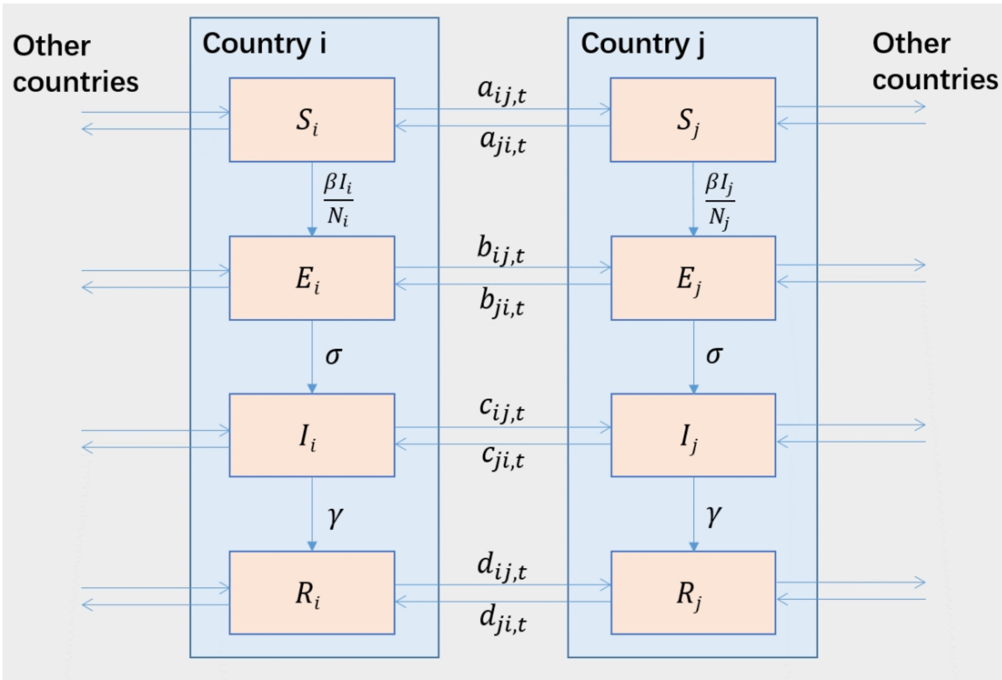

Fig.1 The flowchart of transitions between compartments and movements between countries

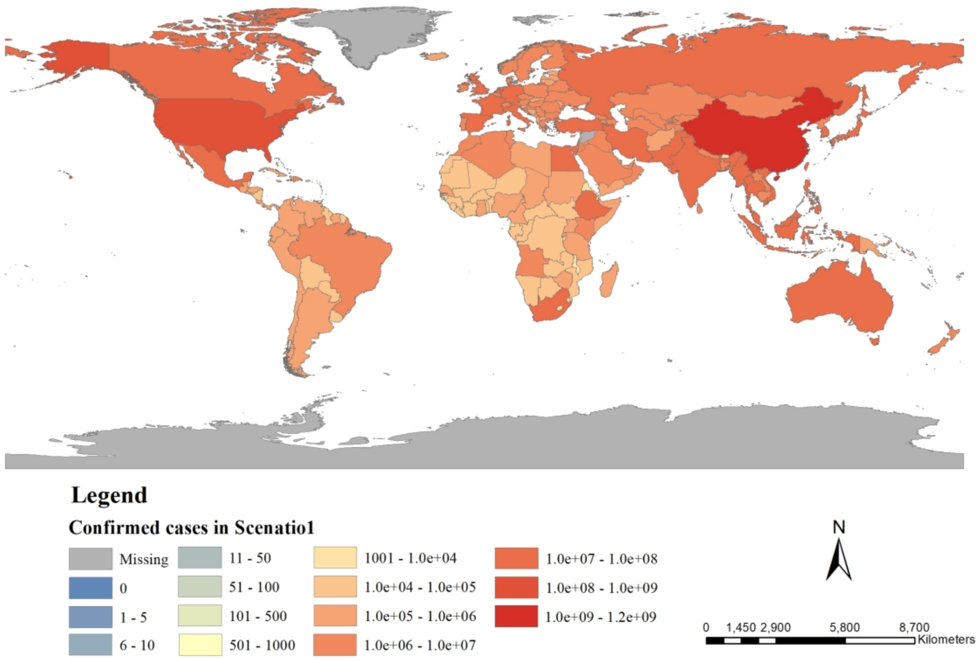

Fig.2 Cumulative cases at days 150 in scenario 1

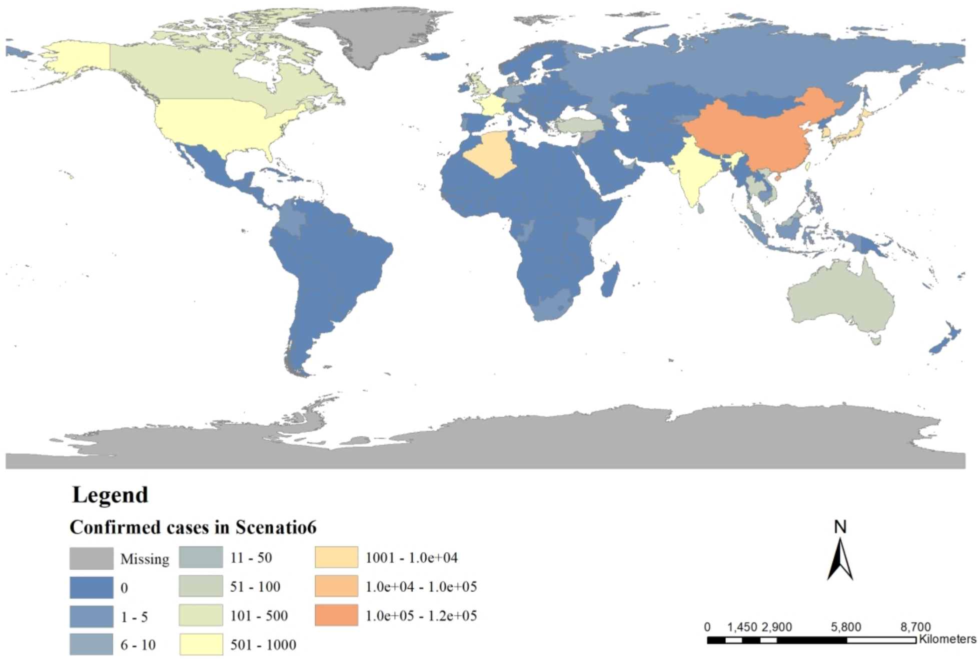

Fig.3 Cumulative cases at days 150 in scenario 7

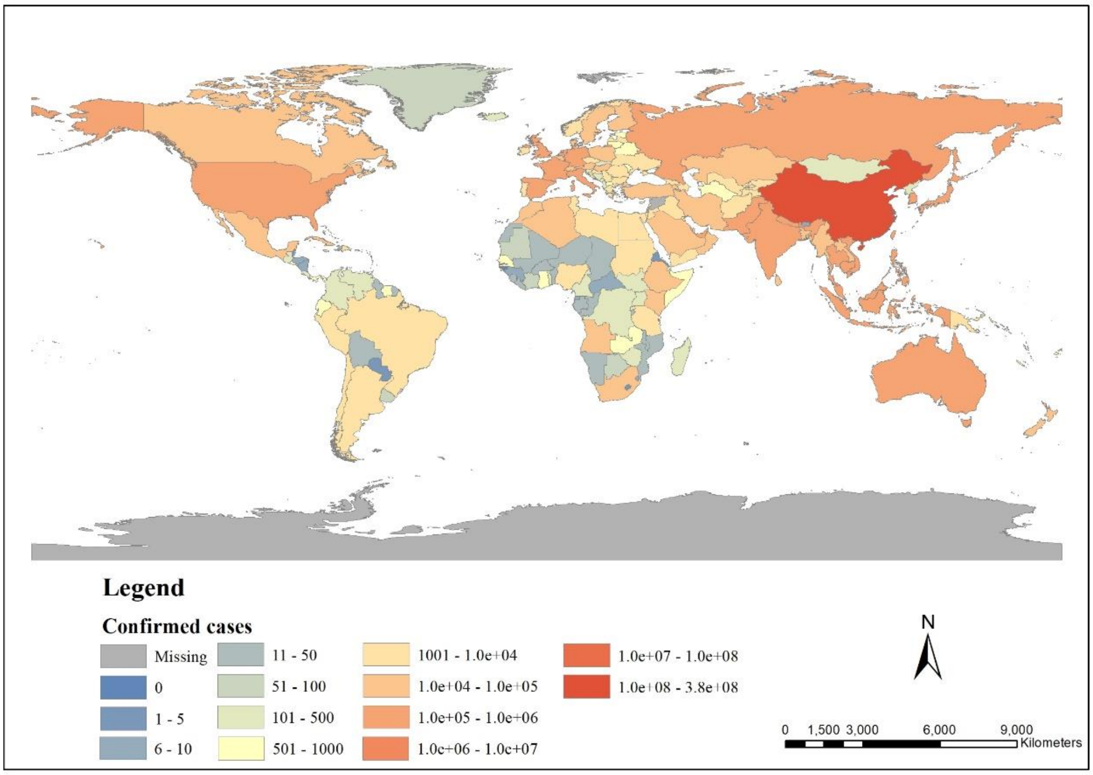

Fig.S1 Cumulative cases at days 150 in scenario 2.

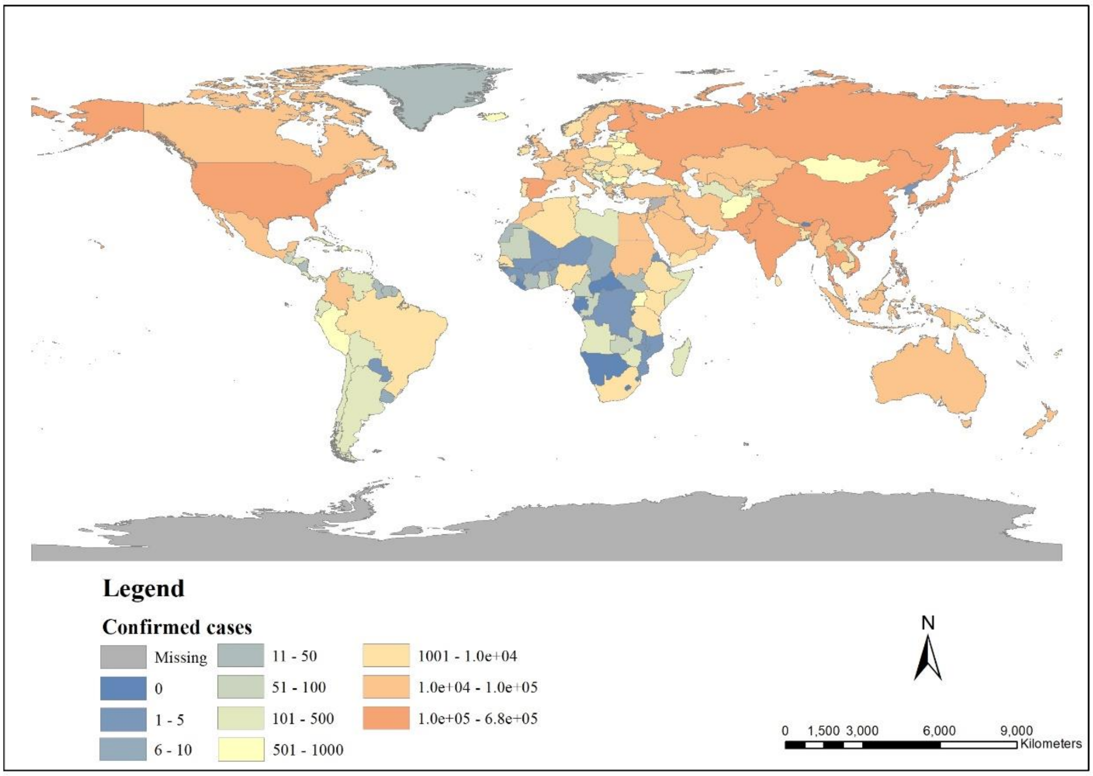

Fig.S2 Cumulative cases at days 150 in scenario 3.

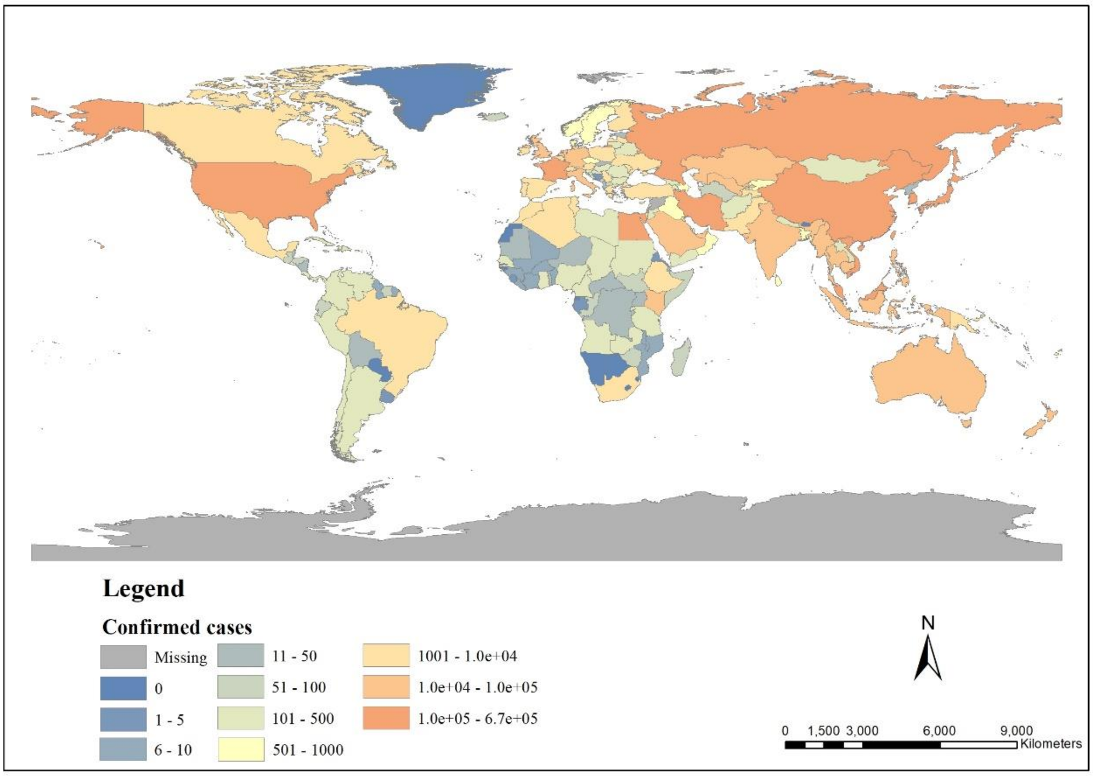

Fig.S3 Cumulative cases at days 150 in scenario 4.

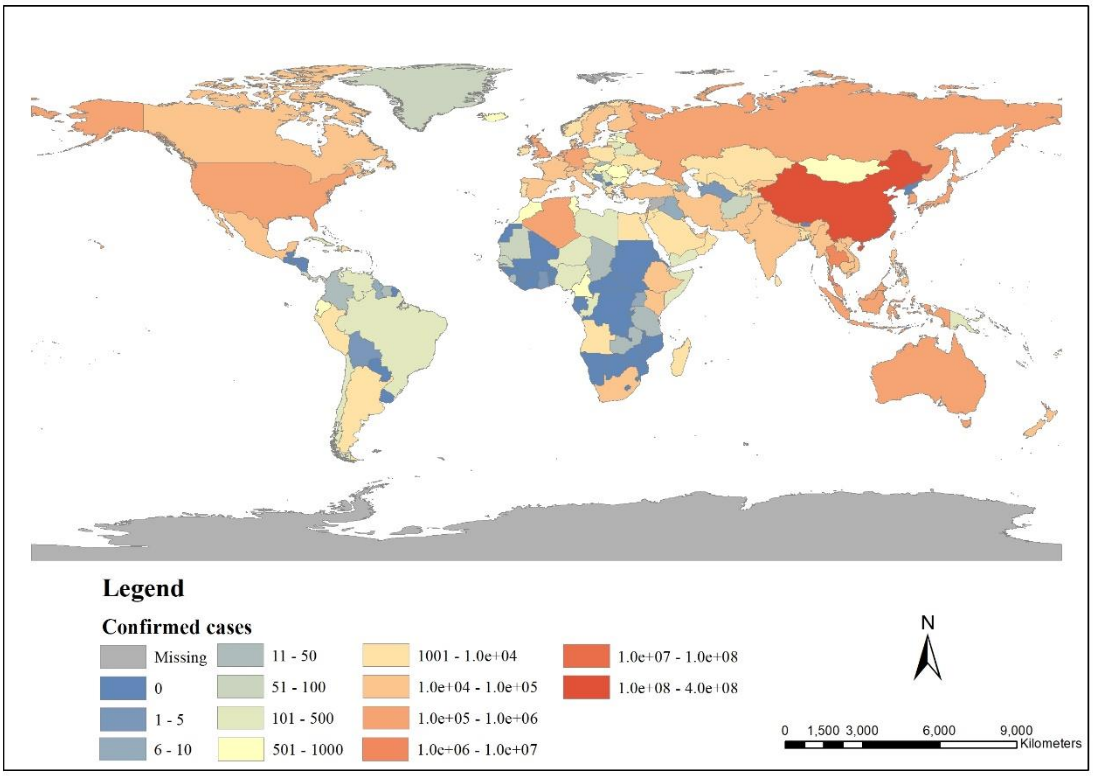

Fig.S4 Cumulative cases at days 150 in scenario 5.

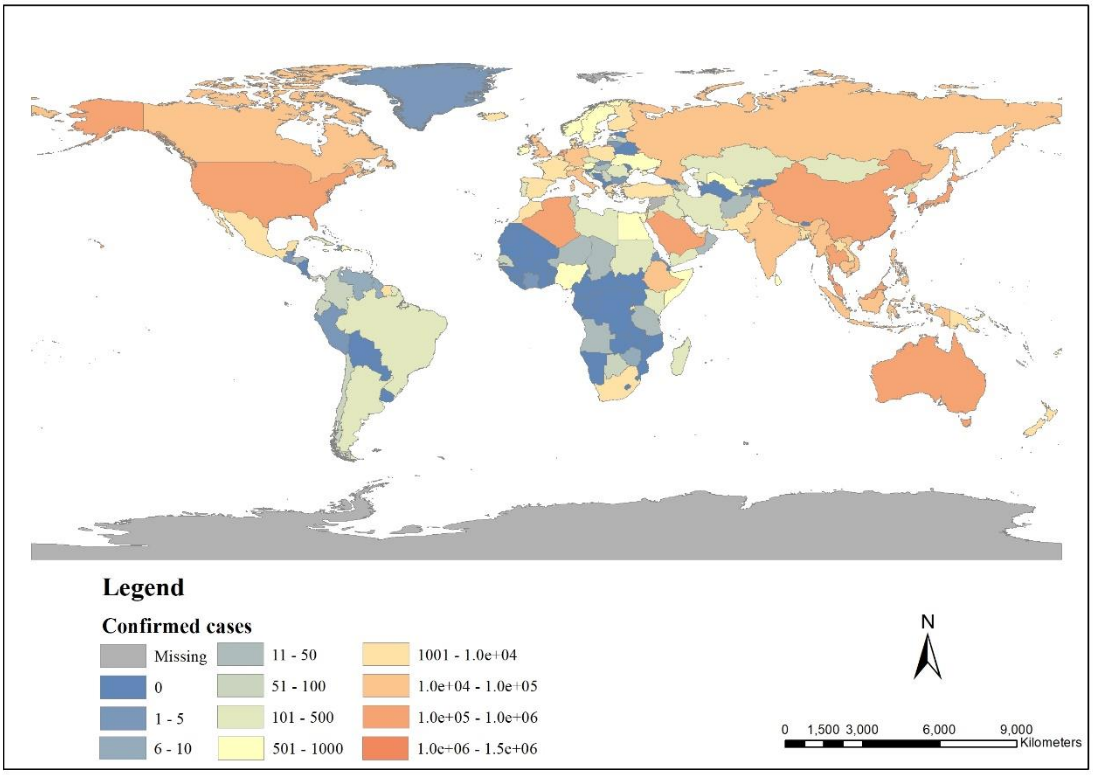

Fig.S5 Cumulative cases at days 150 in scenario 6.

STROBE Statement—checklist of items that should be included in reports of observational studies

	Item No	Recommendation	Page No
Title and abstract	1	(a) Indicate the study's design with a commonly used term in the title or the abstract	1
		(b) Provide in the abstract an informative and balanced summary of what was done and what was found	2
Introduction			
Background/rationale	2	Explain the scientific background and rationale for the investigation being reported	3-4
Objectives	3	State specific objectives, including any prespecified hypotheses	4
Methods			
Study design	4	Present key elements of study design early in the paper	5-7
Setting	5	Describe the setting, locations, and relevant dates, including periods of recruitment, exposure, follow-up, and data collection	5
Participants	6	(a) Cohort study—Give the eligibility criteria, and the sources and methods of selection of participants. Describe methods of follow-up Case-control study—Give the eligibility criteria, and the sources and methods of case ascertainment and control selection. Give the rationale for the choice of cases and controls Cross-sectional study—Give the eligibility criteria, and the sources and methods of selection of participants	NA
		(b) Cohort study—For matched studies, give matching criteria and number of exposed and unexposed Case-control study—For matched studies, give matching criteria and the number of controls per case	NA
Variables	7	Clearly define all outcomes, exposures, predictors, potential confounders, and effect modifiers. Give diagnostic criteria, if applicable	7
Data sources/ measurement	8*	For each variable of interest, give sources of data and details of methods of assessment (measurement). Describe comparability of assessment methods if there is more than one group	6
Bias	9	Describe any efforts to address potential sources of bias	7
Study size	10	Explain how the study size was arrived at	5
Quantitative variables	11	Explain how quantitative variables were handled in the analyses. If applicable, describe which groupings were chosen and why	6-7
Statistical methods	12	(a) Describe all statistical methods, including those used to control for confounding	6
		(b) Describe any methods used to examine subgroups and interactions	NA
		(c) Explain how missing data were addressed	NA
		(d) Cohort study—If applicable, explain how loss to follow-up was addressed Case-control study—If applicable, explain how matching of cases and controls was addressed Cross-sectional study—If applicable, describe analytical methods taking account of sampling strategy	NA
		(e) Describe any sensitivity analyses	NA

Continued on next page

Results			
Participants	13*	(a) Report numbers of individuals at each stage of study—eg numbers potentially eligible, examined for eligibility, confirmed eligible, included in the study, completing follow-up, and analysed	8
		(b) Give reasons for non-participation at each stage	NA
		(c) Consider use of a flow diagram	NA
Descriptive data	14*	(a) Give characteristics of study participants (eg demographic, clinical, social) and information on exposures and potential confounders	NA
		(b) Indicate number of participants with missing data for each variable of interest	NA
		(c) Cohort study—Summarise follow-up time (eg, average and total amount)	NA
Outcome data	15*	Cohort study—Report numbers of outcome events or summary measures over time	NA
		Case-control study—Report numbers in each exposure category, or summary measures of exposure	NA
		Cross-sectional study—Report numbers of outcome events or summary measures	NA
Main results	16	(a) Give unadjusted estimates and, if applicable, confounder-adjusted estimates and their precision (eg, 95% confidence interval). Make clear which confounders were adjusted for and why they were included	NA
		(b) Report category boundaries when continuous variables were categorized	NA
		(c) If relevant, consider translating estimates of relative risk into absolute risk for a meaningful time period	NA
Other analyses	17	Report other analyses done—eg analyses of subgroups and interactions, and sensitivity analyses	NA
Discussion			
Key results	18	Summarise key results with reference to study objectives	9
Limitations	19	Discuss limitations of the study, taking into account sources of potential bias or imprecision. Discuss both direction and magnitude of any potential bias	11-12
Interpretation	20	Give a cautious overall interpretation of results considering objectives, limitations, multiplicity of analyses, results from similar studies, and other relevant evidence	11-12
Generalisability	21	Discuss the generalisability (external validity) of the study results	9-10
Other information			
Funding	22	Give the source of funding and the role of the funders for the present study and, if applicable, for the original study on which the present article is based	12-13