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Impacts of Export Restrictions on the Global Personal Protective Equipment Trade Network During COVID-19

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The COVID-19 pandemic has caused a dramatic surge in demand for personal protective equipment (PPE) worldwide. Many countries have imposed export restrictions on PPE to ensure the sufficient domestic supply. The surging demand and export restrictions cause shortage contagions on the global PPE trade network. Here, an integrated network model is developed, which integrates a metapopulation model and a threshold model, to investigate the shortage contagion patterns. The metapopulation model captures disease contagion across countries. The threshold model captures the shortage contagion on the global PPE trade network. Due to the Pareto distribution in global exports, the shortage contagion pattern is mainly determined by the export restriction policies of the top exporters. Export restrictions exacerbate the shortages of PPE and cause the shortage contagion to transmit even faster than the disease contagion. To some extent, export restrictions can provide benefits for self-sufficient countries, at the sacrifice of immediate economic shocks at not-self-sufficient countries. With export restrictions, a large amount of PPE is hoarded instead of being distributed to where it is most needed, particularly at the early stage. Cooperation between countries plays an essential role in preventing global shortages of PPE regardless of the production level. Except for promoting global cooperation, governments and international organizations should take actions to reduce supply chain barriers and work together to increase global PPE production.

1. Introduction

The COVID-19 pandemic is spreading rapidly around the world. As of April 29, 2021, it has infected more than 150 million people and claimed more than 3 million lives worldwide.[1,2] Many countries have adopted a series of public health measures to contain the epidemic, such as the closure of commercial activities, bans on travel, and export restrictions.[3–5] Personal protective equipment (PPE), such as face and eye protection devices, protective garments, and gloves, is the most heavily affected category of commodities in export restrictions. Over 73 governments have imposed export restrictions on PPE exports.[6,7] Since the COVID-19 pandemic has caused a growing demand for PPE worldwide,[8–10] countries impose export restrictions to prepare for the potential domestic demand.

Recently, several empirical studies have discussed the pros and cons of export restrictions on medical supplies, foods, drugs, etc., in the time of COVID-19. They concluded that export restrictions might cause uncertainty in supply and other negative security consequences, though these restrictions seem logical and justifiable.[5,7,11] Demand surges and export restrictions cause shortage contagion on the trade network. There is rich economic literature using quantitative models to investigate the contagion patterns and their impacts on international trade.[12–16] In physics, a wide range of research proposed different models to analyze the dynamics of contagion propagation on interdependent networks,[17] for example, the

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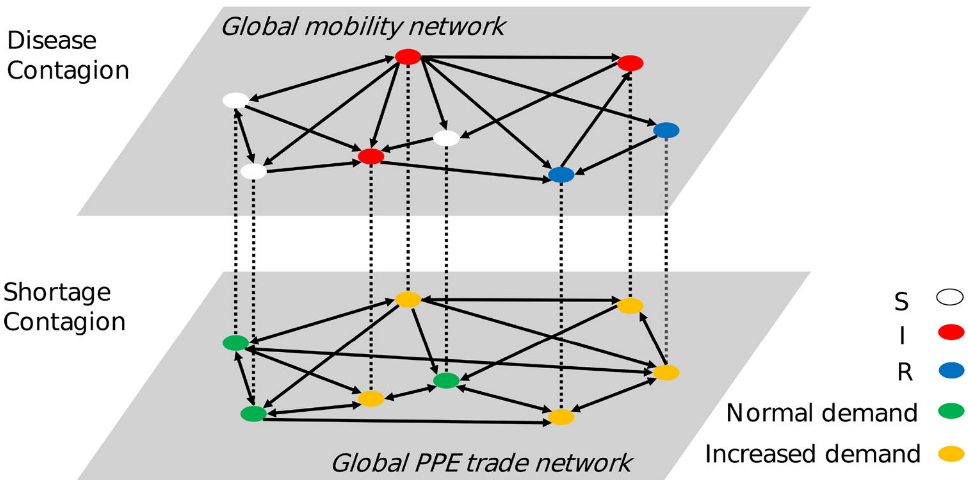

Figure 1. Overview of the integrated network model. The top (disease contagion) and bottom (shortage contagion) layers are the global mobility network where the epidemic spreads, and the global PPE trade network where the shortage contagion transmits, respectively. Nodes represent countries. Edges on the top layer represent the aggregated number of seats on scheduled commercial flights between countries per day. Edges on the bottom layer represent the daily trade value between countries (in US dollars). Countries' domestic demand for PPE will increase since they are infected.

diffusion model[18] and the threshold model.[19,20] However, how the shortage contagion transmits on the global PPE trade network during large-scale epidemic like the ongoing COVID-19 pandemic is under-researched. Most, if not all, existing studies examined the disease contagion and shortage contagion separately, and did not take into consideration the dynamic interplay between them. It is critical to characterize such interplay because the surging demand is caused by the epidemic arrival.

In this paper, we develop a novel integrated network model to examine the impacts of export restrictions on the global PPE trade network during the COVID-19 pandemic. We illustrate the structure of the model in **Figure 1**. The proposed model integrates a susceptible-infected-recovered (SIR) based metapopulation model, which captures the dynamics of disease contagion on the global mobility network (top layer of Figure 1), and a threshold model, which captures the dynamics of shortage contagion on the global PPE trade network (bottom layer of Figure 1). We investigate the shortage propagation patterns of eight sections of PPE commodities for five scenarios on export restrictions. We provide quantitative evidence that export restrictions cause shortage contagion to transmit even faster than that of the disease contagion. Besides, export restrictions delay the occurrence of shortages for self-sufficient countries, but accelerate the occurrence of shortages for not-self-sufficient countries. In addition, export restrictions lead to ineffective and inefficient allocation of PPE worldwide.

2. Results

To capture the interplay between the disease contagion and the demand for PPE, we adapt a threshold model[14,19] by a) representing the increase of domestic demand for PPE as a result of the epidemic arrival, and b) adding an inventory module as the buffering mechanism. We construct the global PPE trade network using data from the United Nations Comtrade Database (UNCD).[21] Here, nodes represent countries and edges represent the annual trade value between countries (in US dollars). We select commodities with the World Customs Organization's Harmonized System codes for COVID-19 medical supplies.[22] All commodities are classified into eight sections.

Following Brockmann and Helbing,[23] the SIR-based metapopulation model is constructed based on the global mobility network, which is defined by the daily air traffic data.[24] Here, nodes represent countries and edges represent the aggregated number of seats on scheduled commercial flights between countries. The population data used for constructing the global mobility network is obtained from the United Nations World Population Prospects national estimates.[25] After excluding the countries that do not appear in these datasets, the proposed model has 195 countries.

The model works on a daily time step. At time t, each country i distributes its imports $imp_i^{(s)}(t)$, production $pro_i^{(s)}(t)$, and inventory $inv_i^{(s)}(t)$ of commodities in section s to meet the domestic demand $dem_{i,dom}^{(s)}(t)$ and foreign demand $dem_{i,for}^{(s)}(t)$. We assume that domestic demand has higher priority than foreign demand. The maximum amount of commodities in section s that country i can distribute at time t is

$$D_{i,max}^{(s)}(t) = imp_i^{(s)}(t) + pro_i^{(s)}(t) + inv_i^{(s)}(t) \quad (1)$$

If the epidemic arrives in country i at time t, the domestic demand for commodities in all sections will increase since then. Denote N_i as the population size of country i, and $S_i(t)$, $I_i(t)$, and $R_i(t) = N_i - S_i(t) - I_i(t)$ as the number of susceptible, infected, and recovered individuals at time t, respectively. Then, following ref. [23], the dynamics of disease contagion is given by

$$\begin{aligned} \partial_t I_i(t) &= \frac{\beta S_i(t) I_i(t) \sigma(\frac{I_i(t)}{\epsilon N_i})}{N_i} - \gamma I_i(t) + \chi N_i \sum_{j \neq i} P_{ji}[\frac{I_j(t)}{N_j} - \frac{I_i(t)}{N_i}] \\ \partial_t S_i(t) &= -\frac{\beta S_i(t) I_i(t) \sigma(\frac{I_i(t)}{\epsilon N_i})}{N_i} + \chi N_i \sum_{j \neq i} P_{ji}[\frac{S_j(t)}{N_j} - \frac{S_i(t)}{N_i}] \end{aligned} \quad (2)$$

Here, β, γ, χ, and ϵ are the infection rate, recovery rate, average mobility rate, and local invasion parameter, respectively. $\sigma(x) = x^\eta/(x^\eta + 1)$ is the sigmoid function with parameter η. Denote F_{ji} as the number of passengers traveling from country i to country j per day, and $F_i = \sum_j F_{ji}$. Then, $P_{ji} = F_{ji}/F_i$ is the fraction of individuals traveling from country i to country j, and $\sum_j P_{ji} = 1$. We obtain F_{ji} by averaging the daily traffic data on the global mobility network.

Assuming that, before the pandemic, the domestic demand for commodities in section s is $\mu_i^{(s)}$ per capita per day for country i, thus, the total domestic demand for commodities in section s for country i before the pandemic is $Dem_i^{(s)} = \mu_i^{(s)} N_i$ per day. We adopt the common assumption that the domestic demand for PPE increases with the number of confirmed cases, and then reaches a plateau. To capture this relationship, we modify the relationship function in[26] and represent $dem_{i,dom}^{(s)}(t)$ as

$$\begin{aligned} dem_{i,dom}^{(s)}(t) &= Dem_i^{(s)}[1 + \theta_{d,i}(t)] \\ &= Dem_i^{(s)} + \theta_{d,i}(t)\mu_i^{(s)} N_i \end{aligned} \tag{3}$$

Here, $\theta_{d,i}(t)$ is the demand increase factor for country i at time t, which is represented as follows.

$$\theta_{d,i}(t) = k_1 \left\{ \frac{2}{1 + e^{-k_2\left[1 - \frac{S_i(t)}{N_i}\right]}} - 1 \right\} \tag{4}$$

where $k_1 > 0$ quantifies the upper limit of $\theta_{d,i}(t)$ and $k_2 > 0$ quantifies the level of "panic buying" effect (i.e., consumers buy unusually large amounts of PPE commodities in anticipation of, or after, the epidemic arrival). Country i's domestic demand (for commodities in section s) fulfilled by i itself can be expressed as

$$dem_{i,dom,a}^{(s)}(t) = \min\{D_{i,max}^{(s)}(t), dem_{i,dom}^{(s)}(t)\} \tag{5}$$

Without export restrictions, the maximum foreign demand for commodities in section s to be fulfilled by country i can be expressed as

$$\begin{aligned} dem_{i,for,max}^{(s)}(t) = \min\{&D_{i,max}^{(s)}(t) - dem_{i,dom,a}^{(s)}(t) \\ &dem_{i,for}^{(s)}(t)\}. \end{aligned} \tag{6}$$

Denote the proportion of commodities in section s being exported from country i to country j as

$$x_{i,j}^{(s)} = \frac{W_{i,j}^{(s)}}{Exp_i^{(s)}} \tag{7}$$

and we assume that $x_{i,j}^{(s)}$ is constant. Here, $W_{i,j}^{(s)}$ is the amount of commodities in section s that country i exports to country j before the pandemic, and $Exp_i^{(s)}$, country i's total exports of commodities in section s is

$$Exp_i^{(s)} = \sum_j W_{i,j}^{(s)} \tag{8}$$

$W_{i,j}^s$ is obtained from the UNCD. Then, we can derive the actual amount of commodities that country i exports to country j at time t as

$$w_{i,j}^{(s)}(t) = x_{i,j}^{(s)} dem_{i,for,max}^{(s)}(t) r_{i,j} \tag{9}$$

where $r_{i,j} \in \{0, 1\}$, and $r_{i,j} = 0$ if country i restricts exports to country j; otherwise $r_{i,j} = 1$. Thus,

$$imp_j^{(s)}(t+1) = \sum_i w_{i,j}^{(s)}(t) \tag{10}$$

and the inventory of commodities in section s that country i holds at the beginning of the next period (i.e., the end of the current period) is

$$inv_i^{(s)}(t+1) = D_{i,max}^{(s)}(t) - dem_{i,dom,a}^{(s)}(t) - \sum_j w_{i,j}^{(s)}(t) \tag{11}$$

A lower inventory level than the initial level will result in an increase in production; thus, the production at the next period is decided as follows.

$$pro_i^{(s)}(t+1) = \begin{cases} Pro_i^{(s)} & inv_i^{(s)}(t) \geq inv_i^{(s)}(0) \\ Pro_i^{(s)}[1 + \theta_{p,i}(t)] & \text{otherwise,} \end{cases} \tag{12}$$

where $\theta_{p,i}(t)$ is the production increase factor for country i at time t. We assume that $\theta_{p,i}(t)$ is non-negative for the following reasons. During the pandemic, PPE production may decline due to the lockdown of cities, infection of workers, etc, but in the meanwhile, governments have provided supports for PPE production and manufacturers worldwide have retooled to produce more PPE to combat the pandemic. Therefore, we assume the production after the pandemic is no less than that before the pandemic.

Assuming that countries cannot anticipate economic shocks, they issue orders to other countries at the end of each time period based on $pro_i^{(s)}(t+1)$, $dem_{i,dom}^{(s)}(t)$, and $dem_{i,for}^{(s)}(t)$. The total amount of commodities in section s that country i orders from other countries is

$$\begin{aligned} imp_{i,o}^{(s)}(t) = \max\{&dem_{i,dom}^{(s)}(t) + dem_{i,for}^{(s)}(t) \\ &- pro_i^{(s)}(t+1), 0\} \end{aligned} \tag{13}$$

Denote the proportion of commodities in section s being imported from country j to country i as

$$y_{j,i}^{(s)} = \frac{W_{j,i}^{(s)}}{Imp_i^{(s)}} \tag{14}$$

and we assume that $y_{j,i}^{(s)}$ is constant. Here, the total amount of commodities in section s that country i imports from other countries is

$$Imp_i^{(s)} = \sum_j W_{j,i}^{(s)} \tag{15}$$

Table 1. Description of five export restriction scenarios.

Scenario	Description
S_{none}	No country restricts exports
S_1	The largest exporter restricts exports
$S_{5\%}$	The top 5% of exporters restrict exports
S_{lower}	The lower half (50%) of exporters restrict exports
S_{all}	All countries restrict exports

Therefore, the amount of commodities that country i orders from country j is $\gamma_{j,i}^{(s)} imp_{i,o}^{(s)}(t)$, and

$$dem_{j,for}^{(s)}(t+1) = \sum_i \gamma_{j,i}^{(s)} imp_{i,o}^{(s)}(t) \tag{16}$$

We assume that, before the pandemic,

$$Imp_i^{(s)} + Pro_i^{(s)} = Exp_i^{(s)} + Dem_i^{(s)} \tag{17}$$

We initialize the model by setting $pro_i^{(s)}(0) = Pro_i^{(s)}$, $imp_i^{(s)}(0) = Imp_i^{(s)}$, and $dem_{i,for}^{(s)}(0) = Exp_i^{(s)}$. We assume that

$$inv_i^{(s)}(0) = \phi_i^{(s)} Imp_i^{(s)} \tag{18}$$

This assumption means that country i can still meet the domestic demand and foreign demand without imports for $\phi_i^{(s)}$ days before the pandemic.

In the simulations, we consider the simplest pandemic scenario, where no travel bans or other public health measures are considered. For simplicity, we assume $k_1 = 2$, $k_2 = 100$, and $\mu_i^s = 10$ for all countries and all commodities. Following epidemiology literature, the mean infectious period is set as 14 days[27,28] leading to the recovery rate $\gamma = 0.071$. The basic reproduction number R_0 is set as 2.6,[29] leading to the infection rate $\beta = R_0\gamma = 0.186$. From the OAG data, the average mobility rate χ is estimated to be 0.0003 per day. We adopt the choices for ϵ and η in,[23] $\epsilon = 10^{-8}$ and $\eta = 8$. We set that China is initially infected with 100 infected cases at $t = 0$, which corresponds to December 31, 2019, the date when the World Health Organization was informed of unknown pneumonia cases detected in Wuhan, China.[30] We run the simulation for 1 year.

Now, we model five different export restriction scenarios among countries, and present their impacts on the trade network for each commodity section. The description of each scenario is given in **Table 1**. We consider two typical situations: a) the initially infected country is not the largest exporter (situation 1), and b) the initially infected country is also the largest exporter (situation 2). These two situations may lead to different shortage contagion patterns. If the largest exporter is initially infected, the reduced exports resulting from the surging domestic demand may trigger the earlier occurrence of PPE shortages globally. For the rest of this paper, we take commodities in section 1 (COVID-19 test kits and apparatus used in diagnostic testing) and section 2 (protective garments and the like) as examples in situation 1 and situation 2, respectively. Results for other sections are consistent with the results for these two sections, and thus are presented in the Supporting Information.

First, we give an overview of the trade network for situation 1 where the initially infected country is not the largest exporter and situation 2 where the initially infected country is the largest exporter. In **Figure 2**, we present the daily exports and the cumulative percentage of daily global exports in both situations for the top five exporters and other countries. We observe a Pareto distribution in global exports in Figure 2, where the top five exporters share about 70% and 52% of global exports in situation 1 and situation 2, respectively.

In **Figure 3**, we plot the number of infected countries and the number of countries facing shortages at the end of each month in different scenarios. Country i will face shortages of commodities in section s at time t if its domestic demand cannot be met, that is, $D_{i,max}^{(s)}(t) < dem_{i,dom}^{(s)}(t)$. As illustrated in Figure 3, if the production stays unchanged for all countries (i.e., $\theta_{p,i}(t) = 0$), nearly all countries will face shortages at the end of 2020 in all scenarios. Generally, export restrictions exacerbate global supply shortages. We can observe that, compared with scenario S_{all} where all countries restrict exports, the number of countries facing shortages decreases greatly in the early periods (from January to June) in scenario S_{none} where no country restricts exports. Besides, the number of countries facing shortages in scenario $S_{5\%}$ (only the top 5% of exporters restrict exports) is nearly the same as scenario S_{all}, which can be explained by the Pareto distribution in global exports. Counterintuitively, the number of countries facing shortages in scenario S_{lower} (the lower half of the exporters restrict exports) is slightly fewer than that in scenario S_{none}. The reason is as follows. The total percentages of world exports that the lower half of the exporters share are only 0.005% and 0.053% for situation 1 and situation 2, respectively. They can hardly help other countries manage supply shortages. Besides, exports lower the inventory level of these countries, thus, in scenario S_{lower}, restricting exports can delay the shortages when disease arrives at these countries. These findings show that, on the one hand, agreements are urgently needed to ensure open trade between countries during the pandemic; on the other hand, such agreements should also allow countries that contribute little to global exports to impose some export restrictions in order to ensure a sufficient inventory for the upcoming pandemic.

In situation 1 where the initially infected country is not the largest exporter, we find that scenario S_1 leads to many more countries facing shortages as compared to scenario S_{none}, because Germany (the largest exporter) is not the initially infected country but stops supplying commodities to others. This gap shrinks in situation 2 where the initially infected country is the largest exporter, because the largest exporter (China) is the initially infected country as well. So even without export restrictions (such as scenario S_{none}), China has to meet the domestic demand by lowering the exports significantly. When the epidemic progressed to a global pandemic, even the largest exporter is not the initially infected country, the domestic demand still surged and eventually led to the export restriction, similar to the case when the largest exporter is also the initially infected country. Of course, the global shortage of situation 1 would come later because of the delayed export restriction of the largest exporter. However, in the long run, the PPE shortage would take place in most countries, if without proper cooperative allocation and increased production of PPE commodities. Moreover, we find that for both situations, there are more countries facing shortages

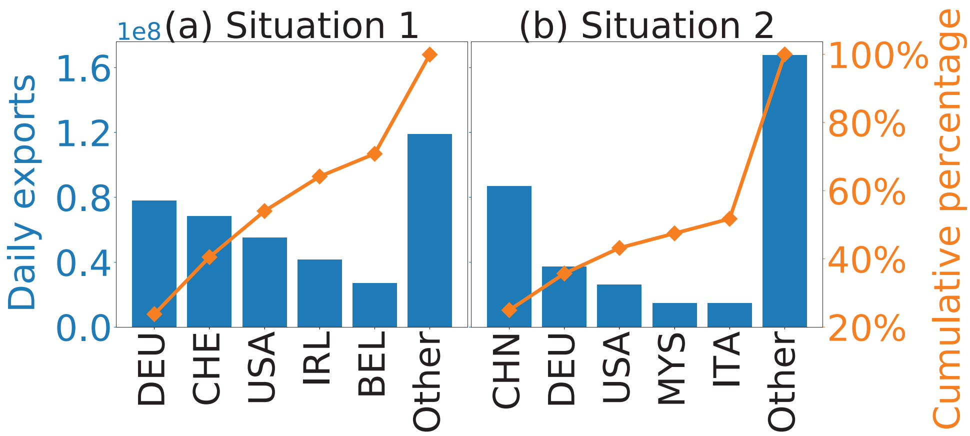

Figure 2. The Pareto distribution in global exports. The daily exports (left) and the cumulative percentage of daily global exports (right) in a) situation 1 where the initially infected country is not the largest exporter and b) situation 2 where the initially infected country is the largest exporter for the top five exporters and other countries. DEU, Germany; CHE, Switzerland; USA, the United States of America; IRL, Ireland; BEL, Belgium; CHN, China; MYS, Malaysia; ITA, Italy.

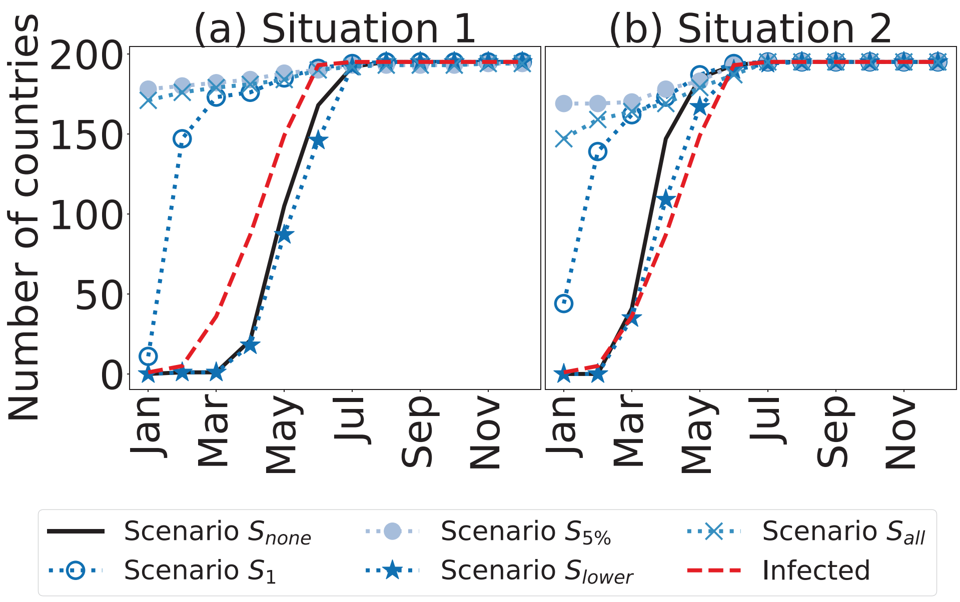

Figure 3. The number of infected countries and the number of countries facing shortages of commodities in a) situation 1 where the initially infected country is not the largest exporter and b) situation 2 where the initially infected country is the largest exporter at the end of each month. The description of scenarios is given in Table 1. Parameters are set as follows: $\theta_{p,i}(t) = 0$, $\phi_i^{(s)} = 10$.

than infected countries in scenarios S_1, $S_{5\%}$, and S_{all}. This finding indicates that pandemic-resulted export restrictions can make shortage contagion transmit even faster than disease contagion.

Next, we compare the epidemic arrival time T_a and the first shortage time T_s for each country in different scenarios. We present the results for scenarios S_{none} and S_{all} in **Figure 4**. Note that countries not facing shortages within the simulation periods are not represented in Figure 4. The epidemic arrival time T_a is defined as the date of the first infected case after the initial outbreak. The first shortage time T_s is defined as the date when a country first faces PPE shortages. Nodes represent countries. The size of a node represents the export value of commodities in the corresponding situation. The color of a node indicates if it is a self-sufficient country for the situation. Country i is self-sufficient for commodities in section s if its production is no less than its domestic demand before the pandemic, that is, $Pro_i^{(s)} \geq Dem_i^{(s)}$. Accordingly, non-self-sufficient countries in section s are those with higher domestic demand than the production before the pandemic, that is, $Pro_i^{(s)} < Dem_i^{(s)}$. The blue line corresponds to $T_a = T_s$. If a country faces shortages before infected, it locates below the blue line. Otherwise, it locates above the blue line.

As illustrated in Figure 4a,b, we can observe in situation 1 where the initially infected country is not the largest exporter that, compared with scenario S_{all}, more not-self-sufficient

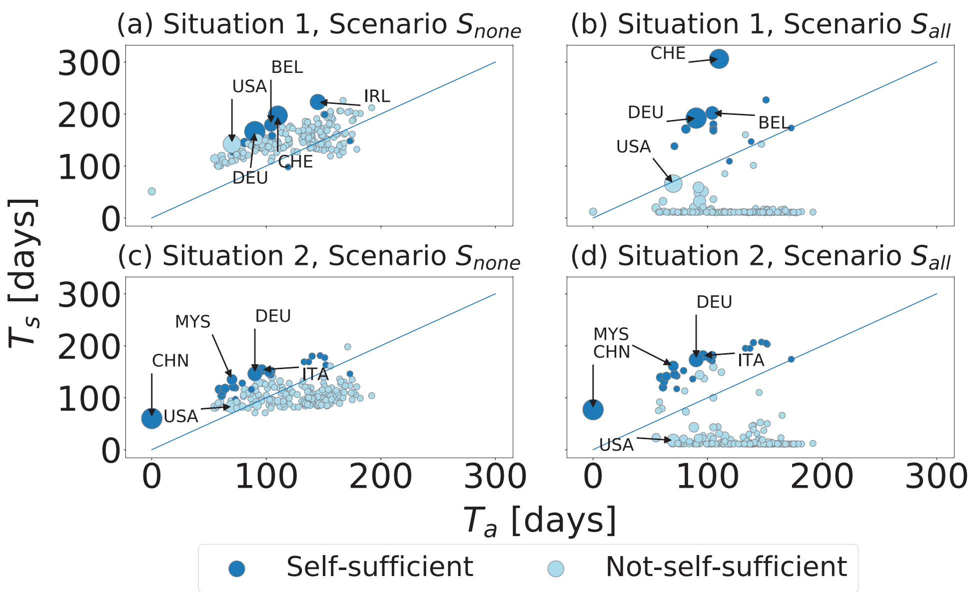

Figure 4. Comparison of the epidemic arrival time T_a and the first shortage time T_s for each country in a) situation 1, scenario S_{none}, b) situation 1, scenario S_{all}, c) situation 2, scenario S_{none}, and d) situation 2, scenario S_{all}. In situation 1, the initially infected country is not the largest exporter. In situation 2, the initially infected country is the largest exporter. Nodes represent countries. The size of a node represents the export value of commodities in the corresponding situation. The color of a node indicates if it is a self-sufficient country for the situation. The blue line corresponds to $T_a = T_s$. Parameters are set as follows: $\theta_{p,i}(t) = 0$, $\phi_i^{(s)} = 10$. For clarity, only the top five exporters are presented with the three-letter country code. DEU, Germany; CHE, Switzerland; USA, the United States of America; IRL, Ireland; BEL, Belgium; CHN, China; MYS, Malaysia; ITA, Italy.

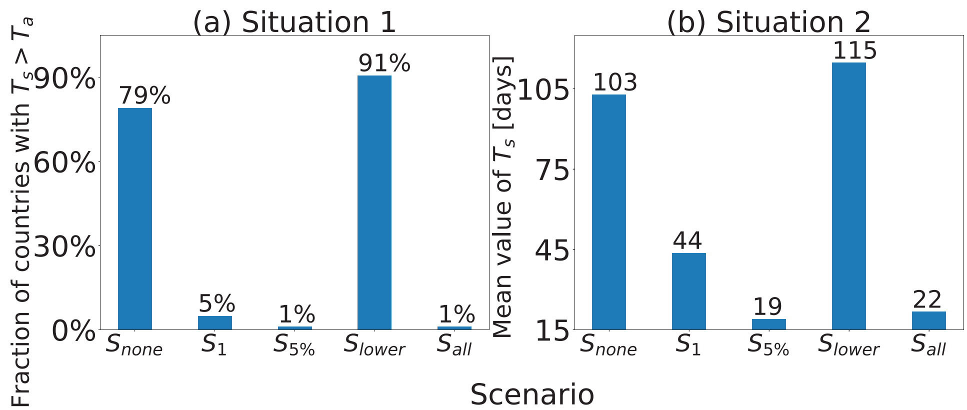

Figure 5. a) Fraction of not-self-sufficient countries with $T_s > T_a$ in situation 1 where the initially infected country is not the largest exporter and b) the mean value of T_s in situation 2 where the initially infected country is the largest exporter for not-self-sufficient countries under all export restriction scenarios. Parameters are set as follows: $\theta_{p,i}(t) = 0$, $\phi_i^{(s)} = 10$.

countries locate above the blue line in scenario S_{none}. The fraction of not-self-sufficient countries above the blue line increases to 79% in scenario S_{none} from 1% in scenario S_{all}. In situation 2 where the initially infected country is the largest exporter, we also observe that export restrictions lead to a much earlier occurrence of shortages for not-self-sufficient countries in Figure 4c,d. The mean value of T_s decreases to 22 days in scenario S_{all} from 103 days in scenario S_{none}. In **Figure 5**, we also present the fraction of countries with $T_s > T_a$ in situation 1 and the mean value of T_s in situation 2 for not-self-sufficient countries in all scenarios. The differences in scenarios are consistent with that in Figure 3.

To sum up, when all countries restrict exports, almost all not-self-sufficient countries locate below the blue line, which can be observed in both situations, indicating that they encounter PPE shortages even before the epidemic arrival. Besides, both self-sufficient countries and not-self-sufficient countries locate farther away from each other in scenario S_{all} than in scenario S_{none}. Similar results to scenario S_{all} are found in scenario S_1 and scenario $S_{5\%}$. These results indicate that export restrictions delay the occurrence of shortages for self-sufficient countries, but accelerate the occurrence of shortages for not-self-sufficient countries.

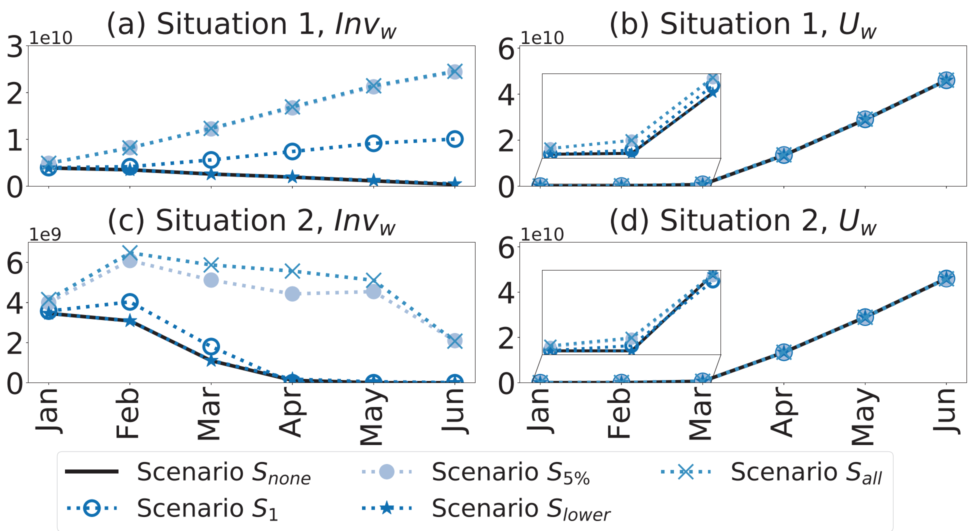

Figure 6. Average world total inventory $Inv_w^{(s)}(t)$ (a,c) and world total unmet domestic demand $U_w^{(s)}(t)$ (b,d) in situation 1 where the initially infected country is not the largest exporter (a,b) and situation 2 where the initially infected country is the largest exporter (c,d) from January to June in all scenarios. Parameters are set as follows: $\theta_{p,i}(t) = 0$, $\phi_i^{(s)} = 10$

We further investigate the numbers of high-income (HICs) and low- and middle-income countries (LMICs) among all self-sufficient and non-self-sufficient countries. The income classification is based on the gross national income (GNI) per capita (calculated using the World Bank Atlas method in US dollars) [31]. According to the latest definition from the World Bank, high-income countries are those with a GNI per capita of \$12 696 or more. In total, there are 66 HICs and 129 LMICs in our model. We find that in all sections, LMICs account for 70% of non-self-sufficient countries. Over 90% of LMICs are non-self-sufficient countries in all sections. Compared to LMICs, a lower proportion (72%, 81% in different sections) of HICs are non-self-sufficient countries. Please refer to Table S1, Supporting Information, for details. In general, export restrictions lead to PPE shortages in most countries, particularly LMICs.'

These results also present the double-edged nature of the PPE trade relationship between countries. On the one hand, such relationships allow countries (especially not-self-sufficient countries) to address the pandemic with the help of trading partners. On the other hand, shortage contagion can also transmit through these relationships. As illustrated in Figure 4c, 156 countries suffer from shortages while only 87 countries are infected at $t = 120$. The surge in domestic demand in infected countries leads to a reduction in their exports. The shortage contagion then spills over to non-infected countries because the domestic demand cannot be met. However, countries can mitigate such spillover effects by increasing production while facing shortages. We present the averaged fraction of countries facing shortages for each month with different production increase factor $\theta_{p,i}(t)$ in scenarios S_{none} and S_{all} in the Supporting Information. We observe in both situations that, the number of countries facing shortages decreases greatly as $\theta_{p,i}(t)$ grows, especially at the early stage (from January to June). Besides, even as $\theta_{p,i}(t)$ grows, there are still more countries facing shortages in scenario S_{all} than that in scenario S_{none} for the same $\theta_{p,i}(t)$. These results indicate that cooperation between countries (no export restrictions) always plays an essential role in preventing global shortages of PPE regardless of the production level, but at the same time, a higher production level leads to less dependence on imports, which greatly helps countries cope with PPE shortages. Therefore, except for promoting global cooperation, governments and international organizations should take actions to reduce supply chain barriers and work together to increase global PPE production.

Then, we compare the world total inventory $Inv_w^{(s)}(t)$ and the world total unmet domestic demand $U_w^{(s)}(t)$ for both situations at the end of time t. We define $Inv_w^{(s)}(t) = \sum_i inv_i^{(s)}(t+1)$ and $U_w^{(s)}(t) = \sum_i dem_{i,dom}^{(s)}(t) - dem_{i,dom,a}^{(s)}(t)$. We present the average values of $Inv_w^{(s)}(t)$ and $U_w^{(s)}(t)$ from January to June in **Figure 6**. If $Inv_w^{(s)}(t) > 0$, the world total inventory level $Inv_w^{(s)}(t)$ and the world total unmet domestic demand $U_w^{(s)}(t)$ in scenarios S_{none}, S_1, and S_{lower} are all lower than that in scenarios $S_{5\%}$ and S_{all}. Compared with scenario S_{all}, $U_w^{(s)}(t)$ in scenario S_{none} is reduced by 100%, 94%, and 20% for January, February, and March in situation 1, respectively. In situation 2, $U_w^{(s)}(t)$ is reduced by 100%, 100%, and 0.4% for January, February, and March, respectively. These results show that, with export restrictions, a large amount of PPE is hoarded instead of being distributed to where it is most needed, particularly at the early stage. We can also find that, although there are more countries facing shortages in scenario $S_{5\%}$ than that in scenario S_{all} (Figure 3), $Inv_w^{(s)}(t)$ and $U_w^{(s)}(t)$ in scenario $S_{5\%}$ are almost the same as or even slightly lower than that in scenario S_{all}. From this perspective, we can conclude that the more top exporters restrict exports, the less effective the global PPE supply chain is. These findings further indicate that export restrictions are not an appropriate solution to address the pandemic. A fully functional PPE supply chain system could leave countries more time to adapt their production and identify alternative supply sources.

We also investigate the benefits of cooperation between countries on global PPE allocation. We assume that countries without export restrictions will maintain sufficient PPE inventory for domestic use, and export the extra commodities to other

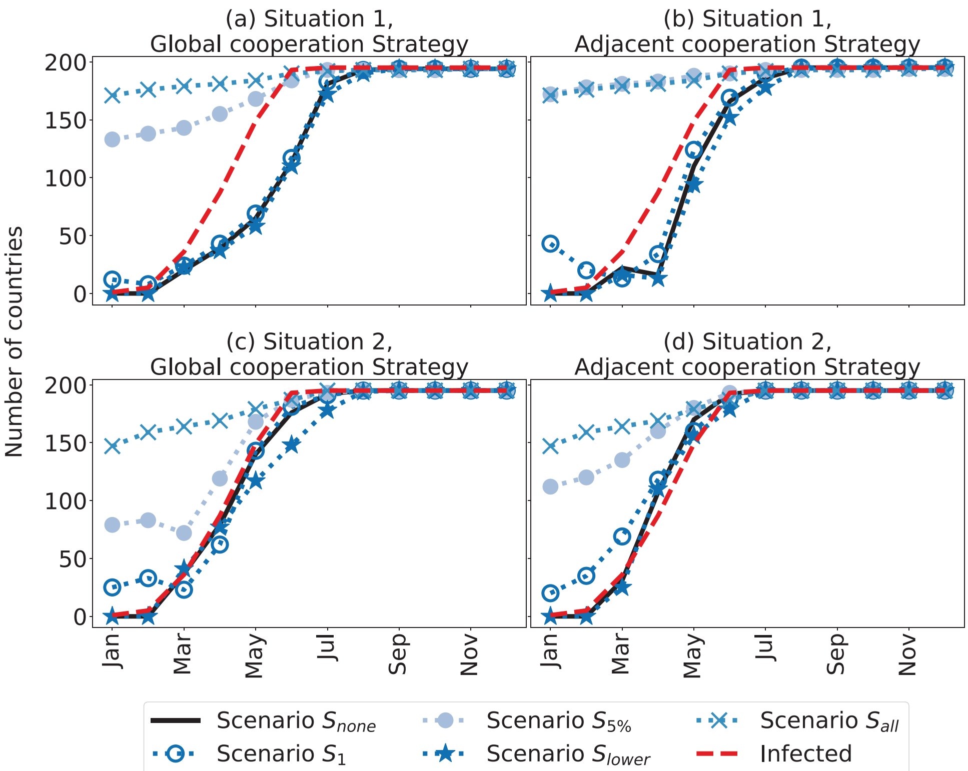

Figure 7. The number of infected countries and the number of countries facing shortages a) in situation 1 under the global cooperation strategy, b) in situation 1 under the adjacent cooperation strategy, c) in situation 2 under the global cooperation strategy, and d) in situation 2 under the adjacent cooperation strategy for different export restriction scenarios at the end of each month. The description of each export restriction scenario is given in Table 1. In situation 1, the initially infected country is not the largest exporter. In situation 2, the initially infected country is the largest exporter. Parameters are set as follows: $\theta_{p,i}(t) = 0$, $\phi_i^{(s)} = 10$.

countries with PPE shortages. Two export cooperation strategies are considered: extra commodities are equally distributed to all countries facing shortages (the global cooperation strategy), and extra commodities are equally distributed to adjacent countries facing shortages (the adjacent cooperation strategy). The adjacency between two countries is determined by the existence of direct flights between them. Compared to the results in Figure 3, both expert cooperation strategies result in fewer countries facing shortages in all scenarios (**Figure 7**). These results indicate that even some countries impose export restrictions on PPE, cooperation between the other countries can substantially delay the occurrence of shortages. Comparing the two cooperation strategies, the global cooperation strategy yields better outcome, indicating that the worldwide cooperation is needed.

3. Conclusion

In summary, we investigated how the shortage contagion, induced by demand surges and export restrictions, transmits on the global PPE trade network during the COVID-19 pandemic. We simulated the impacts of five export restriction scenarios based on an integrated network model, which integrates the real-world PPE trade data and global mobility data. We find evidence that the shortage contagion pattern is mainly determined by the export restriction policies of the top exporters. Export restrictions can cause shortage contagion to transmit even faster than the disease contagion, with only the top 5% of exporters imposing export restrictions. To some extent, export restrictions can provide benefits for self-sufficient countries, at the sacrifice of immediate economic shocks at not-self-sufficient countries. Cooperation between countries can help allocate PPE more effectively and efficiently around the world. To better respond to the next wave of COVID-19 and other emerging infectious diseases, countries should keep global PPE trade open and reduce reliance on only a small number of PPE exporters.

Supporting Information

Supporting Information is available from the Wiley Online Library or from the author.

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Conflict of Interest

The authors declare no conflict of interest.

Data Availability Statement

The data is from open source repositories. Processed data is available upon request (qingpeng.zhang@cityu.edu.hk).

Author Contributions

Q.Z., H.E.S., and D.D.Z. supervised the project. Y.Y. and Q.Z. proposed and implemented the model. Y.Y., Q.Z., Z.C., F.Y.C., and H.Y. analyzed the results. All authors contributed to the writing.

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coronavirus disease 2019, export restrictions, network, personal protective equipment, severe acute respiratory syndrome coronavirus 2

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