Global supply-chain effects of COVID-19 control measures

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Global economic impacts of COVID-19 lockdowns

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Countries around the world have sought to stop the spread of the 2019 novel coronavirus (COVID-19) by severely restricting travel and in-person commercial activities. While it is too early to assess the cost of the current pandemics, we analyse the economic impacts of a set of "lockdowns" scenarios, using the latest developed modelling framework of global supply chains. We find that economic losses related to initial COVID-19 lockdowns are largely dependent on the number of countries imposing restrictions, and that losses are more sensitive to the duration of a lockdown than its strictness—suggesting that more severe restrictions can reduce economic damages if they successfully shorten the duration of a lockdown. However, a longer containment that can eradicate the disease imposes lower economic damages than a series of shorter ones. Our results also reveal some important vulnerabilities in global supply chains: Even countries that are not directly affected by COVID-19 can experience large losses (e.g., >20% of their GDP)—with such cascading impacts often occurring in low- and middle-income countries. Open and highly-specialized economies suffer particularly large losses (e.g., energy-exporting Central Asian countries or tourism-focused Caribbean countries). Supply bottlenecks and declines in consumer demand lead to especially large losses in globalized sectors such as electronics (production decreases of 13-53% across our scenarios) and automobiles (2-49%). Our findings suggest that earlier, stricter, and thus shorter lockdowns are likely to minimize overall economic damages, that a "go-slow" approach to lifting restrictions may reduce overall damages if it avoids further lockdowns, and that global supply chains will magnify economic losses in some countries and industry sectors regardless of direct effects of the coronavirus. Pandemics control is a public good but is dependent on the weakest link in the global division of production. Economic impacts can be only minimized if collective efforts are made to strengthen the least effective providers.

The disease caused by 2019 novel coronavirus (COVID-19) emerged in China in late December, but quickly spread to other major countries[1] in Asia, Europe and North America and was declared a pandemic by the World Health Organization (WHO) on March 11[2]. There are now confirmed COVID-19 cases in nearly every country in the world, and the WHO has urged affected countries to slow the spread of the virus by imposing containment and suppression measures[3,4] ranging from strict controls on travel, social gatherings, and commercial activities aimed at "flattening the curve" (i.e. decreasing the rate of new infections to avoid overwhelming health care systems) to less strict measures designed to shield immunologically-compromised individuals, treat victims, and achieving "herd immunity" (i.e. a sufficiently large number of recovered and thus immune individuals to prevent effective spread of the virus)[5]. Differences in the strictness of such policies and the rapidity with which jurisdictions have imposed and relaxed the policies reflect divergent (and perhaps hasty) assessments of both the public health risk of COVID-19 and the social and economic impacts of the different policies[6,7]. Here, using a newly-developed economic disaster model[8-10], we quantitatively assess the economic impacts of different containment strategies across countries and industry sectors in order to both inform ongoing efforts to contain COVID-19 and to reveal more generally how pandemic-related economic losses will be distributed along global supply chains.

Details of our analytic approach are provided in the *Methods* section. In summary, we model the short-term economic shocks of different COVID-19 response scenarios as sector-specific transportation and labour supply constraints. The model operates at weekly time-steps, using the latest available global input-output data[11] and taking into account interactions throughout complex global supply chains and the contexts of scarcity and imbalance that prevail in most markets[10, 12]. It should be noted that our model is distinct from computable general equilibrium (CGE) models in that it is specifically designed to assess economic impacts in response to disasters that unfold over weeks or months, before production structures and trade networks have time to adjust to new production patterns. Moreover, the goal of this study is not to predict the true cost of the COVID-19 pandemic, but to identify the most important factors (e.g., the strictness, duration, and recurrence of lockdowns) and test the sensitivity of economic impacts to those factors as those impacts ripple through global supply chains, supporting by several sets of scenarios for containment measures. Thus, in addition to showing how overall damages might change under different policy scenarios, the incidence of damages across sectors and countries may inform the allocation of international aid and economic stimulus.

We model four different sets of pandemic scenarios, three of which represent different spread extents and containment responses to the COVID-19 pandemic (shown in Fig. 1 & 5 and Fig. S2), and the last of which assesses both the damages of sustaining some restrictions over a longer period as well as the losses if lockdowns are imposed again next autumn or winter. Spatial spread refers to the global extent of the pandemic: the number of countries affected. Duration refers to the number of months lockdown measures are in place. Strictness is measured by the percentage by which labour availability and transportation capacity[13] are reduced relative to pre-pandemic levels. Given that the impacts of lockdown measures on labour availability depend on the characteristics of production, we develop specific impact-to-labour 'multipliers' for each sector based on three factors: the level exposure to the virus (i.e., the degree and proximity of in-person interactions), essential or lifeline sectors (e.g., electricity), and the option of performing work from home (e.g., education). Therefore, sector-specific constraints on labour availability are determined by both the strictness of lockdown measures represented in the scenario (e.g., 80% strictness will reduce overall transportation capacity by 80%) and the sector-specific multipliers (e.g., 0.5 for wheat production as the level of exposure is low and 0.1 for electricity and gas supply as essential activities; see *Methods* for further detail). Each of the 39 scenarios is a different combination of spatial spread, duration, and strictness, with results presented in terms of economic impacts measured in absolute terms of loss in value added (e.g., billions of US dollars) or relative terms (as a percentage of pre-pandemic value added).

Results

Figure 1 summarizes the results of several representative pandemic scenarios. Panels in the first column (Figs. 1a, 1d, 1g, 1j) show the economic impacts if COVID-19 had been successfully contained in China only. Panels in the second column (Figs. 1b, 1e, 1h, 1k) show the economic impacts if COVID-19 had spread from China to Europe and the U.S., which had implemented lockdowns, but no further. And panels in the last column (Figs. 1c, 1f, 1i, 1l) show the economic impacts when the virus further spreads globally and all remaining countries place containment measures. Although some of these results are outdated given the reality of the disease's global spread, it may nonetheless be useful to examine the differences in impacts as a function of spatial spread (see *Supplementary Information* for further details). For each of the different spatial spreads (columns in Fig. 1), Figure 1 also shows results of 3 different lockdown strictness-duration combinations: from 80% restriction for 2 months (Figs. 1a-1c) to 60% restriction for 6 months (Figs. 1g-1i). Note that China's lockdown is consistently modelled as an 80% restriction for the 2 months of January and February[14] in the scenarios of greater spatial spread, with restrictions in Europe and the U.S. beginning in March, and restrictions in the remaining countries (in the global scenario) beginning in April (see *Methods* and Supplementary Fig. S2).

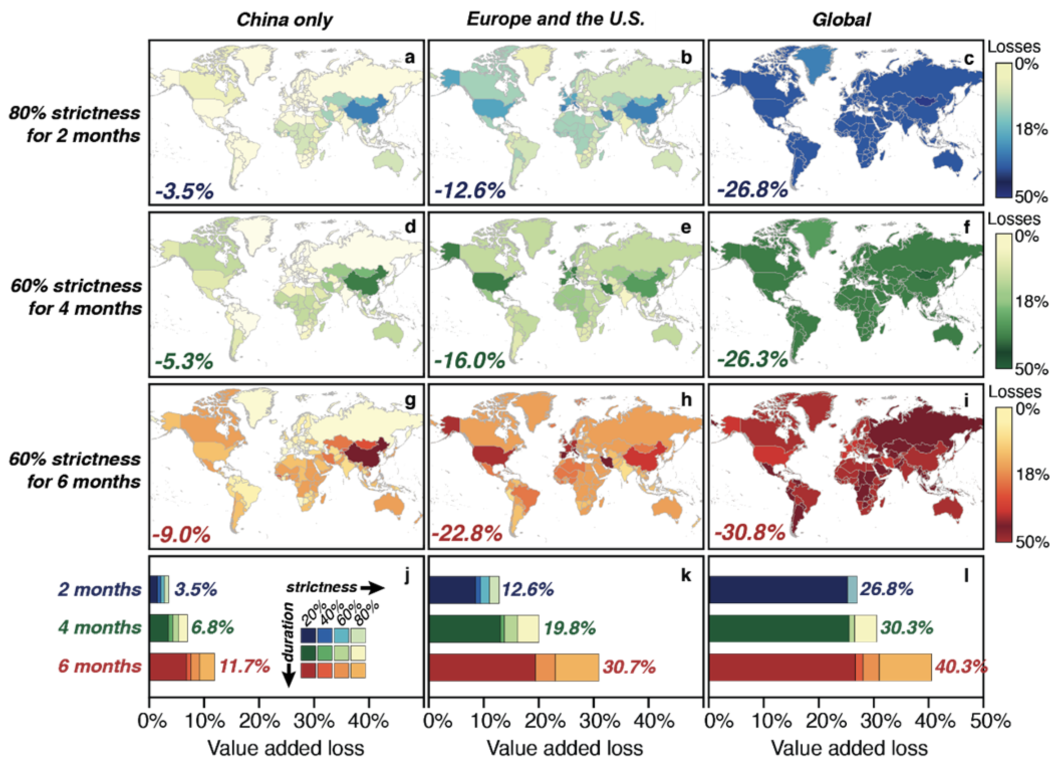

Figure 1 | Economic impacts (value-added loss) of COVID-19 under different lockdown scenarios. Maps show results from 9 scenario of the 36 modelled scenarios, with different combinations of spatial spread (columns of panels), lockdown duration and strictness (rows of panels; see *Methods*, scenario set table). Strictness represents the level of reductions in transportation capacity and labour availability relative to pre-pandemic levels. Percentages in the corner of each map indicate the global value-added losses for each scenario, with shading denoting the regional distributions of these losses. The bar charts **(j-l)** summarize all 36 scenarios, showing the sensitivity of global value-added losses to duration (different stacks) and strictness (shading of stacked bars).

The first insight from the model is that the global cost of the pandemic depends foremost on the number of affected countries, and then on the required duration of lockdown policies; in contrast, the strictness of these policies is comparatively less important. The spatial extent of the pandemic is the most important driver of the global cost. If only China had been affected, our results suggest that the global economic impacts (measured by value-added) would have been 3.5% of global GDP (Fig.1a). With the spread to highly developed western countries and containment measures placed in Europe and the U.S., we find the global economic impacts increase almost four-fold to 12.6% (Fig.1b). Finally, the modelled impacts of global lockdowns in response to COVID-19 are greater still: 26.8% of global GDP (Fig.1c). The magnitude of lockdown duration is illustrated by Figures 1f and 1i, which both show the effects of global spread and relatively strict (60%) lockdowns for 4 and 6 months, respectively. In this case, global value-added losses increase slightly more than 4% (from 26.3% to 30.8%; Figs. 1f and 1i).

Figures 1j, 1k, and 1l further emphasize the rapid increase in global losses with the duration of lockdowns, especially under stricter policies. For example, in the strictest lockdown scenarios (i.e., 80%) with global spread, the global economic impacts rise from \$20.0 trillion under a 2-month duration (blue bars in Fig 1l) to \$22.7 trillion under a 4-month duration (green bars in Fig 1l) and \$30.1 trillion (equivalent to 40.3% of global value-added) under a 6-month duration (red bars in Fig 1l). However, the same bar charts show that global economic losses are relatively less sensitive to the strictness of lockdown measures than either the extent of pandemic or duration of the lockdown. For example, if only China is affected (China only scenario, Fig. S3), double the strictness would lead to almost linear economic impact under 2 months duration. As the duration increases, the economic impact is less sensitive to changes of strictness. In the global scenario the global impacts of 2 months of lockdown are only 7.2% larger under a strictness of 80% than 20% (darker and lighter blue bars in Fig 1l). Although both duration and strictness determine domestic production (via labour supply) and transportation capacity linking to upstream suppliers and downstream consumers, the economic damages via supply chain linkages are much more sensitive to the former.

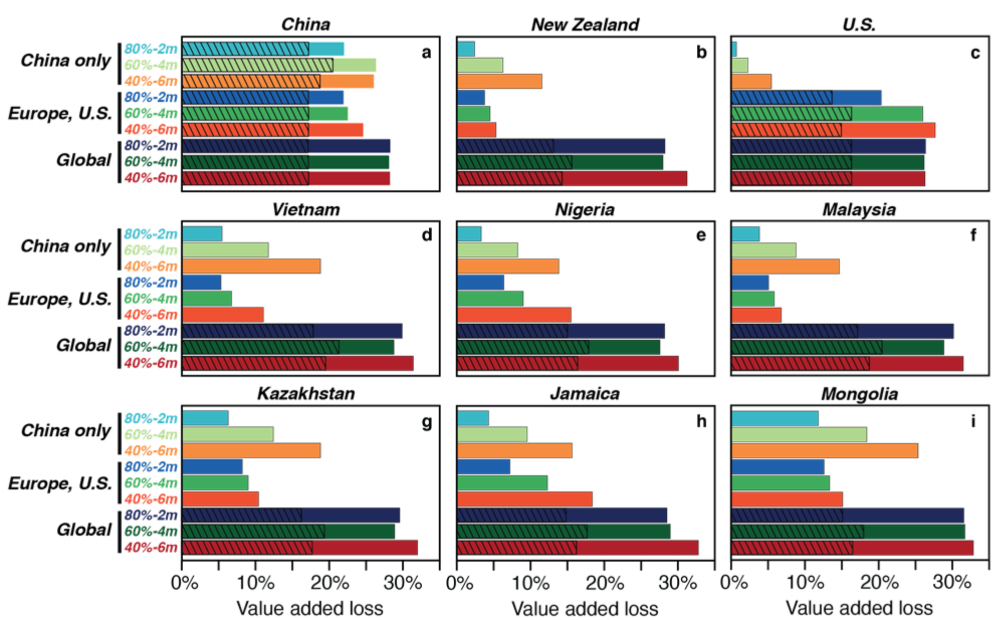

Figure 2 | Direct and indirect value-added losses of COVID-19 in selected countries under 9 scenarios. The bar charts a-i present economic loss (measured by the percentage of value-added losses) in selected nine countries. The top row country includes China (affected in China-only scenario), and developed countries such as the US (affected in Europe + U.S. scenario) and New Zealand (only affected in Global scenario). The middle row is countries (affected in Global scenario) which have close supply chain relationships with China to assess propagation effects. The bottom row shows countries with a dominant economic sector. Each sub-figure contains three selected scenarios from the three scenario sets (12 per figure). Three colour bars respond to 2 (blue), 4 (yellow), 6 (red) months in duration. The gridded area in bars represent direct losses due to containments and the solid area represents the propagation. See Fig. S4 - S11 for the results of some other selected counties.

The second insight is the importance of propagation through global supply chains: even countries that are not directly affected by the virus experience large losses, and low- and middle-income countries are more vulnerable to indirect effects. Figure 2 presents direct (i.e. due to domestic containment measures such as lockdown or suppression; hashed areas of bars) and propagation effects via international supply chains across the three scenarios sets (not hashed areas of bars). In the scenarios of an outbreak contained in China, direct losses by definition occur in China only, but are nonetheless substantial: 16.7% of China's annual GDP (Fig. 2a). However, even if the virus had been confined to China, its economic disruption would not have been. Forward and backward propagations along supply chains within China and with other countries add another 4.8% to China's losses to cause overall impacts of 21.5% of annual value-added. For example, although the United States (U.S.) and New Zealand are not directly affected by COVID-19 in this scenario, they would still suffer respectively 0.6% and 2.2% value-added losses during an 80% strict, 2-month lockdown in China due to the decline in China's output (i.e. negative forward effects) as well as shrinking of China's final demand for their products (negative backward effect). Under the same scenario, countries such as Vietnam, Malaysia and Nigeria, which are closely linked to China's supply chains, would experience losses of 5.2%, 3.6% and 3.1% of their GDP, respectively. Perhaps surprisingly, specialized economies like Kazakhstan (energy), Mongolia (livestock), and Jamaica (tourism) experience even larger losses, with 6.1%, 4.2% and 11.4% drops in their annual GDP, respectively (Figs. 2d-2i). Similarly, countries where the virus has been controlled can be continuously affected by imported losses. Assuming the virus is controlled in China over two months but spreads globally, China nonetheless suffers ongoing economic due to propagations: $5.77 trillion in the global scenario where lockdowns are 40% strict for 6 months (see "China" in GB panel in Supplementary Fig. S2).

Despite the propagation of lockdown losses through supply chains[15], pandemic control remains a public goods. In particular, non-affected countries benefit enormously from effective containment measures in affected countries. For example, if only China had been affected, most of the economic impacts in other countries would have been delayed by weeks or months (depending on which country; see Supplementary Fig. S2), as firms used their inventories to smooth the shock. Specifically, with 2 months of the strictest lockdown measures in China, but no spread of the virus beyond China (i.e. China only, 80%-2m; top blue bar of each panel in Fig. 2), our results indicate 21.6% of China's value-added is lost, while economic impacts in other countries are much smaller than in the scenarios when those countries are also directly affected (i.e., the global scenario bars in Fig. 2).

Similarly, if the virus had been contained in those highly developed western countries by a strict 2-months containment (i.e. Europe + U.S., 80%-2m; blue bars near the center of each panel in Fig. 2), Europe and the U.S. suffer much larger direct losses of 15%-20% of their GDP. The economic impacts in countries not directly affected increase with the duration of lockdowns in affected countries. For example, the loss in Ethiopia will increase from 2.5% under the Europe and the U.S. 80% - 2 month lockdown to 9.8% under a 6 month lockdown (Fig. S2). But this is still much less than the 27.9% losses in Ethiopia under the global spread and 6 months of 40% strict lockdowns. Although these findings are too late to affect public health policies for the first round of the COVID-19 pandemic, they demonstrate that containment has both substantial positive externalities, in that all countries benefited considerably when China placed the strictest measures, and negative externalities, in that all countries suffer from containment in the U.S. due to reduced demand in global markets. But our estimates show the positive externality of containments dominates.

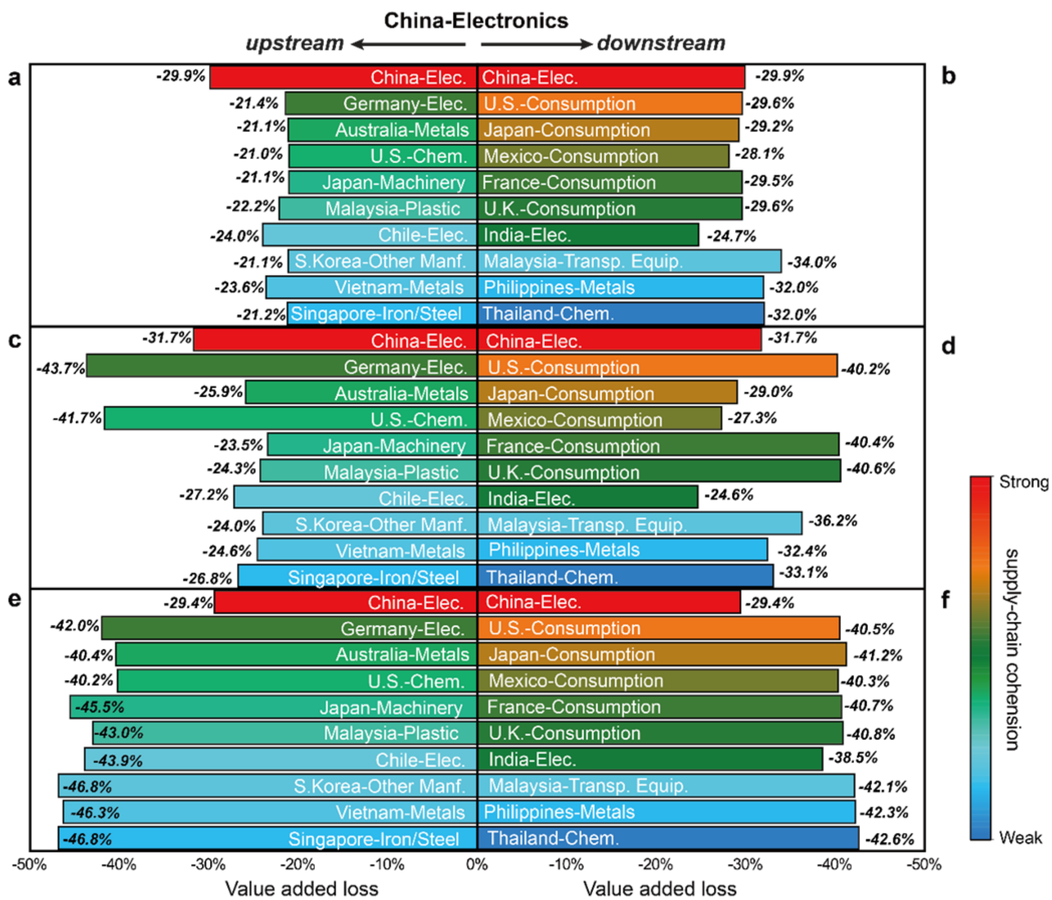

Figure 3 | Examples of supply chain effects on Chinese electronics and German automotive sectors in scenarios of global spread. Supply chain impacts to China's electronic-manufacturing industries under three scenario-sets (China only 80%-2 months (**a, b**), Europe and the U.S. 60%-4 months (**c, d**) and Global 40%-6 months (e, f). **a, c** and **e** show the economic impacts to China's electronics industry's upstream supply chain; and **b, d, f** represent the economic impacts from the perspective of downstream supply chains. Different colours of each bar represent the strength of linkage between industries and China's electronics industry (change from blue to red). In the upstream supply chains, the redder the bar is, the more important suppliers of China's electronics industry would be; downstream, the redder bar indicates that these sectors are the main clients of China's electronics industry. The length of bars in **a-f** depict the industries' relative production losses compared with the original capacity under different scenario-sets. Colors of bars represent the cohesion level of the particular sector to Chinese electronics from blue (weak) to red (strong), which is measured by the trade volume between the particular sector and Chinese electronics. See Fig. S12 - S14 for the results of some other industries in different countries.

The third insight is that specific country-sectors are quite vulnerable to impacts propagated via global supply chains, even in scenarios where COVID-19 does not spread globally. Figures 3 and 4 show the upstream and downstream impacts related to the Chinese electronics and German automotive sectors, respectively. Each of these sectors are important to the economies of China and Germany, respectively, and each also depend upon extensive international supply chains.

China's electronics supply-chain is labour intensive and has 'scale-free' property[7], i.e. there is a clustered hub in China with connections to a large number of firms in electronics, chemical and metal production in countries throughout Asia[16]. In scenarios where COVID-19 is confined to China by a strict, 2-month lockdown (i.e., China only, 80%-2m scenario), the global value-added related to China's electronics sector would have been reduced by 27.3% (including 20.8% in direct losses) (Supplementary Fig. S15). However, the impacts to China's electronics sector trigger substantial upstream production declines in South Korean electronics, Japanese electronics and Australian metals (in each case by roughly 21%; Fig. 3a). Although electronic products are largely substitutable, major production lines are centralised in China[16], such that there are also large downstream impacts as reduced output limits final consumption, particularly in the U.S., Japan, Mexico, and France (where reductions are >28%; Fig. 3b). In the scenario of global spread and 6 months of lockdowns (i.e. global, 40%-6m), the recovery of China's labour supply and transportation capacity to pre-disaster levels do not prevent ongoing impacts to its electronics sector via global supply chains (largely forward effects from upstream Asian countries), which further reduce the sector's output from 29.9% to 32.8% (Fig. 3e, Supplementary Fig. S15). In this global scenario, downstream consumption in countries like the U.S., Japan, Mexico and France are reduced by a total of 40% (Fig. 3f).

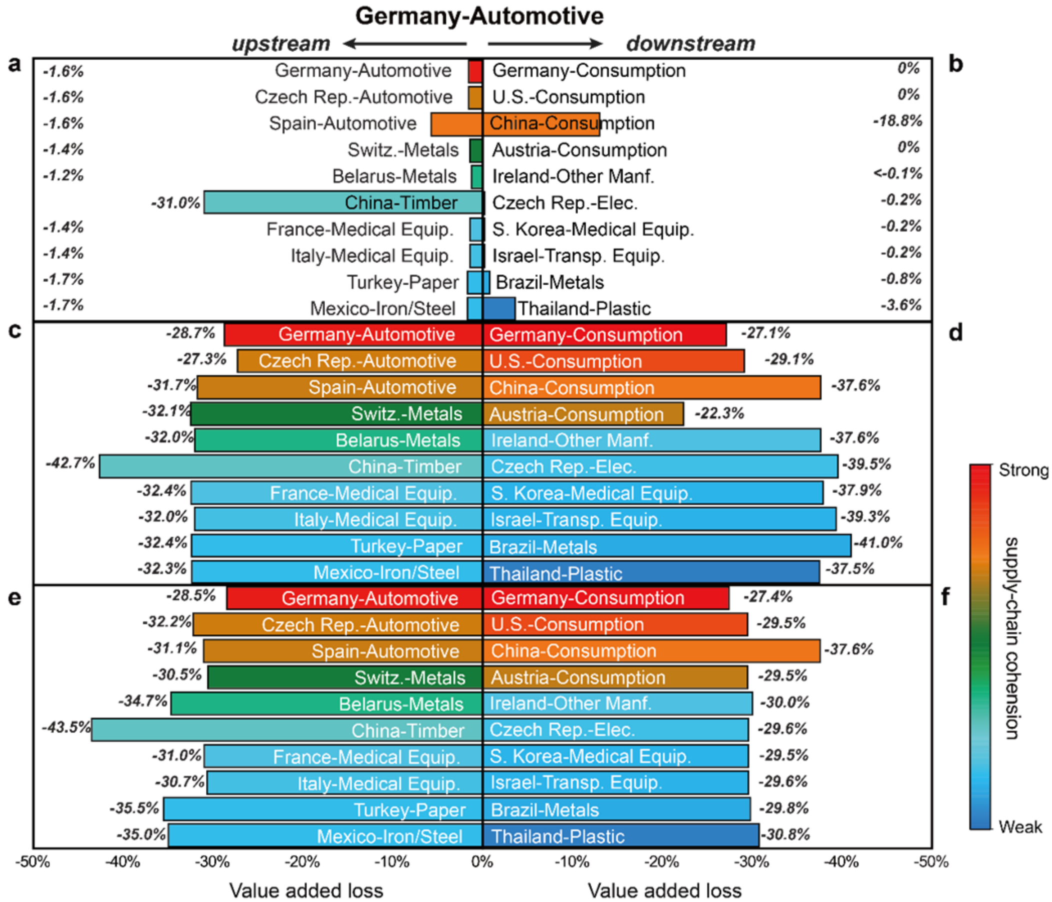

Figure 4 | Supply chain impacts to German automobile industries under three main scenario-sets. **a, c** and **e** show the economic impacts to supply chain upstream of German automobile industries and **b, d, f** represent the economic impacts from the perspective of downstream supply chain. The setting of scenario-sets, circle colour and area are similar with that of Fig 3. The length of bars in **a-f** depict the industries' relative production losses compared with the original capacity under different scenario-sets. Colors of bars represent the cohesion level of the particular sector to German Automotive from blue (weak) to red (strong), which is measured by the trade volume between the particular sector and German Automotive.

Automotive sectors are similarly international[17], with highly-specialized suppliers that make short-term substitution difficult[18]. In the scenario where only China imposes lockdown measures (i.e. the China only 80%-2m scenario), economic impacts to the German automobile are modest: losses of 1.8% of value-added as China's demand for German motor parts and vehicles fall by roughly 20% (Fig. 4b; Supplementary Fig. S16) and reductions in the output of various Chinese sectors (e.g., electronics, metals and rubber and plastics) constrain upstream production of motor parts in the U.S. and the U.K and electronics in Germany. With the spread of COVID-19 to highly developed western countries (i.e. Europe and the U.S., 60%-4m scenario), however, labour and transportation constraints in Germany and many of the countries that supply auto parts and raw materials (Supplementary Fig. S16) cause production by the German automotive sector to fall by 28.8% (24.8% directly due to local containment, and 4.0% due to effects upstream, Fig. 4c). Such decreases in German production ripple upstream to suppliers in Hungary, Spain, Italy, and the U.S., and downstream demand for German cars declines in the U.S., China and Austria by 29.1%, 37.6% and 22.3%, respectively (Fig. 4d). In the case of global spread and more widespread and longer-term lockdowns (i.e. global, 40%-6m scenario; Fig. 4e), the output of German automobile industries decreases by a further 0.9%. Reduced supplies from low- and middle-income countries to Germany (Fig. S16) lead German producers to look for new suppliers ("substitution effect"). On the other hand, the production of motor parts in the U.S. rebounds slightly in this scenario, but the overall impacts of such global spread remain strongly negative everywhere. Consumption of German cars in the U.S. and Austria fall by 29.5%., and—although Chinese demand for German cars in this scenario returns to pre-pandemic levels in April—supply chain and transportation constraints nonetheless reduce Chinese consumption of German cars by 37.5%.

Our results also highlight the vulnerability of sectors like catering and tourism to pandemic lockdowns[19] which are exposed to both very large decreases in demand and the propagation of losses from upstream suppliers such as food and business sectors[20]. For example, in scenarios of global pandemic (e.g., the global, 40%-6m scenario), very large reductions in domestic and international travel and tourism (Fig. S17) cause tourism in Jamaica to decline by 56.3%, in turn reducing imports of beverages and tobacco products from the U.S. falling to 46.7% of pre-pandemic levels (Fig. S17).

As a final analysis, we model three different scenarios of recovery from the global spread of the COVID-19 pandemic: (1) a "new normal" scenario in which each country's lockdown (i.e. China 80%-2m, then all other countries 60%-4m) is first relaxed to 20% strictness and then back to 0% over a period of 12 months; (2) a "recurrent *with* global cooperation" scenario, in which, Round 1: each country's lockdown (i.e. China 80%-2m, Europe and the U.S. 60%-3m, all other countries 40%-4m) is first relaxed to 0% strictness over a period of 2 months, followed by a 3-month period of no restrictions, and then Round 2: all countries act together by placing strictest (80%), 2-month global lockdown to minimize virus spreading; and (3) a "recurrent *without* global cooperation" scenario, in which, Round 1: each country's lockdown (i.e. China 80%-2m, Europe and the U.S. 60%-3m, all other countries 40%-4m) is first relaxed to 0% strictness over a period of 2 months, followed by a 3 month period of no restrictions, and then Round 2: all countries place same less strict but longer lockdowns as the first round.

These recovery scenarios lead to a fourth and final insight: relaxing lockdown restrictions gradually over a long time period (in our "new normal" scenario, 12 months) results in substantially lower economic impacts than lifting restrictions quickly if it means avoiding another round of strict lockdowns in the coming year. Globally, we estimate overall value-added losses in the "new normal" scenario to be 39.5%, as compared to 49.5% and 61.5% in the "recurrent" scenarios (Fig. 5a-5c). The differences are particularly striking in the U.S., where losses related to recurrent lockdowns are 24.6%-54.8% greater than the slow relaxation of restrictions (see light-blue shading in Figs. 2d-2f). As shown in our scenarios of initial lockdowns, if the pandemic does recur, stricter and shorter lockdowns (which may depend upon global coordination) also greatly reduce losses, by 11% globally in our estimates (Figs.

5b, 5c). The implications of these different recovery trajectories for selected sectors are shown in Figures 5g-5i; as with losses globally or in specific countries, recurrent lockdowns are considerably worse (e.g., by 33.1-90.8% worse in the sectors depicted).

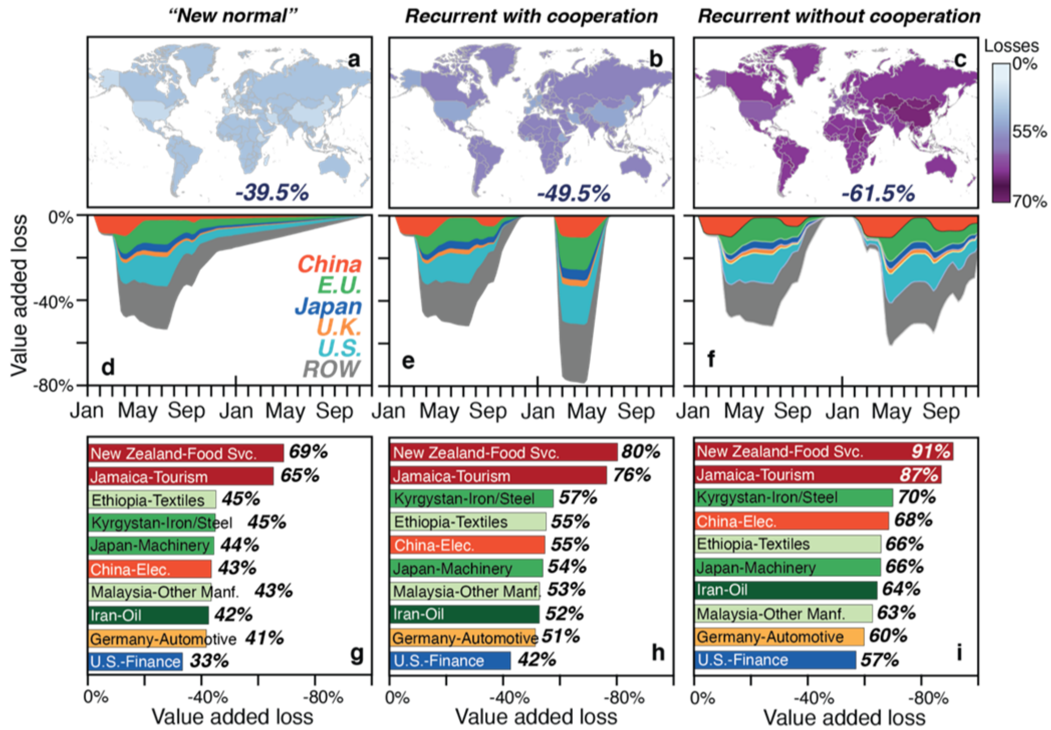

Figure 5 | Economic impacts of recovery scenarios. Maps (**a-c**) show results from three post pandemic recovery scenarios, with different potential recovery strategies. Percentages in the bottom of each map indicate the global value-added losses. Changes of color shades represent the severity of economic impact by countries. The stacked area plots (**d-f**) show the dynamics of the value-added loss in different countries or regions. The bar charts **(g-i)** illustrate the value-added loss in ten selected sectors under different recovery trajectories.

Discussion

Our modelling of COVID-19 lockdowns demonstrate the enormous economic impacts of the number of affected countries, the duration and strictness of lockdowns, and how restrictions are relaxed as the pandemic abates—in each case factors influenced or determined by public health policy choices across the globe[21, 22]. We have enumerated several insights based on our results, which together suggest that economic losses will be minimized by stricter initial lockdowns, provided that such strictness would reduce the duration of the measures. And indeed, emerging results of related research seem to support exactly this relationship[14]. Yet our modelling of recovery scenarios suggests that an extended period of some restrictions (e.g., 20% reductions in labour and transportation capacity in our "new normal" scenario) is nonetheless economically preferable to a more rapid return to pre-pandemic activities followed by another round of global lockdowns. This is a critical but perhaps inconvenient finding for policymakers eager to lift restrictions and stimulate economic recovery.

Our results also illustrate the substantial and heterogenous impacts propagated via global supply chains, which affect the level of economic impacts to a country or sector in ways that are not always intuitive. Moreover, just as individuals staying home protect others as well as themselves, so countries imposing strict lockdowns provide a public good to other countries[23, 24]. For example, we estimate that a strict lockdown which contained the COVID-19 outbreak to China would reduce global GDP by 3.5% while costing China 21% of its GDP. The relatively positive externalities of public health measures to prevent a pandemic may lead to market failures, leading to under-investment and delayed action from the perspective of global optimization. In preparing for the next emerging disease, a global cost-sharing instrument could ensure that the costs of monitoring, containment, and suppression are fairly distributed, removing some of the disincentives to early action and providing enormous global health and economic benefits over the long term.

Data availability

All data and R codes are deposited at our data publishing website – China Emission Accounts and Datasets (http://www.ceads.net/?ddownload=3188). Those data can be also obtained from the corresponding author on reasonable request.

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Methods

Disaster impact model. Our impact model is an extension of the adaptive regional input-output (ARIO) model[23, 24], which is widely used in the literature to simulate the propagation of negative shocks throughout the economy[11, 12, 25-27]. Our model improves the ARIO model in two ways. The first improvement is related to the substitutability of products from the same sector sourced from different regions. Second, in our model, clients will choose their suppliers across regions based on their capacity. These two improvements contribute to a more realistic representation of bottlenecks along global supply chains. It should be noted that, although general equilibrium models which are often used for economic assessment can also handle the above two points well, it does not model well short-term (disruption in a few weeks or months after a shock) simulations and disequilibrium situations as shocks present. In CGE models, we assume that changes in relative prices balance supply and demand. This is an ideal description in the long run. However, in the short run, because of socioeconomic inertia, transaction costs, and antigouging legislation, adjustment through prices appears unlikely in the aftermath of a disaster[24]. Hence, IO models are frequently preferred to represent short-term economic dynamics, in which production technologies are fixed and prices cannot adjust. CGE models, on the other hand, are preferred for modelling long-term dynamics, in which flexibility in production processes and markets allow for an adjustment of the economic system[24]. Our model also has some disadvantages. For example, the effect of expectations is not considered. Another limitation of our model is the inability to endogenously consider changes in technology. But in these short-term scenarios and situations following a shock technical changes are rather unlikely. Our model is designed to identify the most important containment factors among the strictness, duration, and recurrence of lockdowns and measure the magnitude of propagation effects through global supply chains. The analytical framework setting are fundamentally different to other macroeconomic analysis[28-30] aiming at predicting true cost of the COVID-19.

Our disaster impact model includes 4 main modules, i.e., production module, allocation module, demand module and simulation module. The production module is designed for characterizing the firm's production activities. The allocation module is used to describe how firms allocate output to their clients, including downstream firms (intermediate demand) and households (final demand). The demand module is used to describe how clients place orders to their suppliers. And the simulation module is designed for executing the whole simulation procedure.

Production module. The production module is used to characterize production processes. Firms rent capital and employ labour to process natural resources and intermediate inputs produced by other firms into a specific product (see figure S1). The production process for firm i can expressed as follows,

$$x_i = f\left(\text{for all } p, z_i^p; va_i\right)$$

where x_i denotes the output of the firm, in monetary values; p denotes type of intermediate products; z_i^p denotes intermediate products used in production processes; va_i denotes the primary inputs to production, such as labour (L), capital (K) and natural resources (NR). $f(\cdot)$ is the production function for firms. There are a wide range of functional forms, such as Leontief [31], Cobb-Douglas (C-D) and Constant Elasticity of Substitution (CES) production function[32]. Different functional forms reflect the possibility for firms to substitute an input for another. Considering that epidemics often cause large-scale economic fluctuations in the short term, during which economic agents do not have enough time to adjust other inputs to substitute temporary shortages, we use Leontief production function which does not allow substitution between inputs.

$$x_i = min\left(\text{for all } p, \frac{z_i^p}{a_i^p}; \frac{va_i}{b_i}\right)$$

where a_i^p and b_i are the input coefficients calculated as

$$a_i^p = \frac{\bar{x}_i}{\bar{z}_i^p}$$

and

$$b_i = \frac{\bar{x}_i}{\overline{va}_i}$$

where the horizontal bar indicates the value of that variable in the equilibrium state. In an equilibrium state, producers use intermediate products and primary inputs to produce goods and services to satisfy demand from their clients. After a disaster, output will decline. From a production perspective, there are mainly the following constraints:

Labour supply constraints. Labour constraints after a disaster may impose severe knock-on effects on the rest of the economy[33-35]. This makes labour constraints a key factor to consider in disaster impact analysis. For example, in the case of a pandemic, these constraints can arise from employees' inability to work as a result of illness or death, or from the inability to go to work and the requirement to work at home (if possible). In this model, the proportion of surviving productive capacity from the constrained labour productive capacity (x_i^L) after a shock is defined as[36-38]:

$$x_i^L(t) = \left(1 - \gamma_i^L(t)\right) * \bar{x}_i$$

Where $\gamma_i^L(t)$ is the proportion of labour that is unavailable at each time step t during containment. $(1 - \gamma_i^L(t))$ contains the available proportion of employment at time t.

$$\gamma_i^L(t) = (\bar{L}_i - L_i(t))/\bar{L}_i$$

The proportion of the available productive capacity of labour is thus a function of the losses from the sectoral labour forces and its pre-disaster employment level. Following the assumption of fixed input-output relationships, the productive capacity of labour in each region after a disaster (x_i^L) will represent a linear proportion of the available labour capacity at each time step[39, 40]. Take COVID-19 as an example, during an outbreak of an infectious disease, authorities often adopt social distancing and other measures to reduce the risk of infection. This imposes an exogenous negative shock on the economic network.

Supply constraints. Firms will purchase intermediate products from their supplier in each period. Insufficient inventory of a firm's intermediate products will create a bottleneck for production activities. The potential production level that the inventory of the p^{th} intermediate product can support is

$$x_i^p(t) = \frac{S_i^p(t-1)}{a_i^p}$$

where $S_i^p(t-1)$ refers to the amount of p^{th} intermediate products held by firm i at the end of time step $t-1$.

Considering all the limitation mentioned above, the maximum supply capacity of firm i can be expressed as

$$x_i^{max}(t) = min\left(x_i^L(t); x_i^K(t); \text{for all } p, x_i^p(t)\right)$$

The actual production of firm i, $x_i^a(t)$, depends on both its maximum supply capacity and the total orders the firm received from its clients (see the Demand Module),

$$x_i^a(t) = min(x_i^{max}(t), TD_i(t-1))$$

The inventory held by firm i will be consumed during the production process,

$$S_i^{p,used}(t) = a_i^p * x_i^a(t)$$

Allocation module. The allocation module mainly describes how suppliers allocate products to their clients. When some firms in the economic system suffer a negative shock, their production will be constrained by a shortage to primary inputs such as a shortage of labour supply in the outbreak of COVID-19. In this case, a firm’s output will not be able to fill all orders of its clients. A *rationing scheme* that reflects a mechanism based on which a firm allocates an insufficient amount of products to its clients is needed[23, 41]. For this case study, we applied a *proportional* rationing scheme according to which a firm allocates its output in proportion to its orders. Under the proportional rationing scheme, the amounts of products of firm i allocated to firm j and household h is as follows,

$$FRC_j^i(t) = \frac{FOD_i^j(t-1)}{\left(\sum_j FOD_i^j(t-1) + \sum_h HOD_i^h(t-1)\right)} * x_i^a(t)$$

$$HRC_h^i(t) = \frac{HOD_i^h(t-1)}{\left(\sum_j FOD_i^j(t-1) + \sum_h HOD_i^h(t-1)\right)} * x_i^a(t)$$

Firm j received intermediates to restore its inventories,

$$S_j^{p,restored}(t) = \sum_{i \to p} FRC_j^i(t)$$

Therefore, the amount of intermediate p held by firm i at the end of period t is

$$S_j^p(t) = S_j^p(t-1) - S_j^{p,used}(t) + S_j^{p,restored}$$

Demand module. The demand module represents a characterization of how firms and household issues orders to their suppliers at the end of each period. Firm orders its supplier because of the need to restore its intermediate product inventory. We assume that each firm has a specific target inventory level based on its maximum supply capacity in each time step,

$$S_i^{p,*}(t) = n_i^p * a_i^p * x_i^{max}(t)$$

Then the order issued by firm i to its supplier j is

$$FOD_j^i(t) = \begin{cases} \left(S_i^{p,*}(t) - S_i^p(t)\right) * \dfrac{\overline{FOD}_j^i * x_j^a(t)}{\sum_{j \to p}\left(\overline{FOD}_j^i * x_j^a(t)\right)}, & \text{if } S_i^{p,*}(t) > S_i^p(t); \\ 0 & \text{if } S_i^{p,*}(t) \le S_i^p(t). \end{cases}$$

Households issue orders to their suppliers based on their demand and the supply capacity of their suppliers. In this study, the demand of household h to final products q, $HD_h^q(t)$, is given exogenously at each time step. Then, the order issued by household h to its supplier j is

$$HOD_j^h(t) = HD_h^q(t) * \frac{\overline{HOD}_j^h * x_j^a(t)}{\sum_{j \to q}\left(\overline{HOD}_j^h * x_j^a(t)\right)}$$

The total order received by firm j is

$$TOD_j(t) = \sum_i FOD_j^i(t) + \sum_h HOD_j^h(t)$$

Simulation module. At each time step, the actions of firms and households are as follows:

1. Firms plan and execute their production based on three factors: a) inventories of intermediate products they have, b) supply of primary inputs, and c) orders from their clients. Firms will maximize their output under these constraints.
2. Product allocation. Firms allocate outputs to clients based on their orders. In equilibrium, the output of firms just meets all orders. When production is constrained by exogenous negative shocks, outputs may not cover all orders. In this case, we use a proportional rationing scheme proposed in the literature[23, 41](see Allocation Module) to allocate products of firms.
3. Firms and household issue orders to their suppliers for the next time step. Firms place orders with their suppliers based on the gaps in their inventories (target inventory level minus existing inventory level). Households place orders with their suppliers based on their demand. When a product comes from multiple suppliers, the

allocation of orders is adjusted according to the production capacity of each supplier. This discrete-time dynamic procedure can reproduce the equilibrium of the economic system, and can simulate the propagation of exogenous shocks, both from firm and household side, or transportation disruptions, in the economic network. From the firm side, if the supply of a firm's primary inputs is constrained, it will have two effects. On the one hand, the decline in output in this firm means that its clients' orders cannot be fulfilled. This will result in a decrease in inventory of these clients, which will constrain their production. This is the so-called forward or downstream effect. On the other hand, less output in this firm also means less use of intermediate products from its suppliers. This will reduce the number of orders it places on its suppliers, which will further reduce the production level of its suppliers. This is the so-called backward or upstream effect. Similarly, these two effects can also occur if the transport of a firm to its clients or suppliers is restricted. For instance, during the outbreak of COVID-19 in China, the authorities adopted strict isolation measures. These measures have placed constraints on the supply of labour and the transportation of products. This led to a decline in China's output and also triggered the forward and backward effect, which leads to the propagation of the shock through the global economic production web. From the household side, the fluctuation of household demand caused by exogenous shocks will also trigger the aforementioned backward effect. Take tourism as an example, during the outbreak of COVID-19 in China, the demand for visiting China from tourist all over the world will decline significantly. This influence will further propagate to the accommodation and catering industry as well as their suppliers through supplier-client links.

Economic impacts. We define the value-added decrease of all firms in a network caused by an exogenous negative shock as the disaster impacts of the shock. It should be noted that in our estimates, we are not looking at dynamic general equilibrium effects, mortality, Quality-Adjusted Life Year (QALYs) and Disability-Adjusted Life Year (DALYs), whereas economic impacts of the lockdowns are considered. For the firm directly affected by exogenous negative shocks, its loss includes two parts: a) the value-added decrease caused by exogenous constraints, and b) the value-added decrease caused by propagation. The former is the direct loss, while the latter is the indirect loss. A negative shock's total economic impacts ($TEI_{i,r}$), direct economic impacts ($DEI_{i,r}$), and propagated economic impacts ($PEI_{i,r}$) for firm i in region r are,

$$TEI_{i,r} = \overline{va}_{i,r} * T - \sum_{t=1}^{T} va_{i,r}^{a}(t)$$

and,

$$DEI_{i,r} = \overline{va}_{i,r} * T - \sum_{t=1}^{T} va_{i,r}^{max}(t)$$

and,

$$PEI_{i,r} = TEI_{i,r} - DEI_{i,r}$$

Global supply-chain network. We build a global supply chain network based on version 10 of the Global Trade Analysis Project (GTAP) database[11]. GTAP 10 provides a multiregional input-output (MRIO) table for the year 2014. This MRIO table divides the world into 141 economies, each of which contains 65 production sectors. If we treat each sector as a firm (producer), and assume that each region has a representative household, we can obtain the following information in the MRIO table: a) suppliers and clients of each firm; b) suppliers for each household, and c) the flow of each supplier-client connection under the equilibrium state. This provides a benchmark for our model. It should be noted that the MRIO table provided by GTAP is only a sectoral level network, it cannot capture the complexity of supply-chain networks at the firm level. Hence, this study only serves as approximation of the actual effect. Detailed data are rarely available, however, particularly those for supply chains in developing countries and for global supply chains across countries.

When applying such an aggregated network in the disaster impact model, we need to consider the substitutability of intermediate products supplied by suppliers from the same sector in different regions. The substitution between some intermediate products is fairly straightforward. For example, for a firm that extracts spices from bananas it does not make much of a difference if the bananas are sourced from the Philippines or Thailand. However, for a car manufacturing firm in Japan, which uses screws from Chinese auto parts suppliers and engines from German auto parts suppliers to assemble cars, the products of the suppliers in these two regions are non-substitutable. If we assume that all goods are non-substitutable as in the traditional IO model, then we will overestimate the loss of producers such as fragrance extraction firm. If we assume that products from suppliers in the same sector can be completely substitutable, then we will significantly underestimate the losses of producers such as Japanese car manufacturing firm. In order to alleviate the shortcomings of the evaluation deviation under the two assumptions, we set the possibility of substitution for each firm based on the region and sector of supplier supply (see Allocation Module of the model).

Spread and containment scenarios. The number of affected countries, the duration of the containment and the strictness of the containment are the three important factors influencing the loss caused by the epidemic. Using these three indicators as dimensions, and then referring to the actual epidemic situation, we designed three sets of scenarios, i.e., China only (CN), Europe and U.S. (NH) and Global (GB). Different sets of scenarios represent different areas of influence of COVID-19, while scenarios in the same scenario set have different assumptions about duration of the containment and the strictness of the containment.

Our first scenario set, China only, assumes that the outbreak of COVID-2019 is only in mainland China. In this scenario set, labour supply and transportation in mainland China will be restricted due to the need for epidemic control from the fourth week of 2020 (i.e., 22nd January 2020). To examine the impact of policy strictness and duration of the outbreak on the world economic system, we set four strictness (i.e., 20%, 40%, 60%, 80%) and three durations (i.e., 2, 4, 6 months), see the yellow block in the table below. For instance, the scenario "China only 20%-2m" means that the epidemic lasts for two months with labour supply and transportation restrictions of 20%.

Isolation measures have different effects on labour supply in different sectors. We set a specific multiplier for each sector based on three factors, i.e., the exposure level of the sector's work, whether it is the lifeline, and whether it is possible to work at home. If a sector's work exposure level is low, or it is the lifeline sector, or it is easy to work at home, its' multiplier will be small, vice versa.

Then, the constraints on labour supply in each sector are determined by two parts, i.e., benchmark constraint in the scenario and multipliers for the sector. For instance, we assume that the multiplier for the wheat production sector is 0.5 because the level of exposure to its production activities is relatively low. Then, in the scenario "China only 20%-2m", the labour supply in the wheat production sector will fall by 10%, i.e., 20% multiplied by 0.5. At the same time, in the scenario set, transportation between mainland China and other regions will also fall by 50% during the duration of the epidemic.

The epidemic not only affects the global economic system from the supply side, but also affects economic output through its impact on consumer demand. Most obviously, tourism demand for the region with COVID-2019 outbreaks will drop significantly. Due to lack of data, we simply assume that the final demand for the two sectors, "Recreation and other services" and "Accommodation, Food and service activities", in the outbreaking area fell by 99% during the duration of the outbreak.

Scenario-sets table

		China only			Europe and the U.S.			Global		
Duration		**2 months**	**4 months**	**6 months**	**2 months**	**4 months**	**6 months**	**2 months**	**4 months**	**6 months**
Strictness	**20%**	20%-2m	20%-4m	20%-6m	20%-2m	20%-4m	20%-6m	20%-2m	20%-4m	20%-6m
	40%	40%-2m	40%-4m	40%-6m	40%-2m	40%-4m	40%-6m	40%-2m	40%-4m	**40%-6m**
	60%	60%-2m	60%-4m	60%-6m	60%-2m	**60%-4m**	60%-6m	60%-2m	60%-4m	60%-6m
	80%	**80%-2m**	80%-4m	80%-6m	80%-2m	80%-4m	80%-6m	80%-2m	80%-4m	80%-6m

In the second set of scenarios (Europe and the U.S.), we assume that regions with the current severe epidemic situation have taken measures from the eleventh week (11th March 2020) to control their epidemic. These countries include the United States, France, Germany, Italy, the Netherlands, the United Kingdom, Switzerland, Spain, and Iran. The labour and transportation restrictions are consistent with the settings of the scenario set China only, and take “China only 80%-2m” as default in mainland China, which basically matches with the reality shown in the Baidu big data.

In the last set of scenarios (Global), we assume that in addition to mainland China and the economies in the scenario set Europe and the U.S., other economies in the world also began to take measures to control the epidemic in the 15th week (8th April 2020). The labour and transportation restrictions are consistent with the settings of the scenario set China only and Europe and the U.S., and take “China only 80%-2m” as default for mainland China, “Europe and the U.S. 60%-4m” as default in economies in the scenario set Europe and the U.S..

Finally, we design and model three post-pandemic scenarios of recovery as follows:

- Pandemic as a new normal scenario: Starting with January 2020, China only placed 80% strictness for 2 months, then reduced to 20% for 12 months. EU and the U.S. placed 60% strictness for 4 months, then reduced to 20% strictness for 12 months. Global placed 40% strictness for 6 months, then reduced to 20% and gradually relaxing to 0% over a period of 12 months.
- Recurrent pandemic scenario with global cooperation: Starting with January 2020, each country’s lockdown (i.e. China 80%-2m, Europe and the U.S. 60%-4m, all other countries

40%-6m) is first relaxed to 0% strictness over a period of 2 months, followed by a 3-month period of no restrictions and then another round of strict (80%), 2-month global lockdown starting January 2021.

- Recurrent pandemic scenario without global cooperation: Starting with January 2020, each country's lockdown (i.e. China 80%-2m, Europe and the U.S. 60%-4m, all other countries 40%-6m) is first relaxed to 0% strictness over a period of 2 months, followed by a 3 month period of no restrictions, and then another round of the same less strict, longer lockdowns starting January 2021, as the first round.

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