

Equitable vaccine distribution promotes socioeconomic benefits globally

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1 **Equitable vaccine distribution promotes socioeconomic benefits globally**

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15

16 **Abstract**

17 **Ensuring a more equitable distribution of vaccines worldwide is an effective strategy to control**
18 **the COVID-19 pandemic and support global economic recovery. Here, we analyze the**
19 **socioeconomic effects - defined as health gains, lockdown-easing benefit, and supply-chain**
20 **rebuilding benefit - of a set of idealized vaccine distribution scenarios, by coupling an**
21 **epidemiological model with a global trade-modeling framework. We find that overall a**
22 **perfectly equitable vaccine distribution across the world (Altruistic Age-informed Distribution**
23 **Strategy) would increase global economic benefits by 11.7% (\$950 billion) per year, compared**
24 **to a strategy focusing on vaccinating the entire population within vaccine-producing countries**
25 **first and then distributing vaccines to non-vaccine-producing countries (Selfish Distribution**
26 **Strategy). With limited doses among mid- and low-income countries, prioritizing the elderly**
27 **who are at high risk of dying, together with the key workforce who are at high risk of**
28 **exposure, is found to be economically beneficial. We further show that such a strategy would**
29 **cascade the protection to other production sectors while rebuilding the supply chains. Our**
30 **results point to a benefit-sharing mechanism which highlights the potential of collaboration**
31 **between vaccine-producing and other countries to guide an economically preferable vaccine**
32 **distribution worldwide.**

33 The subsequent waves of COVID-19 pandemics continue to threaten public health and society across
34 the globe¹⁻⁵. Though vaccination has proven beneficial to avert the substantial tolls, global inequity
35 in vaccine distribution and manufacturing is crucial at present⁶⁻⁸. Given the rapid evolution of SARS-
36 CoV-2, it is clear that nobody wins the race until everyone wins. This motivates us to consider the

1 potential of collaboration between vaccine-producing and other countries, guiding the optimal
2 vaccine distribution across countries and allowing a faster recovery of health systems and society.
3 The dilemma is: Should vaccine-producing countries (e.g., USA, EU, UK, China, India, and Russia)
4 prioritize their own populations (a Selfish Distribution Strategy), or allocate at any time the limited
5 amount of vaccines to all countries according to their population and age structure (two Altruistic
6 Distribution Strategies)? To lay out our general insights, we, by linking epidemiological and
7 socioeconomic modeling frameworks, probe the potential gains of global vaccine allocation
8 strategies from the socioeconomic perspective.

9 It is worth noting that countries are highly connected by global supply chains. This indicates the
10 cascading effect of intervention strategies across countries. For example, evidence has shown the
11 negative impacts of the lockdown intervention to curb virus transmission in one country spread to
12 other countries along supply chains^{1,5,9-11}. On the other hand, vaccination decisions in one country
13 may be beneficial to the economic recovery of other countries, which is often referred to as one type
14 of externality of vaccination¹²⁻¹⁵. The presence of these externalities is a major driver that makes a
15 market-oriented global vaccine distribution a socially non-optimal solution^{16,17}. Advancing our
16 understanding of the positive health and economic externalities is the key to maximize the
17 socioeconomic gains of global vaccine roll-out^{12,14,16,18}.

18 Here, we quantify the socioeconomic benefits of a set of idealized COVID-19 vaccine-distribution
19 scenarios (Box 1) by linking epidemiological^{3,19} and socioeconomic^{1,20,21} modeling frameworks.
20 Details of our analytical approach are provided in the **Methods**. In brief, we base our evaluation on
21 three main outcomes: **i) the health gains**, i.e., the value of lives saved through vaccination. Leveraging
22 our realistic age-stratified epidemiological (RAS) model¹⁹, we project mortality averted under varying
23 vaccination scenarios as compared to the ‘no vaccination’ scenario. With the estimates, we used the
24 value of statistical life (VSL) to project the health benefit quantified in US dollars. **ii) the lockdown-**
25 **easing benefit**. Assuming that the speed of vaccine rollout is equivalent to the easing of the
26 lockdown^{1,19}, we multiply the lockdown reduction by sectoral value-added to obtain what we call the
27 lockdown-easing benefit. **iii) the supply-chain rebuilding benefit**. We developed a global trade
28 model based on the widely used ARIO approach^{20,21} to assess the economic losses over 6 years, i.e.,
29 2020-2025, under vaccination scenarios. We translate the estimates to the total economic benefit
30 brought by the vaccines by quantifying the difference of economic losses with vaccination versus the
31 ‘no vaccination’ scenario. We further subtract the lockdown-easing benefit from the total economic
32 benefit to project the supply-chain rebuilding benefit.

33 We modeled three sets of idealized scenarios integrated into a tiered structure (see Box 1,
34 Supplementary Fig. 1). Basically, Tier Global set of scenarios address the issue of the cooperative
35 attitude of vaccine-producing (or vaccine-exporting) countries and vaccine-importing countries,
36 while Tier Domestic set of scenarios address the issue of how received vaccines (vaccines sent by
37 producing countries) are allocated within each destination country (Box 1). We consider different

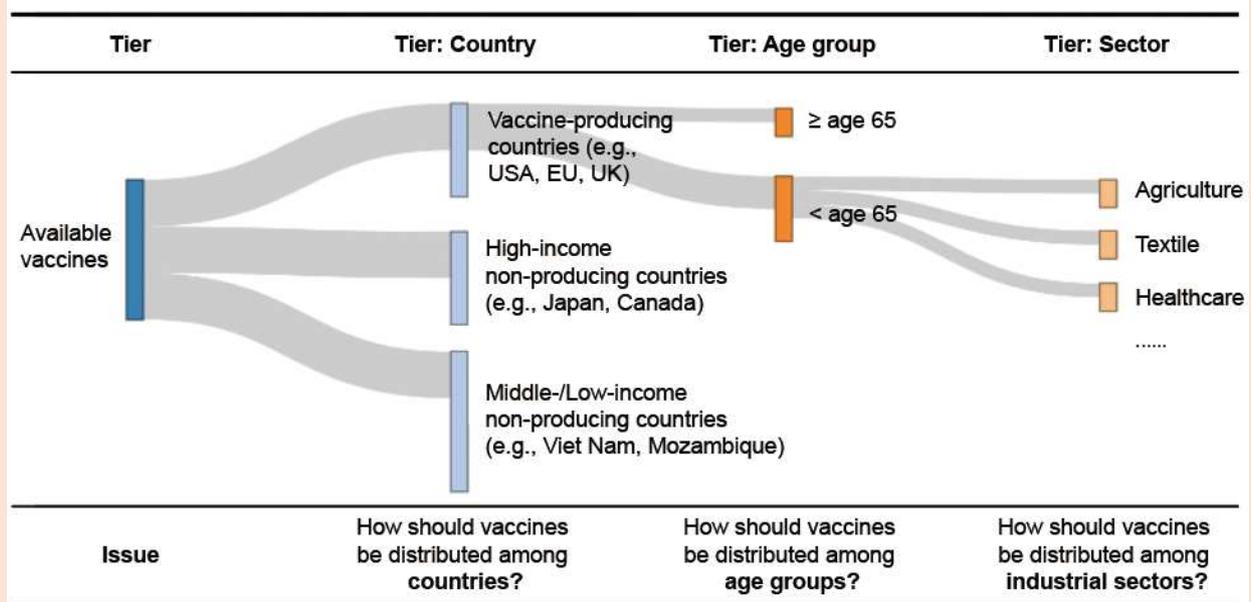
Box 1 | Scenario settings, explanations, justification

We designed three sets of scenarios integrated into a tiered structure. Basically, Tier Country set of scenarios address the issue of the cooperative attitude of vaccine-producing (or vaccine-exporting) countries and vaccine-importing countries, while Tier Domestic set of scenarios address the issue of how received vaccines (vaccines sent by producing countries) are allocated within each destination country. Among tier domestic, sub-scenario A defines the allocation of the received vaccines within destination countries by age group, while sub-scenario S defines the allocation of the received vaccines within destination countries by industrial sectors.

Scenario settings and descriptions

Tier	Scenario set	Strategies	Description
Global	Country	Selfish Distribution	Vaccine-producing country first, and then distribute globally.
		Altruistic Distribution	Countries put all their vaccines into a global pool and vaccinate uniformly according to the population of each country.
		Altruistic Age-informed Distribution	Countries put all their vaccines into a global pool and vaccinate uniformly according to the population 65 years and older of each country first.
Domestic	Age Group	Old first	Vaccination prioritization to the old (65 y.o. and older).
		Young first	Vaccination prioritization to the younger age classes (under 65 y.o.).
		Uniform	Uniform vaccination to all people.
	Industrial Sector	Equally	Distributed to the working populations equally distributed to all industrial sectors.
		High risk	Distributed to the working populations in terms of the exposure risk rank of economic sectors.
		Critical	Distributed to the working populations in terms of the critical worker proportion in each industrial sector.

Tiered Structure of the scenario sets design



1

2 sub-scenarios within each scenario set (Box 1, Supplementary Fig. 1). In summary, sub-scenario C
 3 represents to what extent the vaccine-exporting country is willing to share the vaccine with other

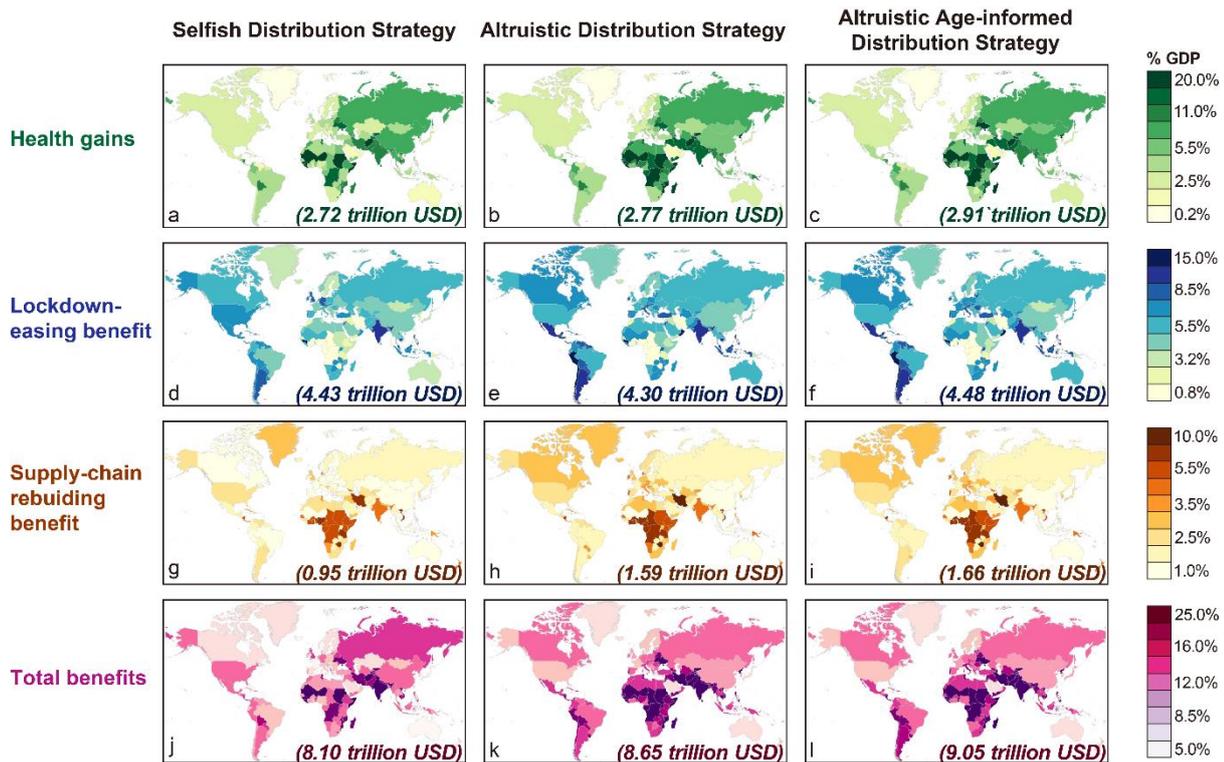
1 countries (specifically, a Selfish Distribution Strategy vs two Altruistic Distribution Strategies). Sub-
2 scenario *A* defines the allocation of the received vaccines within destination countries by age group.
3 And sub-scenario *S* defines the allocation of the received vaccines within destination countries by
4 industrial sectors (Box 1). In the following analysis, when comparing the results of one dimension of
5 the scenario sets, “Altruistic Distribution Strategy”, “Elderly First”, and “High Risk” are used as the
6 default scenario.

7 **Results**

8 Figure 1 summarizes the results of a set of global vaccine distribution scenarios (Fig. 1 only shows
9 the results under the combination of ‘Elderly First’ and ‘High risk’ scenarios, and the results under
10 other scenario combinations are documented in Supplementary Fig. 3-6, Supplementary Table 3-5).
11 The maps show different types of benefits of 141 modeled regions (see Supplementary Table 7). The
12 panels in the left column (Fig. 1a,d,g,j) show the benefits if the major vaccine-producing countries
13 only distributing vaccines globally after their own population is fully vaccinated (the Selfish
14 Distribution Strategy); the panels in the middle column (Fig. 1b,e,h,k) show the results when the
15 major vaccine-producing countries share their vaccine altruistically with other countries (the
16 Altruistic Distribution Strategy; a pure per capita allocation); and panels in the right column (Fig.
17 1c,f,i,l) show the benefits when the major vaccine-producing countries share their vaccine
18 altruistically with other countries with age profile (the Altruistic Age-informed Distribution Strategy;
19 an age-adjusted per capita allocation). Three kinds of benefits are shown in the first three rows,
20 namely health gains (Fig. 1a,b,c), lockdown-easing benefit (Fig. 1d,e,f), and supply-chain rebuilding
21 benefit (Fig. 1g,h,i). The total benefit is then shown in the bottom row of Fig. 1 (Fig. 1j,k,l).

22 **Altogether Fig. 1 shows that a more equitable distribution of vaccines across the world (i.e.,**
23 **Altruistic Distribution Strategies) would bring more societal benefits globally than a vaccine**
24 **distribution that is focused on vaccine-producing countries (i.e., the Selfish Distribution**
25 **Strategy). If the Selfish Distribution Strategy is adopted, the total global benefit from vaccination is**
26 **estimated to be US\$8.10 trillion (~9.6% of world GDP) per year. If the Altruistic Distribution**
27 **Strategy is adopted, the total global benefit from vaccination increases to \$8.65 (~10.2% world GDP)**
28 **per year. And if the Altruistic Age-informed Distribution Strategy is adopted, the total global benefit**
29 **from vaccination further increases to \$9.05 (~10.7% world GDP) per year. This finding holds under**
30 **other combinations of domestic scenarios (see Supplementary Fig. 2-5).**

31



1

2 **Figure 1 | Vaccination-related benefits under different global vaccine-distribution schemes.**

3 Each row represents the distribution of a category of benefit and the global total under different
4 scenarios, **a-c**, the health benefits; **d-f**, benefits from the alleviation of lockdown; **g-i**, the benefits
5 from global supply chain recovery; **j-l**, total benefits. Each column represents a global vaccine
6 allocation scenario (see Box 1): the left column shows the results under the Selfish Distribution
7 Strategy; the middle column shows the results under the Altruistic Distribution Strategy; and the
8 right column shows the results under the Altruistic Age-informed Distribution Strategy. The depth of
9 the color indicates the size of the benefit (expressed as a percentage of the country's GDP). The
10 number in the lower right corner of each map represents the total benefit of the world (expressed as
11 trillion US dollars in 2020). Fig. 1 shows the results under the combination of 'Elderly First' and
12 'High risk' scenarios, and the results under other scenario combinations are shown in Supplementary
13 Figure 3-6 and Supplementary Table 3-5.

14 **A more equitable distribution of vaccines covering a larger number of high-risk populations**
15 **would not only increase health benefits by protecting more lives and direct domestic**
16 **production benefits by reducing the need of strict lockdowns, but would also facilitate the**
17 **recovery of the inter-industrial linkages and intra-/inter-regional supply chains. First,**
18 compared to the Selfish Distribution Strategy, the overall health gains have increased by 1.8% under
19 the Altruistic Distribution Strategy and 7.0% under the Altruistic Age-informed Distribution Strategy
20 (Fig. 1a-c). Under two Altruistic Distribution Strategies, the elderly with a high infection-mortality
21 rate and workforce with high exposure risk are covered more, resulting in more lives saved globally
22 (Supplementary Table 8). For example, in Mozambique (one of the least developed economy), the
23 health gains under the Selfish Distribution Strategy and Altruistic Age-informed Distribution

1 Strategy are 9.5% and 13.3% of annual GDP, respectively (Fig. 1a,c). In the other hand, vaccine-
2 producing countries deliver more vaccines to other countries in two Altruistic Distribution Strategies,
3 leading to a decline in their health gains unsurprisingly. For example, in Germany, the health gains
4 under the Altruistic Age-informed Distribution Strategy would be reduced by 1.03% of annual GDP
5 compared to the Selfish Distribution Strategy (Fig. 1a,c). These results of healthy gains show that **the**
6 **marginal health gains of vaccine (i.e., health gains created by each additional unit of vaccine)**
7 **in countries lacking vaccines are greater than that in countries where vaccines are relatively**
8 **abundant.** Implicit assumptions in the above conclusion are that vaccine supply is the only
9 constraint, while demand is sufficient (e.g., no vaccine hesitancy issue), and distribution processes
10 (e.g., cold chain) are effective.

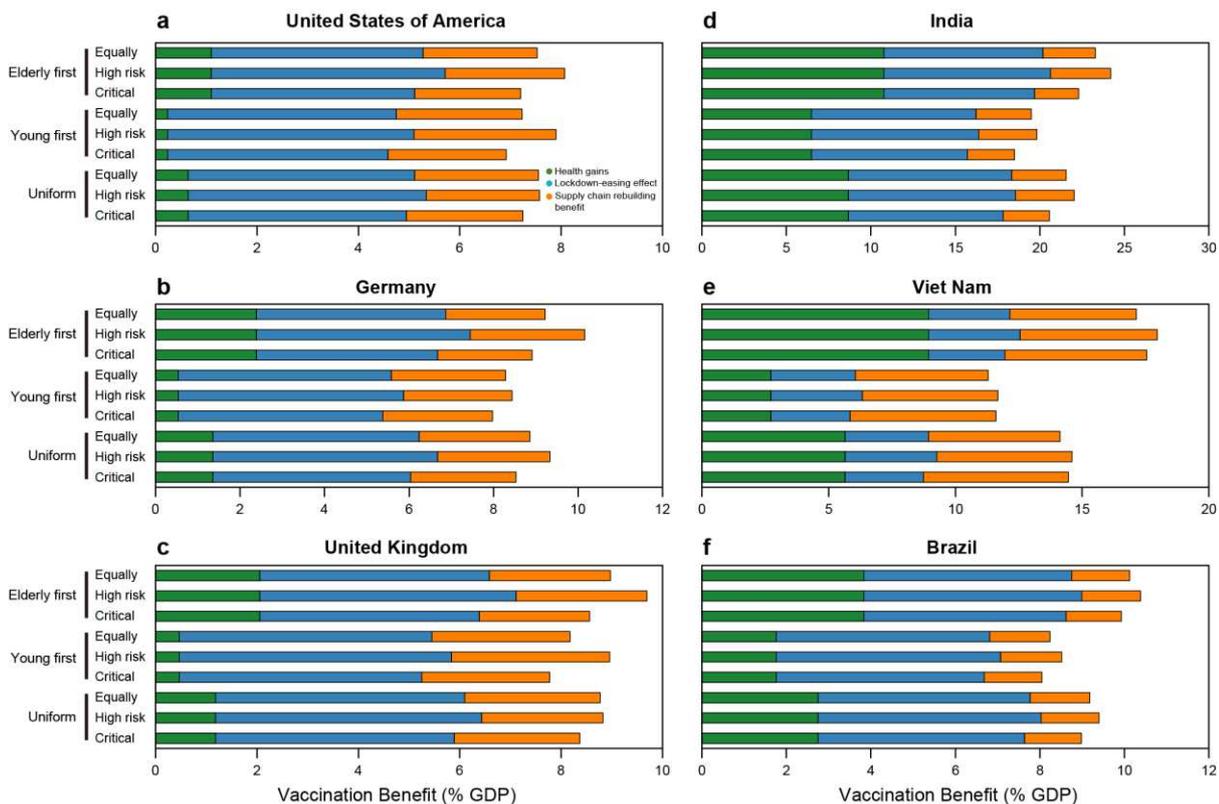
11 **Second,** the overall lockdown-easing benefit under the Altruistic Distribution Strategy would
12 decrease by 2.9% (Fig. 1d-f), mostly because the economic benefits due to the same degree of
13 lockdown-easing are different between well-developed economies and others representing a lower
14 share of the world GDP. For example, in Germany, benefits from lockdown easing under the Selfish
15 Distribution Strategy and Altruistic Distribution Strategy are 7.4% and 5.1% of annual GDP,
16 respectively (US\$82.1 billion decrease; Fig. 1d,e), whereas in Peru, the benefits of the same level of
17 lockdown easing under the Selfish Distribution Strategy and Altruistic Distribution Strategy are
18 6.9% and 12.3% of annual GDP, respectively (US\$10.9 billion increase; Fig. 1d,e). While, the
19 overall lockdown-easing benefit under the Altruistic Age-informed Distribution Strategy would
20 increase by 1.1% compared to the Selfish Distribution Strategy (Fig. 1d-f). This is mainly because
21 the altruistic allocation strategy has been adjusted according to the age profile of each country,
22 resulting in countries with more elderly people getting more vaccines per capita. These countries
23 with more elderly people also tend to be well-developed economies representing a higher share of
24 the world GDP. Therefore, if only in terms of maximizing direct economic benefits (lockdown-
25 easing benefit), the priority of vaccination should be based on GDP per capita. This is very
26 straightforward and seems to reflect the current vaccine distribution situation. But when we take
27 indirect economic effects (supply-chain rebuilding benefit) into consideration, the results will be
28 different.

29 **Finally,** compared to the Selfish Distribution Strategy, the overall supply-chain rebuilding benefit
30 has increased by 67.4% under the Altruistic Distribution Strategy and 74.7% under the Altruistic
31 Age-informed Distribution Strategy (Fig. 1g-i). A better recovery within each country under two
32 Altruistic Distribution Strategies is crucial to the recovery of the global supply chains. For example,
33 Portugal has a high degree of trade openness (the total of imports and exports as a percentage of
34 GDP, 65.6%), meaning that the country has close supply-chain linkages with other countries across
35 the world. By switching from the Selfish Distribution Strategy to the Altruistic Age-informed
36 Distribution Strategy, Portugal would experience the most significant increase in supply-chain
37 rebuilding effect from 0.9% to 5.0% of annual GDP (Fig. 1g,i). Its largest trading partner, Spain, has
38 a lockdown-easing benefit of 6.3% under the Altruistic Age-informed Distribution Strategy scenario,

1 which is 46.2% higher than under the Selfish Distribution Strategy. The recovery of Spain has a
 2 positive spillover effect on Portugal.

3 In addition to the difference between Selfish and Altruistic Distribution Strategies, our modeling of
 4 the two Altruistic Distribution Strategies, without- and with age adjustment, shows the potential
 5 benefit from considering both the population and age structure of the countries when allocating
 6 vaccines internationally. Until now, COVAX has not taken age or disease prevalence into account in
 7 country allocation despite strongly urging age-based allocation within countries.

8 Figure 2 depicts the benefits for six representative countries under 9 scenarios with different
 9 combinations of vaccination priority groups by age (set of scenario A) and priority of workforce in
 10 different industrial sectors (set of scenario S; Fig. 2 shows results under ‘Altruistic Distribution
 11 Strategy’ scenario for six countries, see Supplementary Table 3-5 for the results of other scenario
 12 combinations for all countries). The panels in the left column (Fig. 2a-c) show the results for three
 13 well-developed major vaccine-producing countries (i.e., the United States of America, Germany, and
 14 the United Kingdom). The panels in the right column (Fig. 2d-f) show the results for three emerging
 15 economies (i.e., India, Vietnam, and Brazil).



16

17 **Figure 2 | Vaccination-related benefits under different domestic vaccine-distribution strategies**
 18 **for selected countries.** Three types of benefits (health gains, lockdown-easing benefit and supply-
 19 chain rebuilding benefit) under 9 scenarios with different combinations of vaccination priority
 20 groups by age and priority of workforce in different industrial sectors (see Box 1, Supplementary
 21 Fig. 1). Colors indicate the category of benefit: the health gains (**Green**), the lockdown-easing

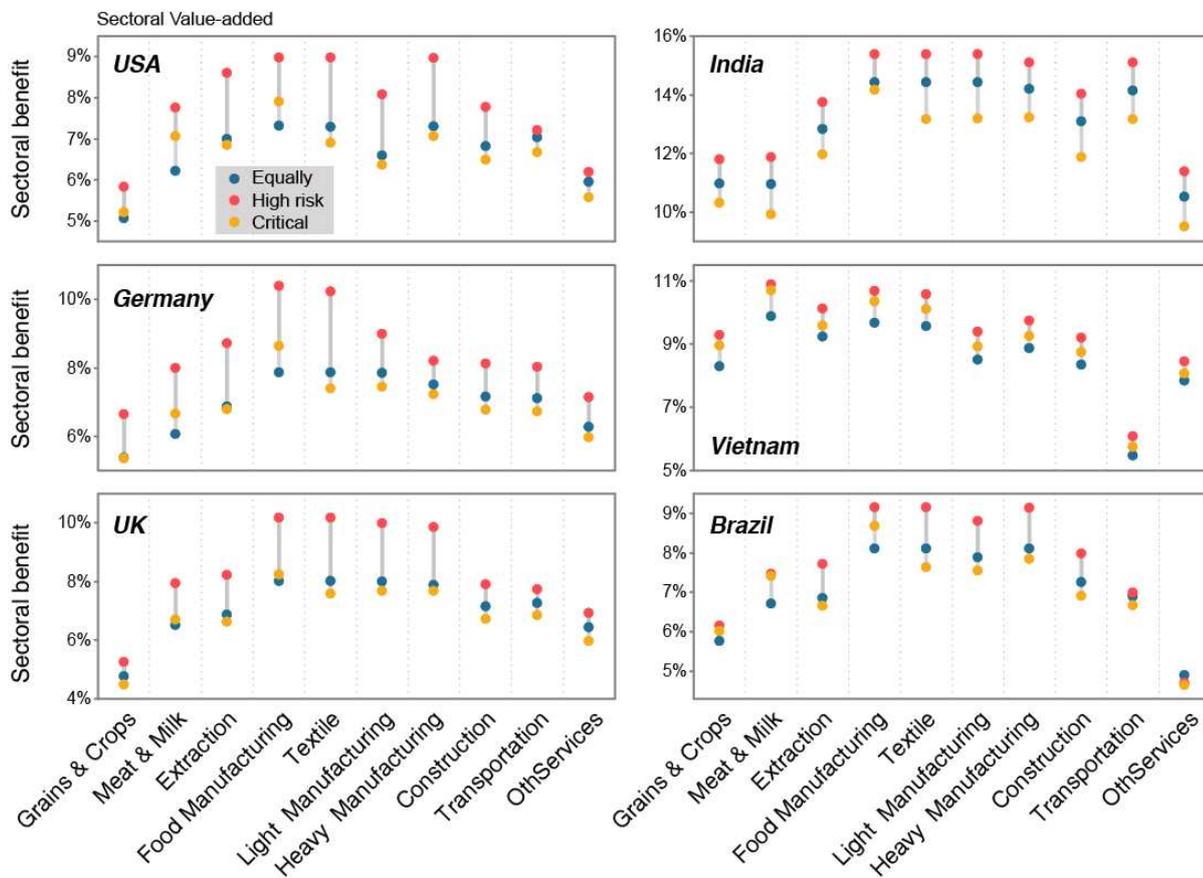
1 benefit (**Blue**), and the supply-chain rebuilding benefit (**Orange**). The length of each bar indicates
2 the amount of benefit per year (expressed as a percentage of the country's annual GDP). The
3 "Altruistic Distribution Strategy" scenario is the default scenario in this comparison (see
4 Supplementary Table 3-5 for the results of other scenario combinations for all countries).

5 **Fig. 2 shows that economic benefits are largest when the priority of domestic vaccine**
6 **distribution is given to the elderly segment, i.e., 65 years old and above, of the population**
7 **followed by workforce with high exposure risk, such as workers in transportation,**
8 **accommodation, and catering industrial sectors.** Fig. 2 shows that giving priority to the elderly
9 generally provides higher economic benefits, even though the difference is not as large as could have
10 been expected. For example, the total benefit from vaccination in the USA is about 7.5%
11 (7.2%~8.1%) of annual GDP when the elderly group is prioritized, whereas the total benefits
12 decrease to about 7.2% (6.9%~7.9%) of annual GDP when young people are prioritized. This
13 reduction is mainly explained by the difference in health gains from vaccination. The health benefit
14 from vaccination of the USA population is 1.1% of annual GDP when the vaccine is given first to the
15 elderly, about 4 times higher than the health benefit if priority is given to young people (0.2% of
16 USA annual GDP). The results of other countries also support this conclusion (Fig. 2b-f,
17 Supplementary Table 3-5). The infection-mortality rate among the elderly is relatively high.
18 Prioritizing the elderly can thus save more lives (see Supplementary Fig. 6) and result in higher
19 health gains.

20 Once the elderly are fully vaccinated, moving to vaccinate workforce in sectors with high exposure
21 risk would bring higher economic benefits than an equally distribution across sectors ('Equally'
22 scenario), through both lockdown-easing benefit and supply-chain rebuilding benefit (Fig. 2). For the
23 United States, Germany, Vietnam, and Brazil, this pattern is more pronounced. For example, the
24 lockdown-easing benefit from vaccination in the USA is 4.6% of annual GDP when workforce with
25 high exposure risk is prioritized (note that 'Altruistic Distribution Strategy' and 'Elderly First' is the
26 default when we discuss results of sectoral distribution), 10.3% higher than the lockdown-easing
27 benefit if vaccinating the whole workforce equally (4.2% of annual GDP). Meanwhile, the supply-
28 chain rebuilding benefit from vaccination in the USA is 2.4% of annual GDP when the vaccine is
29 given first to workforce with high exposure risk, 9.1% higher than the lockdown-easing benefit if
30 vaccinating the whole workforce equally (2.2% of annual GDP). The results of other countries also
31 support this conclusion (Fig. 2b-f, Supplementary Table 3-5). Prioritizing vaccination of workers
32 with high exposure risk can greatly reduce the need of strict lockdown, which is conducive to the
33 recovery of the local economy, and further the global supply chains.

34 **Figure 3, representing the sectoral benefits under different domestic vaccine-distribution**
35 **strategies, shows that prioritizing workforce with high exposure risk (Supplementary Table 1),**
36 **would maximize economic recovery in those sectors but also create strong positive spillover**
37 **effects to other production sectors.** Generally, the entire economy would obtain the largest benefits
38 when workers in production sectors at high risk of exposure are prioritized (scenario S - High risk;

1 red dots in Fig. 3) – this being due to the inter-sector spillovers²²⁻²⁴. Prioritizing high-risk groups
 2 (red dots in Fig. 3) contributed 0.1%-10.9% extra spillover benefits as compared with an equal
 3 distribution strategy across industrial sectors (blue dots in Fig. 3; see Supplementary Table 9). This
 4 highlights the importance of considering externalities when designing domestic vaccine allocation
 5 strategies.



6
 7 **Figure 3 | Vaccination-related sectoral benefits under different sectoral vaccination strategies**
 8 **in selected countries.** Total economic benefits under 3 scenarios with different priorities of workforce in
 9 different industrial sectors (see Box 1) in selected countries. The “Altruistic Distribution” and “Elderly
 10 First” scenarios are the default scenario in this comparison. The **x-axis** represents 10 industrial sectors
 11 (see Supplementary Table 10 for sector aggregation information), and **y-axis** represents the total economic
 12 benefit of each industrial sector (expressed as a percentage of the value-added of corresponding industrial
 13 sector). Color represents different vaccination scenarios: **blue**, any available dose will be equally allocated
 14 from the outset to the working populations across all economic sectors (Equally); **red**, any available dose will
 15 be first given to the working populations of specific sectors as ranked in terms of the exposure risk (High
 16 risk); (3) **orange**, any available dose will be first given to the working populations in each economic sector
 17 based on the proportion of critical workers (Critical, total labor requirements to meet demand for basic
 18 necessities, see²⁵ and Supplementary Table 2).

19 The tighter the association among domestic sectors, the larger the spillover benefits from the
 20 recovery of one sector to all other economic sectors. In the well-developed economies, i.e., the USA,

1 Germany, and the UK, the association among domestic sectors is relatively high. Therefore, giving
2 priority to workforce with high exposure risk not only help the rapid recovery of these departments,
3 but the recovery effect will quickly cascade to other sectors. For example, in the USA and Germany,
4 the benefits of ‘Grains and Crops’ sector would increase by 15.2% and 23.6%, respectively, under
5 ‘High risk’ scenario compared to ‘Equally’ scenario. This is because machinery is a key input in
6 modern agriculture in well-developed countries^{26,27}. The recovery of light and heavy manufacturing
7 industries is conducive to the recovery of the agricultural sector, which may otherwise suffer, e.g.,
8 from missing parts for equipment. Given that in low-income countries, the association among sectors
9 along the domestic supply chains is weaker than in developed countries, the spillover benefits would
10 be lower than in high-income countries. For example, Viet Nam and in Brazil would see the spillover
11 benefit to the agriculture sector increasing by only 11.9% and 6.6%, respectively, under ‘High risk’
12 scenario compared to ‘Equally’ scenario.

13 We also analyzed the benefits under the ‘Critical’ scenario (orange dots in Fig. 3) in which any
14 available dose will be firstly given to the working populations in terms of the critical worker
15 proportion in each industrial sector (see Supplementary Table 2). For example, compared to the
16 recreation sector, workers in the food manufacturing sector will be given priority. Fig. 3 shows that
17 the benefits of the ‘Critical’ scenario (orange dots) are generally the lowest among the three
18 vaccination strategies, which indicates that there is a trade-off between guaranteeing food/daily
19 necessities and overall economic recovery. Therefore, in the most urgent situation, we should give
20 priority to workforce in the critical sector. But after the food and necessities are met, we should give
21 priority to workforce in high-risk sectors to optimize the economic recovery.

22 **Discussion**

23 Our modeling of vaccines distribution demonstrates the potentially significant differences in the
24 socioeconomic benefits brought by different global and domestic vaccines distribution modes.
25 Insights extracted from our scenario analysis suggesting that economic benefits will be maximized
26 by giving priority to vaccinating high-risk populations all over the world, including the elderly with
27 high infection-mortality rate and workers with a high risk of exposure. Indeed, recent results from
28 related research seem to support this same conclusion^{28,29}. Our modeling of the benefits of
29 vaccination in terms of health gains, lockdown-easing benefit, and supply-chain rebuilding benefit,
30 quantifies the spillover effects of vaccination providing further support, beyond the arguments in
31 terms of infection-mortality rate and probability of exposure, to the choice of an altruistic vaccine
32 distribution strategy across the world.

33 Our study has some limitations. We do not build a feedback mechanism between the epidemiological
34 and the economic model, i.e., the interaction between the intensity of economic activity and the
35 spread of the virus. We acknowledge that a feedback mechanism is theoretically feasible. The current
36 practical knowledge in this area, however, is still very limited, which means that the introduction of a
37 feedback mechanism will bring about very large uncertainties. Our model is also limited by taking no

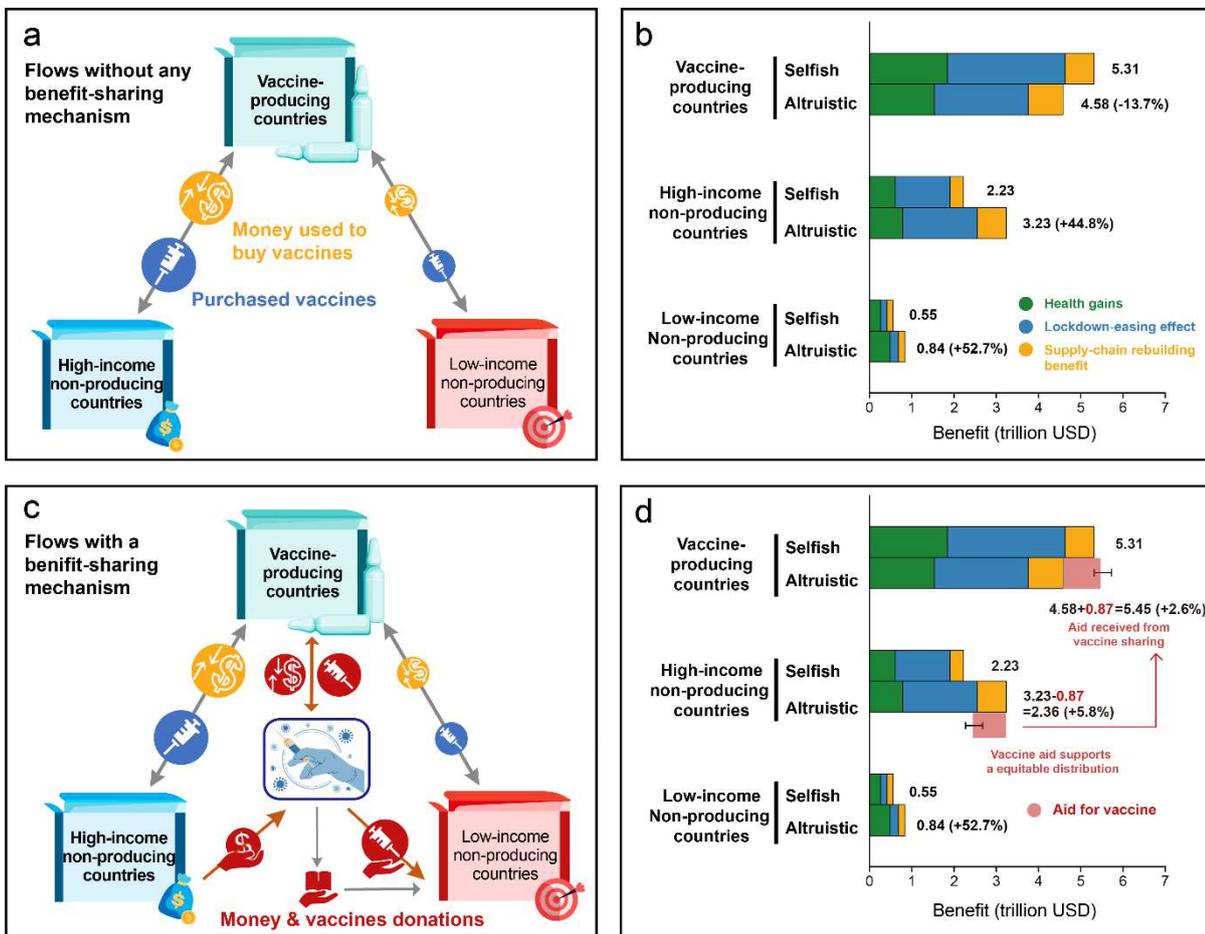
1 consideration of technological changes and adjustment of behaviors and by assuming that production
2 and consumption patterns remain the same as pre-crisis. Our model has a focus on the short-term
3 scenarios, and therefore the above two assumptions are rather unlikely to have a significant impact
4 on the results¹. Our model is further constrained by the trade relationship at the sectoral level among
5 countries, and has no ability to capture the complexity of supply-chain networks at the firm level and
6 may therefore underestimate the benefits³⁰. In addition, this study only focuses on economic benefits.
7 We acknowledge that maximize the aggregate benefit is not the only criteria that need to be
8 accounted for, but also fairness and feasibility. But these are beyond the scope of this study.

9 **While our scenarios are idealized cases, the current vaccine distribution is closer to the Selfish**
10 **distribution one^{6,7}. As a final analysis, we explore opportunities for Pareto improvement with**
11 **an improved distribution of vaccines.** In order to simplify the analysis, 1) we group all countries
12 into three categories: (i) the major vaccine-producing countries; (ii) the non-vaccine-producing
13 countries with high-income levels (>US\$4046 per year; World Bank high-income and upper-middle-
14 income countries); and (iii) the non-vaccine-producing countries with low-income levels (<US\$4046
15 per year; World Bank low-middle-income and low-income countries); 2) we assume that, in our
16 scenarios, vaccines are traded at their production costs so that vaccine-producing countries do not
17 benefit from vaccine sales (mimicking the current situation of vaccine-producing countries donating
18 vaccines to low-income countries).

19 **Figure 4 shows that globally the Altruistic Distribution Strategy would create 6.8% additional**
20 **benefits as compared to the Selfish Distribution Strategy, implying that there is room for**
21 **Pareto improvement from the Selfish Distribution Strategy (i.e., a change in which the**
22 **reallocation of vaccines can make at least one group better off without making any of them**
23 **worse off).** Flows of money and vaccines without any benefit-sharing mechanism are shown in Fig.
24 4a. In this case, the distribution of vaccines is quite unequal due to differences in consumption
25 capacity of different groups of countries. If the vaccine-producing countries choose the Selfish
26 Distribution Strategy, the world's annual average benefit from vaccination is estimated at US\$8.10
27 trillion (about two times the annual US government spending; Fig. 4b). The benefit to the vaccine-
28 producing countries is US\$5.31 trillion, while the benefit to non-vaccine-producing countries with
29 high-income and low-income levels are US\$2.23 trillion and US\$0.55 trillion, respectively. When
30 vaccine-producing countries adopt the Altruistic Distribution Strategy, the world's annual average
31 benefit from vaccination is US\$8.65 trillion (Fig. 4b). In this case, the benefit to the vaccine-
32 producing country is US\$4.58 trillion, whereas the benefit of non-producing countries with high-
33 income levels and low-income levels are US\$3.23 trillion and US\$0.84 trillion, respectively (Fig.
34 4b). **Based on these results, it appears clear why the current global vaccine distribution tends to**
35 **be a Selfish Distribution Strategy rather than an Altruistic Distribution Strategy even if only**
36 **economic benefits are considered.** That is, without any benefit-sharing mechanism, vaccine-
37 producing countries are more willing to choose the Selfish Distribution Strategy that is most
38 beneficial to themselves, while other countries have no option but to accept an unequal distribution
39 of vaccines. Note that political pressure faced by governments of vaccine-producing countries to

1 prioritize their population before exporting, and even the rise of the so-called “vaccine nationalism”³¹
 2 during the COVID-19 pandemic can also be major reasons for the current unequal distribution
 3 situation, which is out of the scope of this study.

4 This dilemma has reproduced the current unequal situation. That is, vaccine-producing countries
 5 prefer to give priority to vaccinating their residents, high-income non-producing countries buy large
 6 amounts of vaccines for their domestic use, while, middle- and low-income non-producing countries
 7 can only obtain very few vaccines due to their insufficient consumption capacity. The reason for this
 8 situation is that the benefits of health (health gains) are straightforward and easy to be taken into
 9 consideration, but the benefits of the economic recovery (lockdown-easing benefit and supply-chain
 10 rebuilding benefit) are often not well understood and considered. A key significance of the
 11 quantitative analysis presented in this article is that it provides countries with a comprehensive
 12 understanding of their potential payoffs in the global vaccine distribution game, which is a
 13 prerequisite for players to make the right decision.



14

15 **Fig. 4 | Vaccination-related benefits of three groups under different global vaccine-distribution**
 16 **strategies and the potential incentives (benefit-sharing mechanism) to promote a more**
 17 **equitable distribution. a)** shows flows of money and vaccines without any benefit-sharing
 18 **mechanism; b)** shows the benefits of the three groups of countries without any benefit-sharing
 19 **mechanism; c)** shows flows of money and vaccines with the proposed benefit-sharing mechanism; **d)**

1 shows the new situation (payoffs of the three groups of countries under different distribution
2 strategies) with the benefit-sharing mechanism. The yellow money symbol in Fig.4a and c indicates
3 money used to buy vaccines and the blue vaccine symbol in Fig. 4a and c indicates vaccines
4 purchased. The red money symbol with a hand below in Fig. 4c indicates money donations and red
5 vaccine symbol with a hand below in Fig.4c indicates vaccine donations. The “Selfish” and
6 “Altruistic” in Fig.4b and d represent the “Selfish Distribution Strategy” scenario and “Altruistic
7 Distribution Strategy” scenario. The number on the horizontal bars in Fig.4b and d indicates the
8 benefit (expressed in trillion US dollars). The light red horizontal bars in Fig.4d represent the aids
9 from high-income countries to promote a more equitable distribution of vaccines around the world.
10 The ‘Elderly First’ and ‘High risk’ scenario is the default scenario in this comparison.

11 **Based on the distribution of benefits shown in Fig. 4b, we propose a benefit-sharing**
12 **mechanism, shown in Fig. 4c, that can incentivize vaccine-producing countries to share**
13 **vaccines early and promote global vaccine distribution towards a “win-win” equilibrium.** As
14 shown in Fig. 4c, through the proposed benefit-sharing mechanism based on an international
15 platform, high-income non-producing countries donated vaccine aid to the platform to seek a
16 globally equitable distribution of vaccines. Vaccine-producing countries deliver vaccines to the
17 platform and obtain corresponding benefits. Middle- and low-income countries actively cooperate
18 with the platform in completing vaccine delivery and capacity building. The basis for this proposal to
19 become economically rational is the positive externality of vaccination implicit in the global supply
20 chain recovery. Note that the benefit-sharing mechanism proposed here only provides a potential
21 economically rational way of international cooperation on the basis of the modeling of the externality
22 of vaccination. It does not mean that the current situation is not an economically rational equilibrium,
23 while it highlights that the current situation has room for Pareto improvement through cooperation.

24 **Figure 4d shows that the three parties are willing to implement this mechanism when the**
25 **donation required is within a certain amount.** High-income non-producing countries can share
26 part of the additional benefits gained as a result of the Altruistic Distribution Strategy (US\$0.87
27 trillion) with vaccine-producing countries in order to persuade vaccine-producing countries to choose
28 the Altruistic Distribution Strategy. If the extra cost is less than US\$1.00 trillion, high-income non-
29 producing countries are willing to do so because their benefit will be still greater than the benefit in
30 the Selfish Distribution Strategy after they have paid the cost. Meanwhile, if the transfer is greater
31 than US\$0.73 trillion, vaccine-producing countries will be willing to choose the Altruistic
32 Distribution Strategy because their benefit will exceed the benefit of choosing a Selfish Distribution
33 Strategy (US\$5.31 trillion). And undoubtedly, middle- and low-income countries are willing to
34 receive vaccines or build local production capacity as these are beneficial to them. With this
35 incentive mechanism, the benefits of the three groups of countries will be improved simultaneously.

36 **Our quantification of benefits shows that only when the incentive reaches a certain level can all**
37 **groups achieve the “win-win” situation.** Current proposal made by G7 countries to provide US\$10
38 billion to COVAX³² is, however, insufficient to motivate vaccine-producing countries to largely

1 distribute the vaccines to mid- and low-income countries. To ease off the large divide of vaccine
2 distribution, global governance is needed. On the other hand, the benefit-sharing mechanism
3 proposed here is based on the perspective of externalities and market failures. The specific measures
4 are not necessarily in monetary form. High-income countries would need to provide necessary
5 capacity building to key personnel in establishing production facilities in mid- and low-income
6 countries, where the local government would need to provide necessary space and tax waiving
7 mechanisms for fast and scale productions in order to minimize the cost of vaccinations (including
8 the manufacturing, transportation and logistics, and implementing). All these actions that can
9 increase global vaccine production capacity and reduce distribution costs are part or complementary
10 of the benefit-sharing mechanism proposed here.

11 In preparing for the next pandemics, a global benefit-sharing instrument should be developed so as to
12 remove some of the disincentives for early equitable vaccines distribution globally. Such an
13 instrument would provide enormous global health and economic benefits in an economically
14 sustainable manner.

15

16 **Methods**

17 **Vaccine-distribution scenario sets**

18 To evaluate the economic benefits of allocating the vaccines across the globe, we propose three
19 scenario sets which are designated in a tiered structure. Basically, **Tier Global** scenario sets address
20 the issue of the cooperative attitude of vaccine exporting countries and importing countries, while
21 **Tier Domestic** scenario sets address the issue of allocating the received vaccines within the
22 destination countries. We treat each scenario set as an individual parameter in the model, such that
23 we will have three parameters (i.e., **C**, **A**, **S**). We vary the value of each parameter by considering
24 different sub-scenarios within each scenario set (see Box 1, Supplementary [错误!未找到引用源。](#)).
25 In summary, parameter **C** indicates whether the vaccine exporting country is more willing to share
26 the vaccine with other countries. Parameter **A** define the allocation of the received vaccines within
27 destination countries according to the age. And parameter **S** define the allocation of the received
28 vaccines within workforce in destination countries according to the feature of industrial sector.

29 It is worth noting that countries/regions in this article do not only refer to governments. When we say
30 a country, we mean to abstract this country into a representative agent. For example, vaccines are
31 generally produced by private firms. But for the convenience of discussion, we abstract all private
32 firms combined with all other economic participant in a vaccine production into an agent.

33 Global Vaccine Distribution (Tier Global):

1 Scenario set C (Country): what extent the vaccine-exporting country is willing to share the vaccine
2 with other countries. The acronym C is ‘Country’.

- 3 • **Selfish Distribution Strategy:** Countries producing vaccines use production to fully vaccinate
4 their own population first, and then distribute globally.
- 5 • **Altruistic Distribution Strategy:** Countries put all their vaccines into a global pool and
6 vaccinate uniformly.
- 7 • **Altruistic Age-informed Distribution Strategy.** Countries put all their vaccines into a global
8 pool and vaccinate uniformly according to the population 65 years and older of each country
9 first, if sufficient, then vaccinate uniformly according to the population under 65 years old (y.o.,
10 hereafter) of each country.

11 Domestic Vaccine Distribution (Tier Domestic):

12 Scenario set A (Age group): prioritized age groups in the destination countries. Old first or young
13 first. The acronym A is ‘age’.

- 14 • **Elderly first:** Vaccination prioritization to the old (over 65 y.o.). We assume a mass
15 vaccination for the 65+. If sufficient, the doses will then be distributed to people between 20
16 to 65 y.o. This follows the schedule in most countries.
- 17 • **Young first:** Vaccination prioritization to the younger age classes (20 - 65 y.o.). We assume a
18 mass vaccination for people between 20 to 65 y.o. If sufficient, the doses will then be
19 distributed to the old over 65 y.o. This follows the schedule in China.
- 20 • **Uniform:** Mass vaccination to all people over 20 y.o.

21 Scenario set S (Industrial sector): Prioritized socially vulnerable groups in the destination countries.
22 Considering labors in different sectors, critical workers first or mass distribution. The acronym S is
23 ‘industrial sector’.

- 24 • **High risk:** Any available dose will be firstly given to the working populations in terms of the
25 exposure risk rank of economic sectors.
- 26 • **Equally:** Any available dose will be firstly given to the working populations equally distributed
27 to all economic sectors.
- 28 • **Critical:** Any available dose will be firstly given to the working populations in terms of the
29 critical worker proportion in each economic sector.

30 Combination of each variation of above 3 parameters gives a distribution strategy. In this analysis,
31 we will have $3 \times 3 \times 3 = 27$ scenarios. When comparing the results of a scenario set, “Altruistic
32 Distribution”, “Elderly first”, and “High risk” are used as the default scenario.

33 **Estimation of vaccine production capacity**

34 We consider seven major vaccine-manufacturing countries, including China, US, Germany, India,
35 UK, Netherlands, and Russia³³. We collected the current vaccine production capacity of these
36 countries, and based on this, we predicted the future vaccine production capacity.

- The overall capacity of all manufacturing countries in the “Approved in use” development stage and in the future (i.e., 2022-2023) is collected from the United Nations International Children's Emergency Fund (UNICEF)³³. (see Supplementary Fig. 6-7, Supplementary Table 11)
- With the data, we project the annual capacity of all manufacturing countries by using the logarithmic function to fit the growth trend of capacity. (Supplementary Fig. 6)
- Assuming an invariant relative capacity across countries over time, we further partition the annual capacity to each of the manufacturing country according to their capacity documented on March 3, 2021. (Supplementary Table 11, Supplementary Fig. 7)

10 The epidemiological model

11 Model structure. Built upon our age-structured SIR model¹⁹, we project the fraction of incidence and
12 mortality over age groups by using chains of differential equations:

$$13 \quad \frac{dS_i^p}{dt} = a_{i-1}S_{i-1}^p - \lambda_i S_i^p - a_i S_i^p \quad (1)$$

$$14 \quad \frac{dI_i^p}{dt} = a_{i-1}I_{i-1}^p + \lambda_i S_i^p - \gamma I_i^p - a_i I_i^p \quad (2)$$

$$15 \quad \frac{dR_i}{dt} = a_{i-1}R_{i-1} + \gamma(I_i^p + I_i^{np}) - \omega R_i - a_i R_i \quad (3)$$

$$16 \quad \frac{dS_i^{np}}{dt} = \omega R_i + a_{i-1}S_{i-1}^{np} - \lambda_i S_i^{np} - a_i S_i^{np} \quad (4)$$

$$17 \quad \frac{dI_i^{np}}{dt} = a_{i-1}I_{i-1}^{np} + \lambda_i S_i^{np} - \gamma I_i^{np} - a_i I_i^{np} \quad (5)$$

18 where S_i^p, I_i^p are the number of susceptible individuals and primary infections in age group i ;
19 accordingly, I_i^{np} is the number of non-primary infections. The recovered individuals (R_i) may lose
20 immunity and return to susceptibility (S_i^{np}) after an average duration of immunity of $1/\omega$. The
21 force-of-infection on susceptible in age-class i is designated as $\lambda_i = \beta \sum_j^n C_{ij} (I_i^p + I_i^{np})/N_i$, where
22 $\beta = R_0 \gamma$ is the baseline rate of transmission and C_{ij} is the contact rate between age group i and j .
23 $1/\gamma$ to be the average duration of infection which is taken to be 7 days³⁴. For simplicity, we assume
24 a uniform 1-year duration rate of aging (a_i) across ages, i.e., $a_i = 1$ for all i . Assuming $R_0 = 3.5$,
25 we parameterize the model with country-specific population pyramid³⁵ and social mixing³⁶ over 16
26 age groups. Details of model parameters is provided in Supplementary Table 12.

27 Model simulation. Simulation was initialized with 1% infections and 0.1% recovered individuals,
28 i.e., $S^p(0) = 0.989, I^p(0) = 0.01, R = 0.001$, and $S^{np}(0) = I^{np}(0) = 0$. We project the model to
29 predict dynamics of COVID-19 in the next 6 under different vaccine allocation strategies. To
30 appropriately model the *fraction* of individuals vaccinated, we define the *rate* of vaccination (Q_i) as
31 $-\log(1 - P_i)/D_i$ where P_i and D_i is the vaccine coverage and duration of vaccination in age group

1 i , respectively ^{37,38}; q is the vaccine efficacy. We do not explicitly model the timing of the
2 vaccination campaign; instead, we assume that vaccines are uniformly distributed over the year.
3 With the simulation we estimate the age-specific fraction of infection and further infer the fraction of
4 deaths by multiplying the age-infections with infection fatality ratio (IFR) ³⁹. Considering the current
5 spread and variation of COVID-19, we used the current infection and death data to scale up the
6 simulation results. By comparing the results of scenarios with or without vaccines, we can obtain the
7 benefits of different vaccine distribution strategies.

8 Model assumptions. To appropriately lay out our insights, we make several assumptions. First, we
9 assume the homogeneous susceptibility to infection, clinical fraction and infection vs case-fatality
10 ratio as well as the immunity-dependent infectiousness of reinfection across age classes.
11 Additionally, we assume a one-year duration of immunity, given the brief immunity from natural
12 infection of seasonal coronavirus ⁴⁰. Moreover, we assume a uniform distribution of vaccine roll-out
13 over the year. Relaxing the assumptions by explicitly consider age-specific heterogeneities, differing
14 durations of immunity and the timing of vaccination are easy extensions giving the general nature of
15 our model framework.

16 **The estimation of VSL**

17 The value of statistical life (VSL) is widely used throughout the world to monetize fatality risks in
18 benefit-cost analyses ⁴¹. The VSL represents the individual's local money-mortality risk tradeoff
19 value ⁴², which is the value of small changes in risk not the value attached to identified lives. The
20 country based VSL estimation used in this research is adopted from the COVID-19 global health
21 risks pricing study by Viscusi (Table 6) ⁴³. The estimation is based on the estimated VSL in the U.S.
22 (11 million in 2019 US dollar). Based on this, we do two VSL estimation. We first use an income
23 elasticity (=1.0) to adjust the VSL to other countries using the fixed effects specification ⁴⁴.
24 Supplementary Fig. 10, shows the spatial distribution of estimated VSL for 175 countries used in this
25 approach. And then, to keep in line with the idea that every life is equal, we value each life equally
26 with a global average a uniform global VSL (= 11 USD million times average global GDP per
27 capita/US GDP per capita; 2.94 USD million).

28 **Estimation of required strictness of control measures**

29 COVID-19 has resulted in varying degrees of social lockdown in countries all around the world. The
30 lockdown strictness by each country is measured by the percentage by which labour availability and
31 transportation capacity are reduced relative to pre-pandemic levels. The Google Community
32 Mobility Reports ([COVID-19 Community Mobility Reports \(google.com\)](https://www.google.com/covid19/mobility/)), which aim to provide
33 insights into changes in response to policies aimed at combating COVID-19, are used to measure the
34 strictness specifically. The reports chart movement trends over time by geography, across different
35 categories of places such as retail and recreation, groceries and pharmacies, parks, transit stations,
36 workplaces, and residential. We averaged the changes in the five types of visitors as a parameter to
37 measure the extent of a country's lockdown strictness. The data are monthly, starting in February

1 2020 and the latest up to April 2021. For countries where Google data are not available, we
2 supplement them with data from the nearest country based on geographical location.

3 **The recursive dynamic disaster impact assessment model (estimation of lockdown-easing effect** 4 **and supply-chain rebuilding benefit)**

5 In addition to the life-saving benefits calculated by infectious disease models, vaccine distribution
6 also generates lockdown-easing effect and supply-chain rebuilding benefits through the global
7 supply chains. The global economic benefits will be calculated using the following recursive
8 dynamic disaster impact assessment model ^{1,20,21,45}. The simulation code and examples can be found
9 in GitHub (<https://github.com/DaopingW/economic-impact-model>).

10 We do two simulations and compared the results to obtain the benefits of vaccination. The first
11 simulation is the counterfactual scenario, i.e., a world with no vaccines at all. The results of the first
12 simulation represent global economic loss (includes direct lockdown losses and supply-chain
13 propagations damages) if there is no vaccine. The second simulation is used to calculate the global
14 economic loss under a specific vaccine distribution scenario. The amount by which the loss of the
15 second simulation is less than the loss of the first simulation is defined as the economic benefit of
16 vaccination.

17 In detail, our disaster impact assessment model is an extension of the adaptive regional input-output
18 (ARIO) model ^{20,21}, which was widely used in the literature to simulate the propagation of negative
19 shocks throughout the economy ^{1,5,30,46}. Our model improves the ARIO model in two ways. The first
20 improvement is related to the substitutability of products from the same sector sourced from different
21 regions. Second, in our model, clients will choose their suppliers across regions based on their
22 capacity. These two improvements contribute to a more realistic representation of bottlenecks along
23 global supply chains.

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

31 **Production module.** The production module is used to characterize production processes. Firms rent
32 capital and employ labour to process natural resources and intermediate inputs produced by other
33 firms into a specific product (see Supplementary Fig. 11). The production process for firm i can
34 expressed as follows,

$$35 \quad x_i = f(\text{for all } p, z_i^p; va_i)$$

1 where x_i denotes the output of the firm, in monetary value; p denotes type of intermediate products;
 2 z_i^p denotes intermediate products used in production processes; va_i denotes the primary inputs to
 3 production, such as labour (L), capital (K) and natural resources (NR). $f(\cdot)$ is the production function
 4 for firms. There are a wide range of functional forms, such as Leontief⁴⁵, Cobb-Douglas (C-D) and
 5 Constant Elasticity of Substitution (CES) production function⁴⁷. Different functional forms reflect
 6 the possibility for firms to substitute an input for another. Considering that epidemics often cause
 7 large-scale economic fluctuations in the short term, during which economic agents do not have
 8 enough time to adjust other inputs to substitute temporary shortages, we use Leontief production
 9 function which does not allow substitution between inputs.

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

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

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

13 and

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

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

19 *Labour supply constraints.* Labour constraints after a disaster may impose severe knock-on effects
 20 on the rest of the economy^{20,48}. This makes labour constraints a key factor to consider in disaster
 21 impact analysis. For example, in the case of a pandemic, these constraints can arise from employees'
 22 inability to work as a result of illness or death, or from the inability to go to work and the
 23 requirement to work at home (if possible). In this model, the proportion of surviving productive
 24 capacity from the constrained labour productive capacity (x_i^L) after a shock is defined as:

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

26 Where $\gamma_i^L(t)$ is the proportion of labour that is unavailable at each time step t during containment.
 27 $(1 - \gamma_i^L(t))$ contains the available proportion of employment at time t .

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

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

8 *Constraints on productive capital.* Similar to labour constraints, the productive capacity of
 9 industrial capital in each region during the aftermath of a disaster (x_i^K) will be constrained by the
 10 surviving capacity of the industrial capital^{46,49,50}. The share of damage to each sector is directly
 11 considered as the proportion of the monetized damage to capital assets in relation to the total value of
 12 industrial capital for each sector, which is disclosed in the event account vector (EAV) for each
 13 region (γ_i^K), following⁵⁰. This assumption is embodied in the essence of the IO model, which is
 14 hard-coded through the Leontief-type production function and its restricted substitution. That is, as
 15 capital and labour are considered perfectly complementary as well as the main production factors,
 16 and the full employment of those factors in the economy is also assumed, we assume that damage in
 17 capital assets is directly related with production level and therefore, value added level. Then, the
 18 remaining productive capacity of the industrial capital at each time step is defined as:

$$19 \quad x_i^K(t) = (1 - \gamma_i^K(t)) * \bar{x}_i$$

20 Where, \bar{K}_i is the capital stock of firm i in the pre-disaster situation, and $K_i(t)$ is the surviving capital
 21 stock of firm i at time t during the recovery process.

$$22 \quad \gamma_i^K(t) = (\bar{K}_i - K_i(t))/\bar{K}_i$$

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

$$27 \quad x_i^p(t) = \frac{S_i^p(t-1)}{a_i^p}$$

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

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

$$32 \quad x_i^{\text{max}}(t) = \min(x_i^L(t); x_i^K(t); \text{for all } p, x_i^p(t))$$

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

$$3 \quad x_i^a(t) = \min(x_i^{max}(t), TD_i(t-1))$$

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

$$5 \quad S_i^{p,used}(t) = a_i^p * x_i^a(t)$$

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

$$14 \quad FRC_j^i(t) = \frac{FOD_i^j(t-1)}{(\sum_j FOD_i^j(t-1) + \sum_h HOD_i^h(t-1))} * x_i^a(t)$$

$$15 \quad HRC_h^i(t) = \frac{HOD_i^h(t-1)}{(\sum_j FOD_i^j(t-1) + \sum_h HOD_i^h(t-1))} * x_i^a(t)$$

16 Firm j received intermediates to restore its inventories,

$$17 \quad S_j^{p,restored}(t) = \sum_{i \rightarrow p} FRC_j^i(t)$$

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

$$19 \quad S_j^p(t) = S_j^p(t-1) - S_j^{p,used}(t) + S_j^{p,restored}$$

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

$$24 \quad S_i^{p,*}(t) = n_i^p * a_i^p * x_i^{max}(t)$$

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

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

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

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

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^{20,21} (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

1 isolation measures. These measures have placed constraints on the supply of labour and the
 2 transportation of products. This led to a decline in China's output and also triggered the forward and
 3 backward effect, which make the shock to propagate to the global economic network. From the
 4 household side, the fluctuation of household demand caused by exogenous shocks will also trigger
 5 the aforementioned backward effect. Take tourism as an example, during the outbreak of COVID-19
 6 in China, the demand for Chinese tourism from households all over the world will decline
 7 significantly. This influence will further propagate to the accommodation and catering industry
 8 through supplier-client links.

9 Economic footprint. We define the value-added decrease of all firms in a network caused by an
 10 exogenous negative shock as the disaster footprint of the shock. For the firm directly affected by
 11 exogenous negative shocks, its loss includes two parts: a) the value-added decrease caused by
 12 exogenous constraints, and b) the value-added decrease caused by propagation. The former is the
 13 direct loss, while the latter is the indirect loss. A negative shock's total economic footprint ($TEF_{i,r}$),
 14 direct economic footprint ($DEF_{i,r}$), and propagated economic footprint ($PEF_{i,r}$) for firm i in region r
 15 are,

$$16 \quad TEF_{i,r} = \bar{v}\bar{a}_{i,r} * T - \sum_{t=1}^T va_{i,r}^a(t)$$

17 and,

$$18 \quad DEF_{i,r} = \bar{v}\bar{a}_{i,r} * T - \sum_{t=1}^T va_{i,r}^{max}(t)$$

19 and,

$$20 \quad PEF_{i,r} = TEF_{i,r} - DEF_{i,r}$$

21 Global supply-chain network. We build a global supply chain network based on version 10 of the
 22 Global Trade Analysis Project (GTAP) database ⁵¹. GTAP 10 provides a multiregional input-output
 23 (MRIO) table for the year of 2014. This MRIO table divides the world into 141 economies, each of
 24 which contains 65 production sectors. If we treat each sector as a firm (producer), and assume that
 25 each region has a representative household, we can obtain the following information in the MRIO
 26 table: a) suppliers and clients of each firm; b) suppliers for each household, and c) the flow of each
 27 supplier-client connection under the equilibrium state. This provides a benchmark for our model.

28 When applying such a realistic and aggregated network in the disaster footprint model, we need to
 29 consider the substitutability of intermediate products supplied by suppliers from the same sector in
 30 different regions. The substitution between some intermediate products is fairly straightforward. For
 31 example, for a firm that extracts spices from bananas it does not make much of a difference if the
 32 bananas are sourced from the Philippines or Thailand. However, for a car manufacturing firm in
 33 Japan, which use screw from Chinese auto parts suppliers and engines from German auto parts

1 suppliers to assemble cars, the products of the suppliers in these two regions are non-substitutable. If
2 we assume that all goods are non-substitutable as in the traditional IO model, then we will
3 overestimate the loss of producers such as fragrance extraction firm. If we assume that products from
4 suppliers in the same sector can be completely substitutable, then we will significantly underestimate
5 the losses of producers such as Japanese car manufacturing firm. In order to alleviate the
6 shortcomings of the evaluation deviation under the two assumptions, we set the possibility of
7 substitution for each firm based on the region and sector of supplier supply (see Allocation Module
8 of the model).

9

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28

29 **Competing interests:** Authors declare that they have no competing interests.

30 **Data and materials availability:** The simulation code can be accessed at
31 <https://github.com/DaopingW/economic-impact-model> . The minimal input for the code is
32 multiregional input–output table. The sample code and test data for the minimal inputs are also
33 provided. The global trade dataset used to stimulate the presented results are licensed by from the
34 Global Trade Analysis Project at the Center for Global Trade Analysis in Purdue University’s
35 Department of Agricultural Economics. The GTAP version 10 can be obtained for a fee from its
36 official website: <https://www.gtap.agecon.purdue.edu/databases/v10/index.aspx>. Owing to the
37 restriction in the licensing agreement with GTAP, the authors have no right to disclose the
38 original dataset publicly.

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