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PIGOVIAN EXPORT PROMOTION AND COOPERATION IN A PANDEMIC*

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Abstract

We develop a model in which two vaccine-producing firms from two developed countries supply vaccines to the developing world during a pandemic. Exporting developed countries experience a negative externality from incomplete global vaccination. Both domestic and trade policies are examined. Alternative policy regimes of non-intervention, independent national policy and cooperation among exporters are considered. For each alternative, welfare levels of exporting and importing countries and global welfare are calculated. We derive conditions for cooperation among producing countries to attain higher global welfare than non-cooperation. In fact, in some circumstances cooperation among developed countries can even achieve the global optimum.

Keywords: Cooperative and non-cooperative trade policy, Export promotion, Global externality, Global welfare. Pigovian subsidies.
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1 Introduction

In a world beset with negative externalities originating from global problems − from pandemics to climate change and diminishing biodiversity− Pigovian policies (Pigou, 1920) have gained renewed significance. The absence of supranational authorities with the power to implement corrective global policies gives national governments −particularly during times of crises− an increased incentive to intervene unilaterally. At the start of the Covid-19 pandemic in March 2020, the use of unilateral trade policy measures increased.[1] Baldwin and Evenett (2020), among others, have pointed to the need for enhanced trade policy cooperation through the World Trade Organisation (WTO). While global cooperation initiatives to fight and prevent future pandemics have been repeatedly called for by the World Health Organisation (WHO), they are extremely hard, if not impossible, to achieve.[2]

There exists a large literature on the formation of cooperative agreements. While that literature is concerned with the mechanism design for coalition formation for the provision of a global public good (for a recent survey, see Bucholz and Sadler (2021)), the focus in our paper is different. Abstracting from the difficulties of reaching cooperative agreements, we explore how trade policy cooperation among a limited number of countries affects global welfare when countries face a global externality. We ask when policy cooperation among vaccine-exporting countries only can be sufficient to raise global welfare during a pandemic.

We adopt a setting in which two oligopolistic pharmaceutical firms from developed countries have developed a vaccine, which they export to other countries. Our modelling choice reflects the fact that during the Covid-19 pandemic, the market was dominated by a few widely authorised vaccines from very few countries.[3] We assume that the domestic population of the exporting countries has been vaccinated. However, the unvaccinated population of a developing country causes a negative externality for the rest of the world, including the exporting countries. To mitigate the effects of the externality, the governments of the exporting countries are assumed to have two policy instruments: socio-economic restrictions[4], which limit the contagion from the unvaccinated abroad, and export subsidies, which promote the take-up of vaccines abroad.[5] Hence, we model the behaviour of several agents −firms and governments− and

[1] High-income countries tightened export restrictions of crucial medical equipment, while low-income importing countries lowered import restrictions. While some of these policies have been reversed, others remain (Espitia *et al.*, 2020). Evenett (2020) argues that export promotion schemes have been abundant, and that Covid-19 can act as a catalyst for export mercantilism.

[2] Barrett (1992) shows that international environmental agreements become less effective as the number of signatories increases. Also, Barrett (2003) argues that a global eradication of infectious diseases −which is only possible if these diseases are eliminated in every country− requires strong international institutions. Although in April 2020 a global cooperative scheme −Covax− was established to fight the COVID-19 pandemic, with richer countries subsidising costs for poorer nations, it has been slow to deliver. Brown and Susskind (2020) discuss what cooperation during a pandemic should entail and suggest how it can be financed.

[3] Using pre-pandemic data, Espitia et al. (2020) report that four countries account for more than 70% of world exports in critical medical supplies, while 80-85% of imports of developing countries tend to originate from the top three exporters. During the Covid-19 pandemic, China and India, who were vaccine-producers, would not qualify as third markets in our model.

[4] The costs of the restrictions imposed in the COVID-19 pandemic are examined in IMF (2020). An estimate of the cost of the restrictions on the US labour market is provided by Coibion, *et al.* (2020).

[5] For a survey on export promotion in oligopolistic industries, see Leahy and Neary (2011). The classic reference is Brander and Spencer (1985).

consider different levels of international cooperation.[6]

We derive the level of vaccine outputs that developed vaccine-producing countries export to less developed importing countries under alternative policy stances, ranging from non-intervention to non-cooperative export promotion and export policy cooperation. Each of these policies is then assessed from the perspective of the exporting countries and from a global welfare perspective. We find that, while cooperation among vaccine-exporting countries can mimic the global optimum under certain conditions, it also has the potential to reduce global welfare below the welfare attained under non-intervention. Although we apply our framework to the issue of provision of vaccines to mitigate a pandemic, our set-up has more general relevance.

Our framework is akin to the set-up in other papers that examine trade policy when externalities are present. The literature on trade and environmental policy offers several examples. Barrett (2001) analyses optimal environmental policy for governments with firms that operate in imperfectly competitive export markets. Yamase (2010) examines the effect of trade on cooperative and non-cooperative environmental policy. Mukherjee and Chakraborty (2016) provide a review of the link between environmental policy instruments and trade policy.

Our paper also relates to work that examines the interdependence between local policy and trade policy. Ederington (2001) studies how to design international agreements that coordinate both trade policy and domestic policy. In an environmental set-up, Ahlvik and Liski (2021) ask how to fight global problems with local policies when firms can relocate externality-producing activities. In our paper we show how local policy regarding socio-economic restrictions interacts with the global social effects of export policy cooperation. Thus, we add to work that examines the interaction between local policies and international policy when dealing with global problems.

Finally, we investigate when the cooperative agreement among export countries alone needs to include some ethical concern for countries outside the cooperative agreement to approach the global optimum. This question echoes a concern by Derviş (2020), who asks whether a “values-based” incentive for co-operation can complement self-interested cooperation.[7] In our model, a concern by the members of the cooperative agreement for the welfare of outsiders is captured by including “empathy” −akin to Edgeworth’s (1881) “effective sympathy”− into the objective function of the cooperating countries. In doing this, we follow the approach by Lopez and Vives (2019), albeit in a very different context.[8]

Section 2 outlines the general setting. In subsequent sections 3 to 6, we show our results, using simple functional forms to facilitate clarity of exposition and to derive explicit solutions. In section 3,

[6] Buchholz and Sandler (2021) argue that policies attempting to deal with global externalities need to recognise that several “layers of actors” are involved.

[7] This is reminiscent of Andreoni’s (1990) “warm-glow” giving. In fact, some studies use a normatively inspired approach in modelling cooperation, whereby countries are assumed to act as “Kantian maximisers”: they choose an action that maximises their objective, assuming that all countries act in a similar way (see, for instance, Bilodeau and Gravel (2004) and Roemer (2010)).

[8] They explore how overlapping ownership affects R&D efforts by firms and use Edgeworth’s “effective sympathy” parameter to model overlapping ownership between firms.

the expressions for optimal vaccine export and optimal restrictiveness in the exporting countries are derived. These are valid for all alternative policy stances considered. In section 4, the actual vaccine export levels under non-intervention, non-cooperative subsidisation and cooperative subsidisation by the exporting countries are determined. In section 5, we derive the global optimum and assess each of the alternative policies in terms of global welfare. In section 6, the objective function of the cooperating vaccine-exporting countries is augmented with "empathy" for the importing country. Section 7 generalises our results beyond the specific functional forms used in earlier sections and section 8 concludes.

2 The general setting

In the presence of a global pandemic, two firms, each in a different developed country i ($i = 1, 2$), produce vaccines. We assume that the population of each of these countries is already "fully" vaccinated against the pathogen.[9] Both firms produce and export their vaccine to the developed world at the same marginal cost, c. We ignore any fixed costs and any R&D costs as we assume that the vaccines have already been developed. The developing world is modelled as a single country with a single market and referred to as the third market. We assume that the vaccines are perfect substitutes. The third market's inverse demand is $p(Q)$ with p and Q respectively denoting the price and quantity of the vaccine. We have $Q = \sum_i q_i$, with q_i denoting country i's export to the third market; in addition, $p'(Q) = -b(Q) < 0$, with $b(Q)$ denoting the absolute slope of the inverse demand. To boost take-up, the governments of the exporting countries may decide to subsidise vaccine exports. Hence, firm profit generated by the exports are given by $\Pi_i(q_i, q_j, s_i) = \pi_i + s_i q_i$, where s_i denotes country i's subsidy per unit exported and $\pi_i(q_i, q_j) = [p(Q) - c]q_i$ stands for firm profit net of the export subsidy.

Incomplete vaccine coverage in the less developed world leads to a social cost to each of the developed exporting countries and the developing world. The social cost of the direct damage (generated by incomplete global vaccination) experienced by developed country i is represented by D_i and henceforth referred to as the direct "damage" function. This cost does not include any secondary costs resulting from social and economic restrictions or lockdowns. The direct cost of socio-economic restrictions is captured by a "loss" function, L_i. The degree of such restrictions imposed by government i is denoted by r_i, which represents an index of national restrictions. An increase in r_i reduces the damage of incomplete vaccination, D_i, while increasing the cost of the restrictions, L_i.[10] Hence, welfare in developed exporting country i, w_i, is given by:

[9] By fully vaccinated we do not necessarily mean 100% of the developed countries' population is vaccinated. Rather we mean that demand in the developed countries has been fully satisfied and so exports are not constrained by the need to service the domestic market.

[10] Clearly, the extent to which the restrictiveness index affects D_i and L_i depends on many factors; also, the cost efficiency may improve through time with learning or may worsen with fatigue. For simplicity, we take the cost effectiveness as given when the government is optimising though we will also explore some comparative statics later.

$$w_i(q_i, q_j, r_i) = \pi_i(q_i, q_j) - D_i(r_i, \overline{Q} - Q) - L_i(r_i) \tag{1}$$

We assume that $L_i'(r_i) > 0$ and $L_i''(r_i) > 0$ for $r_i > 0$. The damage, D_i, is also affected by r_i, but crucially depends on the gap between the vaccine coverage needed to eliminate the externality, $\overline{Q}$, and the actual level, Q. We will refer to $\overline{Q}$ as "full" vaccine coverage though it does not necessarily imply 100% vaccination. In addition, we impose:

$$D_i(r_i, \overline{Q} - Q) \begin{cases} > 0 \text{ for } \overline{Q} - Q > 0 \\ = 0 \text{ for } \overline{Q} - Q \leq 0 \end{cases} \tag{2}$$

where the partial derivatives are:

$$\frac{\partial D_i}{\partial Q} = -\beta_i(r_i, \overline{Q} - Q) \begin{cases} < 0 \text{ for } \overline{Q} - Q > 0 \\ = 0 \text{ for } \overline{Q} - Q \leq 0 \end{cases} \quad \text{and} \quad \frac{\partial D_i}{\partial r_i} = -\delta_i(r_i, \overline{Q} - Q) \begin{cases} < 0 \text{ for } \overline{Q} - Q > 0 \\ = 0 \text{ for } \overline{Q} - Q \leq 0 \end{cases} \tag{3}$$

and the cross partial derivative $\frac{\partial^2 D_i}{\partial Q \partial r_i} = \frac{\partial^2 D_i}{\partial r_i \partial Q} = \theta_i(r_i, \overline{Q} - Q) > 0$.

Turning to the export market, welfare of the developing country, w^*, is given by:

$$w^*(Q) = CS^*(Q) - D^*(\overline{Q} - Q) \tag{4}$$

where the first term stands for the consumer surplus from vaccination. We assume consumer surplus measures consumer welfare in the absence of the externality, so the inverse demand $p(Q)$ is the marginal utility. A natural assumption is that marginal utility is zero at "full vaccination" so that $p\left(\overline{Q}\right) = 0$. However, while $\overline{Q}$ is the level of Q at which there is no externality there may still be some private benefit. We allow for this possibility and instead assume $0 \leq p\left(\overline{Q}\right) \leq c$ so that in the absence of subsidy it can never be profitable to produce $\overline{Q}$ or beyond. In addition to consumer surplus there is also a direct social cost from the negative externality accruing from incomplete vaccination, D^*, but we assume any restrictions in the third market are non-effective or non-existent.[11]

The model consists of two types of agents: firms and developed-country governments . These play a two-stage game. The governments simultaneously choose export subsidies in the first stage. We allow for two cases: one in which they choose the subsidies non-cooperatively and the other in which they cooperate in the subsidies and thus in the provision of vaccines to the less developed country. In stage two, firms choose exports in a Cournot manner and the governments simultaneously and independently set social and economic restrictions, modelled as $r_i (i = 1, 2)$. We assume subgame perfection in each case and use backward induction to determine the outcome.

[11] Including restrictions in the third market would merely add notation without yielding any additional insight. It is straightforward to extend the model to cater for these.

Although we choose to model government support as taking the form of per-unit export subsidies to keep the analysis as simple as possible, alternative forms of export promotion would work just as well. Fixed subsidies or other incentives in return for target outputs would give qualitatively similar results. The results we want to highlight do not hinge on asymmetries between firms or between developed countries so, avoiding unnecessary notation, we focus on a setting in which the developed-countries' governments and their firms face the same production cost functions, firms produce homogeneous goods and governments face identical D and L functions. This allows us to focus attention on symmetric equilibria.

For expositional ease, we turn to specific functional forms in sections 3 to 6. We subsequently generalise our results in section 7.

3 Vaccine output and restrictions in a simple model

In this and the next two sections we assume linear demand and quadratic direct damage, D, and loss, L, functions. This allows us to obtain explicit solutions and present our results as clearly as possible. The demand for vaccines in the third market is given by:

$$p = a - bQ \tag{5}$$

Welfare in each vaccine-producing country is given by expression (1). The direct damage to country i from incomplete vaccine coverage in the third market is represented in this section by $D_i = (\overline{Q} - Q)\beta_i$ with $\beta_i = \alpha - \theta r_i \geq 0$; a positive constant, α, measures the direct damage per unvaccinated person in the absence of restrictions and is henceforth referred to as the "unmitigated externality" parameter; this damage can be mitigated by restrictions, but the extent to which this is possible depends on the effectiveness of those restrictions, θ, where θ is a strictly positive constant. Here and in the next three sections, we assume the cost of those restrictions to country i is simply given by $L_i = \frac{\gamma r_i^2}{2}$. Given our demand function in (5), full vaccine coverage is $\overline{Q} \equiv \mu a/b$, where $(a - c)/a \leq \mu \leq 1$ stands for the minimum proportion of the population that needs to be vaccinated to eliminate the externality from incomplete vaccination. So, with these specifications, expression (1) amounts to:

$$w_i = \pi_i - \beta_i(\overline{Q} - Q) - \frac{\gamma r_i^2}{2} \tag{6}$$

We first examine stage two of the game, in which firms choose outputs and the governments choose restrictions. The first-order condition for the profit-maximising typical firm is:

$$p - c - bq_i + s_i = 0 \tag{7}$$

implying firm i's optimal output:

$$q_i = \frac{A + 2s_i - s_j}{3b} \tag{8}$$

with $A \equiv a - c$. From expression (7) and adding each country's output together, total output as a function of each country's subsidy is given by:

$$Q = \frac{2A + s_i + s_j}{3b} \tag{9}$$

In addition, for each government, the first-order condition for restrictiveness associated with welfare maximisation is given by:

$$\frac{\partial w_i}{\partial r_i} = \theta(\overline{Q} - Q) - \gamma r_i = 0 \tag{10}$$

with $\theta = -\partial\beta_i/\partial r_i$. Letting $\eta \equiv \theta^2/b\gamma$ denote the relative effectiveness of restrictions, expression (10) reduces to:

$$\theta r_i = \eta b(\overline{Q} - Q) \tag{11}$$

We impose $\eta < 1/2$. This condition is sufficient to guarantee the existence of each of the equilibria we will consider. As can be seen from these expressions if *either* government increases its subsidy, more people in the third market are vaccinated (expression (9)); this results in both governments lowering their restrictiveness (expression (11)). Clearly, with full vaccination ($Q = \overline{Q}$), no restrictions are necessary. Note that the maximum value for θr_i is $\eta b\overline{Q}$ (i.e., when $Q = 0$). Since β_i cannot be negative for any θr_i, we impose $\alpha - \eta b\overline{Q} \geq 0$. It proves useful to define the composite parameter $\varepsilon \equiv \alpha - \eta b\overline{Q}$. Since the vaccine output and the government's restrictiveness in each country are always set in stage two, taking the vaccine subsidies set in stage one as given, expressions (9) and (11) are always valid, irrespective of how the subsidies are chosen.

4 Vaccine subsidisation

We now determine the subsidy when it is chosen non-cooperatively (subsection 4.1) and when it is set under cooperation by the vaccine-exporting countries (subsection 4.2). We subsequently compare the two policy regimes in terms of welfare of vaccine-exporters and the vaccine-importing country (subsection 4.3). Throughout this section, we assume that the vaccine output chosen does not reach full vaccination. We will explore the conditions under which full vaccination is the outcome in section 5.

4.1 Non-cooperation: "Enlightened" self-interest versus non-intervention

The typical vaccine-exporting government maximises its welfare, choosing its subsidy in stage one, taking into account how it affects both firms' quantities and the restrictions that will be set in stage two. The first-order condition for the optimal subsidy is:

$$\frac{\partial w_i(s_i,s_j)}{\partial s_i} = \frac{\partial w_i}{\partial q_i}\frac{\partial q_i}{\partial s_i} + \frac{\partial w_i}{\partial q_j}\frac{\partial q_j}{\partial s_i} + \frac{\partial w_i}{\partial r_i}\frac{\partial r_i}{\partial s_i} = 0 \tag{12}$$

Note that there is no *direct* effect of the subsidy on welfare since the subsidy is a transfer between the government and the firm and so welfare is profit net of the subsidy (π_i) minus damage (D_i) and the losses due to restrictions (L_i). The subsidy only affects welfare through its effect on the second-stage variables outputs and restrictions. We have $\frac{\partial w_i}{\partial q_i} = A - 2bq_i - bq_j + (\alpha - \theta r_i)$, $\frac{\partial w_i}{\partial q_j} = -bq_i + (\alpha - \theta r_i)$ and $\frac{\partial w_i}{\partial r_i} = 0$ (from the fact that the government chooses optimal restrictiveness in the second stage). In addition, $\frac{\partial q_i}{\partial s_i} = \frac{2}{3b}$ and $\frac{\partial q_j}{\partial s_i} = -\frac{1}{3b}$ from expression (8). Then, using (11), expression (12) yields the optimal subsidy under non-cooperation, s^N:

$$s^N = \frac{(1+2\eta)A + 3\varepsilon}{5-2\eta} \tag{13}$$

Since the subsidy is identical for both countries (because of the symmetry assumption), subscript i can be dropped. Since $\eta < 1/2$ and $\varepsilon > 0$, the optimal non-cooperative export subsidy, s^N, is strictly positive.

Substituting expression (13) for the subsidies in expression (9) yields the reduced-form expression for total output when governments do subsidise vaccine exports but do so non-cooperatively, denoted by Q^N:

$$Q^N = \frac{4A + 2\varepsilon}{b\,(5-2\eta)} \tag{14}$$

Expression (9) also allows us to derive the total vaccine export under non-intervention, in which case $s_i = s_j = 0$. Denoting non-intervention by superscript F (indicating a "free-trade" policy stance), we have $Q^F = 2A/3b$. Naturally, when firms are subsidised, they export a larger vaccine quantity to the third market than under non-intervention ($Q^N > Q^F$). The externality generated by the unvaccinated in the third market on the exporting countries is smaller when vaccine export is subsidised, implying that the degree of restrictiveness in the domestic economies can be lower too. For this reason, we refer to this case as "enlightened" non-cooperation. However, net profits of the country (profits minus subsidy costs) are lower than without subsidies.

4.2 Cooperation

Alternatively, governments of exporting countries may decide to cooperate in their vaccination policy: optimal subsidies are then obtained from maximising those countries' joint welfare, $W = w_1 + w_2$. The first-order condition for joint welfare maximisation is given by:

$$\frac{\partial W(s_i, s_j)}{\partial s_i} = \frac{\partial W}{\partial q_i}\frac{\partial q_i}{\partial s_i} + \frac{\partial W}{\partial q_j}\frac{\partial q_j}{\partial s_i} + \frac{\partial w_i}{\partial r_i}\frac{\partial r_i}{\partial s_i} = 0 \tag{15}$$

The last term of expression (15) involves a partial derivative of w_i rather than W as restrictions in country i do not directly affect welfare of country j. The derivatives are mentioned after expression (12). Hence the optimal cooperatively chosen subsidy by the exporting countries, denoted by s^C, is given by:

$$s^C = \frac{-(1-4\eta)A + 6\varepsilon}{4(1-\eta)} \tag{16}$$

When governments of exporting countries cooperate, they internalise the negative externality from the unvaccinated on both their economies. This works towards setting a higher subsidy than under non-cooperation. However, cooperation among governments of vaccine-exporting countries also involves internalising their firms' business-stealing. In the absence of the negative social externality from non-vaccination, the cooperating governments would "effectively" determine exports as a monopoly. This implies reducing exports and hence works towards a negative export subsidy. For this reason, the sign of the optimal cooperative subsidy is ambiguous and depends on the relative strength of the two effects. Substituting expression (16) for s_i and s_j in expression (8) and adding the outputs of each firm then gives total output under a cooperative export policy:

$$Q^C = \frac{A + 2\varepsilon}{2b(1-\eta)} \tag{17}$$

How does the vaccine output under cooperation (expression (17)) compare with the output obtained when subsidies are set non-cooperatively (expression (14)) and when outputs are chosen without intervention by the governments of the vaccine-exporting countries? Figure 1 depicts vaccine production as a function of the unmitigated externality parameter, α, under the three alternative policy regimes. Naturally, the export subsidy increases in the externality parameter (see expressions (13) and (16), bearing in mind that $\varepsilon = \alpha - \eta b\overline{Q}$), and hence both Q^N and Q^C increase in α. Two $\alpha-$thresholds prove useful. (Note that the proofs of all the lemmas and propositions are in the appendix)

Lemma 1 *At $\alpha = \alpha_1$, we have $Q^C(\alpha_1) = Q^F$, with $\alpha_1 = \frac{[1+2\eta(3\mu-2)]a-(1-4\eta)c}{6}$; for $\alpha > \alpha_1$, $Q^C(\alpha) > Q^F$, while $Q^C(\alpha) < Q^F$ for $\alpha < \alpha_1$.*

Lemma 2 *At $\alpha = \alpha_3$, we have $Q^C(\alpha_3) = Q^N(\alpha_3)$, with $\alpha_3 = \frac{[1-2\eta(1-\mu)]a-(1-2\eta)c}{2}$; for $\alpha > \alpha_3$, $Q^C(\alpha) >$*

$Q^N(\alpha)$, while $Q^C(\alpha) < Q^N(\alpha)$ for $\alpha < \alpha_3$.

Lemma 3 $\alpha_1 < \alpha_3$.

When the externality is sufficiently small ($\alpha < \alpha_1$), Figure 1 shows that the cooperative vaccine output is lower than the non-intervention output ($Q^C(\alpha) < Q^F$), implying that the cooperative export subsidy is, in fact, negative and is an export tax ($s^C < 0$). The reason for this lies in the fact that, for such low externality levels, the output reduction from the internalisation of the business-stealing effect under cooperation is far greater than the output increase from the internalisation of the externality. This also results in the equilibrium level of restriction being higher in the cooperative subsidy case than in the non-intervention case ($r^C < r^F$). For intermediate externality levels ($\alpha \in (\alpha_1, \alpha_3)$), vaccine production under cooperative subsidisation exceeds the level attained under non-intervention ($Q^C(\alpha) > Q^F$), but still stays below the level reached under non-cooperative subsidisation ($Q^C(\alpha) < Q^N(\alpha)$). In this α-range, cooperation involves an export subsidy, albeit a lower one than the one set under non-cooperative subsidisation. Only for sufficiently high levels of the externality ($\alpha > \alpha_3$) does vaccine production under cooperative subsidisation exceed the level under non-cooperative subsidisation. In that case vaccine output is larger ($Q^C(\alpha) > Q^N(\alpha)$) and restrictions are lower under cooperative than under non-cooperative subsidisation.

[*Figure 1 about here*]

4.3 Welfare

We now discuss the welfare implications for the vaccine-exporting and the vaccine-importing countries. While the welfare function for each vaccine-exporting country is given by expression (6), the welfare function of the third market, given our specified functional firms, amounts to:

$$w^* = \frac{b}{2}Q^2 - \beta^*(\overline{Q} - Q) \tag{18}$$

where the first term stands for the consumer surplus in the third market and the second denotes the country's social cost of the externality accruing from the unvaccinated section of the population. Also, we have $\beta^* = \alpha^*$, given our simplifying assumption that restrictions in the third market are completely ineffective or non-existent. From expression (18), welfare of the importing country increases in the vaccine level. Hence, welfare of the importing country will be highest under the vaccine-exporters' policy regime that yields the highest vaccine production. Proposition 1 summarises this.

Proposition 1. *The welfare ranking of the alternative policy regimes of cooperative subsidisation, non-cooperative subsidisation and non-intervention for the importing country is: (i) $w^{*N} > w^{*F} > w^{*C}$ for $\alpha < \alpha_1$; (ii) $w^{*N} > w^{*F} = w^{*C}$ for $\alpha = \alpha_1$; (iii) $w^{*N} > w^{*C} > w^{*F}$ for $\alpha \in (\alpha_1, \alpha_3)$; (iv)*

$w^{*N} = w^{*C} > w^{*F}$ *for* $\alpha = \alpha_3$*; (v)* $w^{*C} > w^{*N} > w^{*F}$ *for* $\alpha > \alpha_3$.

Thus, unless the externality is sufficiently high ($\alpha \geq \alpha_3$), the importing country is worse off under cooperative subsidisation of the vaccine-exporting countries than under non-cooperative subsidisation.

By contrast, the vaccine-exporting countries always prefer cooperation to non-cooperation, irrespective of the magnitude of the externality. Without externality, non-cooperative subsidisation by exporting countries is a prisoner's dilemma: subsidising the export of vaccines is a dominant strategy, but it lowers the price and hence profits. In that case, non-intervention avoids the prisoner's dilemma outcome, thereby generating higher welfare for the exporting countries. Cooperation among vaccine-exporting countries even goes further: when there is no externality (or the externality is sufficiently low), cooperation involves an export tax, thereby effectively extracting rent from the developing country. Furthermore, since cooperation internalises the externality on the exporting countries, it implies another welfare gain to the exporting countries. For this reason and regardless of the degree of the externality, cooperation of the exporting countries is always the preferred policy regime for the exporting countries. When cooperation is not available, exporting countries prefer non-intervention to non-cooperative subsidisation, but only when the externality is sufficiently small. This threshold is defined as α_2, with $\alpha_2 = \frac{a-c}{6(4-\eta)}(7-20\eta+4\eta^2)+a\mu\eta$ [derived in the appendix]. The following proposition establishes the welfare ranking of the alternative policy regimes for vaccine-exporting countries:

Proposition 2. *The welfare ranking of the alternative policy regimes of cooperative subsidisation, non-cooperative subsidisation and non-intervention for the exporting country is*:

(i) $w_i^C > w_i^F > w_i^N$ for $\alpha < \alpha_2$;

(ii) $w_i^C > w_i^F = w_i^N$ for $\alpha = \alpha_2$;

(iii) $w_i^C > w_i^N > w_i^F$ for $\alpha > \alpha_2$;

with $\alpha_1 < \alpha_2 < \alpha_3$.

Table 1 summarises the welfare ranking for the exporting countries and the importing country. The welfare ranking of the three alternative policy regimes for the exporting countries is the opposite to that of the importing country when the externality per unvaccinated person is "small" ($\alpha < \alpha_1$). In that case, all countries agree on the second-best regime and prefer non-intervention to the regime that gives the lowest welfare. Importantly, for intermediate levels of the externality ($\alpha \in (\alpha_1, \alpha_3)$), it is hard to see how countries can agree on a particular regime, given that their welfare rankings are very different.

Table 1: *Welfare ranking of cooperative subsidisation, non-cooperative subsidisation and laissez faire*

Externality	Output	Welfare ranking	
		Importing country	Exporting country
$\alpha > \alpha_3$	$Q^C > Q^N > Q^F$	$w^{*C} > w^{*N} > w^{*F}$	$w^C > w^N > w^F$
$\alpha_2 < \alpha < \alpha_3$	$Q^N > Q^C > Q^F$	$w^{*N} > w^{*C} > w^{*F}$	$w^C > w^N > w^F$
$\alpha_1 < \alpha < \alpha_2$	$Q^N > Q^C > Q^F$	$w^{*N} > w^{*C} > w^{*F}$	$w^C > w^F > w^N$
$\alpha < \alpha_1$	$Q^N > Q^F > Q^C$	$w^{*N} > w^{*F} > w^{*C}$	$w^C > w^F > w^N$

Since the welfare rankings of different possible regimes tend to be different for vaccine-exporting and the vaccine-importing countries, it is not surprising that the WHO presses for "global" cooperation.[12] In the next section, we discuss such "global" cooperation initiative.

5 The global optimum

We start by deriving the global optimum, that is, the vaccine output that maximises global welfare, Ω, which is the sum of the welfare of exporting and importing countries:

$$\Omega = W + w^* \tag{19}$$

The vaccine output that maximises global welfare, denoted by Q^G, may involve complete vaccination coverage ($Q^G = \overline{Q}$), but this is not necessarily the case. When the optimal vaccine output falls below complete vaccination, the export subsidy exporting countries have to set to maximise *global* welfare is given by:

$$s^G = \frac{(1+4\eta)A + 6\varepsilon + 3\alpha^*}{2\,(1-2\eta)} \qquad \text{with } Q^G < \overline{Q} \tag{20}$$

Substituting expression (20) into (9) yields the globally optimal vaccine output level when it falls below complete vaccination:

$$Q^G = \frac{A + 2\varepsilon + \alpha^*}{b\,(1-2\eta)} \qquad \text{with } Q^G < \overline{Q} \tag{21}$$

Whether the global optimum involves full vaccination coverage depends on the level of the global externality on the one hand and on the cost of producing the vaccine on the other hand.

Proposition 3. The global optimum, Q^G, (i) entails full vaccination coverage ($Q^G = \overline{Q}$) and no restrictions ($r^G = 0$) for $\alpha \geq \overline{\alpha}^G$, with $\overline{\alpha}^G = \frac{1}{2}(c - (1-\mu)a - \alpha^*)$; (ii) entails incomplete vaccination coverage otherwise ($Q^G < \overline{Q}$), with $Q^G > Max(Q^C, Q^N)$ and $r^G > 0$.

[12] During the Covid-19 pandemic, the WHO repeatedly called for global cooperation and solidarity to fight Covid-19 and prevent and combat future pandemics.

For $Q^G < \overline{Q}$, a comparison of expressions (14), (17) and (21) shows that the globally optimal vaccine output is larger than both the non-cooperative ($Q^G > Q^N$) and cooperative output ($Q^G > Q^C$). Figure 2 shows the globally optimal vaccination output, Q^G, along Q^C and Q^N, as a function of the unmitigated externality parameter, α. The complete vaccination level, $\overline{Q}$, is also indicated. Figure 3 shows global welfare as a function of vaccine output for different levels of α. Given expression (2), we know that w_i and w^*, and therefore Ω, display a kink at $Q = \overline{Q}$. Like the welfare ranking for the importing country, the global welfare ranking of the alternative exporting countries' policies corresponds to the output ranking. When the externality parameter is sufficiently low ($\alpha < \overline{\alpha}^G$), the global optimum entails incomplete vaccination. In that case, cooperation among the exporting countries alone cannot replicate the global optimum (see Figure 3(a)). For larger levels of α ($\alpha \geq \overline{\alpha}^G$), the global optimum entails full vaccination coverage ($Q^G = \overline{Q}$). For $\mu = 1$, $Q^G = \overline{Q}$ if $c \leq 2\alpha + \alpha^*$. Intuitively, only when the marginal cost of producing the vaccine is lower than the global externality cost of the non-vaccinated, does the global optimum prescribe complete vaccination coverage. The global optimum occurs now at the kink in the global welfare function (see Figures 3(b) and 3(c)). In fact, when the global optimum involves full vaccination, it is possible that cooperation by the exporting countries alone entails complete vaccination coverage.

Proposition 4. *Cooperative subsidisation by the vaccine-exporting countries entails full vaccination coverage for* $\alpha \geq \overline{\alpha}^C$*, with* $\overline{\alpha}^C = \frac{1}{2}((2\mu - 1)a + c)$.

As shown in Figure 2 and Figure 3(c), cooperation entails full vaccination coverage and coincides with the global optimum ($Q^C = Q^G = \overline{Q}$) for $\alpha \geq \overline{\alpha}^C$. In that case too, restrictions are completely removed ($r^C = r^G = 0$). Hence, in this instance the global welfare optimum is reached, even when the exporting countries cooperate without taking into account the importing country's welfare.

[*Figures 2 and 3 about here*]

6 Cooperation with "empathy"

For a range of levels of the externality ($\alpha \in (\overline{\alpha}^G, \overline{\alpha}^C)$), global cooperation entails full vaccination coverage, while cooperation among vaccine exporters does not yield that outcome. While the global optimum is an important benchmark, it is legitimate to ask how, in the absence of a supranational entity with enforcement power, such an outcome could actually be implemented. One possibility that we explore below is that the exporters may for some reason (e.g., international goodwill or political pressure from their electorate) care about the welfare of other countries. Let us explore how embedding such a concern in the objective function of cooperating vaccine-exporting countries affect their exports. Following Edgeworth's concept of "effective sympathy", we introduce "empathy", denoted by parameter λ ($0 \leq$

$\lambda \leq 1$). This generates the empathy-enhanced welfare function of the developed countries, Λ, given by:

$$\Lambda = W + \lambda w^* \tag{22}$$

This objective function in (22) nests "pure" welfare of the vaccine-exporting countries ($\lambda = 0$) and global welfare ($\lambda = 1$). Although the vaccine output that maximises (22), Q^E, may imply complete vaccination ($Q^E = \overline{Q}$), it may fall short of that ($Q^E < \overline{Q}$). In the latter case, exporting countries need to set the export subsidy, s^E, given by:

$$s^E = \frac{-(1 - 4\eta - 2\lambda)A + 6\varepsilon + 3\lambda\alpha^*}{4(1 - \eta) - 2\lambda} \quad \text{where } Q^E < \overline{Q} \tag{23}$$

Substituting expression (23) into expression (9) yields the vaccine output with empathy when it falls below the full vaccination level, Q^E, given by:

$$Q^E = \frac{A + 2\varepsilon + \lambda\alpha^*}{2b(1 - \eta) - b\lambda} \quad \text{where } Q^E < \overline{Q} \tag{24}$$

Naturally, under cooperation with empathy, the vaccination level increases as the degree of empathy (λ) goes up.

We argue that, if the global optimum entails full vaccination coverage ($Q^G = \overline{Q}$), then it is sufficient for the cooperating vaccine-exporters to display merely "partial" empathy (i.e., $\lambda < 1$) with the importing country to replicate the global optimum ($Q^E = Q^G = \overline{Q}$). With cooperation, the internalisation effect of a large externality will dominate the monopolisation effect and thus generate a large cooperative optimal output. Hence, the difference with the full-vaccination global optimum is smaller if the externality is larger. Adding a small level of empathy for the vaccine-importing country to the welfare function of the cooperating exporting countries can be sufficient to lead to full vaccination coverage.

Proposition 5. The critical level of empathy (λ^G) for cooperative subsidisation by the vaccine-exporting countries to yield the global optimum $\left(Q^E(\lambda^G) = Q^G\right)$ is:

(i) $\lambda^G = 1$ for $\alpha \leq \overline{\alpha}^G$;

(ii) $\lambda^G = \frac{a(2\mu-1)+c-2\alpha}{\mu a+\alpha^*}$ for $\overline{\alpha}^G < \alpha < \overline{\alpha}^C$ with $0 < \lambda^G < 1$;

(iii) $\lambda^G = 0$ for $\alpha \geq \overline{\alpha}^C$.

From Proposition 5, we see that when λ^G is strictly between 0 and 1, it falls in the externality parameters (α and α^*) and increases in the marginal production cost of the vaccine (c). The reason why λ^G falls in the externality is that higher externality levels lead to a higher optimal level of vaccine output, even under cooperation among vaccine-exporters. Hence, a smaller level of empathy is needed to bridge the gap between full vaccination and the cooperative output level. Figure 4 depicts the critical threshold, λ^G, as a function of the externality parameter (assuming $\alpha = \alpha^*$ for simplicity). When the global optimum implies incomplete vaccination coverage (i.e., for $\alpha < \overline{\alpha}^G$), cooperation among exporting countries requires "complete" empathy ($\lambda = 1$) for the importing country, otherwise it will not replicate the global optimum. But, when the level of externality is sufficiently high for the global optimum to entail complete vaccination ($\alpha > \overline{\alpha}^G$), then partial empathy ($\lambda^G \leq \lambda < 1$) is sufficient for exporting countries to reach this global optimum under cooperative subsidisation. Figure 4 also shows that for $\alpha \geq \overline{\alpha}^C$, cooperation among exporting countries generates the global optimum without any empathy ($\lambda = 0$).

[Figure 4 about here]

7 General model

In previous sections we assumed linear demand and quadratic D and L functions. This allowed us to obtain explicit solutions. Here we consider a much more general model and examine the extent to which the results obtained in the previous sections are dependent on the linear-quadratic specification. We show that the most important results do not depend on these functional forms. We begin as usual by examining the final stage of the game.

7.1 Outputs and restrictions

The first-order condition for output is the same as in (7) apart from the fact that $p(Q)$ and $b(Q)$ are now general. In particular $b(Q)$ is not constant, and we can define $\rho(Q)$ as the convexity of demand where $\rho(Q) = -Qp''/p' = -Qb'/b$. Of course this is zero when demand is linear. The equilibrium outputs as functions of the subsidies are $q_i(s_i, s_j)$, with derivatives:

$$\frac{\partial q_i(s_i, s_j)}{\partial s_i} = \frac{2 - \rho q_j/Q}{b(3-\rho)} > 0 \quad \text{and} \quad \frac{\partial q_i(s_i, s_j)}{\partial s_j} = -\frac{1 - \rho q_i/Q}{b(3-\rho)} \tag{25}$$

where $\partial q_i/\partial s_j$ is ambiguous in sign and is negative only when demand is not too convex (i.e., $\rho(Q)$ is not too big). However, $\partial q_i/\partial s_j > 0$ since $2 - \rho q_j/Q > 0$ from the second-order condition for firm j and $\rho < 3$ follows from the stability of the Cournot game[13]. The first-order condition for an interior optimum in restrictions can be written as:

$$\delta_i(r_i, \overline{Q} - Q) = L_i'(r_i) \tag{26}$$

and the second-order condition can be written as: $(\partial \delta_i/\partial r_i) - L_i'' \equiv -\gamma_i(r_i, \overline{Q} - Q) < 0$. Here γ depends on output and restrictions while in the linear-quadratic special case discussed earlier γ is a constant. From equation (26) we can, given symmetry, rewrite the the first order condition for r as $\delta(q, r) - L'(r) = 0$,

[13]The second-order condition for firm j is $2p' + q_j p'' < 0$ and the stability condition is $(2p' + q_j p'')(2p' + q_i p'') - (2p' + q_j p'')(2p' + q_i p'') > 0$. Straightforward calculations show that that the second-order condition holds only if $2 - \rho q_j/Q > 0$, while stability holds only if $\rho < 3$.

where q and r without subscripts are levels of symmetric-country quantity and restrictions. We solve this for optimal r given q, which we write as $r(q)$ and illustrate in Figure 5 as a locus in a space whose coordinates are the symmetric output of vaccines and the symmetric level of restrictions of developed countries. Provided full vaccination has not been reached $\frac{\partial \delta(q,r)}{\partial q} = -\theta < 0$ and $-\gamma < 0$, and the $r(q)$ locus must be negatively sloped. The downward slope captures the substitutability between exports of vaccines and restrictions in reducing the negative externality. When q reaches the full vaccination level $\overline{q}$, where $\overline{q} = \frac{1}{2}\overline{Q}$, no restrictions are required so $r(\overline{q}) = 0$.

[Figure 5 about here]

7.2 Incomplete vaccination

With incomplete vaccination the equilibrium q falls short of $\overline{q}$. In this subsection we compare the different regimes of non-intervention, non-cooperation, cooperation, and the global optimum for the case in which complete vaccination is not reached.

7.2.1 Non-cooperation

The first-order condition for the non-cooperative subsidy of country i is still given in (12) above. Now of course the functional forms of demand, D and L are general. The symmetric equilibrium non-cooperative subsidy is obtained from the the first-order conditions for the two countries in (12) combined with the expressions in (25). This yields:

$$s^N = \frac{2-\rho}{4-\rho}bq + \beta\left(\frac{2}{4-\rho}\right) \tag{27}$$

Note that for notational convenience we supress the arguments of b, β and ρ. This subsidy is positive for $\beta > -bq\frac{(2-\rho)}{2}$. This can be thought of as the "usual" case because it is guaranteed if the Cournot quantities are strategic substitutes and also holds if quantities are strategic complements ($\rho > 2$) for a sufficiently large externality. We can substitute expression (27) into (7), the typical firm's first-order condition and make use of symmetry to write the first-order condition for non-cooperative output:

$$h^N(q,r) = (p-c) - \frac{2}{4-\rho}bq + \beta\left(\frac{2}{4-\rho}\right) = 0 \tag{28}$$

with q and r without subscripts representing symmetric quantity and restrictions. We impose the natural assumption that $\frac{\partial h^N(q,r)}{\partial q} < 0$. The cross-effect, $\frac{\partial h^N(q,r)}{\partial r}$, is also negative since $\frac{\partial \beta}{\partial r} = -\theta < 0$ and $\frac{2}{4-\rho} > 0$. The first-order condition $h^N(q,r) = 0$ can be solved for the optimal q as a function of r and is illustrated in Figure 5 as the locus $q^N(r)$. Since $h^N(q,r)$ is falling in both q and r, the $q^N(r)$ locus is downward sloping The symmetric non-cooperative equilibrium occurs at the intersection of the $q^N(r)$ and the $r(q)$ loci, represented by N in Figure 5.

We also illustrate the symmetric equilibrium in which the governments do nothing to promote vaccine exports so that the subsidies are zero. In that case, $h^F(q) = p - c - bq = 0$ is the firm first-order condition for output in the absence of any subsidy and it independent of symmetric r depending only symmetric output, q. The implied q^F is illustrated in Figure 5 by a flat line. The non-intervention equilibrium occurs at the intersection of this (flat locus) and the $r(q)$ locus (point F in Figure 5).

7.2.2 Exporting country cooperation

When the exporter countries cooperate the optimal subsidies are obtained from maximising those countries' joint welfare, $W = w_1 + w_2$. We assume that this function has a unique maximum and is strictly quasiconcave in the subsidies. These conditions are guaranteed in the linear-quadratic case discussed earlier. The first-order condition is given by expression (15). Invoking symmetry and following some algebraic manipulation, the optimal cooperative subsidy can be written as:

$$s^C = -bq + 2\beta \tag{29}$$

which is positive for a sufficiently large externality. We can substitute the expression for the optimal subsidy in equation (29) into the output first-order condition (7) to get:

$$h^C(q, r) = (p - c) - 2bq + 2\beta = 0 \tag{30}$$

The first-order condition $h^C(q, r) = 0$ can be solved for the optimal cooperative q as a function of r and it is represented in Figure 5a as the locus $q^C(r)$. Since the governments still set the restrictions independently the $r(q)$ locus continues to apply in the cooperative case and the symmetric equilibrium occurs where the $r(q)$ and $q^C(r)$ curves intersect at the point C in Figure 5a .

7.2.3 Global optimum

Global welfare is given by (19) with $w^*(Q)$, given by the general expression in (4). We assume that global welfare has a maximum and is strictly quasi-concave in the subsidies. The change in importer country welfare is made up of the change in consumer surplus, $dCS = bQdQ = 2bqdQ$ and the change in the damage $dD^* = -\beta^* dQ$ where $\beta^*(\overline{Q} - Q)$ is not in general constant. Hence, a policy-induced increase in Q unambiguously raises importer welfare. Thus, if the subsidies s_1 and s_2 are chosen to maximise global welfare, the resulting output is above the level in the cooperative case discussed above. The resulting symmetric global cooperative subsidy $s_1^G = s_2^G = s^G$ is:

$$s^G = bq + 2\beta + \beta^* > 0 \tag{31}$$

We substitute (31) into the typical firm's output first-order condition in (7) and make use of symmetry to get:

$$h^G(q,r) = (p-c) + 2\beta + \beta^* = 0 \tag{32}$$

The optimal price is equal to the global social marginal cost $p = c - (2\beta + \beta^*)$. The first-order condition, $h^G(q,r) = 0$ can be written as $q^G(r)$ and is illustrated in Figure 5a. The global cooperative equilibrium occurs at the intersection of the $q^G(r)$ and the $r(q) = 0$ curves (point G). Global welfare, Ω, can alternatively be expressed as a function of q and r. Making use of $r(q)$ allows us to write Ω as a function of q. We assume that the function $\Omega = M^G(q)$, which has a unique optimum, is strictly quasiconcave in q.

7.2.4 Comparing the equilibria in the different regimes

We first illustrate the results and develop the intuition using figure 5a. We then introduce the requisite technical assumptions and outline the corresponding formal analysis (proofs are provided in appendix B).

First we compare the non-cooperative equilibrium to that under non-intervention. The "usual" case will involve a positive subsidy s^N which implies that the $q^N(r)$ curve is above q^F in Figure 5a. This will result in higher exports with non-cooperation compared to non-intervention, $q^N > q^F$, and since the $r(q)$ locus slopes down, this implies lower restrictions $r^N < r^F$. This result is only overturned in the unusual case in which quantities are strategic complements under Cournot and the effect of exports on the externality, β, is small enough.[14]

The cooperative subsidy, s^C, will be positive, and thus the $q^C(r)$ curve is above q^F, provided β is large enough. This is the case that is illustrated in Figure 5a with $q^C > q^F$ and $r^C < r^F$. However, this ranking will be reversed when β is sufficiently small. In that case the optimal cooperative policy is a tax, resulting in lower exports and necessitating higher restrictions than those under non-intervention. Cooperation is anti-competitive unless the governments are able to reduce the externality enough by increasing exports (This will occur if β is large enough).

In figure 5a the $q^C(r)$ curve is above the $q^N(r)$ curve. This will be the case for sufficiently large β. (The intuition for this is that positive effect of β on the cooperative subsidy is larger than its effect on the non-cooperative subsidy because cooperation takes account of the effect of the externality on both countries.) As Figure 5 shows we then have $q^C > q^N$ and $r^C < r^N$. However, when β is small enough, the ranking of these curves, the subsidies, the exports and the restrictions will be reversed.

As demonstrated below and illustrated in Figure 5a, the global optimum always yields higher exports and lower restrictions than any of the other equilibria.

[14] Formally, this reversal only occurs when demand is sufficiently convex $\rho > 2(1 + \beta/bq)$.

To formalise the analysis that is illustrated in Figure 5a requires some mild assumptions that we will set out below. We can use $r = r(q)$ to eliminate r in each of $h^j(q,r) = 0$ for $j = N, C$ and G, and express the first-order conditions compactly as $m^j(q^j) = 0$ for $j = N, C$ and G. For purposes of comparison we can also relabel $h^F(q^F) = 0$ as $m^F(q^F) = 0$. Assumptions 1 and 2 allow us to compare the equilibria.

Assumption 1: *Equilibria of each type, N,C,F and G are unique.*

At any common q, we can compare $m^j(q)$ and $m^k(q)$ for $j, k = F, N, C$ and G but $j \neq k$. Since we have used $r(q)$ in the derivation of the $m(q)$ functions r is also common. The second-order and stability conditions of the model ensure that the derivatives of the $m(q)$ functions evaluated at their equilibrium q, are negative. That is $m^j_q(q^j) < 0$, for $j = F, N, C$ and G but the following assumption extends these conditions beyond the purely local.

Assumption 2: *For any two equilibria j and k to be compared the derivatives $m^j_q(q) < 0$ and $m^k_q(q) < 0$ at any intermediate q between q^j and q^k.*

The following proposition gives the comparison of the symmetric equilibrium outputs and level of restrictions in the different equilibria.

Proposition 6. *When the outputs to be compared are below the full vaccination level,*

(i) $q^N > q^F$ and $r^N < r^F$ iff $\beta > -\frac{2-\rho}{2}bq$ evaluated at these equilibria;

(ii) $q^C > q^F$ and $r^C < r^F$ iff $\beta > \frac{1}{2}bq$ evaluated at the these equilibria;

(iii) $q^C > q^N$ and $r^C < r^N$ iff $\beta > bq$ evaluated at these equilibria;

(iv) $q^G > \max\{q^C, q^N, q^F\}$ and $r^G < \min\{r^C, r^N, r^F\}$

Corollary. *The global welfare ranking of the different regimes F,N and C is the same as the q rankings of those regimes.*

7.3 Full vaccination

The case in which cooperation achieves full vaccination is illustrated in Figure 5b. We have defined full vaccination as the output level at which the externality disappears. When this is reached the optimal restrictions are zero. The $q^C(r)$ curve is valid when $\overline{q}$ has not been reached. For sufficiently high β the $q^C(r)$ curve will intersect the $\overline{q}$ output level. This is case is depicted in Figure 5b. Once $\overline{q}$ has been reached, the externality no longer exists and the cooperative would wish to reduce the subsidy and the output to exploit market power. However, it cannot reduce output below $\overline{q}$ without the return of the externality. Hence, cooperative output never rises above $\overline{q}$. More formally, let $\widetilde{r}^C$ be the r level at which the $q^C(r)$ curve intersects $\overline{q}$. This is implicitly defined as $q^C(\widetilde{r}^C) = \overline{q}$. So the optimal symmetric output under cooperation is $\overline{q}$ for $r \leq \widetilde{r}^C$ and $q^C = q^C(r) < \overline{q}$ for $r > \widetilde{r}^C$. When the cooperative optimal q is $\overline{q}$ the optimal level of restrictions are zero. The cooperative equilibrium when cooperation achieves full vaccination is represented by C in figure 5b.

A similar argument applies to the global optimum. Since the $q^G(r)$ curve is above the $q^C(r)$ curve it intersects $\overline{q}$ at a higher level of r denoted by $\widetilde{r}^G > \widetilde{r}^C$. Again nothing is gained from increasing q above $\overline{q}$. The global optimum equilibrium when exporting country cooperation achieves full vaccination is represented by G in figure 5b. Here, G and C coincide and the exporting countries cooperative outcome achieves the global optimum.

Proposition 7. *The maximum output at the equilibrium with cooperation among exporting countries only is* $\overline{q}$. When $q^C = \overline{q}$, *cooperation among exporting countries achieves the global optimum.*

8 Conclusion

This paper developed a model in which vaccine-producing developed countries are experiencing a negative externality from incomplete global vaccination during a pandemic. The countries can respond to this externality with trade policy, promoting the export of their vaccines. The alternative policy regimes of non-intervention, independent national policies, and cooperation among exporters are considered.

From the point of view of the exporting countries, cooperation is best. In fact, a unilaterally chosen trade policy can be counterproductive, lowering exporting countries' welfare below the non-intervention level. We have derived the crucial externality threshold below which this occurs.

From a global welfare perspective, export policy cooperation −widely seen as a panacea during a pandemic or a situation with similar global externalities− is not necessarily superior to the policy alternatives considered. When the externality of the pandemic on the vaccine-producing exporting countries falls below a critical threshold, export policy cooperation among exporting countries alone is worse for global welfare than exporting countries setting their trade policy independently and can even be worse than non-intervention by exporting countries. However, when the pandemic involves an externality that is so high that it exceeds a specific threshold, cooperation among exporting countries can potentially mimic global cooperation. We derived these crucial thresholds and showed what variables determine them. As a rule, trade policy cooperation among exporting countries becomes less desirable from a global perspective the better the exporting countries can shield themselves from effects of the externality and the more costly is vaccine production. Hence, ineffective domestic policies and policy initiatives that reduce the cost of manufacturing vaccines make it more likely that cooperative rather than non-cooperative export policy will benefit global welfare.

Enhancing our model by including "empathy" enabled us to investigate to what extent ethical values need to complement self-interest to achieve the global optimum. We found that the level of "empathy" needed for a cooperative export policy among producing countries to deliver the global optimum, falls in the magnitude of the externality that those countries experience. In fact, if the externality is sufficiently large, the global optimum can be attained by a cooperative trade policy among exporting countries alone.

APPENDICES

A Proof of lemmas and propositions for linear-quadratic model.

Proof of Lemma 1:

Use (17) with $\varepsilon = \alpha - \eta b\overline{Q}$, $\overline{Q} = \mu\frac{a}{b}$ and $A \equiv a - c$. Setting $Q^C(\alpha) = Q^F$ with $Q^F = \frac{2A}{3b}$ allows us to derive $\underline{\alpha}$. Since Q^C is increasing in α while Q^F is not, we have $Q^C(\alpha) > Q^F$ for $\alpha > \underline{\alpha}$, whereas $Q^C(\alpha) < Q^F$ for $\alpha < \underline{\alpha}$. ■

Proof of Lemma 2:

Use (14) and (17) with $\varepsilon = \alpha - \eta b\overline{Q}$, $\overline{Q} = \mu\frac{a}{b}$ and $A \equiv a - c$. Setting $Q^C(\alpha) = Q^N(\alpha)$ allows us to derive $\overline{\alpha}$. Since Q^C is increasing faster in α than Q^N implies $Q^C(\alpha) > Q^N(\alpha)$ for $\alpha > \overline{\alpha}$, whereas $Q^C(\alpha) < Q^N(\alpha)$ for $\alpha < \overline{\alpha}$. ■

Proof of Lemma 3:

Calculating $\overline{\alpha} - \underline{\alpha} = \frac{1}{3}(1-\eta)(a-c)$, we find $\overline{\alpha} - \underline{\alpha} > 0$ (since $\eta < 1$ and $a > c$.) Hence, $\underline{\alpha} < \overline{\alpha}$. ■

Proof of Proposition 1:

From (18), it is easy to see that $\frac{\partial w^*}{\partial Q} > 0$. Hence, the importing country's welfare ranking is the same as the Q ranking. Combining Lemma 3 with Lemma 1 and 2, we thus obtain (i) $Q^N > Q^F > Q^C$ and hence $w^{*N} > w^{*F} > w^{*C}$ for $\alpha < \underline{\alpha} < \overline{\alpha}$; (ii) $Q^N > Q^F = Q^C$ and hence $w^{*N} > w^{*F} = w^{*C}$ for $\alpha = \underline{\alpha} < \overline{\alpha}$; (iii) $Q^N > Q^C > Q^F$ and hence $w^{*N} > w^{*C} > w^{*F}$ for $\underline{\alpha} < \alpha < \overline{\alpha}$; (iv) $Q^N = Q^C > Q^F$ and thus $w^{*N} = w^{*C} > w^{*F}$ for $\underline{\alpha} < \alpha = \overline{\alpha}$; (v) $Q^C > Q^N > Q^F$ and hence $w^{*C} > w^{*N} > w^{*F}$ for $\underline{\alpha} < \overline{\alpha} < \alpha$. ■

Proof of Lemma 4:

(i) Using expressions (14), (17) and $Q^F = \frac{2A}{3b}$ with $A \equiv a - c$, $\varepsilon = \alpha - \eta b\overline{Q}$ and $\overline{Q} = \mu\frac{a}{b}$. Setting $Q^N - Q^C = Q^C - Q^F$ allows us to derive $\widetilde{\alpha} = \frac{a-c}{6(4-\eta)}(7 - 20\eta + 4\eta^2) + a\mu\eta$, where $Q^N(\widetilde{\alpha}) - Q^C(\widetilde{\alpha}) = Q^C(\widetilde{\alpha}) - Q^F$. Direct calculations yield $\widetilde{\alpha} - \underline{\alpha} = \frac{1}{2}\frac{1-\eta}{4-\eta}(a-c) > 0$ and $\overline{\alpha} - \widetilde{\alpha} = \frac{a-c}{6(4-\eta)}\left(2\eta^2 - 7\eta + 5\right) > 0$, implying $\underline{\alpha} < \widetilde{\alpha} < \overline{\alpha}$. Since $\frac{\partial(Q^N - Q^C)}{\partial\alpha} < 0$ and $\frac{\partial(Q^C - Q^F)}{\partial\alpha} > 0$, we have (ii) $Q^N - Q^C > Q^C - Q^F$ for $\alpha < \widetilde{\alpha}$ and (iii) $Q^N - Q^C < Q^C - Q^F$ for $\alpha > \widetilde{\alpha}$. ■

Proof of Proposition 2:

Using (5), (11) and the expressions for π_i and β_i in (6), and making use of symmetry of the exporting countries and their firms, it follows that the welfare of an exporting country is quadratic in Q, reaching a maximum at Q^C. From Lemma 1 and 2, $Q^N > Q^C > Q^F$ for $\underline{\alpha} < \alpha < \overline{\alpha}$. Given the symmetry of the quadratic $w(Q)$ function, we have (i) when $\alpha < \widetilde{\alpha}$ and hence $Q^N - Q^C > Q^C - Q^F$ (from Lemma 4(ii)), $w^C > w^F > w^N$; (ii) when $\alpha = \widetilde{\alpha}$ and hence $Q^N - Q^C = Q^C - Q^F$ (from Lemma 4(i)), $w^C > w^F = w^N$; (iii) when $\alpha > \widetilde{\alpha}$ and hence $Q^N - Q^C < Q^C - Q^F$ (from Lemma 4(iii)), we have $w^C > w^N > w^F$. ■

Proof of Proposition 3:

Output at full vaccination is $Q = \overline{Q} = \frac{a}{b}\mu$. For $Q \geq \overline{Q}$, there is no externality, while there is for $Q < \overline{Q}$. Thus, the global welfare function, $\Omega(Q)$, differs depending on the sign of $\overline{Q} - Q$. When $Q < \overline{Q}$, the output that maximises $\Omega(Q)$ is $Q^G = \frac{A+2(\alpha-\eta\mu a)+\alpha^*}{b(1-2\eta)}$ (see (21)). Otherwise, the output that maximises $\Omega(Q)$ is $\overline{Q}$, with $\Omega(Q)$ falling for $Q \geq \overline{Q}$. In general, the globally optimal output is $Q^G = min\left\{\frac{a}{b}\mu, \frac{A+2(\alpha-\eta\mu a)+\alpha^*}{b(1-2\eta)}\right\}$. Solving for the α-value for which $\frac{A+2(\alpha-\eta\mu a)+\alpha^*}{b(1-2\eta)} = \frac{a}{b}\mu$ yields $\alpha^l = \frac{1}{2}\left(a(\mu-1) + c - \alpha^*\right)$. Since $\frac{A+2(\alpha-\eta\mu a)+\alpha^*}{b(1-2\eta)}$ increases in α, $\frac{a}{b}\mu < \frac{A+2(\alpha-\eta\mu a)+\alpha^*}{b(1-2\eta)}$ for $\alpha > \alpha^l$, whereas $\frac{a}{b}\mu > \frac{A+2(\alpha-\eta\mu a)+\alpha^*}{b(1-2\eta)}$ for $\alpha < \alpha^l$. Thus, for $\alpha \geq \alpha^l$, it follows that $Q^G = \frac{a}{b}\mu = \overline{Q}$ and $r^G = 0$; for $\alpha < \alpha^l$, $Q^G = \frac{A+2(\alpha-\eta\mu a)+\alpha^*}{b(1-2\eta)} < \overline{Q}$ and $r^G > 0$. It remains to be shown that, when $\alpha < \alpha^l$, $Q^G = \frac{A+2(\alpha-\eta\mu a)+\alpha^*}{b(1-2\eta)} > \max(Q^C, Q^N)$. It is then immediate that $Q^G = \frac{A+2(\alpha-\eta\mu a)+\alpha^*}{b(1-2\eta)} > Q^C =$

$\frac{A+2(\alpha-\eta\mu a)}{2b(1-\eta)}$ (from (21) and (17)) and straightforward calculations give $Q^G - Q^N = \frac{A+2\varepsilon+\alpha^*}{b(1-2\eta)} - \frac{4A+2\varepsilon}{b(5-2\eta)} = \frac{1}{b(5-12\eta+4\eta^2)} \left(A\left(1+6\eta\right)+8\varepsilon+\alpha^*(5-2\eta)\right) > 0$ (from (21) and (14)). ■

Proof of Proposition 4:

Output at full vaccination is $Q = \overline{Q} = \frac{a}{b}\mu$. For $Q \geq \overline{Q}$, there is no externality, while there is for $Q < \overline{Q}$. .Thus, the exporting countries' joint welfare function, $W(Q)$, differs depending on the sign of $\overline{Q} - Q$. When $Q < \overline{Q}$, the output that maximises $W(Q)$ is $Q^C = \frac{a-c+2(\alpha-\eta\mu a)}{2b(1-\eta)}$ (from expression (17)). Otherwise, the output that maximised joint welfare of the exporting countries is $\overline{Q}$, with $W(Q)$ falling when $Q \geq \overline{Q}$. In general, the optimal cooperative exported output is $Q^C = min\left\{\frac{a}{b}\mu, \frac{a-c+2(\alpha-\eta\mu a)}{2b(1-\eta)}\right\}$. Solving for the α-value for which $\frac{a-c+2(\alpha-\eta\mu a)}{2b(1-\eta)} = \frac{a}{b}\mu$ yields $\alpha^h = \frac{1}{2}\left(\left(2\mu-1\right)a+c\right)$. Since $\frac{a-c+2(\alpha-\eta\mu a)}{2b(1-\eta)}$ increases in α, it follows that $Q^C = \overline{Q} = \frac{a}{b}\mu$ for $\alpha > \alpha^h$. ■

Proof of Proposition 5:

When $Q < \overline{Q}$ the output that maximises Λ is $Q^E(\lambda) = \frac{a-c+2(\alpha-\eta\mu a)+\lambda\alpha^*}{b(2(1-\eta)-\lambda)}$ (from expression (25)). In general, the optimal output for the cooperating exporting countries with empathy is $Q^E(\lambda) = min\left\{\frac{a}{b}\mu, \frac{a-c+2(\alpha-\eta\mu a)+\lambda\alpha^*}{b(2(1-\eta)-\lambda)}\right\}$. We have defined λ^F as the level of λ at which $Q^E(\lambda^F) = Q^G$. For $\alpha < \alpha^l$, $Q^G = \frac{A+2(\alpha-\eta\mu a)+\alpha^*}{b(1-2\eta)} < \overline{Q}$ (from proposition 3). Thus, for $\alpha \leq \alpha^l$, $Q^E(\lambda^F) = Q^G = \frac{A+2(\alpha-\eta\mu a)+\alpha^*}{b(1-2\eta)}$ at $\lambda^F = 1$, since then $\frac{a-c+2(\alpha-\eta\mu a)+\lambda\alpha^*}{b(2(1-\eta)-\lambda)}$ reduces to $Q^G = \frac{A+2(\alpha-\eta\mu a)+\alpha^*}{b(1-2\eta)}$. At $\alpha \geq \alpha^h$, we have $Q^C = \overline{Q} = Q^G$ (from proposition 4). Thus, $Q^E(\lambda^F) = Q^G$ even at $\lambda^F = 0$. For $\alpha^l < \alpha < \alpha^h$, λ^F depends on α. For $\alpha^l < \alpha < \alpha^h$, setting $\frac{a-c+2(\alpha-\eta\mu a)+\lambda\alpha^*}{b(2(1-\eta)-\lambda)} = \frac{a}{b}\mu$ and solving for $\lambda^F(\alpha)$, yields $\lambda^F(\alpha) = \frac{1}{\mu a+\alpha^*}\left(a(2\mu-1)+c-2\alpha\right)$.■

B Proof of propositions and corollary for general model.

Proof of Proposition 6:

First we we compare any two equilibria j and k where $(j = F, N, C, G), (k = F, N, C, G)$ but $j \neq k$. These equilibria are unique from assumption 1. Write the first-order conditions as $m^j(q^j) = 0$ and $m^k(q^k) = 0$. At any common q we can compare $m^j(q)$ and $m^k(q)$. Suppose that at equilibrium j, $m^k(q^j) > m^j(q^j) = 0$. It follows from assumption 2 ($m^j_q(q) < 0$ and $m^k_q(q) < 0$, for q between q^j and q^k) that $m^k(q^j) > m^k(q^k) = 0$ and thus $q^k > q^j$. Furthermore, since $r(q)$ is monotonically declining it follows that $r^k = r\left(q^k\right) < r\left(q^j\right) = r^j$. Note that together, $m^k(q^k) = 0$, assumption 1, and $m^k(q^j) > m^j(q^j) = 0$ imply that $0 = m^k(q^k) > m^j(q^k)$ so that a local ranking at one of the equilibria to be compared cannot be reversed at the other equilibrium.

Next we apply the general comparision of equilibria to prove part (i) of the proposition: At the F equilibrium compare $m^F(q^F) = h^F(q^F) = p(q^F) - c - b(q^F)q^F = 0$ and $m^N(q^F) = h^N(q^F, r(q^F))$. The latter can be written as $h^N(q^F, r(q^F)) = h^F(q^F) + s^N(q^F, r(q^F))$. Hence the difference is $m^N(q^F) - m^F(q^F) = s^N(q^F, r(q^F))$. From (28) this is positive iff $\beta > -\frac{2-\rho}{2}bq$ evaluated at the F equilibrium. Thus when $\beta > -\frac{2-\rho}{2}bq$ evaluated at the F equilibrium it follows that $m^N(q^F) > m^F(q^F) = 0$ and from above this implies $m^N(q^F) > m^N(q^N) = 0$, giving $q^N > q^F$ and $r^N < r^F$. Using the same argument it follows that $\beta < -\frac{2-\rho}{2}bq$ evaluated at the F equilibrium implies $q^N < q^F$. Furthermore since a local ranking at one of the equilibria cannot be reversed at the other it follows that if $\beta > (<)\frac{2-\rho}{2}bq$ when evaluated at the F equilibrium then also $\beta > (<)\frac{2-\rho}{2}bq$ when evaluated at the N equilibrium.

Applying the general comparison of equilibria to part (ii): At the F equilibrium compare $m^F(q^F) = h^F(q^F) = 0$ and $m^C(q^F) = h^C(q^F, r(q^F))$ where the latter can be written as $h^C(q^F, r(q^F)) = h^F(q^F) + s^C(q^F, r(q^F))$. The difference is $m^C(q^F) - m^F(q^F) = s^C(q^F, r(q^F))$ which from (30) is positive iff $\beta > bq/2$. Thus, from if $\beta > (<)bq/2$ then $m^C(q^F) > (<)m^F(q^F) = 0$, $q^C > (<)q^F$ and $r^C < (>)r^F$.

Part (iii): At the N equilibrium compare $m^C(q^N) = h^C(q^N, r(q^N))$ and $m^N(q^N) = h^N(q^N, r(q^N)) = 0$. The difference $m^C(q^N) - m^N(q^N) = h^C(q^N, r(q^N)) - h^N(q^N, r(q^N)) = s^C(q^N, r(q^N)) - s^N(q^N, r(q^N))$ which is positive (negative) if $\beta > (<)bq$ evaluated at the N equilibrium. Thus $q^C > (<)q^N$ and $r^C < (>)r^N$ if $\beta > (<)bq$.

Part (*iv*): This proof is analogous to that of the earlier parts. Compare $m^F(q), m^N(q)$ and $m^C(q)$ to $m^G(q) = h^G(q, r(q))$ at common symmetric equilibria. It is clear that $m^G(q)$ is the largest and hence q^G is always larger and thus r^G is always lower than at any of the other equilibria.■

Proof of corollary:

Given the strict quasiconcavity of $M^G(q)$ and given that $q^G > \max\{q^C, q^N, q^F\}$.it follows that the global welfare ranking of the regimes is the same as their output ranking.■

Proof of Proposition 7:

Consider the the C equilibrium. Exporter country welfare can be written as $W(q, r)$. From earlier, for $q < \overline{q}$, the cooperative optimal q given r is $q^C(r)$. Since $p(\overline{Q}) \leq c$ and $\frac{\partial D}{\partial Q} = 0$ at $q = \overline{q}$ exporter country welfare $W(q, r)$ falls in q for $q \geq \overline{q}$. In general denote optimal q given r as $\widetilde{q}^C(r) = \max\{q^C(r), \overline{q}\}$. Let $\widetilde{r}^C$ be implicitly defined from $q^C(\widetilde{r}^C) = \overline{q}$ then it follows that $\widetilde{q}^C(r) = \overline{q}$ for $r \leq \widetilde{r}^C$ and thus $\widetilde{q}^C(0) = \overline{q}$ when $\widetilde{r}^C \geq 0$. Thus when $\widetilde{r}^C \geq 0$, since $r(\overline{q}) = 0$ the C equilibrium is $q = \overline{q}$ and $r = 0$. (The equilibrium C, in figure 5b is at the intersection of $\widetilde{q}^C(r)$ and $r(q)$.) Next consider the global optimum. Writing global welfare as $\Omega = H^G(q, r)$, let $q = \widetilde{q}^G(r)$ be globally optimal q conditional on r. Global welfare falls in q for $q \geq \overline{q}$ so $\widetilde{q}^G(r) = \max\{q^G(r), \overline{q}\}$. Let $\widetilde{r}^G$ be implicitly defined from $q^G(\widetilde{r}^G) = \overline{q}$, then since at a common r, $q^G(r) > q^C(r)$ (See proof of proposition 6) it follows that $\widetilde{r}^G > \widetilde{r}^C$. When $\widetilde{r}^C > 0$, it follows that $\widetilde{r}^G > 0$ and since $r(\overline{q}) = 0$ the G equilibrium is $q = \overline{q}$ and $r = 0$ which is identical to the C equilibrium. Finally since (q, r) is the same in the C and G equilibria when C entails full vaccination it follows that global welfare is also maximised under exporter cooperation when C yields full vaccination. ■

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Figure 1: Vaccine output under the alternative policy regimes

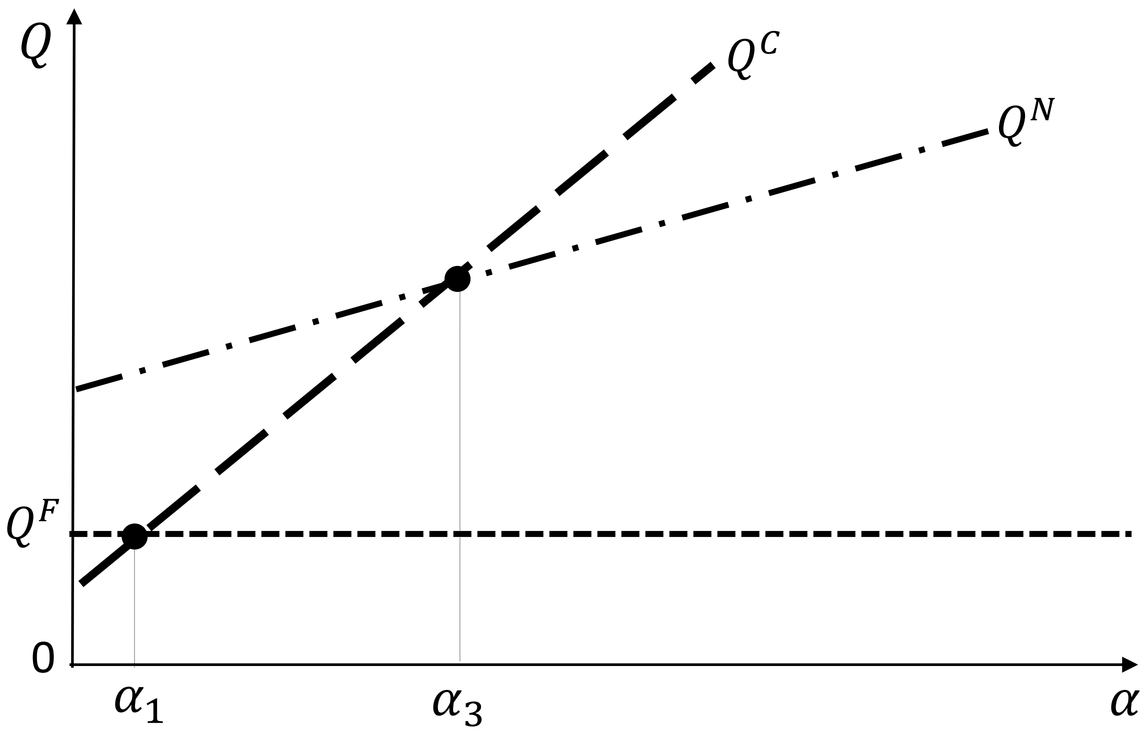


Figure 2: Complete vaccination coverage under the alternative policy regimes

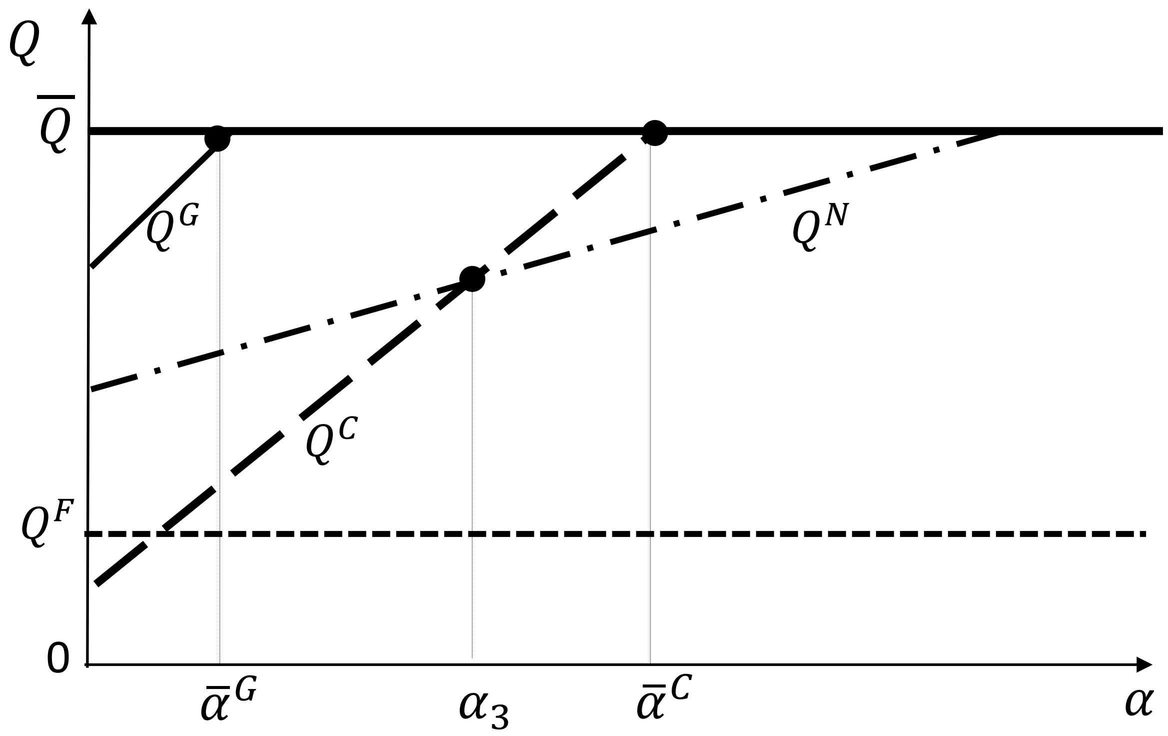


Figure 3: Global welfare and the externality

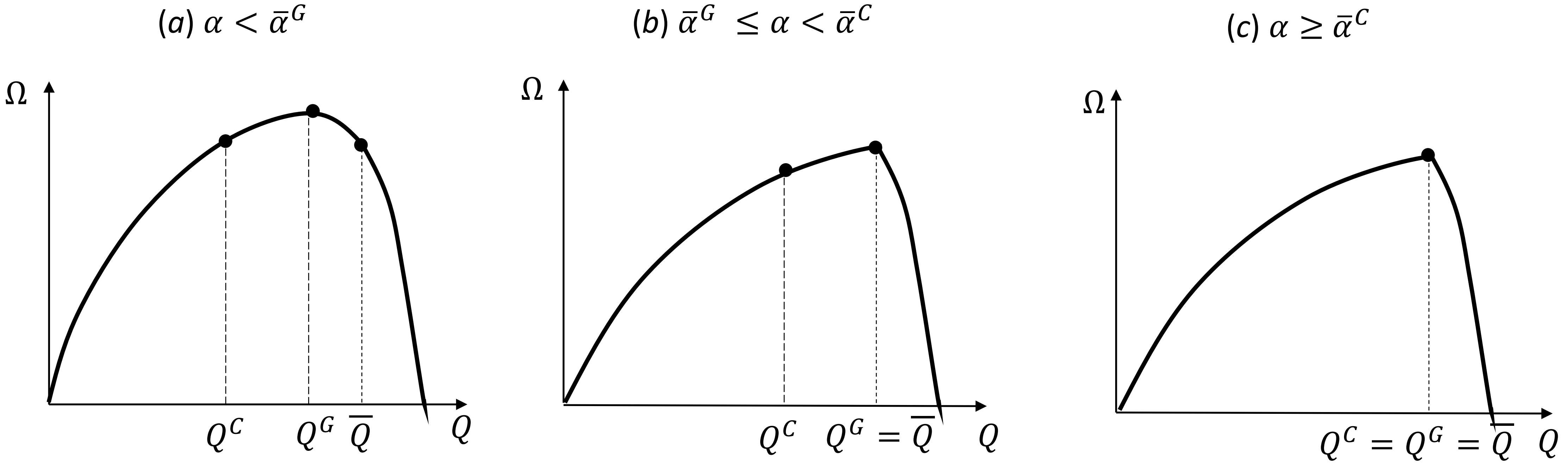


Figure 4: The critical empathy threshold at which cooperation entails full vaccination coverage

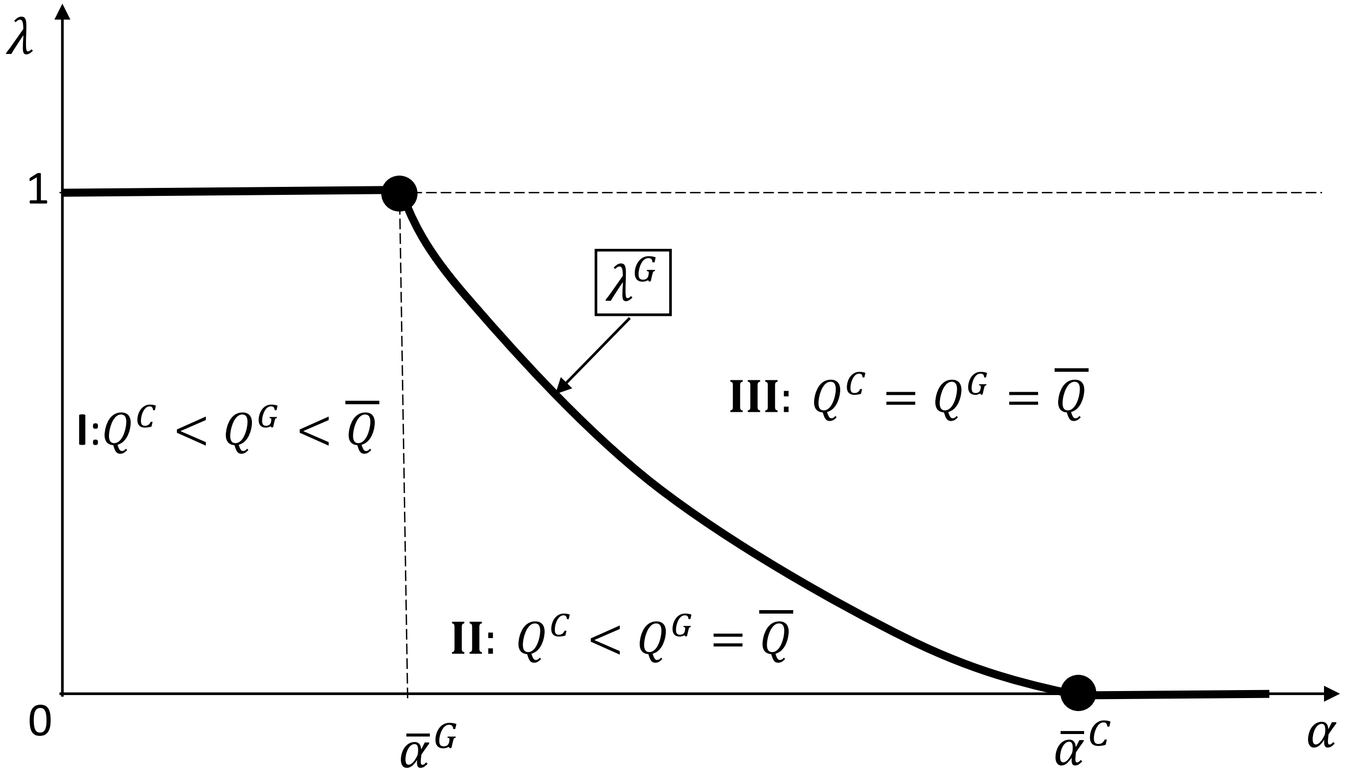
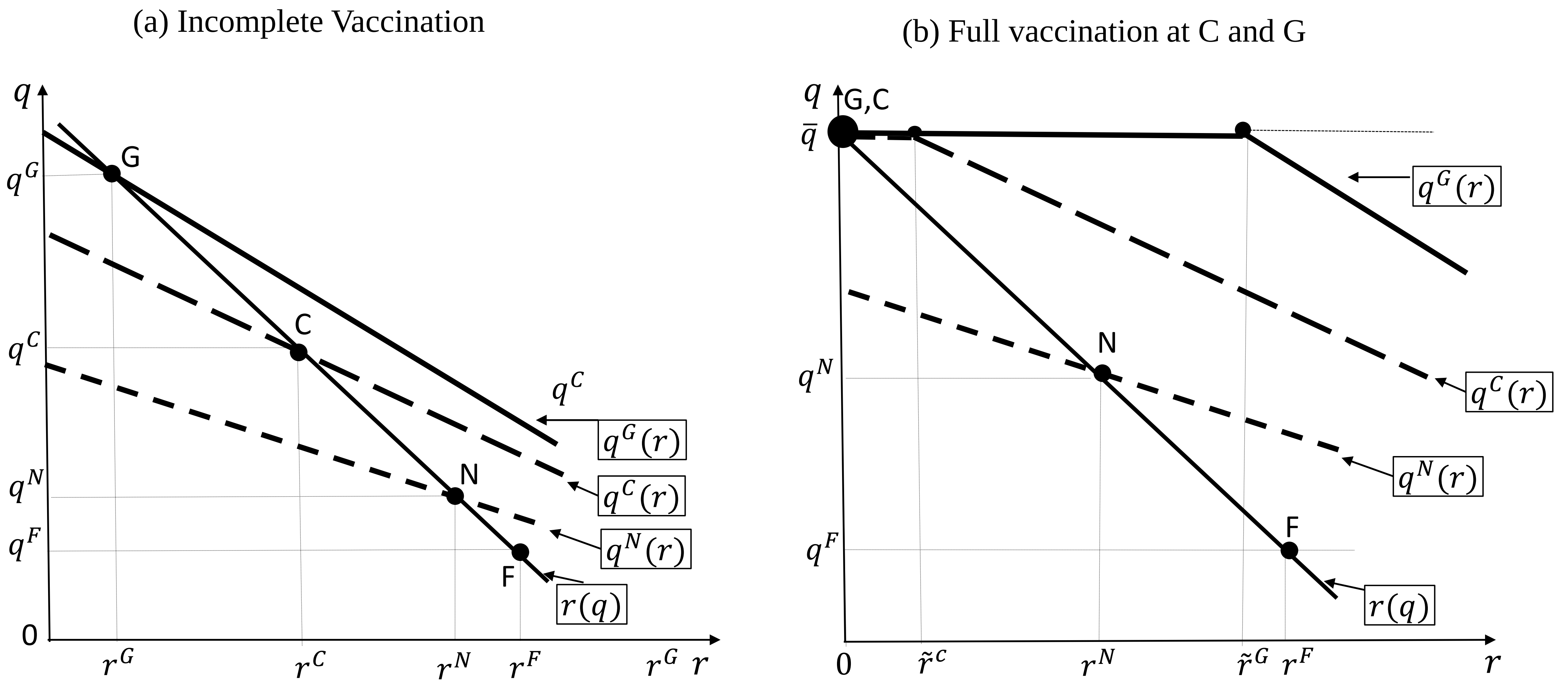


Figure 5: Outputs and restrictions in different equilibria



Note: $r^G = r^C = 0$ and $q^G = q^C = \bar{q}$