Accepted: 17 September 2024

DOI: 10.1111/ecca.12552

ORIGINAL ARTICLE

Economica LSE

Export policy cooperation in a pandemic: the good, the bad and the hopeful

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Abstract

We develop a model in which vaccine-producing firms from different developed countries supply vaccines to the developing world during a pandemic. Exporting countries experience a negative externality from incomplete global vaccination, which they try to mitigate by exporting vaccines to developing countries. A cooperative export policy is compared to the alternative regimes of non-cooperation and non-intervention. When the negative externality is low, cooperation among exporting countries is worse for global welfare than non-intervention. However, at high externality levels, export policy cooperation is globally superior to non-cooperative export subsidization. It then even has the potential to maximize global welfare.

JEL CLASSIFICATION

F12; F13; H23; L13

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 global character of these externalities suggests that Pigovian policies should be internationally coordinated. This paper focuses on vaccine trade policy during a pandemic, examining the global welfare effects of cooperative export initiatives, and comparing them to the policy alternatives of non-cooperation and non-intervention.

As argued in a recent study (Marani *et al.* 2021), large pandemics like the Spanish flu (1918) and COVID-19 (2019) are becoming increasingly likely.[1] In fact, pharmaceutical companies have launched programmes to prepare for 'disease X', an unknown future pathogen with the potential to cause a very serious pandemic.[2] Although there have recently been important pharmaceutical vaccine innovations (such as those based on the relatively new mRNA technology) to combat future pandemics (Miranda *et al.* 2022), securing global access to essential vaccines is lagging far behind the rapid progress in their development. Apart from the directly harmful consequences for countries that cannot access the vaccines, incomplete global vaccination causes a negative externality on countries that have the means to inoculate their populations.[3] Among others, Baldwin and Evenett (2020) point out the need for enhanced trade policy cooperation through the World Trade Organization, maintaining that it should be part of the solution to global health crises. While cooperation initiatives to make vaccines globally available and to fight and prevent future pandemics have been called for repeatedly by the World Health Organization, they are extremely hard to achieve.[4] In fact, the absence of a supranational authority with the power to implement corrective global policies gives national governments—particularly during times of crisis—an increased incentive to intervene unilaterally.[5]

Given the difficulties around reaching global cooperative agreements, we explore the global welfare effects of a more limited form of trade policy cooperation.[6] We investigate whether export policy cooperation among vaccine-exporting countries alone can ever be sufficient to raise global welfare during a global health emergency. We show when this form of trade policy cooperation is bad for global welfare, and find that it is even worse than non-intervention when the externality of non-vaccination lies below a specific threshold. However, provided that the externality of non-vaccination on the exporting countries is large enough, a cooperative export policy is good for global welfare. In that case, the Pigovian incentive for export promotion dominates, and this form of trade policy cooperation benefits both importing and exporting countries. Moreover, there is reason to be hopeful about exporter cooperation *in extremis*, that is, when the externality of non-vaccination on exporting countries is very high. Then cooperating vaccine-exporting countries attain the global welfare maximum, even when their objective is purely to maximize exporter joint welfare without taking the interests of importers into account.

We adopt a setting in which 'disease X' (caused by a new lethal pathogen) is causing a pandemic. We assume that, thanks to prior research, a transmission-reducing vaccine has been developed by some pharmaceutical firms from developed countries. Since the pharmaceutical industry is dominated by a few firms from a few countries, we choose an oligopolistic vaccine market setup.[7] In the basic model there are, for simplicity, two firms, each from a different country exporting the vaccine to other countries. As our focus is on the problem of global access to vaccines, we assume that the demand for vaccines within the exporting countries themselves has been satisfied, so it does not constrain exports. 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, governments of the exporting countries have an incentive to encourage vaccine exports, and do so through export subsidies. Thus the basic setup is that of a strategic trade model, but one that incorporates a global externality.[8] Incorporating the behaviour of both firms and governments, we consider different export policy regimes, comparing export policy cooperation to non-cooperative export promotion and non-intervention. Each of these policy stances is then assessed from the perspective of the exporting countries and the importing country, and from a global welfare perspective.

In an extended version of our model, we discuss how multiple firms and firm entry affect our results. Another extension allows for governments to impose socioeconomic restrictions,[9] and shows how such a domestic policy interacts with the vaccine export policy in each of the policy regimes. A final extension considers policies that can be used as alternatives to per-unit export subsidies.

Our paper contributes, first, to the literature on government trade policy initiatives and global health, in particular the global provision of vaccines against infectious diseases. Our focus is on trade policy that enhances the market for new vaccines and increases vaccine accessibility. In two papers, Kremer (2001a,b) argues that instead of just rewarding R&D effort, governments need to commit to rewarding firms after they have developed a marketable vaccine, and then ensure vaccine accessibility to poorer countries.[10] Our paper explores the potential of export subsidization, and compares cooperative and non-cooperative export policy stances. For diseases with low international externalities,[11] our analysis confirms the pitfalls of monopolization of patented vaccine producers, as pointed out by Kremer (2001a): cooperation by exporting countries is then bad for global welfare. However, our work points out that cooperation by exporting countries leads to higher global welfare than non-cooperative export subsidization in the presence of large international externalities of non-vaccination. In fact, we show that during a pandemic, a cooperative export policy stance may even produce the global optimum.

Second, although we apply our framework to the issue of provision of vaccines to mitigate a pandemic, our paper contributes to the general understanding of the role of cooperative government policy among a subset of countries in the presence of global externalities. Some earlier work has examined trade policy in the presence of externalities. The literature on trade and environmental policy offers several examples. Barrett (1994) 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. Fischer and Fox (2012) compare the effectiveness of trade policy instruments to combat emissions leakage. Mukherjee and Chakraborty (2016) provide a review of the link between environmental policy instruments and trade policy.

Finally, our analysis contributes 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 setup, Ahlvik and Liski (2022) 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 socioeconomic restrictions interacts with the global social effects of export policy cooperation when dealing with global problems.

Section 2 outlines the general setting. In Section 3, we derive our results, using specific functional forms to facilitate clarity of exposition and to derive explicit solutions. We obtain an expression for optimal vaccine exports for firms, given the export subsidy that they face, and determine actual vaccine export levels under non-intervention, non-cooperative subsidization and cooperation by vaccine-exporting countries. Subsequently, the global optimum is discussed, which allows us to assess each of the alternative policies in terms of global welfare. Section 4 generalizes our results beyond the specific functional forms used earlier. Section 5 discusses the extensions of our basic model, and Section 6 concludes.

2 | THE SETTING

We start by discussing the general setting. Assume that 'disease X' causes a pandemic. Two firms, each located in and wholly owned by residents of a different developed country i ($i = 1, 2$), have developed and produce effective vaccines.[12] Vaccines are assumed to be perfect substitutes. Both firms produce and export their vaccine to the developing world. Vaccine export by each firm is represented by q_i ($i = 1, 2$). We assume that demand in the developed countries has been fully satisfied so that exports are not constrained by the need to service the domestic market.[13] This allows us to focus entirely on the developing country's market. The developing world does not produce a vaccine itself but imports vaccines from countries 1 and 2. For simplicity, it is modelled as one country with a single market and referred to as country 3 (see Figure 1).

Country 3 is a small open economy, suffering a loss $L^*(Q)$ from not being fully vaccinated that falls with the quantity of the vaccine that the country consumes, $Q = \sum_i q_i$. Its total social benefit of consuming the vaccine is thus given by $V^*(Q) \equiv -L^*(Q)$. The country's marginal social benefit is $V^{*\prime}(Q)$ and is strictly positive until Q reaches the full vaccination level $\overline{Q}$, when

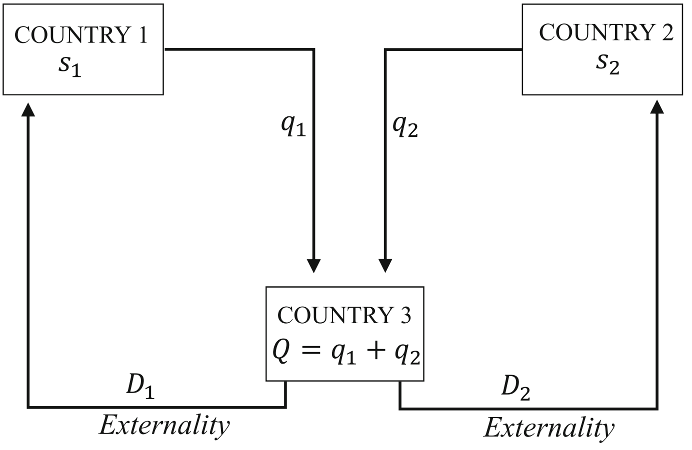

FIGURE 1 A three-country model with vaccine exports.

it falls to zero. Letting p denote the price of the vaccine in the developing country, the inverse demand—which equals the marginal social benefit—is

$$p(Q) = V^{*\prime}(Q), \quad \text{with } p(\overline{Q}) = 0. \tag{1}$$

The inverse demand $p(Q)$ is downward sloping and is a twice continuously differentiable function; $p'(Q) = -b(Q) < 0$, with $b(Q)$ denoting the absolute value of the slope of the inverse demand. The welfare w^* of the developing country is its social surplus from vaccination, which is equal to the difference between total social benefit $V^*(Q)$ and the expenditure on the vaccine Qp. It is given by

$$w^*(Q) = V^*(Q) - Q\,p(Q). \tag{2}$$

In addition to the benefit in the developing country, vaccination in country 3 also entails benefits for the developed world. Incomplete vaccine coverage in the less-developed world imposes a social cost to both developed exporting countries. The social cost of the direct damage (generated by incomplete global vaccination) experienced by developed country i is represented by D_i and is henceforth referred to as the direct 'damage'. This can take many forms, but the most obvious is that the unvaccinated in the developed countries remain exposed to illness, hence the health services would be under increased pressure. It also includes the economic costs of fractured supply chains and even the increased potential of pathogen mutation leading to a prolonging of the pandemic. Crucially, $D_i(Q)$ falls with the vaccine take-up Q, and is twice continuously differentiable:

$$D_i(Q)\begin{cases} > 0 & \text{for } Q < \overline{Q}, \\ = 0 & \text{for } Q = \overline{Q}, \end{cases} \quad \text{with} \quad \frac{\partial D_i}{\partial Q}\begin{cases} < 0 & \text{for } Q < \overline{Q}, \\ = 0 & \text{for } Q = \overline{Q}. \end{cases} \tag{3}$$

To boost vaccine take-up in country 3, the governments of the exporting countries may decide to subsidize vaccine exports. Although we choose to model government intervention 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.[14] Firm profits generated by exports are given by $\Pi_i(q_i, q_j, s_i) = \pi_i(q_i, q_j) + s_i q_i$, 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. Here, c is the marginal production cost plus marginal cost of delivery inclusive of transport cost. Hence welfare w_i in developed exporting country i is given by

$$w_i(q_i, q_j) = \pi_i(q_i, q_j) - D_i(Q). \tag{4}$$

The total derivative of welfare of exporting country i is given by

$$\mathrm{d}w_i = \frac{\partial \pi_i}{\partial q_i}\,\mathrm{d}q_i + \frac{\partial \pi_i}{\partial q_j}\,\mathrm{d}q_j + \beta_i\,\mathrm{d}Q, \tag{5}$$

where we have suppressed the arguments of the functions for brevity. In equation (5), $\beta_i = \beta_i(Q)$ denotes country i's marginal external benefit from vaccination, with $\beta_i = -\partial D_i/\partial Q \geq 0$. For simplicity, we will often refer to it as the 'marginal externality'. When either country 1 or country 2 exports more of the vaccine, both exporting countries benefit equally through a fall in their 'direct damage', with the effect on country i captured by $\beta_i(Q)$. Whether β_i is large or small depends on the characteristics of the vaccine and how it interacts with the pathogen.

The model consists of two types of agents: firms and developed exporting country governments. These agents play a two-stage game. 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 setting the subsidies and thus in the provision of vaccines to the less-developed country. In stage two, firms choose vaccine exports in a Cournot manner. Assuming subgame perfection in each case, we use backward induction to determine the outcome.

The results that 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 functions. This allows us to focus on symmetric equilibria. For expositional ease, we turn to specific functional forms in Section 3 and generalise our results in Section 4.

3 | VACCINE EXPORT POLICY IN A LINEAR–QUADRATIC MODEL

The specific functional forms that we introduce here allow us to obtain explicit solutions and present our results as clearly as possible. Country 3's total social benefit, $V^*(Q) = aQ - b(Q^2 + \overline{Q}^2)/2$, increases with vaccine consumption Q until full vaccination is reached ($\overline{Q} \equiv a/b$).[15] The demand for vaccines by country 3 (see equation (1)) is represented by the linear function $p = a - bQ$, where a and b are now constants. The direct damage to country i from incomplete vaccine coverage in country 3 takes the simple form $D_i = (\overline{Q} - Q)\beta_i$, with a developed country's marginal external benefit from vaccinating the people in country 3 given by β_i, the 'marginal externality'. In this section, it is a positive constant, and since exporting countries are symmetric, we drop the subscripts on β and D. With these specifications, equation (4) amounts to

$$w_i = \pi_i - (\overline{Q} - Q)\beta. \tag{6}$$

3.1 | Vaccine exports

We first examine stage two of the game, in which firms choose exports. The first-order condition for a profit-maximizing firm i is

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

Standard calculations allow us to derive firm i's equilibrium export quantity as a function of the subsidies:

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

From equation (8) and adding each country's output together, total exports as a function of each country's subsidy are given by

$$Q = \frac{2(a - c) + s_i + s_j}{3b}. \tag{9}$$

If *either* government increases its subsidy, then more people in country 3 are vaccinated. Since vaccine exports of each country are determined in stage two, taking the vaccine subsidies set in stage one as given, equation (9) is valid irrespective of how the subsidies are chosen. Equation (9) also allows us to derive total vaccine exports under the useful benchmark of non-intervention, in which case $s_i = s_j = 0$. Denoting non-intervention by superscript F (indicating a 'free-trade' policy stance), we have $Q^F = 2(a - c)/3b$. As governments are policy inactive in that case, and private firms do not care about the external social effect of non-vaccination, vaccine exports are lower than under subsidization and do not change with β. As a result, the damage from the externality in the exporting countries is larger than when vaccine export is subsidized.

3.2 | Vaccine export policy: non-cooperation versus cooperation

We first determine the export subsidy when exporting countries act independently. Subsequently, the export subsidy under cooperation by exporting countries is derived. We start by deriving interior solutions, implying that export levels in the various export policy regimes all fall short of complete vaccination ($Q < \overline{Q}$).[16] We impose a condition on the marginal externality β to ensure this. Here and henceforth, this will be referred to as the 'policy interior equilibrium condition' (PIEC). From Subsection 3.5 onwards, this condition will be relaxed.

PIEC. We assume $\beta < (a + c)/2$, implying that all export policy equilibria are interior solutions, that is, entail incomplete vaccination ($Q < \overline{Q}$).

When the export subsidy is set non-cooperatively, each exporting country i chooses s_i in stage one to maximize national welfare (equation (6)). It does so taking into account how the subsidy affects both firms' export quantities (equation (8)), set in stage two. The first-order condition for the optimal subsidy is

$$\frac{\partial w_i(s_i, s_j)}{\partial s_i} = \frac{\partial w_i}{\partial q_i}\frac{\partial q_i}{\partial s_i} + \frac{\partial w_i}{\partial q_j}\frac{\partial q_j}{\partial s_i} = 0. \tag{10}$$

Note that there is no *direct* effect of the subsidy on welfare since the subsidy is a transfer between the government and the firm. Hence the subsidy affects welfare only through its effect on the second-stage variables, that is, firm exports. We have

$$\frac{\partial w_i}{\partial q_i} = a - c - 2bq_i - bq_j + \beta \quad \text{and} \quad \frac{\partial w_i}{\partial q_j} = -bq_i + \beta.$$

In addition

$$\frac{\partial q_i}{\partial s_i} = \frac{2}{3b} \quad \text{and} \quad \frac{\partial q_j}{\partial s_i} = -\frac{1}{3b},$$

from equation (8). Substituting these in equation (10) and making use of symmetry between the exporting countries yields the equilibrium subsidy under non-cooperation, s^N:

$$s^N = \frac{a - c + 3\beta}{5}. \tag{11}$$

Because of the symmetry assumption, the subsidy is identical for both countries in equilibrium, allowing us to drop subscript i. Non-cooperative governments of exporting countries subsidize exports for two reasons. The first reason is to reduce the damage D by increasing vaccine exports Q. As β increases, the damage from non-vaccination is higher, hence the benefit of vaccine export subsidization is stronger. The second reason is a strategic trade policy one: to reinforce their firm's 'business stealing' from the foreign rival. A government's export subsidy shifts its own firm's reaction function out, thus reducing the rival firm's export. As both (symmetric) governments act in this way, the outcome of the export rivalry results in higher exports to the developing country than under non-intervention, while firms' market shares remain unchanged. Due to this rent-shifting effect, the non-cooperative export subsidy s^N is strictly positive, even when the marginal externality of exporting vaccines is zero ($\beta = 0$).

Substituting equation (11) in equation (9) yields the reduced-form expression for total exports when governments subsidize vaccine exports non-cooperatively, denoted by Q^N:

$$Q^N = \frac{4(a - c) + 2\beta}{5b}. \tag{12}$$

Since the export subsidy increases with β, vaccine exports do so too.

Instead of deciding unilaterally on the subsidy, governments of exporting countries may cooperate: optimal subsidies are then obtained from maximizing joint welfare, $W = w_1 + w_2$. The first-order condition for joint welfare maximization is given by

$$\frac{\partial W(s_i, s_j)}{\partial s_i} = \frac{\partial W}{\partial q_i}\frac{\partial q_i}{\partial s_i} + \frac{\partial W}{\partial q_j}\frac{\partial q_j}{\partial s_i} = 0.$$

All derivatives are mentioned under equation (10). The cooperatively chosen subsidy of the exporting countries, denoted by s^C, is given by

$$s^C = -\frac{a - c}{4} + \frac{3}{2}\,\beta. \tag{13}$$

Export policy cooperation allows exporting countries to do two things. First, cooperating governments internalize their firms' mutual business-stealing effect. Since the export policy of the two governments is now cooperative, they wish to curtail exports, aiming to fully exploit their joint market power and effectively mimic a monopoly; this works towards taxing exports and is reflected in the first term of equation (13), which is negative. Second, cooperating governments do not just consider the beneficial effect of vaccine exports on their own domestic welfare, but also internalize the positive welfare effect of their own vaccine exports on each other, thus giving them an incentive to subsidize. This is reflected in the second term of equation (13), which is positive and increasing in the marginal externality β. The optimal export subsidy under export policy cooperation thus combines two opposite forces. For this reason, the sign of the cooperative subsidy is ambiguous and depends on the relative strength of the two effects. When β is low, the first effect dominates and the cooperative export subsidy is in fact an export tax ($s^C < 0$). Conversely, for high β, the second effect dominates and the export subsidy is positive ($s^C > 0$). Note that because countries also take the externality on each other's welfare into account, s^C increases faster in β than s^N does ($\partial s^C/\partial\beta > \partial s^N/\partial\beta$ from equations (13) and (11)).

Substituting equation (13) for s_i (with $s_i = s_j$) in equation (9) gives the total exports under a cooperative export policy, Q^C:

$$Q^C = \frac{a - c + 2\beta}{2b}. \tag{14}$$

For a comparison of vaccine exports under the alternative policy regimes, two β thresholds, $\widehat{\beta}_1$ and $\widehat{\beta}_3$, prove useful. The smaller $\widehat{\beta}_1$ threshold is the externality level at which Q^C equals Q^F, while at the higher $\widehat{\beta}_3$ threshold, Q^C equals Q^N. A third threshold, $\widehat{\beta}_2$, which proves useful later, lies strictly in between $\widehat{\beta}_1$ and $\widehat{\beta}_3$.

Lemma 1. *We have*

(i) $Q^C(\widehat{\beta}_1) = Q^F$, *with* $Q^C(\beta) > Q^F$ *for* $\beta > \widehat{\beta}_1$, *while* $Q^C(\beta) < Q^F$ *for* $\beta < \widehat{\beta}_1$

(ii) $Q^C(\widehat{\beta}_3) = Q^N(\widehat{\beta}_3)$, *with* $Q^C(\beta) > Q^N(\beta)$ *for* $\beta > \widehat{\beta}_3$, *while* $Q^C(\beta) < Q^N(\beta)$ *for* $\beta < \widehat{\beta}_3$

(iii) $\widehat{\beta}_1 < \widehat{\beta}_3$, *with* $\widehat{\beta}_1 = (a-c)/6$ *and* $\widehat{\beta}_3 = (a-c)/2$.

The proof of Lemma 1 (and the proofs of all this section's lemmas and propositions) is given in Appendix Subsection A.1. Since these β thresholds are below the level specified in the PIEC (i.e. $(a+c)/2$), the rankings in Lemma 1 are consistent with interior solutions (i.e. vaccine exports below full vaccination levels).

Figure 2 depicts vaccine exports as a function of the marginal externality parameter β under the alternative export policy regimes. Exports under non-intervention (Q^F) do not depend on β and are represented by a horizontal line. Also, since the cooperative export subsidy increases faster with β than the non-cooperative one, $Q^C(\beta)$ is steeper than $Q^N(\beta)$.

At $\widehat{\beta}_1$, the vaccine export levels under export policy cooperation and non-intervention coincide ($Q^C(\widehat{\beta}_1) = Q^F$). For lower externality levels ($\beta < \widehat{\beta}_1$), exports under policy cooperation are even lower than under non-intervention ($Q^C(\beta) < Q^F$), implying that the cooperative policy is then an export tax. For higher externality levels ($\beta > \widehat{\beta}_1$), the cooperative export subsidy is positive; exports then exceed the level under non-intervention ($Q^C(\beta) > Q^F$).

At $\widehat{\beta}_3$, a cooperative export policy generates the same level of vaccine exports as the non-cooperative export policy stance ($Q^C(\widehat{\beta}_3) = Q^N(\widehat{\beta}_3)$). Under non-cooperation, each

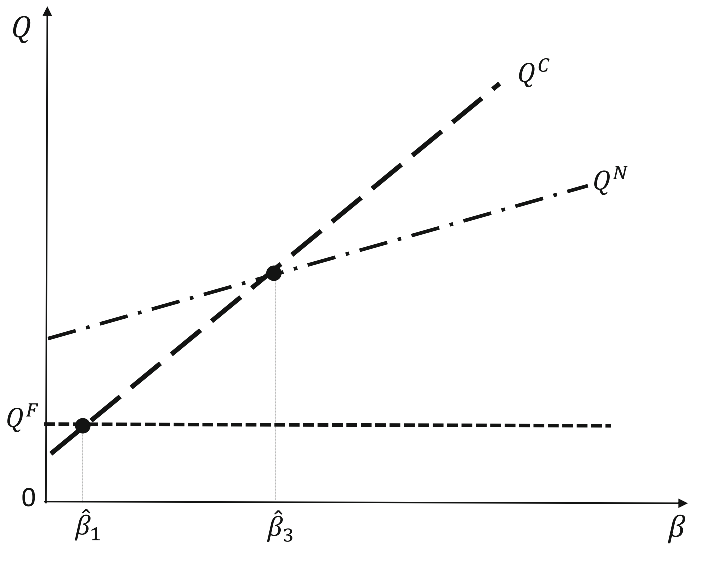

FIGURE 2 Vaccine export under the alternative policy regimes.

government always subsidizes vaccine exports, even when there is no externality. Therefore, exports under policy cooperation are lower than under non-cooperation when β is low and the internalization of the business-stealing effect dominates ($Q^C(\beta) < Q^N(\beta)$). However, unlike cooperation, a non-cooperative policy stance does not take into account the beneficial effect of vaccine exports on the other exporting country's welfare. Hence when β is sufficiently high ($\beta > \widehat{\beta}_3$), the full internalization of the externality raises the cooperative subsidy above the non-cooperative level ($s^C > s^N$), which is reflected in higher vaccine exports ($Q^C(\beta) > Q^N(\beta)$).

Figure 2 is extremely helpful in explaining the ranking of these two thresholds ($\widehat{\beta}_1 < \widehat{\beta}_3$). When there is no externality (at $\beta = 0$), cooperation results in the lowest and non-cooperative export subsidization in the highest export level, with exports under non-intervention in between ($Q^C < Q^F < Q^N$). We know that Q^F does not depend on β, and exports under a non-cooperative export policy always involve a subsidy hence always exceed the export level under non-intervention ($Q^F < Q^N$). Furthermore, since the $Q^C(\beta)$ locus is the steepest ($Q^C(\beta)$ increases fastest with β), it has to be true that as β rises, Q^C will reach the lower export level Q^F (at $\widehat{\beta}_1$) before it will attain level Q^N (at $\widehat{\beta}_3$).

3.3 | Importing and exporting country welfare

We now discuss the welfare implications for the vaccine-exporting and vaccine-importing countries. Given our specified functional forms, the welfare function of the vaccine-importing country (see equation (2)) amounts to

$$w^* = \frac{1}{2}(a-p)Q - \frac{b}{2}\overline{Q}^2, \tag{15}$$

where $b\overline{Q}^2/2$ is a constant and is hence unaffected by the export policy regime. Welfare of the importing country increases with the vaccine level. So welfare of the importing country is highest under the vaccine exporters' policy regime that yields the highest vaccine exports. Proposition 1 summarizes this.

Proposition 1. *Welfare levels for the importing country in the export policy regimes of cooperative export policy (w^{*C}), non-cooperative subsidization (w^{*N}) and non-intervention (w^{*F}) are ranked as:*

(i) $w^{*N} > w^{*F} > w^{*C}$ *for* $\beta < \widehat{\beta}_1$
(ii) $w^{*N} > w^{*F} = w^{*C}$ *for* $\beta = \widehat{\beta}_1$
(iii) $w^{*N} > w^{*C} > w^{*F}$ *for* $\beta \in (\widehat{\beta}_1, \widehat{\beta}_3)$
(iv) $w^{*N} = w^{*C} > w^{*F}$ *for* $\beta = \widehat{\beta}_3$
(v) $w^{*C} > w^{*N} > w^{*F}$ *for* $\beta > \widehat{\beta}_3$.

Only when β is sufficiently high ($\beta > \widehat{\beta}_3$) does a cooperative export policy yield higher welfare for the importing country than the alternatives. Non-cooperative subsidization is preferred otherwise. The reason is straightforward. Since the importing country cares only about the net social benefit from the vaccine imports, it favours the regime that generates the higher exports and thus the lower import price; for $\beta < \widehat{\beta}_3$, this is the non-cooperative export policy stance. For low enough β ($\beta < \widehat{\beta}_1$), even non-intervention is preferred to cooperation as cooperation then implies an export tax, lowering exports below the non-intervention level.

The welfare ranking of the alternative policy regimes is different for vaccine-exporting countries. Using the welfare function in equation (6), the following proposition establishes this.

Proposition 2. *Welfare levels for an exporting country in the policy regimes of cooperative export policy (w_i^C), non-cooperative export subsidization (w_i^N) and non-intervention (w_i^F) are ranked as*

(i) $w_i^C \geq w_i^F > w_i^N$ *for* $\beta < \hat{\beta}_2$, *with* $w_i^C > w_i^F$ *when* $\beta \neq \hat{\beta}_1$

(ii) $w_i^C > w_i^F = w_i^N$ *for* $\beta = \hat{\beta}_2$

(iii) $w_i^C \geq w_i^N > w_i^F$ *for* $\beta > \hat{\beta}_2$, *with* $w_i^C > w_i^N$ *when* $\beta \neq \hat{\beta}_3$,

where $w_i^N(\hat{\beta}_2) = w_i^F$ *and* $\hat{\beta}_2 = 7(a-c)/24$ *with* $\hat{\beta}_2 \in (\hat{\beta}_1, \hat{\beta}_3)$.

A direct argument establishes why cooperation is, from the exporting countries' perspective, never inferior to the other regimes, irrespective of the magnitude of the externality. Since they are free to choose any export level—including Q^N and Q^F—exporting countries will never do worse by cooperating. So if the cooperative chooses a different export level from the one in the other regimes, then this implies a higher welfare level.

When comparing *non-cooperative export promotion* and *non-intervention*, export countries' preferences depend on the marginal externality β. Recall the two reasons for non-cooperative export subsidization: encouraging rent shifting through business stealing, and reducing the damage of under-vaccination. At $\beta = 0$, business stealing is the only subsidy motive. In that case, non-cooperative export policy reduces to standard strategic export policy, with each government subsidizing its firm to help it capture market share from its foreign rival. But since this results in governments driving the price of exports down, the international rivalry results in a prisoner's dilemma, with each exporting country ending up with a lower welfare level than they would under non-intervention. When β is positive, the subsidy also has another effect; this effect is positive as it reduces D. As β rises, this effect becomes stronger and increases welfare under non-cooperation while leaving welfare under non-intervention unchanged. When the externality is sufficiently high ($\beta > \hat{\beta}_2$), the benefits of the export subsidy are high enough that a non-cooperative export policy leads to higher welfare in an exporting country than non-intervention.

At $\hat{\beta}_2$, welfare in an exporting country is the same under a non-cooperative export policy as under non-intervention. The intuition for $\hat{\beta}_2 \in (\hat{\beta}_1, \hat{\beta}_3)$ is as follows. Knowing that the welfare of an exporting country is always highest under cooperation, we have also established (see Lemma 1(i)) that non-intervention yields the same welfare as cooperation at $\hat{\beta}_1$. Hence we have that at $\hat{\beta}_1$, an exporting country's welfare is higher under non-intervention than with a non-cooperative export policy ($w_i^C = w_i^F > w_i^N$ at $\hat{\beta}_1$). Similarly, we know that at $\hat{\beta}_3$, exporting countries' preferred policy stance of cooperation yields the same welfare as non-cooperation (see Lemma 1(ii)); this immediately implies that at $\hat{\beta}_3$, non-intervention yields a lower welfare level ($w_i^C = w_i^N > w_i^F$ at $\hat{\beta}_3$). Thus since $\hat{\beta}_1 < \hat{\beta}_3$ (see Lemma 1(iii)), it follows logically that at a β level in between $\hat{\beta}_1$ and $\hat{\beta}_3$, exporting countries must attain the same welfare under a non-cooperative export policy and non-intervention ($\hat{\beta}_1 < \hat{\beta}_2 < \hat{\beta}_3$).

Table 1 summarizes the welfare ranking for the exporting countries and the importing country, and makes it easy to see when the interests of importers and exporters are aligned, and when they are in conflict. When the marginal externality is smaller than $\hat{\beta}_3$, export policy preferences of the importing and exporting countries are not aligned: the importing country prefers exporting countries not to cooperate, while cooperation is the preferred policy stance of exporting countries. Hence it is not clear from a *global* welfare perspective which export policy regime is preferable. However, there is no longer any ambiguity when the marginal externality parameter is large ($\beta > \hat{\beta}_3$): both prefer export policy cooperation in that case. But even then, it is not clear by how much export policy cooperation falls short of the global optimum. We explore all this in the next subsection.

TABLE 1 Welfare ranking of cooperative subsidization, non-cooperative subsidization and laissez faire.

		Welfare ranking	
Externality	Exports	Importing country	Exporting country
$\beta > \hat{\beta}_3$	$Q^C > Q^N > Q^F$	$w^{*C} > w^{*N} > w^{*F}$	$w_i^C > w_i^N > w_i^F$
$\hat{\beta}_2 < \beta < \hat{\beta}_3$	$Q^N > Q^C > Q^F$	$w^{*N} > w^{*C} > w^{*F}$	$w_i^C > w_i^N > w_i^F$
$\hat{\beta}_1 < \beta < \hat{\beta}_2$	$Q^N > Q^C > Q^F$	$w^{*N} > w^{*C} > w^{*F}$	$w_i^C > w_i^F > w_i^N$
$\beta < \hat{\beta}_1$	$Q^N > Q^F > Q^C$	$w^{*N} > w^{*F} > w^{*C}$	$w_i^C > w_i^F > w_i^N$

3.4 | Global welfare and the global optimum

We start this subsection by deriving the vaccine export level that maximizes global welfare, which combines the interests of both importing and exporting countries. This facilitates a comparison of the different policy regimes from a *global* welfare perspective. Giving equal weight to the welfare of importing and exporting countries, global welfare, denoted by Ω, is given by

$$\Omega = W + w^*.$$

The export level that maximizes Ω is denoted by Q^G. We will henceforth refer to this as the global optimum. The global optimum may entail full vaccination ($Q^G = \overline{Q} = a/b$). However, since vaccines are costly, it is possible that full vaccination does not maximize global welfare ($Q^G < \overline{Q}$); Ω is then maximized when the global social benefit of vaccination, $p + 2\beta$, is equal to the global social cost c, and we have $Q^G = (a - c + 2\beta)/b$. Hence the globally optimal vaccine export level is given by[17]

$$Q^G = \min\left\{(a - c + 2\beta)/b, \overline{Q}\right\}. \tag{16}$$

Lemma 2. *The global optimum Q^G entails:*

(i) incomplete vaccination coverage ($Q^G < \overline{Q}$) for $\beta < \overline{\beta}^G$, with $\overline{\beta}^G = c/2$
(ii) full vaccination coverage ($Q^G = \overline{Q}$) otherwise.

Since $\overline{\beta}^G < (a + c)/2$, it satisfies the PIEC. So at externality levels that yield interior solutions (incomplete vaccination) for all the export policy regimes, the global optimum may also be an interior solution and not entail full vaccination. Whether it does so depends on the level of the externality (β) on the one hand, and on the cost of producing and distributing the vaccine (c) on the other hand. We have $Q^G = \overline{Q}$ if $c \leq 2\beta$. Intuitively, the global optimum prescribes complete vaccination coverage only when c is lower than the externality on both exporting countries. Figure 3(a) illustrates the case in which the global optimum involves incomplete vaccination, while Figure 3(b) shows the case in which complete vaccination is globally optimal.[18]

So how do the alternative policy regimes compare to the global optimum? We first compare Q^G to export levels Q^C, Q^N and Q^F. Figure 4 clearly illustrates that when the exports in these regimes fall short of full vaccination, they are always below the globally optimal level ($Q^C < Q^G$, $Q^N < Q^G$ and $Q^F < Q^G$), regardless of whether the global optimum entails full or partial vaccination. Lemma 3 formalizes this.

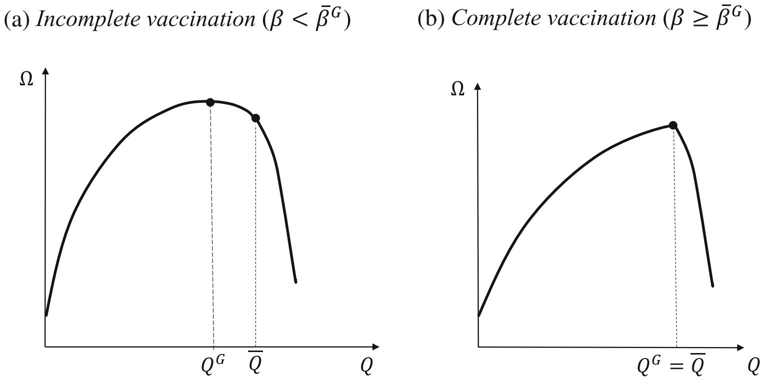

FIGURE 3 Global welfare and the global optimum.

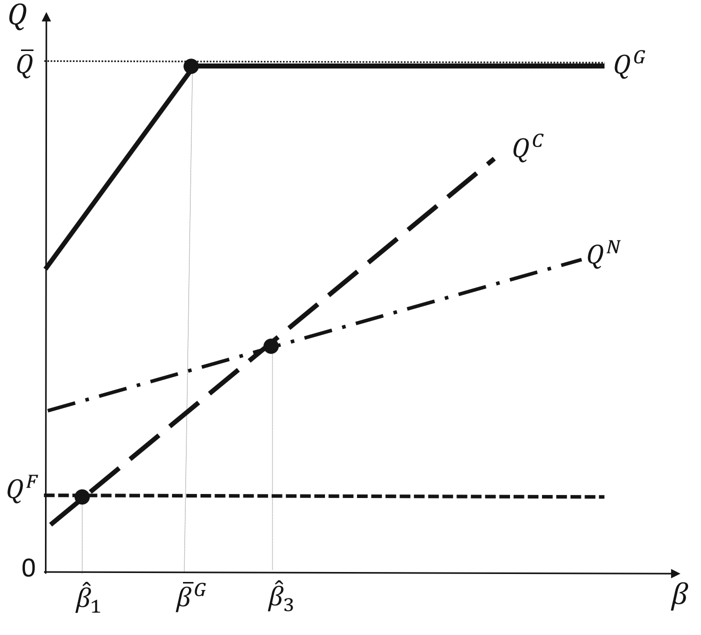

FIGURE 4 Vaccine exports in the alternative policy regimes versus the global optimum.

Lemma 3. *When cooperative subsidization, non-cooperative subsidization and non-intervention do not achieve full vaccination ($\beta < (a+c)/2$), we have $Q^G >$ $\max\{Q^C, Q^N, Q^F\}$.*

Proposition 3 establishes the global welfare ranking of the alternative policy regimes when they entail incomplete vaccination ($\max\{Q^C, Q^N, Q^F\} < \overline{Q}$), that is, under the PIEC.

Proposition 3. *When cooperative subsidization, non-cooperative subsidization and non-intervention do not achieve full vaccination (i.e. when $\beta < (a+c)/2$), their global welfare ranking is:*

(i) $\Omega^N > \Omega^F > \Omega^C$ *for* $\beta < \widehat{\beta}_1$
(ii) $\Omega^N > \Omega^F = \Omega^C$ *for* $\beta = \widehat{\beta}_1$
(iii) $\Omega^N > \Omega^C > \Omega^F$ *for* $\beta \in (\widehat{\beta}_1, \widehat{\beta}_3)$
(iv) $\Omega^N = \Omega^C > \Omega^F$ *for* $\beta = \widehat{\beta}_3$
(v) $\Omega^C > \Omega^N > \Omega^F$ *for* $\beta > \widehat{\beta}_3$.

Intuitively, the global optimum Q^G achieves global social efficiency. Under the PIEC, the three policy regimes *all* fall short of this ($\max\{Q^C, Q^N, Q^F\} < \overline{Q}$). In our setup, there are two sources of global social efficiency. First, because all the policy regimes are characterized by imperfect competition, the export levels are all below Q^G. The motivation to restrict exports to raise rents is highest under export policy cooperation, and lowest under a non-cooperative export policy. As this source of global inefficiency dominates when the externality is small, cooperation is particularly harmful to global welfare at low β: when $\beta < \hat{\beta}_1$, welfare is lowest under a cooperative policy and highest under non-cooperation. Second, global social efficiency requires that the externality experienced by exporting countries from under-vaccination in the importing country must be internalized. Under policy cooperation, this externality of non-vaccination is fully internalized, while it is not at all taken into account by exporting firms under non-intervention. This source of inefficiency is the most important at high β levels. When $\beta > \hat{\beta}_3$, welfare is highest under export policy cooperation, and lowest under non-intervention. In fact, the global welfare ranking of the alternative export policy regimes is completely aligned with the welfare ranking of the various regimes for the importing country. This also implies that the global welfare ranking follows the export volume ranking of the various export regimes.

3.5 | Export policy cooperation, complete vaccination and the global optimum

We now relax the PIEC, the condition on β that was imposed earlier, allowing for higher externality levels. Exports under active policy may now reach the full vaccination level. So allowing for a complete vaccination level $\overline{Q}$, we ask when export policy cooperation will actually lead to this.[19]

Lemma 4. *Threshold* $\overline{\beta}^C$ *is the minimum level of* β *for which* $Q^C\left(\overline{\beta}^C\right) = \overline{Q}$, *with* $\overline{\beta}^C = (a + c)/2$. *For* $\beta < \overline{\beta}^C$, $Q^C(\beta) < \overline{Q}$, *while* $Q^C(\beta) = \overline{Q}$ *for* $\beta \geq \overline{\beta}^C$.

The threshold $\overline{\beta}^C = (a + c)/2$ is exactly the maximum β value that is specified in the PIEC for an interior solution. So by relaxing the PIEC, we allow for values of β that are consistent with full vaccination under export cooperation. The threshold $\overline{\beta}^C$ is always higher than $\overline{\beta}^G$; thus if export cooperation entails full vaccination, then so does the global optimum.

Lemma 5. $\overline{\beta}^C > \overline{\beta}^G$.

As for $\overline{\beta}^G$, the $\overline{\beta}^C$ threshold is higher as the production and distribution cost of vaccines (c) is higher. Lemma 4 and 5 imply the following proposition.

Proposition 4. *For* $\beta \geq \overline{\beta}^C$, *vaccine exports under export policy cooperation yield the global optimum* ($Q^C = Q^G = \overline{Q}$).

Figure 5 shows that exports under cooperation among exporting countries (Q^C) reach full vaccination ($\overline{Q}$) for very high levels of the externality ($\beta \geq \overline{\beta}^C$). So in spite of the fact that this form of cooperation is not global but is limited to exporting countries only, export policy cooperation actually achieves the global optimum for such high externality levels ($Q^C = Q^G = \overline{Q}$). The reason for this lies in the fact that the extremely high externality levels make fully global vaccination worthwhile to the exporting countries. This result may offer a glimmer of hope regarding the policy responses to future pandemics in the sense that limited and therefore easier to implement forms of cooperative initiatives may be sufficient to generate a solution that is optimal from a global perspective.

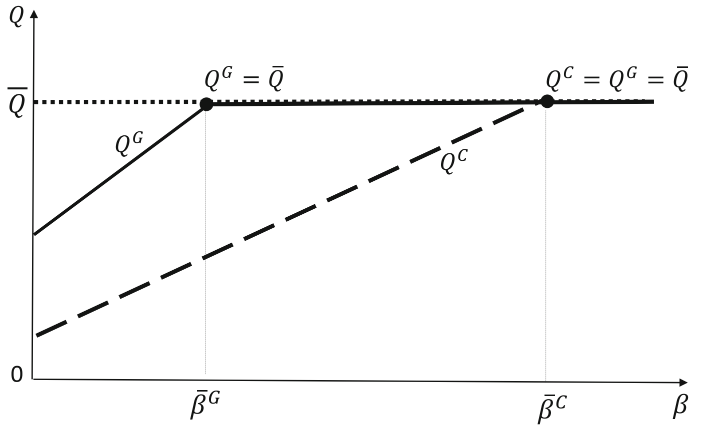

FIGURE 5 Export cooperation and the global optimum.

4 | GENERAL MODEL

While linear demands and D functions have the advantage that they allow us to obtain explicit solutions, they come at the cost of generality. In this section, we demonstrate that the key results of the basic linear–quadratic two-stage game model hold with the general demand and damage functions described in Section 2. More specifically, we now use the general demand function as stated in equation (1), and the general damage function as stated in equation (3). The marginal externality is now a function of vaccine export ($\beta_i = \beta_i(Q)$). With the use of some mild restrictions, we are able to rank equilibrium exports and global welfare in the various equilibria at different levels of the externality. Proofs of the formal results are provided in Appendix Section A.2.

4.1 | Exports

Using backward induction, we first solve the second stage. The firm's first-order condition for exports is still given by equation (7), but $p(Q)$ and $b(Q)$ are now general. We define $\rho(Q)$ as the convexity of demand, where $\rho(Q) = -Qp''/p'$ (where primes indicate derivatives). When demand is linear, $\rho = 0$; when $\rho(Q) > 0$, demand is convex, and when $\rho(Q) < 0$, demand is concave. Firm i's equilibrium exports as a function of the subsidies is $q_i(s_i, s_j)$, with derivatives

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

We have $\partial q_i/\partial s_i > 0$ (since $2 - \rho q_j/Q > 0$ from the second-order condition for firm j) and $\rho < 3$ (from the stability of the Cournot game). We focus on the 'standard' Cournot case, in which exports are strategic substitutes, implying that firms' export reaction functions are negatively sloped. The following assumption ensures this.

> **Assumption 1.** Vaccine exports are strategic substitutes, or $\rho < Q/q_i$, implying $\partial q_i/\partial s_j < 0$.

This simply means that demand is not too convex. It implies that as in our basic model where it holds automatically (as $\rho = 0$), an export subsidy harms the rival foreign exporting firm.

Having solved for firm exports, we examine the first stage of the game and the equilibria and welfare in the different regimes. We first consider the case in which the global optimum implies incomplete vaccination (Subsection 4.2), followed by the case in which it implies full vaccination (Subsection 4.3).

TABLE 2 Symmetric subsidies and first-order conditions for export in the general model with incomplete vaccination.

	Symmetric subsidy s	First-order condition in symmetric equilibrium $h = 0$
Non-intervention (F)	—	$h^F(q) = p - c - bq = 0$
Non-cooperative export policy (N)	$s^N = \left(\frac{2-\rho}{4-\rho}\right)bq + \beta\left(\frac{2}{4-\rho}\right)$	$h^N(q) = p - c - \left(\frac{2}{4-\rho}\right)bq + \beta\left(\frac{2}{4-\rho}\right) = 0$
Cooperative export policy (C)	$s^C = -bq + 2\beta$	$h^C(q) = p - c - 2bq + 2\beta = 0$
Global optimum (G)	—	$h^G(q) = p - c + 2\beta = 0$

4.2 | Incomplete vaccination

Let q without a subscript represent symmetric-country equilibrium exports so that $q = Q/2$. With incomplete vaccination, the equilibrium q falls short of $\overline{q} = \overline{Q}/2$. The procedure for obtaining the first-order conditions for export and subsidy under the various policy regimes is the same as in the linear–quadratic model. Hence we simply report the general solutions in Table 2. Although b, β and ρ are general, their arguments are suppressed for notational convenience.

The symmetric general expressions for the subsidy in the different regimes are given in the middle column of Table 2. The non-cooperative export subsidy is positive (which is guaranteed from Assumption 1). The first term of s^N captures the business-stealing motive for subsidization, while the second term represents the component that corrects for the externality. Also, as in the linear–quadratic model, the optimal cooperative subsidy is positive only for a sufficiently large externality. In the expression for s^C, the internalization of the business-stealing effect is represented by the first term, whereas the internalization of the externality is reflected in the second term. The final column of Table 2 gives the symmetric first-order condition for exports, written in abbreviated form as $h^r(q^r) = 0$, where the superscript refers to the export regime ($r = F, N, C, G$). As in the previous subsection, these are derived by using the regime-appropriate subsidies in the firm's first-order condition, and imposing symmetry.

Comparing the equilibria in the different export regimes requires some mild assumptions.

Assumption 2. Equilibria of each type (F, N, C, G) are unique.

At any common q, we compare $h^r(q)$ and $h^l(q)$ for $r, l = F, N, C, G$, with $r \neq l$. The second-order and stability conditions of the model ensure that the derivatives of the $h(q)$ functions, evaluated at their equilibrium q, are negative; that is, $h^r_q(q^r) < 0$ for $r = F, N, C, G$. The following assumption extends these conditions beyond the purely local.

Assumption 3. For any two equilibria r and l to be compared, $h^r_q(q) < 0$ and $h^l_q(q) < 0$ at *any* q between q^r and q^l.

The following proposition compares exports in the different equilibria.

Proposition 5. *When the exports to be compared are below the full vaccination level:*

(i) $q^C > q^F$ *if and only if* $\beta > bq/2$ *evaluated at these equilibria*

(ii) $q^C > q^N$ *if and only if* $\beta > bq$ *evaluated at these equilibria*

(iii) $q^N > q^F$

(iv) $q^G > \max\{q^C, q^N, q^F\}$.

First, Proposition 5(i) is the general equivalent of Lemma 1(i), with $bq/2$ corresponding to the $\hat{\beta}_1$ threshold in the linear case; it simply generalizes that exports with export policy cooperation exceed exports under non-intervention only if the externality is high enough. Second, exports with export policy cooperation even exceed exports under non-cooperation, provided that the externality is above the higher threshold bq, which corresponds to the $\hat{\beta}_3$ threshold in the linear–quadratic model (Lemma 1(ii)). Third, since non-cooperative export policy always entails a positive subsidy ($s^N > 0$), it implies higher vaccine exports than non-intervention ($q^N > q^F$, hence $Q^N > Q^F$). However, when exports in the different export regimes entail incomplete vaccination, they all fall short of the globally optimal export level ($q^G > \max\{q^C, q^N, q^F\}$). Thus Proposition 5(iv) is a generalization of Lemma 3. The mechanisms that drive these rankings are the same as in the specific-function model and have been explained there.

After having compared exports, we now move to a comparison of global welfare in the different regimes. Global welfare can be expressed as a function $\Omega(q)$ of q with a unique maximum. The following assumption allows us to compare global welfare under the different regimes.

Assumption 4. The function $\Omega(q)$ is strictly quasi-concave.

Corollary 1. *The global welfare ranking of the different regimes F, N and C is the same as the export rankings of those regimes.*

This corollary generalizes Proposition 3. As explained earlier, Proposition 3 implies that the global welfare ranking follows the export volume ranking in the various export regimes. We now turn to the case in which *full* vaccination is globally optimal.

4.3 | Full vaccination

Export policy cooperation achieves full vaccination ($q^C = \overline{q}$) for sufficiently high β. Once $\overline{q}$ has been reached, the externality no longer exists. Nothing is gained from increasing q above $\overline{q}$. A similar argument applies to the global optimum. These results are stated formally in the following proposition.

Proposition 6. *With cooperation among exporting countries:*

(i) the maximum equilibrium vaccine export is $q^C = \overline{q}$
(ii) when $q^C = \overline{q}$*, cooperation among exporting countries achieves the global optimum* ($q^C = q^G = \overline{q}$)*.*

Proposition 6 generalizes Proposition 4. When the global optimum entails full vaccination, export policy cooperation has the potential to replicate the global optimum.

5 | EXTENSIONS

Since the aim of this paper is to compare the welfare effects of vaccine export policy alternatives during a pandemic, our basic model has abstracted from a few issues, thereby allowing us to focus on that aim. In this section, we discuss some extensions of the basic linear–quadratic two-stage game model to examine these additional issues. First, we extend the model to include multiple firms in each exporting country. Second, we extend the game to include firm entry and model domestic vaccination as taking place before vaccine export. Third, we extend the basic model to include domestic policy in the form of socioeconomic restrictions. In a final extension, we discuss the use of alternative policy instruments in achieving welfare-maximizing vaccine exports

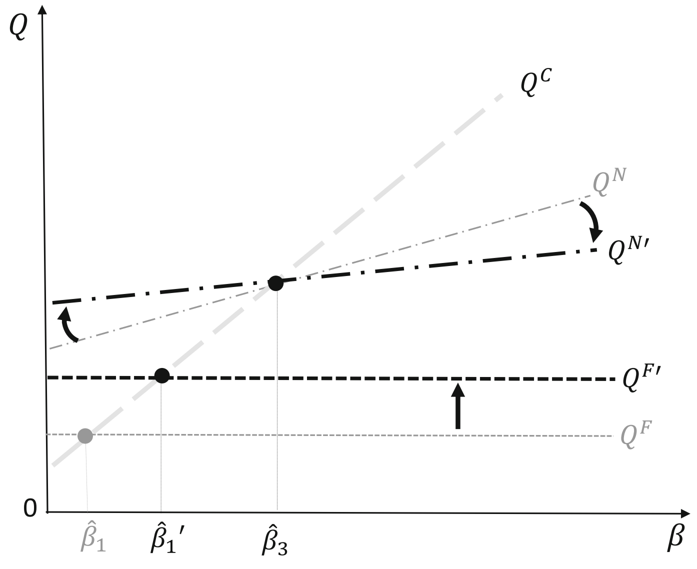

FIGURE 6 Vaccine output in the alternative policy regimes with multiple vaccine-producing firms in each exporting country.

in the different exporting regimes. Proofs of the propositions in this section are given in Appendix Section A.3.

5.1 | Multiple firms

In this section, we extend our basic model to allow for multiple exporting firms in each country, and ask how this affects the welfare comparison between cooperative and non-cooperative export policy stances. Maintaining our symmetry assumption so that the number of firms is the same in each country, we now assume that each country has n (≥ 1) exporting firms. Hence the *total* number of exporting firms from countries 1 and 2 is now $2n$ (rather than 2 in the basic model). Under export policy cooperation, the subsidy is

$$s^C(n) = \frac{-(2n-1)(a-c) + 2(2n+1)\beta}{4n}, \tag{17}$$

while the subsidy under a non-cooperative export policy is given by

$$s^N(n) = \frac{(a-c) + (2n+1)\beta}{(3+2n)n}. \tag{18}$$

The derivations are provided in Appendix Section A.3. If $n = 1$, then the export subsidies are as discussed in our basic model (see equations (11) and (13)). Both s^C and s^N fall with n. The main reason for this is that the non-intervention output increases with the number of firms due to increased market competition. This necessitates smaller subsidies as countries attempt to internalize the negative impact of more competitive export behaviour on the price of their exports.

The effect of an increase in n on the equilibrium vaccine export levels under the various export policy regimes for various β levels is illustrated in Figure 6.

First, as the number of firms in each country increases (i.e. higher n), the non-intervention export level increases. This is represented by the $Q^{F'}$ locus, which lies further above Q^F (the non-intervention vaccine export level in the basic model) when the number of exporting firms increases. Importantly, the equilibrium vaccine export level under export policy cooperation, Q^C, is independent of n: it is simply the output that maximizes joint welfare of the exporting countries, and therefore is unaffected by the number of firms that produce that output. Since the number of vaccine-producing firms does not affect Q^C but raises Q^F, the externality threshold below which non-intervention generates higher vaccine exports than cooperation is higher as n increases. In Figure 6, this threshold is indicated by $\widehat{\beta}_1'$.

Second, we compare vaccine exports under cooperative and non-cooperative policies when $n > 1$. While Q^C is independent of n, Q^N does depend on n, and is given by

$$Q^N(n) = Q^N(1) + \frac{n-1}{2n+3}\,\frac{4}{5b}\left(\frac{a-c}{2} - \beta\right),$$

where $Q^N(1)$ refers to the exports under a non-cooperative policy with just a single vaccine exporter ($n = 1$) in each country (see equation (12)). If the externality is low ($\beta < (a-c)/2$), then $Q^N(n)$ increases with n, whereas it decreases with n if the externality is high ($\beta > (a-c)/2$). At $\beta = (a-c)/2$, the non-cooperative export level $Q^N(n)$ is the same as $Q^N(1)$, and is thus unaffected by the number of firms. Figure 6 illustrates that increasing the number of exporting firms (i.e. n) causes the Q^N locus to pivot at the $\widehat{\beta}_3$ threshold.

The difference between exports under non-cooperation and cooperation is given by

$$Q^N(n) - Q^C = \frac{1}{b}\,\frac{2n+1}{2n+3}\left(\frac{a-c}{2} - \beta\right). \tag{19}$$

In our basic model, $Q^N = Q^C$ at the threshold $\widehat{\beta}_3 \equiv (a-c)/2$. As equation (19) shows, this threshold is the same with multiple vaccine exporters.

Proposition 7. *With n vaccine-exporting firms ($n \geq 1$):*

(i) $Q^N - Q^C > 0$ *for* $\beta < \widehat{\beta}_3$ *and* $\mathrm{d}(Q^N - Q^C)/\mathrm{d}n > 0$

(ii) $Q^C - Q^N > 0$ *for* $\beta > \widehat{\beta}_3$ *and* $\mathrm{d}(Q^C - Q^N)/\mathrm{d}n > 0$

(iii) $Q^C = Q^N$ *at* $\beta = \widehat{\beta}_3$ *and* $\mathrm{d}(Q^C - Q^N)/\mathrm{d}n = 0$.

As explained in the basic model, Q^C differs from Q^N when s^C differs from s^N. At low β ($\beta < \widehat{\beta}_3$), cooperation's main benefit for exporting countries is that it reduces non-cooperation's business-stealing, reducing s^C below s^N, and thus Q^C below Q^N. At high β ($\beta > \widehat{\beta}_3$), the main benefit of cooperation is to internalize the beneficial effect of each country's vaccine exports on the other exporting country, increasing s^C above s^N, and thus Q^C above Q^N. Both these effects are stronger when n is larger. The reason for this lies in the fact that vaccine exports are strategic substitutes: an increase in one firm's export leads to a decrease of its rivals' exports. So under non-cooperation, an increase in a country's export subsidy increases its own exports, but lowers the rival country's. With more foreign firms (higher n), this foreign reaction is stronger. At low β ($\beta < \widehat{\beta}_3$), this strengthens business stealing and increases s^N and Q^N. However, at high β ($\beta > \widehat{\beta}_3$)—when the damage of under-vaccination is the dominant consideration—a greater fall in foreign exports is harmful to the subsidizing country and limits the subsidy. Thus $Q^N(n) > Q^N(1) > Q^C$ for $\beta < \widehat{\beta}_3$, and $Q^N(n) < Q^N(1) < Q^C$ for $\beta > \widehat{\beta}_3$. Hence the divergence between $Q^N(n)$ and Q^C increases with n. This then means that, relative to non-cooperation, the benefit of cooperation ($w^C - w^N(n)$) increases with n (except at $\widehat{\beta}_3$, when $Q^N(n) = Q^C$ and thus $w^C = w^N(n)$).

From the *exporting* countries' perspective, export policy cooperation always remains the preferred export policy stance when there are multiple export firms, with the welfare gap between cooperation and non-cooperation widening as the number of exporting firms increases. From the perspective of the *importing* country, non-cooperation by exporting countries remains the preferred export policy regime when the externality is low (since $Q^N > Q^C$ for $\beta < \widehat{\beta}_3$), confirming the result obtained in the basic model; furthermore, the importing country prefers non-cooperating exporting countries to have many vaccine exporters since vaccine export is then higher ($Q^N(n)$ increases with n for $\beta < \hat{\beta}_3$). However, as in our basic model, the importing country prefers policy cooperation among exporting countries when the externality is high (since $Q^C > Q^N$ for $\beta > \hat{\beta}_3$), but the preference for cooperation is stronger as the number of exporting firms increases.

5.2 | Entry

In the basic model, we assumed that the fixed costs incurred from vaccine development are sunk and that the domestic population of each exporting country has already been vaccinated. We now explicitly explore this pre-export phase. To do this, we extend our basic model to a three-period setup. In period one, a number of firms n (≥ 1) enter into R&D in each country i ($i = 1, 2$) and develop a vaccine. The R&D cost per firm is f. Firms that are risk neutral decide whether to enter into R&D not knowing whether the ensuing export policy will be cooperative or non-cooperative. The probability that the export policy is cooperative is denoted by ϕ, while the non-cooperative policy stance is assigned the complementary probability $1 - \phi$. For simplicity, we assume that these probabilities are common knowledge and are hence the same for all firms. In period two, firms that entered serve their domestic market, for which they receive a subsidy from the government. This subsidy is chosen before firms choose domestic outputs. We assume that the domestic and export markets are segmented. Subsequently, at the start of period three, the uncertainty about the export policy stance is resolved and the export subgame follows. While the details of the extended model are elaborated in Appendix Section A.3, we focus here on intuition and ask how the pre-export phase affects the results of our basic model, paying particular attention to the comparison between cooperative and non-cooperative export policies. The game is solved by backward induction.

Period three. The subgame in this period is identical to the game described in Subsection 5.1. The export subsidy in each policy regime depends on the number of firms ($n \geq 1$) that have entered in each exporting country. Given symmetry, the total number of exporting firms is thus $2n$. The export subsidy in each policy regime is given in equations (17) and (18) for the cooperative and non-cooperative export policy stances, respectively.

Period two. It is to be expected that vaccine nationalism ensures that the domestic market is served before other markets are.[20] We capture this stylized fact in period two; n vaccine-producing firms engage in Cournot competition, simultaneously choosing the vaccine output for their domestic market. The government of each exporting country seeks to maximize domestic welfare by choosing an appropriate production subsidy for the domestic market before the firms set outputs. Since the actions of firms and governments in the domestic market can be separated from their actions in the export market, period-two decisions do not affect those in period three (as shown in Appendix Section A.3, where period two is described in more detail).

Period one. The number n of firms in country i ($i = 1, 2$) is determined in period one. Assuming that n is an integer, it is determined by the fact that—in equilibrium—a firm's expected operating profit $E\Psi$ at least covers the R&D cost f, so $E\Psi(n) - f \geq 0$, but would fail to do so if one more firm was to enter, so $E\Psi(n+1) - f < 0$. Obviously, lower fixed costs of entry f, and larger domestic and export markets, work towards entry of more firms. Entry is also encouraged when firms expect the subsidy to be higher. Since export subsidies increase in the externality β, so too does entry. The effect of ϕ on the incentive to entry is ambiguous. If the probability ϕ of a cooperative export policy increases, then expected firm profit and hence entry will increase only if the externality is high ($\beta > \hat{\beta}_3$), since only then does the cooperative export subsidy exceed the non-cooperative one ($s^C > s^N$). For low externality levels ($\beta < \hat{\beta}_3$), the opposite is true ($s^C < s^N$).

So how does entry affect welfare? From the *exporting* countries' perspective, multiple firms entering in the R&D stage ($n > 1$) generate socially inefficient entry costs $(n-1)f$, thus lowering welfare.[21] However, as n is the same regardless of the export policy stance in period three, the welfare loss due to this inefficiency is the same under cooperative and non-cooperative export policy regimes. Since the actions of firms and exporting countries' governments in the domestic market can be separated from their actions in the export market, the domestic market component of welfare is also independent of the export regime of cooperation or non-cooperation, thus does not affect the comparison of the two regimes.

5.3 | Socioeconomic restrictions

In this subsection, we ask how the results are affected by including domestic policy instruments that mitigate the externality. To focus directly on this issue, we return to the basic model and augment it by allowing exporting countries to introduce socioeconomic restrictions. These include border shutdowns, travel restrictions and quarantine, which—like global vaccination—help to reduce international transmission, but also entail an economic cost. The degree of socioeconomic restrictions imposed by exporting country i is denoted by an index r_i. We assume that the cost of the restrictions to country i is convex and given by $\gamma r_i^2/2$, where γ is a positive constant. Restrictions imposed by the exporting country reduce the damage it incurs due to non-vaccination in the importing country. To capture this, we modify the damage function $D_i = (\overline{Q} - Q)\beta_i$. While β_i was previously a constant, it now depends negatively on r_i. We have $\beta_i = \beta_0 - \theta r_i$ ($\beta_i > 0$), where θ captures the effectiveness of restrictions ($\theta > 0$), and β_0, a positive constant, measures the marginal externality in the absence of restrictions. Hence the damage of incomplete vaccination is now $D_i = (\overline{Q} - Q)(\beta_0 - \theta r_i)$. We assume that restrictions are always set non-cooperatively in stage two of the game, that is, at the same time as exports and after the subsidy.

The first-order condition for optimal restrictions in stage two is given by

$$\frac{\partial w_i}{\partial r_i} = (\overline{Q} - Q)\theta - \gamma r_i = 0. \tag{20}$$

Letting $\eta \equiv \theta^2/b\gamma$ denote the relative effectiveness of restrictions, equation (20) reduces to

$$\theta r_i = \eta b(\overline{Q} - Q). \tag{21}$$

Note that the maximum value for θr_i is $\eta b\overline{Q}$ (i.e. when $Q = 0$); since β_i is assumed to be positive for any θr_i, we impose $\beta_0 - \eta b\overline{Q} = a((\beta_0/a) - \eta) > 0$. We also impose $\eta < 1/2$ to guarantee the existence of each of the equilibria that we will consider. Hence we assume $\eta < \min\{1/2, \beta_0/a\}$. An increase in total vaccine exports Q lowers restrictions in both exporting countries (equation (21)). Export subsidies and restrictions are substitutes in reducing the external damage to an exporting country that results from incomplete global vaccination. An important difference between the two policy measures is that export subsidies increase the export of vaccines, which decreases the damage on *both* exporting countries, while restrictions mitigate the direct external damage only in the domestic country that introduces them. Bearing in mind that restrictions are always set optimally by each country in stage two (i.e. $\partial w_i/\partial r_i = 0$), and that restrictions in country i do not directly affect the welfare of country j ($\partial w_j/\partial r_i = 0$), we calculate the equilibrium subsidy and vaccine exports under the alternative policy regimes with restrictions. These are reported in Table 3 for the case of incomplete vaccination. (The values for complete vaccination are, naturally, the same as those without restrictions since no restrictions are needed when $Q = \overline{Q}$.)

Proposition 8. *When vaccination levels are incomplete, vaccine export levels Q^N, Q^C and Q^G fall in the relative effectiveness of socioeconomic restrictions, η.*

TABLE 3 The effect of socioeconomic restrictions on symmetric subsidies and vaccine exports under incomplete vaccination.

	Symmetric subsidy	Vaccine exports
Non-cooperative export policy (N)	$s^N = \frac{(1+2\eta)A+3\varepsilon}{5-2\eta}$	$Q^N = \frac{4A+2\varepsilon}{b(5-2\eta)}$
Cooperative export policy (C)	$s^C = \frac{-(1-4\eta)A+6\varepsilon}{4(1-\eta)}$	$Q^C = \frac{A+2\varepsilon}{2b(1-\eta)}$
Global optimum (G)	—	$Q^G = \frac{A+2\varepsilon}{b(1-2\eta)}$

Notes: $A \equiv a - c$ and $\varepsilon \equiv \beta_0 - \eta b\overline{Q}$.

Intuitively, export subsidies and restrictions are both policy instruments used to reduce the country's damage that results from incomplete global vaccination. As the effectiveness of imposing restrictions increases, an exporting country will therefore prefer to increase restrictions and export less. While restrictions reduce the level of vaccine exports, the qualitative nature of our results remains intact: Lemmas 1–5 as well as Propositions 1–4 are valid as stated.[22] Obviously, when exports reach the full vaccination level, restrictions are no longer required. Hence it remains the case that when $Q^C = \overline{Q}$, export policy cooperation attains the global optimum.

5.4 | Alternative policy instruments

In our model, exporting countries' governments, whether cooperating or not, manipulate their firms' vaccine export quantities. While per-unit export subsidies and taxes are a simple way to achieve this, the same real outcomes could be achieved with other instruments. Export subsidies and taxes in our model—as in most of the related literature—involve a transfer between the governments and private sector firms.[23] While such transfers do, of course, affect the distribution of welfare within an exporting country between the government and the exporting firm, this is not our concern here. Instead, our focus is on *total* welfare changes in exporting and importing countries. In fact, any policy that targets the same level of exports as in our basic model gives rise to the same qualitative welfare comparison of cooperation and non-cooperation. We briefly point out how fixed subsidies or taxes, voluntary export restraints and vaccine-uptake subsidies can target the desired export level, using the cooperative export level Q^C as an example.

First, suppose that instead of giving a per-unit export subsidy, governments were to grant a fixed subsidy for firms to produce their share of Q^C rather than the non-intervention export level. If this is conditional on firms exporting the target output levels, then it works just as well as a per-unit export subsidy. Provided that this fixed subsidy is set so that firms' profits are above those in the non-intervention case, it would be possible to achieve the desired outcome.

Second, one could use quantitative measures to obtain the desired export policy. When export policy cooperation involves a vaccine export that is below the non-intervention level ($Q^C < Q^F$), our model indicates choosing an export tax. The same export level could be achieved directly, using the quantity equivalent, namely a voluntary export restraint that is set at the desired level, Q^C.

Third, instead of targeting their exporting firms, exporting governments may wish to target vaccine uptake in the importing countries. This may involve governments from exporting countries buying the vaccine from their firms and making the optimal vaccine quantities directly available to the developing countries. This alternative policy could involve subsidizing vaccine uptake. Again, the subsidy would be chosen so that the sales reach the exporting countries' target level.[24]

Note that in the extended model in which entry is modelled explicitly (Subsection 5.2), the incentive to enter responds to the expected operating profits. Policies such as export subsidies tend to encourage entry, while export taxes have the opposite effect. Unlike export subsidies and taxes, policy instruments that target export quantities directly do not have as strong an effect on profitability and hence on entry. However, regardless of which of these alternative policy instruments is used, the welfare comparison between export policy cooperation and non-cooperation remains qualitatively unaffected.

6 | CONCLUSION

This paper developed a model in which vaccine-producing developed countries are experiencing a negative externality from incomplete global vaccination during a pandemic. We examine how various export policy regimes mitigate the externality, created by non-vaccinated populations elsewhere, by promoting the export of externality-reducing vaccines. Cooperation among exporting countries is compared to the alternative export policy regimes of a non-cooperative export policy and non-intervention.

We assess the various policy regimes from the alternative perspectives of the importing and exporting countries, and from an overall global perspective. *Importing countries* prefer the regimes that yield the highest vaccine levels. When assessing the various policy regimes from an *exporting country* perspective, the ranking of the regimes can differ from that of the importer and global ranking. From the point of view of the exporting countries, a non-cooperative export policy potentially lowers their welfare even below the non-intervention level. In fact, when the externality falls below a specific threshold, a prisoner's dilemma between subsidizing exporting countries occurs under non-cooperation. A cooperative export policy stance avoids this by internalizing the business-stealing effect; in addition, it internalizes the externality of non-vaccination on the rival exporting country. Hence export policy cooperation is always best from the exporting countries' perspective.

Viewed 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 export policy alternatives considered. It is particularly bad for global welfare when the externality on the exporting countries is low. Due to the monopolization effect on exports, export policy cooperation then leads to lower vaccine exports, thus lower global welfare than non-cooperation, and for sufficiently low externality levels, even lower welfare than with non-intervention. However, when the pandemic creates a large externality for exporting countries, cooperation among exporting countries leads to higher global welfare than non-cooperation because the internalization of the externality on other exporting countries then dominates the internalization of the business-stealing effect. The threshold above which this is the case falls in the cost of vaccine production and distribution. Thus when vaccine production and distribution costs are high, a cooperative export policy is relatively more likely to lead to higher global welfare than a non-cooperative export policy stance.

The level of vaccine exports that maximizes global welfare was derived and used as a benchmark to assess the potential of export policy cooperation. When the cost of vaccine production and distribution is high, the globally optimal vaccine export level entails incomplete vaccination. In that case, cooperation among exporting countries cannot replicate the global optimum. But if the global optimum involves complete vaccination (which it does for sufficiently low vaccine production and distribution cost) and the externality is high enough, then export policy cooperation generates the global optimum. Our results hold with general functional forms.

We have extended the basic model, thereby testing the robustness of our results. We added multiple firms and entry to our basic setup. Our main results regarding the relative value of cooperation are qualitatively unaffected by incorporating this. In fact, when externalities are low, the relative global welfare losses of export policy cooperation are larger with more firms in each exporting country, whereas its relative global welfare benefits are higher when externalities are high. Countries may also want to impose national socioeconomic restrictions to mitigate the externality. While such national restrictions reduce vaccine export, they do not alter our results in any qualitative way. We also discussed some alternative policy instruments that can achieve the same goal. Finally, we believe that our model can be tailored to examine other global issues with negative global externalities that can be mitigated by the export of appropriate technologies. Studying the potential of export policy cooperation to promote emission-reducing or emission-absorbing technology in the fight against global warming is a possible example.

ACKNOWLEDGMENTS

We are grateful to J. Peter Neary for helpful discussions in the early stages of this paper, and thank participants at the conference 'In light of the evidence: economic, legal, social, and political perspectives on public policy' (Maynooth, 29 March 2023) for useful comments and suggestions. Open access funding provided by IReL.

ENDNOTES

[1] Marani *et al.* (2021) claim that the probability of observing pandemics similar to COVID-19 may double in future decades.

[2] In early 2022, Moderna announced a portfolio of programmes to tackle emerging pathogens in preparation for 'disease X' threats (Steenhuyzen and Erman 2022).

[3] Barrett (2003) argues that a global eradication of infectious diseases—which is possible only if these diseases are eliminated in every country—requires strong international institutions.

[4] Although in April 2020 a global cooperative scheme (Covax) was established to fight the COVID-19 pandemic, with richer countries subsidizing costs for poorer nations, it was slow to deliver.

[5] At the start of the COVID-19 pandemic in March 2020, the use of unilateral trade policy measures increased. High-income countries tightened export restrictions of crucial medical equipment, while low-income importing countries lowered import restrictions (Espitia *et al.* 2020).

[6] There exists a literature on the difficulties in forming cooperative agreements. In a setup with environmental policy, Barrett (1992) shows that international agreements become less effective as the number of signatories increases. Buchholz and Sandler (2021) provide a survey on the mechanism design for coalition formation for the provision of a global public good.

[7] Espitia *et al.* (2020) report that just 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.

[8] The seminal paper on strategic trade policy is by Brander and Spencer (1985). Brander (1995) and Leahy and Neary (2011) survey this literature.

[9] Governments across the world imposed such restrictions at the start of the COVID-19 pandemic. The costs of these are examined in International Monetary Fund (2020). An estimate of the cost of the restrictions on the US labour market is provided by Coibion *et al.* (2020).

[10] Kremer (2001a) compares 'push' and 'pull' programmes; while the former tend to reward a firm's R&D effort, the latter entail rewards for a firm after it has developed a marketable vaccine. In earlier work, Kremer (1998) explores the potential of governments buying out patents as a supplement to encouraging R&D innovation. He argues that the buyout should equal the private value of an invention (determined by auction) times a fixed markup that would roughly cover the difference between the social and private values of inventions.

[11] This is, for instance, the case for diseases that are very infectious locally, but not globally (e.g. Ebola and tuberculosis).

[12] Our main focus is on the supply of vaccines to the less-developed world, so we assume here that vaccines have already been developed, and ignore any sunk R&D costs. We discuss vaccine entry and development in an extension in Subsection 5.2.

[13] Subsection 5.2 also discusses the relationship between the domestic market and the entry of firms into vaccine development.

[14] We discuss alternative policy instruments in Subsection 5.4.

[15] As discussed earlier, we can write $V^*(Q) = -L^*(Q)$. The loss function $L^* = b(Q^2 + \overline{Q}^2)/2 - aQ$ reaches a minimum of zero at $Q = \overline{Q} \equiv a/b$, when $L^*(\overline{Q}) = (b/2)\left((a^2/b^2) + (a^2/b^2)\right) - a(a/b) = 0$.

[16] If a proportion μ of the importing country's population is unwilling to accept the vaccine, then it would not be possible to reach $\overline{Q}$. An interior solution would then hold only for $Q < (1-\mu)\overline{Q}$. For simplicity, we assume $\mu = 0$.

[17] Since more than full vaccination is costly and does not have any beneficial effect, Q^G cannot exceed $\overline{Q}$.

[18] The global welfare function displays a kink at $Q = \overline{Q}$.

[19] As illustrated in Figure 2, Q^C rises faster with β than Q^N does. Since exports under both export policy regimes are equal at $\beta = \hat{\beta}_3$ at a level that falls short of full vaccination ($Q^C = Q^N < \overline{Q}$), full vaccination will be reached at a lower β level under cooperation than under non-cooperation.

[20] This mirrors what happened in most vaccine-exporting countries during the COVID-19 pandemic.

[21] See, for instance, Mankiw and Whinston (1986) for a similar socially inefficient entry result.

[22] The actual levels of the $\hat{\beta}_1$, $\hat{\beta}_2$ and $\hat{\beta}_3$ thresholds are the same with and without restrictions. But with restrictions, these thresholds are no longer exogenous as they depend on the level of restrictions. However, since $\beta = \beta_0 - \theta r$, it is straightforward to calculate the exogenous β_0 value that corresponds to each β threshold level. These β_0 thresholds have the same ranking as the corresponding β thresholds.

[23] This follows from the standard assumptions in the related literature that firms are wholly owned by domestic residents, and that firm profits and government revenues receive equal weight in the exporting countries' welfare functions. Brander (1995) summarizes this standard weighting clearly: 'subsidy dollars and profit dollars are treated as equivalent'. Neary (1994) departs from this standard assumption by examining the effects of a higher opportunity cost of governments funds.

[24] If a proportion of the population in the developing country is vaccine-resistant (denoted in note 16 by μ), then such a policy may reduce μ and bring the constrained vaccination level closer to full vaccination. Exporting countries may wish to do so by financing information campaigns that reduce any vaccine resistance. This could be modelled as an additional cost, which can be interpreted as a cost of 'serving the export market'.

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How to cite this article: Dewit, G. and Leahy, D. (2025). Export policy cooperation in a pandemic: the good, the bad and the hopeful. *Economica*, **92**(365), 199–229. https://doi.org/10.1111/ecca.12552

APPENDIX A

A.1 Proofs of lemmas and propositions for the linear–quadratic model

A.1.1 Proof of Lemma 1

(i) Using equation (14) and setting $Q^C(\beta) = Q^F$ with $Q^F = 2(a-c)/3b$ yields $\hat{\beta}_1$. Since Q^C is increasing in β while Q^F is not, $Q^C(\beta) > Q^F$ for $\beta > \hat{\beta}_1$, whereas $Q^C(\beta) < Q^F$ for $\beta < \hat{\beta}_1$.

(ii) Using equations (12) and (14), and setting $Q^C(\beta) = Q^N(\beta)$, yields $\hat{\beta}_3$. Since Q^C increases faster in β than Q^N does, $Q^C(\beta) > Q^N(\beta)$ for $\beta > \hat{\beta}_3$, whereas $Q^C(\beta) < Q^N(\beta)$ for $\beta < \hat{\beta}_3$.

(iii) We calculate $\hat{\beta}_3 - \hat{\beta}_1 = (a-c)/3 > 0$ (since $a > c$). Hence $\hat{\beta}_1 < \hat{\beta}_3$.

A.1.2 Proof of Proposition 1

From equation (15), $\partial w^*/\partial Q > 0$. Hence the importing country's welfare ranking is the same as the Q-ranking. Using Lemma 1, we have the following.

(i) $Q^N > Q^F > Q^C$, hence $w^{*N} > w^{*F} > w^{*C}$ for $\beta < \hat{\beta}_1$.

(ii) $Q^N > Q^F = Q^C$, hence $w^{*N} > w^{*F} = w^{*C}$ for $\beta = \hat{\beta}_1$.

(iii) $Q^N > Q^C > Q^F$, hence $w^{*N} > w^{*C} > w^{*F}$ for $\hat{\beta}_1 < \beta < \hat{\beta}_3$.

(iv) $Q^N = Q^C > Q^F$, hence $w^{*N} = w^{*C} > w^{*F}$ for $\beta = \hat{\beta}_3$.

(v) $Q^C > Q^N > Q^F$, hence $w^{*C} > w^{*N} > w^{*F}$ for $\beta > \hat{\beta}_3$.

A.1.3 Proof of Proposition 2

Using equation (6), $\pi_i = (p-c)q_i$, and given symmetry, welfare of an exporting country is quadratic in Q, reaching a maximum at Q^C. From Lemma 1, $Q^N > Q^C > Q^F$ for $\hat{\beta}_1 < \beta < \hat{\beta}_3$. Using equations (12) and (14), and $Q^F = 2(a-c)/3b$, we derive $\hat{\beta}_2$, at which $Q^N(\hat{\beta}_2) - Q^C(\hat{\beta}_2) = Q^C(\hat{\beta}_2) - Q^F$, obtaining $\hat{\beta}_2 = 7(a-c)/24$. Direct calculations yield $\hat{\beta}_2 - \hat{\beta}_1 = (a-c)/8 > 0$ and $\hat{\beta}_3 - \hat{\beta}_2 = 5(a-c)/24 > 0$, implying $\hat{\beta}_1 < \hat{\beta}_2 < \hat{\beta}_3$. Since $\partial(Q^N - Q^C)/\partial\beta < 0$ and $\partial(Q^C - Q^F)/\partial\beta > 0$, $Q^N - Q^C > Q^C - Q^F$ for $\beta < \hat{\beta}_2$, and $Q^N - Q^C < Q^C - Q^F$ for $\beta > \hat{\beta}_2$. Given symmetry of the quadratic $w(Q)$ function, we have

(i) $w^C \geq w^F > w^N$ when $\beta < \hat{\beta}_2$, with $w^C > w^F$ when $\beta \neq \hat{\beta}_1$

(ii) $w^C > w^F = w^N$ when $\beta = \hat{\beta}_2$

(iii) $w^C \geq w^N > w^F$ when $\beta > \hat{\beta}_2$, with $w^C > w^N$ when $\beta \neq \hat{\beta}_3$.

A.1.4 Proof of Lemma 2

Full vaccination implies $Q = \overline{Q} = a/b$. For $Q \geq \overline{Q}$, further vaccination can no longer reduce D, while it can for $Q < \overline{Q}$. Thus the global welfare function $\Omega(Q)$ differs depending on the sign of $\overline{Q} - Q$. When $Q < \overline{Q}$, $Q^G = (a - c + 2\beta)/b$ (see equation (16)). Otherwise, $\overline{Q}$ maximizes $\Omega(Q)$, with $\Omega(Q)$ falling for $Q \geq \overline{Q}$. So $Q^G = \min\{a/b, (a - c + 2\beta)/b\}$.

Solving for the β value for which $(a - c + 2\beta)/b = a/b$ yields $\overline{\beta}^G = c/2$. Since $(a - c + 2\beta)/b$ increases with β, $a/b < (a - c + 2\beta)/b$ for $\beta > \overline{\beta}^G$, whereas $a/b > (a - c + 2\beta)/b$ for $\beta < \overline{\beta}^G$. Thus for $\beta \geq \overline{\beta}^G$, we have $Q^G = a/b = \overline{Q}$, and for $\beta < \overline{\beta}^G$, we have $Q^G = (a - c + 2\beta)/b < \overline{Q}$.

A.1.5 Proof of Lemma 3

From equations (12) and (16),

$$Q^N = \frac{4(a-c) + 2\beta}{5b} < \min\left\{\frac{a - c + 2\beta}{b}, \frac{a}{b}\right\} = Q^G$$

when $Q^N < \overline{Q}$. Also, since $Q^N > Q^F$, we have $Q^G > Q^F$. From equations (14) and (16),

$$Q^C = \frac{a - c + 2\beta}{2b} < \min\left\{\frac{a - c + 2\beta}{b}, \frac{a}{b}\right\} = Q^G$$

when $Q^C < \overline{Q}$. Thus $Q^G > \max\{Q^C, Q^N, Q^F\}$ when $Q^r < \overline{Q}$ (for $r = C, N, F$).

A.1.6 Proof of Proposition 3

(i) and (ii) From Lemma 1, we have $Q^N > Q^F \geq Q^C$ for $\beta \leq \hat{\beta}_1$. With $Q^r < \overline{Q}$ $(r = C, N, F)$, $\max\{Q^C, Q^N, Q^F\} = Q^N$ for $\beta < \hat{\beta}_1$, and $Q^G > Q^N$ (from Lemma 3). Since $\Omega^G(Q)$ is concave in Q, $\Omega(Q^G) > \Omega(Q^N)$. Put succinctly, $\Omega^G > \Omega^N > \Omega^F > \Omega^C$ for $\beta < \hat{\beta}_1$. Following similar reasoning, $Q^N > Q^F = Q^C$ for $\beta = \hat{\beta}_1$, thus $\Omega^G > \Omega^N > \Omega^F = \Omega^C$.

(iv) and (v) From Lemma 1, $Q^C > Q^N > Q^F$ for $\beta > \hat{\beta}_3$, and $Q^C = Q^N > Q^F$ for $\beta = \hat{\beta}_3$. From Lemma 3, $Q^G > Q^C > Q^N > Q^F$ for $\beta > \hat{\beta}_3$, and $Q^G > Q^C = Q^N > Q^F$ for $\beta = \hat{\beta}_3$. Concavity of Ω in Q then implies $\Omega^G > \Omega^C > \Omega^N > \Omega^F$ for $\beta > \hat{\beta}_3$, and $\Omega^G > \Omega^C = \Omega^N > \Omega^F$ for $\beta = \hat{\beta}_3$.

(iii) Concavity of Ω in Q, and Lemmas 1 and 3, imply that $\Omega^G > \Omega^N > \Omega^C > \Omega^F$ for $\hat{\beta}_1 < \beta < \hat{\beta}_3$.

A.1.7 Proof of Lemma 4

With $Q^C = \min\{a/b, (a - c + 2\beta)/2b\}$, solving for β for which $(a - c + 2\beta)/2b = a/b$ yields $\overline{\beta}^C = (a + c)/2$. Since $(a - c + 2\beta)/2b$ increases with β, $Q^C = \overline{Q} = a/b$ for $\beta \geq \overline{\beta}^C$, and $Q^C(\beta) < \overline{Q} = a/b$ for $\beta < \overline{\beta}^C$.

A.1.8 Proof of Lemma 5

Since $\overline{\beta}^G = c/2$ (from Lemma 2) and $\overline{\beta}^C = (a + c)/2$ (from Lemma 4), $\overline{\beta}^C > \overline{\beta}^G$ follows.

A.1.9 Proof of Proposition 4

The proof is implied by Lemmas 4 and 5.

A.2 Demand curvature and proofs for the general model

A.2.1 Role of $\rho(Q) = -Qp''/p'$ in second-order condition, cross-effect, strategic substitutability and stability

From the firm i first-order condition $\partial\Pi_i/\partial q_i = p(Q) - b(Q)\, q_i - c + s_i = 0$ (where $-b(Q) = p'(Q)$), we obtain its second-order condition $\partial^2\Pi_i/\partial q_i^2 = -b(2 - \rho q_i/Q) < 0$. The cross-effect is $\partial^2\Pi_i/\partial q_i\,\partial q_j = -b(1 - \rho q_i/Q)$, which is negative from Assumption 1. Cournot stability requires that own effects on marginal profits dominate cross-effects, so $(\partial^2\Pi_i/\partial q_i^2)(\partial^2\Pi_j/\partial q_j^2) - (\partial^2\Pi_i/\partial q_i\,\partial q_j)(\partial^2\Pi_j/\partial q_j\,\partial q_i) > 0$. This can be rewritten as $b^2(3-\rho) > 0$. Hence stability requires $3 - \rho > 0$.

The slope of the firm i reaction function is

$$-\frac{\partial^2\Pi_i/\partial q_i\,\partial q_j}{\partial^2\Pi_i/\partial q_i^2},$$

which is negative from Assumption 1. In the symmetric equilibrium ($q_i/Q = 1/2$), the slope of the firm i reaction function reduces to $-(2-\rho)/(4-\rho)$, which is negative since Assumption 1 then implies $\rho < Q/q = 2$.

A.2.2 Proof of Proposition 5

First, compare any two equilibria r and l (which are unique from Assumption 2), where $r = F, N, C, G$, $l = F, N, C, G$, but $r \neq l$. The first-order conditions are $h^r(q^r) = 0$ and $h^l(q^l) = 0$. At any common q, we can compare $h^r(q)$ and $h^l(q)$. Suppose that at equilibrium r, $h^l(q^r) > h^r(q^r) = 0$. From Assumption 3 ($h^r_q(q) < 0$ and $h^l_q(q) < 0$ for q between q^r and q^l), $h^l(q^r) > h^l(q^l) = 0$, thus $q^l > q^r$. Note that $h^r(q^r) = 0$, which, together with Assumption 2 and $h^l(q^r) > h^r(q^r) = 0$, implies $0 = h^l(q^l) > h^r(q^l)$, so that a local ranking at one of the equilibria to be compared cannot be reversed at the other equilibrium. We apply the general comparison of equilibria to prove parts (i)–(iv).

(i) At the F equilibrium, compare $h^F(q^F) = p(q^F) - c - b(q^F)q^F = 0$ and $h^C(q^F)$. From Table 3, the latter can be written as $h^C(q^F) = h^F(q^F) + s^C(q^F)$. Hence the difference is $h^C(q^F) - h^F(q^F) = s^C(q^F)$. From the expression for s^C in Table 3, this is positive if and only if $\beta > bq/2$ evaluated at the F equilibrium. Thus when $\beta > bq/2$, $h^C(q^F) > h^F(q^F) = 0$, and from above, this implies $h^C(q^F) > h^C(q^C) = 0$, giving $q^C > q^F$. Using the same argument, $\beta < bq/2$, evaluated at the F equilibrium, implies $q^C < q^F$. Since a local ranking at one of the equilibria cannot be reversed at the other, if $\beta > bq/2$ when evaluated at the F equilibrium, then also $\beta > bq/2$ when evaluated at the C equilibrium; and if $\beta < bq/2$ when evaluated at the F equilibrium, then also $\beta < bq/2$ when evaluated at the C equilibrium.

(ii) At the N equilibrium, compare $h^C(q^N)$ and $h^N(q^N) = 0$. The difference is $h^C(q^N) - h^N(q^N) = s^C(q^N) - s^N(q^N)$, which (using Table 3) is positive if $\beta > bq$ evaluated at the N equilibrium, and negative if $\beta < bq$ evaluated at the N equilibrium. Thus when $\beta > bq$, $h^C(q^N) > h^N(q^N) = 0$, and from above, this implies $h^C(q^N) > h^C(q^C) = 0$, giving $q^C > q^N$. Thus $q^C > q^N$ if $\beta > bq$, whereas $q^C < q^N$ if $\beta < bq$.

(iii) At the F equilibrium, compare $h^F(q^F) = 0$ and $h^N(q^F)$. The latter can be written as $h^N(q^F) = h^F(q^F) + s^N(q^F)$. Hence the difference is $h^N(q^F) - h^F(q^F) = s^N(q^F)$. From the expression for s^N in Table 3, this is positive and implies $h^N(q^F) > h^F(q^F) = 0$, and from above, this implies $h^N(q^F) > h^N(q^N) = 0$; thus $q^N > q^F$.

(iv) This proof is analogous to that of the earlier parts. Compare $h^F(q)$, $h^N(q)$ and $h^C(q)$ to $h^G(q)$ at common symmetric equilibria. Clearly, $h^G(q)$ is the largest, hence so is q^G.

A.2.3 Proof of Corollary 1

Given the strict quasi-concavity of $\Omega^G(q)$ from Assumption 4, and since $q^G > \max\{q^C, q^N, q^F\}$ from Proposition 5(iv), the global welfare ranking of the regimes is the same as their export ranking.

A.2.4 Proof of Proposition 6

(i) Consider the C equilibrium. Joint welfare of the exporting countries can be written as $W(q)$. Since $p(\overline{Q}) = 0$ and $\partial D/\partial Q = 0$ at $q = \overline{q}$, $W^C(q)$ falls with q for $q \geq \overline{q}$. Hence $q^C \leq \overline{q}$.

(ii) First, $W^G(q)$ falls with q for $q \geq \overline{q}$. Hence $q^G \leq \overline{q}$.
Suppose $q^C = \overline{q}$. From Assumption 1, it is unique, so $h^C(q) > 0$ when $q < \overline{q}$. However, at any common q, $h^G(q) > h^C(q)$, thus $h^G(q) > 0$ when $q < \overline{q}$. Hence $q^G = \overline{q} = q^C$, and $\Omega(q)$ is also maximized under cooperation.

A.3 Derivations and proofs of propositions in extensions

Here, we give the derivations for the extensions in Subsections 5.1 and 5.2, as well as the proofs of the propositions in Section 5.

A.3.1 Derivations with multiple exporting firms

Each exporting country now has n firms (with $n \geq 1$) rather than a single exporting firm (with symmetry implying that the countries have the same number of firms). Total export is $Q = \sum_k^n (q_{ik} + q_{jk})$, where i and j refer to the exporting country, and k ($k = 1, \ldots, n$) refers to a firm.

Firm k's first-order condition is $p - c - bq_{ik} + s_i = 0$, where s_i ($i = 1, 2$) is country i's subsidy. Country i's exports, denoted by x_i, are

$$x_i = nq_{ik} = n\,\frac{a - c + (n+1)s_i - ns_j}{b(2n+1)},$$

where $j \neq i$. Total vaccine exports are

$$Q = x_1 + x_2 = n\,\frac{2(a-c) + (s_1 + s_2)}{b(2n+1)}.$$

Welfare for country i is $w_i(x_i, x_j) = n\pi_i - (\overline{Q} - Q)\beta$, where symmetry allows us to drop the k firm subscript, with $n\pi_i = (a - c - bx_i - bx_j)x_i$. Under non-cooperation, the first-order condition for the optimal subsidy is

$$(a - c - 2bx_i - bx_j + \beta)\,\frac{\partial x_i}{\partial s_i} + (-bx_i + \beta)\,\frac{\partial x_j}{\partial s_i} = 0.$$

Symmetry and firms' first-order conditions yield

$$s^N = \frac{a - c + (2n+1)\beta}{n(2n+3)}.$$

Hence

$$q^N = \frac{1}{n}\,\frac{(n+1)(a-c) + \beta}{b(2n+3)}, \quad x^N = nq^N = \frac{(n+1)(a-c) + \beta}{b(2n+3)},$$

and total exports under non-cooperation are

$$Q^N = 2x^N = 2\,\frac{(n+1)(a-c)+\beta}{b(2n+3)}.$$

Under cooperation, the cooperative chooses the same exports as in the basic model. Combining equation (14) with the expression for Q as a function of the subsidy yields

$$s^C = \frac{(a-c)(1-2n)+(2n+1)2\beta}{4n}.$$

A.3.2 Derivations of the extended model with entry

Using backward induction, we start by solving the final period of the three-period game.

Period three: export. As in the basic model, this period consists of two stages; subsidies are set before exports are chosen. Given symmetry, each exporting country has the same number n of exporting firms (as described in Subsection 5.1 and Subsubsection A.3.1). At the start of this period, uncertainty about the export policy stance has been resolved. The derivations are given in Subsubsection A.3.1.

Period two: serving the domestic market. Here too, our symmetry assumption implies that the domestic market in each exporting country is identical. We use superscript d to distinguish the domestic from the export market. To economize on notation, we assume that the domestic production cost is zero. Each government sets a domestic output subsidy s^d prior to the firm deciding on its output for the domestic market, denoted by q_k^d, with $k = 1, \ldots, n$. Total vaccine output for the domestic market is $Q^d = \sum_k q_k^d$, resulting in domestic market price $p^d = p^d(Q^d)$.

Welfare in country i accruing from serving the domestic market is simply the social benefit of consuming the vaccine in the domestic country, denoted by $V(Q^d)$ (since national expenditure on the vaccine, $Q^d(p^d + s^d)$, and vaccine-producing domestic firms' operating profit from those vaccines, $n(p^d + s^d)q_k^d$, cancel each other). The government of country i chooses its domestic subsidy instrument s^d to target Q^d in order to maximize $V(Q^d)$. Given market separation, maximized V is the same regardless of whether governments cooperate or not in their export policy in period three. In the linear demand case,

$$p^d = a^d - b^d Q^d, \quad V(Q^d) = a^d Q^d - \frac{b^d}{2}\left((Q^d)^2 + \left(\frac{a^d}{b^d}\right)^2\right),$$

and equilibrium firm output is

$$q_k^d = q^d = \frac{a^d + s^d}{b^d(n+1)} = \frac{1}{n}\,Q^d,$$

while $s^d = a^d/n$ maximizes $V(Q^d)$.

Period one: entry. From the firm's first-order condition for exports, maximized operating profit of a firm in the *export* market is equal to $b(q^r)^2$ for $r = N, C$. Analogously, a firm's maximized operating profit generated from the *domestic* market is $b^d(q^d)^2$, where $b^d \equiv -(p^d)'$. Thus each firm has expected total profit $E\Psi(n;\beta,\phi) - f = b^d(q^d)^2 + \phi b(q^C)^2 + (1-\phi)b(q^N)^2 - f$ in period one. The equilibrium number n of firms in country i ($i = 1, 2$) is an integer such that $E\Psi(n) - f \geq 0$, but $E\Psi(n+1) - f < 0$. Expected total operating profit $E\Psi$ falls with the number of entrants as all its components, q^d, q^C and q^N, do so. Clearly, with expected total profit $E\Psi(n;\beta,\phi) - f$, higher f works towards fewer firms in equilibrium (strictly, n is non-increasing in f). In addition, for a given number of firms, $\partial E\Psi/\partial\beta > 0$, thus an increase in β works towards an increase in n. Also, $\partial E\Psi/\partial Q^d > 0$, so an increase in domestic country sales works towards an increase in n (strictly, n is non-decreasing in β and Q^d). The effect of ϕ on n depends on β. We have $\partial E\Psi(n;\beta,\phi)/\partial\phi = b((q^C)^2 - (q^N)^2)$, with the sign depending on that of $q^C - q^N$, which in turn has the same sign as $\beta - \widehat{\beta}_3$. Hence if $\beta - \widehat{\beta}_3 > (<)\ 0$, then an increase in ϕ works towards an increase (decrease) in the number of firms (strictly, n is non-decreasing with ϕ for $\beta - \widehat{\beta}_3 > 0$, but non-increasing with ϕ for $\beta - \widehat{\beta}_3 < 0$).

Total welfare of an exporting country ω^r ($r = N, C$) is now the sum of welfare from the export market (w^r, $r = N, C$) and welfare from serving the domestic market (V) net of firm entry costs (nf). Since V and nf are not policy-regime-specific, $\omega^C - \omega^N = w^C - w^N$; thus the welfare differentials between the two export policy regimes in the extended and export-only models are the same.

A.3.3 Proof of Proposition 7

From equation (19), we calculate

$$\frac{\mathrm{d}(Q^N - Q^C)}{\mathrm{d}n} = \frac{2(a - c - 2\beta)}{b(2n+3)^2}.$$

Thus

(i) $Q^N > Q^C$ and $\mathrm{d}(Q^N - Q^C)/\mathrm{d}n > 0$ for $\beta < (a-c)/2 = \widehat{\beta}_3$

(ii) $Q^C > Q^N$ and $\mathrm{d}(Q^N - Q^C)/\mathrm{d}n < 0$ or $\mathrm{d}(Q^C - Q^N)/\mathrm{d}n > 0$ for $\beta > \widehat{\beta}_3$

(iii) $Q^C = Q^N$ and $\mathrm{d}(Q^N - Q^C)/\mathrm{d}n = \mathrm{d}(Q^C - Q^N)/\mathrm{d}n = 0$ for $\beta = \widehat{\beta}_3$.

A.3.4 Proof of Proposition 8

With restrictions, we have

$$Q^N = \frac{4(a-c) + 2(\beta_0 - \eta a)}{b(5 - 2\eta)} < \overline{Q} \quad \text{for } \beta_0 < \frac{a+4c}{2},$$

with

$$\frac{\mathrm{d}Q^N}{\mathrm{d}\eta} = \frac{-2a - 8c + 4\beta_0}{b(5-2\eta)^2} < 0 \quad \text{for } \beta_0 < \frac{a+4c}{2}.$$

Also, since

$$Q^C = \frac{a - c + 2(\beta_0 - \eta a)}{2b(1-\eta)} < \overline{Q} \quad \text{for } \beta_0 < (a+c)/2,$$

we have

$$\frac{\mathrm{d}Q^C}{\mathrm{d}\eta} = \frac{-(a+c) + 2\beta_0}{2b(1-\eta)^2} < 0 \quad \text{for } \beta_0 < (a+c)/2.$$

(For $\beta_0 \geq (a+c)/2$, $Q^C = \overline{Q}$, hence $\mathrm{d}Q^C/\mathrm{d}\eta = 0$ for $\beta_0 \geq (a+c)/2$.) Finally,

$$Q^G = \frac{a - c + 2(\beta_0 - \eta a)}{b(1 - 2\eta)} < \overline{Q} \quad \text{for } \beta_0 < \frac{c}{2}.$$

Hence

$$\frac{\mathrm{d}Q^G}{\mathrm{d}\eta} = \frac{-2c + 4\beta_0}{b(1-2\eta)^2} < 0 \quad \text{for } \beta_0 < \frac{c}{2}.$$

(For $\beta_0 \geq c/2$, $Q^G = \overline{Q}$, hence $\mathrm{d}Q^G/\mathrm{d}\eta = 0$ for $\beta_0 \geq c/2$.) Thus with incomplete vaccination, Q^N, Q^C and Q^G fall with η.