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INTERNATIONAL HEALTH AND TRADE COORDINATION DURING A PANDEMIC

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Divided We Fall: International Health and Trade Coordination During a Pandemic
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ABSTRACT

We analyze the role of international trade and health coordination in times of a pandemic by building a two-economy, two-good trade model integrated into a micro-founded SIR model of infection dynamics. Uncoordinated governments with national mandates can adopt (i) containment policies to suppress infection spread domestically, and (ii) (import) tariffs to prevent infection coming from abroad. The efficient, i.e., coordinated, risk-sharing arrangement dynamically adjusts both policy instruments to share infection and economic risks internationally. However, in Nash equilibrium, uncoordinated trade policies robustly feature inefficiently high tariffs that peak with the pandemic in the foreign economy. This distorts terms of trade dynamics and magnifies the welfare costs of tariff wars during a pandemic due to lower levels of consumption and production as well as smaller gains via diversification of infection curves across economies.

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The Covid-19 Pandemic has been truly international, spreading globally through health and economic linkages between countries and regions. To understand the impact of pandemics on the global economy and to analyze the role of coordination in international trade and health, we generalize the Macroeconomic SIR literature to an international context by introducing trade. Our model helps understand how the outbreak of a pandemic in one country is transmitted to other countries by trade (which includes tourism and services), and how national containment measures impact the spread of the pandemic in other countries. Given that the policy response to the pandemic in 2020 has been mostly along national lines, the question of the role and the value of international coordination in combatting the pandemic is of great importance.

By way of motivation, consider the stylized facts for China and the United States presented in Figure 1 for the period December 2019 to October 2020: the evolution of the pandemic (top panel); the exchange rate measured as CNY/USD, i.e., Renminbi per US dollar (second panel); the year on year (y-o-y) growth in industrial production in the two countries (third panel); and, the trade balance for China and the US (bottom two panels, respectively). The pandemic peaked in China in terms of new infections during mid-February to mid-March 2020, while the US reached its second peak in August 2020, with infections remaining higher thereafter relative to its first peak attained during April 2020. Unsurprisingly, the y-o-y change in industrial production evolved in each country according to the pandemic, dipping as the pandemic took grip and recovering (in case of China) as the pandemic subsided.

Significant from an international trade perspective are the observations that (i) each country imported more relative to exports (negative trade balance) during the period it witnessed the pandemic; and, (ii) the terms of trade (expressed in terms of the exchange rate) deteriorate in the country experiencing the pandemic, with USD depreciating sharply relative to CNY during the second wave of the pandemic in the US. Can these outcomes be reconciled with uncoordinated health and tariff policy decisions of national governments? Are these outcomes desirable from a social efficiency standpoint? Put differently, what would the outcomes be if national governments were to coordinate their health and tariff policies? Indeed, how do health and tariff policies affect each other, and in turn, the attendant health and trade outcomes, during a pandemic? By introducing a micro-founded SIR dynamic for international disease transmission in an otherwise standard and simple model of trade, our paper provides a theoretical framework for answering these important policy questions.

It has been widely noted in the recent economic literature (Eichenbaum, Rebelo and Trabandt, 2020; Brotherhood et al., 2020, and others) that if a pandemic hits an economy, local consumption and production create health externalities among its individuals. Our model's key insight is that international trade offers a risk-sharing alternative, as it can help sustain consumption in pandemic-affected economies without excessively aggravating its health externalities through production-related transmissions. However, international trade exposes the foreign economies to the pandemic, requiring an eventual reversal of the roles played by the economies in risk-sharing through trade. In spite of the transmission of infection across borders, the socially efficient arrangement does in general involve trade-based risk-sharing that reflects high contingency on the state of the pandemic in different economies; in particular, tariffs are lowered to counteract the economic fallout on the foreign economy when its infection is peaking, and they can even be negative, i.e. be replaced by import subsidies.

In contrast, uncoordinated, i.e., Nash equilibrium, trade policies adopted by national-mandate governments robustly feature inefficiently high tariffs, which are only reduced during the peak of the pandemic at home and peak when the pandemic in the foreign country peaks. While uncoordinated tariffs are inefficiently high even in the absence of a pandemic (a well known-result from trade theory), the inefficiencies are magnified in the presence of a pandemic, manifesting in the form of lower levels of consumption and production, smaller health gains via diversification of infection curves across economies, and weaker post-pandemic economic recovery. In summary, health outcomes in Nash equilibrium are inferior in terms of a higher incidence of deaths and in terms of less economic burden-sharing via trade compared to the case of policy coordination.

We show these results on the need for international coordination on health and trade in a dynamic two-country model with complete SIR dynamics, a micro-founded international transmission of the pandemic operating via both consumption and labor, policy instruments for domestic containment and international tariffs, and an analysis of uncoordinated international activity in the form of infinite-horizon Nash equilibrium play.

We calibrate our model so that the pandemic starts in one country and spills over to the other country such that the infection in the second country peaks when the infections in the first country have subsided thanks to herd immunity. This is the simplest model to capture the international transmission of the health externality; we do not consider more complicated policy shifts that can give rise to several infection waves in one country. The pandemic induces households to endogenously cut down their consumption and labor provision in order to reduce the probability of getting infected. However, as has been widely noted, households do not internalize health externalities on other agents. In fact, our model features what are probably the two most important such externalities (see, e.g., Garibaldi, Moen and Pissarides (2020) for a careful discussion) and extends them to the international context. First, self-interested infected individuals ignore the health impact of their activity on others. Second, even susceptible individuals ignore the dynamic externality on other not yet infected individuals, as they risk getting infected and thus posing a risk to others in the future. While these externalities have been widely analyzed in the recent macro-SIR literature (see our discussion below), they also constitute an international externality through international trade.

Our model allows us to investigate the optimal domestic containment and tariff policies with and without international coordination. In both the coordinated and the uncoordinated outcomes, the governments impose domestic containment policies (which we model as a possibly non-remunerative “tax" on domestic consumption) during the course of the domestic infection. This policy contains the spread of the pandemic, as it discourages households from consuming goods and internalizes the health externalities. Under our calibration, the domestic containment policy can amount to the equivalent of a tax as high as 70% during the peak of infection, which substantially decreases economic activity. Both uncoordinated governments and the coordinated planner reduce the amount of infection during the pandemic, at the expense of lower consumption and production in both countries. In fact, the levels of consumption and production in each country largely track the evolution of infected cases in each country due to both the government’s containment policies and the households’ endogenous responses.

In addition to the domestic containment policies, our model considers tariffs as a second instrument addressing the international dimension of the problem, and predicts novel import tariff patterns. In the absence of a pandemic, our model features standard tariffs wars. When countries take uncoordinated (Nash) policy decisions, they choose import tariffs that are too high relative to the coordinated (social planner) case. Such tariffs lead to poor consumption levels and poor choice between domestic and foreign goods, resulting in a significant loss of welfare. The pandemic fundamentally alters the temporal structure of tariffs, inducing in them a variation that is linked to the relative state of the pandemic in the two countries, with important welfare consequences.

Consider first the uncoordinated (Nash equilibrium) case. When the pandemic hits the first country, it seeks to limit transmission of the disease domestically by imposing strong containment measures on domestic consumption; this puts a downward pressure on its domestic price level, resulting in both a competitive disadvantage to foreign goods as well as an increase in the risk of infection to the foreign country since it incentivizes imports from the infected country. In response, the foreign country *raises* its import tariffs beyond the case without a pandemic. This weakens the infected country’s output even further and limits its consumption possibilities. On the other hand, the infected country *lowers* import tariffs below the case without a pandemic, in order to encourage its domestic households to consume more foreign goods which are less conducive to infection. In other words, the pandemic modulates the tariff structure in a manner that skews the terms of trade *against* the infected country’s production, aggravating economic risk-sharing possibilities in the midst of a pandemic. The loss of risk-sharing manifests itself in the form of a high domestic bias in the infected country’s consumption basket; nevertheless, the home bias reduces as the pandemic peaks in the infected country given its response of limiting import tariffs to support the economy. As the infected country reaches herd immunity and the pandemic peaks in the foreign country, their roles are reversed in this loss of risk-sharing.

Consider now the case where the two countries coordinate on a jointly optimal outcome. The pandemic modulates the structure of tariffs in this case too, but in a manner that is exactly the *opposite* of the uncoordinated case. As domestic containment measures required to reduce domestic infections aggravate production and consumption in the infected country, the planner lowers the import tariffs in the foreign country and raises the import tariffs in the infected one. The structure of these tariffs is intriguing at first pass because they encourage both countries to consume more goods produced by the more infected country and therefore raise the likelihood of infection. On the other hand, terms of trade are now skewed in favor of the infected country's goods to ameliorate its economic situation. As in the uncoordinated case, these roles reverse once the infected country reaches herd immunity and the pandemic peaks in the foreign country, so that each country ends up with more favorable terms of trade and higher income during the peak of its domestic infection. The better economic risk-sharing manifests itself in the form of efficient home bias in each country, in particular, a home bias far lower than in the uncoordinated case.

It is worth noting that risk sharing in this context refers to individual risk. As is common in the basic SIR models, there is no aggregate risk in our model. Once national policies are determined, the disease runs its course deterministically, with aggregate transmissions determined by the Law of Large Numbers. Government policies, however, influence the laws of motion of the domestic transmissions and can shift aggregate infection rates internationally, since the economies are linked through international trade and infections. This then results in changing infection risks for the individuals in each country. A key result of our analysis is that this intertemporal economic risk-sharing also leads to sharing of health risk: the foreign country imports a part of the infections by facilitating trade with the infected country, which encourages the infected country to shift consumption towards foreign goods and therefore prevents its domestic infection rates from peaking too fast; this risk-sharing then benefits the foreign country at the peak of its own infection.

This implies, from a normative standpoint, that cooperation on trade in times of a pandemic can result in both superior economic and health risk-sharing outcomes across countries. Hence, there is no tradeoff between economic and health performance in the international context. In fact, while Nash equilibrium behavior in tariffs leads to lower international disease transmission compared to laisser-faire policies, uncoordinated behavior still produces worse health outcomes in each country than socially optimal, because it fails to generate the intertemporally optimal modulation of the terms of trade.

This is by no means obvious, as a simple variant of our model shows in which there are no tariffs. If tariffs are exogenously fixed and constant (for example by international trade rules), then both countries are still linked by international trade and infections, but set their domestic containment policies independently. In this model, this leads to outcomes that are, of course, overall inferior to the coordinated outcome, but that result in fewer infections and deaths. In fact, the lack of coordination in Nash equilibrium leads to excessive economic containment, exactly because an instrument to coordinate international economic activity at least implicitly is missing. In this sense, the tradeoff between economic and health performance is resolved differently by uncoordinated governments than in the coordinated outcome, who tolerate more infections in exchange for higher consumption.

From a technical point of view, our analysis is, as far as we know, the first to study Nash Equilibrium in fully dynamic economic and health policies. This is computationally demanding, because strategies are high-dimensional vectors and each iteration of the best-response algorithm requires solving a full dynamic macroeconomic equilibrium model. In order to get sufficiently fast convergence we therefore model economic, health, and policy interactions as parsimoniously as possible.

From a positive standpoint, our model can help to explain why in the real-world scenario of uncoordinated decision-making by countries, terms of trade and economic outcomes may end up being excessively dire for the infected countries. An important insight is that the purely epidemiological consideration of imposing “border controls" on trade and travel to limit the spread of infections should be weighed against its implications for loss of economic risk-sharing; indeed, our model suggests that even health outcomes tend to end up being superior with some coordination on trade.

Our analysis is also informative about the dynamics of health and economic outcomes under uncoordinated policies. In fact, our simulations consistently generate the pattern that Nash equilibrium “does too much too late". This is most striking for the evolution of aggregate consumption, which in Nash equilibrium remains high in the non-affected country for more than half a year after the outbreak in the first country, and then drops dramatically in a short period when the infections hits. In contrast, international coordination reduces consumption even in the non-affected country right from the start of the pandemic, but the overall drop is much smaller. Similarly, in Nash equilibrium tariffs in the originally non-affected country stay high until well into the outbreak and are then reduced drastically, well below levels chosen under coordinated policy. In our benchmark case this results in durations of the pandemic that are around 5% longer in Nash equilibrium than in the coordinated outcome.

Related Literature. Our paper is related to an emerging literature that studies the nexus between economics and disease[1]. On a single country level, Eichenbaum, Rebelo and Trabandt (2020) embed SIR disease dynamics into a macroeconomic model and study the tradeoffs involved with suppression policies. In one of the few papers on the economic consequences

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[1] This literature has grown impressively during the last six months, and we cannot do justice to it here. See Brodeur et al. (2020) and references therein for a broad overview.

of disease dynamics before 2020, Greenwood et al. (2019) analyzed the dynamics of HIV in Africa and its economic consequences. Building on this work, Brotherhood et al. (2020) analyze a rich set of behavioral patterns and show the importance of heterogeneous lockdown policies for the Covid-19 environment. Alvarez, Argente and Lippi (2020) is an early paper studying the optimal lockdown policy in a single country as a planning problem in a macreconomic disease model. Foundational work on the health externalities arising from Covid-19 is, among others, Garibaldi, Moen and Pissarides (2020) and Assenza et al. (2020). A number of papers investigate different containment policies, such as Berger, Herkenhoff and Mongey (2020) on the role of testing and case-dependent quarantine, Alon et al. (2020) on age-specific lockdown policies among sets of developing and advanced economies, and Jones, Philippon and Venkateswaran (2020) on work from home policies. There is a large body of work on national fiscal and macroeconomic stabilization policies in response to the pandemic, on which we build in order to simplify the policy space as much as possible, but that is too large to review here.

Our paper extends these studies to multiple countries and international trade in multiple goods, with associated domestic and trade policies to manage the pandemic. It thus relates to other recent contributions studying hetereogeneity in macroeconomic SIR dynamics, such as Acemoglu et al. (2020) who develop an SIR model with heterogeneous groups and lockdown policies, and Kaplan, Moll and Violante (2020) who integrate the SIR disease dynamics in a heterogeneous agent new Keynesian model and study the distributional consequences of different containment strategies, with a focus similar to Glover et al. (2020). Fernandez-Villaverde and Jones (2020) estimate and simulate an SIR model by using disaggregate data from various locations and provide an impressive overview of the international evolution of the disease on their website.

A very rich recent paper written parallel to ours and with a similar focus on international trade and health, is Antras, Redding and Rossi-Hansberg (2020). They develop a two-country model of household interaction in equilibrium with spatial frictions that provides a microfoundation for the international spread of a disease similar to the one developped here and a gravity model of international trade. Different from our work, they do not consider governments, strategic national policies, and international coordination. This latter theme is the focus of Beck and Wagner (2020) who study cooperation across countries in containment policies in a simple two-stage model that leaves aside the macroeconomic dynamics at the core of our model. Leibovici and Santacreu (2020) studies the role of international trade in essential goods during a pandemic with a multi-country, multi-sector model. Bonadio et al. (2020) examine the role of global supply chains' impact on GDP growth across countries, while Meier and Pinto (2020) study the specific disruption of China-US supply chains and its impact on US production in March/April 2020 in detail. Early empirical work comparing pandemic policies internationally includes Ullah and Ajala (2020), who analyze effects of testing and lockdown in 69 countries, and Noy et al. (2020) who estimate measures of exposure, vulnerability and resilience to Covid-19 across countries.

McKibbin and Roshen (2020) and Liu, Moon and Schorfheide (2020) estimate a DSGE model and a Bayesian panel VAR, respectively., while We explicitly model the international trade and health coordination by studying the dynamic interaction between the SIR dynamics, international trade, and local and global containment policies.

Our paper is also related to the large literature on international business cycles (Backus, Kehoe and Kydland, 1992; Stockman and Tesar, 1990). While the business cycle dynamics in these papers are driven by productivity, investments and savings, the dynamics in our paper are driven by disease and health policies that give rise to interesting cross-country co-movements (as analyzed in different contexts, e.g., by Imbs (2004); Rose and Spiegel (2009)). We identify these co-movements and analyze how different tax and tariff policies affect them.

1 The Model

In thinking about the importance of coordinating health and trade outcomes during a pandemic, a simple two-period consumption and trade model with two countries (sketched in Appendix A.1) provides a useful starting point. Suppose that each country has an initial group of infected individuals and a susceptible group that may become infected by coming in contact with the domestic (foreign) infected group while consuming the domestic (foreign) goods. Two key externalities arise, one in the context of health due to the cross-country spread of the pandemic, and another — more traditional one — in the context of trade. Each government has two instruments, one controlling domestic infections via domestic containment policies, and one controlling imports via tariffs. The two externalities are evaluated differently depending on whether decisions are made by a coordinated “planner" maximizing the sum of the objectives of the two countries or by uncoordinated governments in Nash equilibrium.

On the health front, the infected group in each country exposes the susceptible group in the other country to the risk of infection. This “health externality” is not internalized by uncoordinated governments while setting containment policies, i.e., when effectively choosing consumption, for their respective infected groups. Hence, the coordinated planner imposes stricter domestic containment policies on consumption in each country than the uncoordinated planners. Second, a “trade externality” materializes as is standard in the literature (Brander and Spencer, 1985; Ossa, 2014). Each country views its net imports as a cost to its welfare and chooses a level of consumption of the foreign good for its citizens that is lower than that under coordination, where imports and exports are simply cross-country transfers. Clearly, both instruments are at least partially conflicting, and the health and the trade externalities interact with each other, depending on the state of the pandemic in the two countries

To analyze this broader problem, we study a full dynamic two-country model with complete SIR dynamics, production and costly deaths that builds on the insights from the simple two-period model, but is micro-founded in its domestic and international transmission mechanism and derives richer implications on the need for international coordination on the health and trade fronts.

The model considers 2 countries, $k = A, B$. Time is discrete, $t = 0, 1, 2, ...$ Each country has households, identical competitive firms, and a government.

For all variables we use the following notational convention. Variables describing consumption, production, or government activity in country $k \in \{A, B\}$ have the superscript k. When discussing a single country, the superscript $-k$ denotes the other country. To simplify the presentation, superscripts in equations referring to a single country are dropped whereever possible without ambiguity.

The households in each country are defined over a continuum of unit mass. Let S_t, I_t, R_t, and D_t denote the mass of susceptible, infected, recovered and dead people in any of the two countries. The total population of the country at any date t then is $N_t = S_t + I_t + R_t$. We do not distinguish between individuals and households. Households within each of the three living categories are identical. S_t^{-k}, I_t^{-k}, R_t^{-k}, and D_t^{-k} are the masses of the respective groups in the other country, if we discuss activity in one country k. $h \in \{s, i, r\}$ indicates the three health types.

1.1 The Economy

There are two goods $j \in \{A, B\}$, which are denoted by subscripts throughout the paper. Each period, good j is produced in country j only, by using country j labor according to the linear technology

$$y_t = z\left(\ell_t(s) + \phi\ell_t(i) + \ell_t(r)\right) \tag{1}$$

where $\ell_t(h) = \ell_t^j(h)$ is the amount of labor provided by employees of health status h, and $z = z^j$ is country $k = j$'s productivity, which is assumed to be constant. Infected individuals ($h = i$) have a lower productivity, as given by $\phi < 1$. Firms act competitively, maximizing profits and taking prices as given.

The prices of the goods in both countries are p_j, $j = A, B$. When discussing a single country k, p_{-k} denotes the price of good $j \neq k$. There are no transport costs or other physical trade frictions between countries.

Households in each country provide labor and consume a basket of the two goods A and B. Suppressing the time index for simplicity, denote the per household consumption of good

j by households in country k by $c_j^k = c_j^k(h)$. Households in country k consume the goods as a basket composed by the standard CES aggregator

$$q(c_k^k, c_{-k}^k) = \left(\alpha(c_k^k)^{\frac{\sigma-1}{\sigma}} + (1-\alpha)(c_{-k}^k)^{\frac{\sigma-1}{\sigma}}\right)^{\frac{\sigma}{\sigma-1}} \tag{2}$$

where c_k^k denotes consumption of the domestic good, c_{-k}^k of the foreign good, $\alpha \in (0.5, 1)$ is the home bias for domestic consumption goods, and $\sigma > 1$ the substitution elasticity between the domestic and the foreign good. These two parameters are identical in both countries in order to focus on the pure effects of disease transmission in international trade.

At each time t, the representative households in any of the two countries have the following objective function, where we ignore the household's health status to simplify the presentation:

$$U_t = \mathbb{E}_t \sum_{\tau=t}^{\infty} \beta^{\tau-t}\left[v(x_\tau) - \frac{1}{2}\kappa\ell_\tau^2\right] \tag{3}$$

where $0 < \beta < 1$ is the discount rate, $x_\tau = x_\tau^k(h)$ is the composite consumption basket, $\ell_\tau = \ell_\tau^k(h)$ labor supplied, and

$$x_\tau^k(h) = q(c_{k,\tau}^k(h), c_{-k,\tau}^k(h)) \tag{4}$$

We assume for computational simplicity that the utility of consumption is of the constant-relative-risk-aversion type:

$$v'(x) = x^{-\rho}, \rho > 0 \tag{5}$$

In each country k, we denote aggregate consumption of the home good by

$$H_t^k = S_t^k c_{k,t}^k(s) + I_t^k c_{k,t}^k(i) + R_t^k c_{k,t}^k(r) \tag{6}$$

and by

$$M_t^k = S_t^k c_{-k,t}^k(s) + I_t^k c_{-k,t}^k(i) + R_t^k c_{-k,t}^k(r) \tag{7}$$

that of the foreign good ("imports"). Hence, the exports of country k are M_t^{-k}.

In each country, the government imposes measures to contain the spread of the pandemic. Since we are interested in the international interaction of health and economic policies, which is computationally intensive, we do not attempt to model these measures in their actual richness and complexity, as, e.g., Brotherhood et al. (2020) or Kaplan, Moll and Violante (2020). Without going into any institutional detail, we follow the minimalist approach taken by Eichenbaum, Rebelo and Trabandt (2020) and assume that these measures act like excise "containment taxes" $\mu^k = \mu_t^k$. This means that households in country k have to pay an extra $\mu^k p_j$ per unit of consumption of good j, $j = A, B$. These additional costs include the costs of safety measures, new regulatory product features, waiting times, product substitution, and all other additional costs induced by policies restricting contact and economic activity. Despite their formal similarity, the μ^k are not value-added taxes. They are material or immaterial and partially deadweight costs of consumption. Furthermore, the government may decide to implement additional measures for foreign goods, which may include border controls, the closure of harbours, the restriction of air travel, additional safety checks etc. These measures act like a further excise tax, which we call $\nu^k \geq 0$. Despite their formal similarity, the ν^k are not just import tariffs. They are material or immaterial and partially deadweight costs of consuming foreign goods, on top of those generated by μ^k.

In any of the two countries $k = A, B$, households then have to pay $(1 + \mu^k)p_k$ per unit of consumption of the domestic good and $(1+\mu^k+\nu^k)p_{-k}$ per unit of consumption of the foreign good. For each country, we can thus simplify notation by defining the “consumer prices"

$$\widehat{p}_k = \widehat{p}_k^k = (1 + \mu^k)p_k \tag{8}$$

$$\widehat{p}_{-k} = \widehat{p}_{-k}^k = (1 + \mu^k + \nu^k)p_{-k} \tag{9}$$

for the domestic and foreign goods, respectively.

As noted, the μ^k and ν^k are frictions that do not necessarily generate government revenue. Let δ_μ^k and δ_ν^k be the fraction of these costs received by the government; δ_μ^k and δ_ν^k are exogenous. The fraction $1 - \delta_i^k, i = \mu, \nu$, is pure waste from a public finance perspective and represents pure frictions to reduce consumption activity or make it safer in health terms. To simplify the presentation, we assume that $\delta_\nu^k = 1$, i.e. that the friction on international trade comes in the form of pure tariffs. The domestic policy μ^k may raise money as it is related to consumption and business activity, but it is purely dissipative as long as it simply disrupts consumption to contain the pandemic. In our simulations, we consider the two extreme cases $\delta_\mu^k = 0, 1$.[2] δ_μ^k is a measure of the cost of containment measures: the lower δ_μ^k the more damaging the measures are economically.

The government's budget in either country therefore is

$$G_t^k = \delta_\mu^k \mu^k p_{k,t} H_t^k + (\delta_\mu^k \mu^k + \nu^k)p_{-k,t} M_t^k \tag{10}$$

In order to simplify the dynamics, we again follow Eichenbaum, Rebelo and Trabandt (2020), Brotherhood et al. (2020) and others, by assuming that households do not save or borrow. Hence, the only intertemporal link of household decisions is given by health concerns,

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[2] Like most of the literature, Kaplan, Moll and Violante (2020) recognize that, factually, containment measures mostly generate costs rather than revenue, but propose, in a normative sense, to replace pure frictions by equivalent Pigouvian taxes, i.e. to make δ_μ^k a policy instrument and set it as large as possible.

and the budget constraint of a household of type h in country k at time t is static and given by

$$\widehat{p}_{k,t}c_{k,t}(h) + \widehat{p}_{-k,t}c_{-k,t}(h) = w_t(h)\ell_t(h) + g_t(h) + v_t. \tag{11}$$

where we have dropped the superscript k for notational convenience, and $w_t(h)$ is the domestic wage, $g_t(h)$ the per household government transfer to type h households, and v_t the per household profit of the corporate sector in the country. In our baseline framework we exclude redistributionary policy and let $g_t(h) = g_t$ for all h. Using our other simplifying assumptions, the government's budget constraint therefore is

$$G_t^k = (1 - D_t^k)g_t^k \tag{12}$$

where $1 - D_t^k$ is the size of the population at time t, determined by the disease dynamics to which we turn now.

1.2 The Disease

Like Eichenbaum, Rebelo and Trabandt (2020), Brotherhood et al. (2020) and other recent economic contributions, we augment the classic SIR model by economic activity. Different from these contributions we do not only include domestic economic interactions, but also interactions due to international trade. In the basic SIR model following Kermack and McKendrick (1932), an infectious individual in any given area can spread the virus at the rate ηS_t (so-called “mass action incidence"), where S_t is the number of susceptibles in that area. Hence, the mass of newly infected people in that area at time t is given by $T_t = \eta S_t I_t$. Eichenbaum, Rebelo and Trabandt (2020) generalize this to transmission through consumption and work activities in a single country by splitting the individual transmission rate ηS_t into three components to obtain

$$T_t = [\pi_1 c_t(s)c_t(i) + \pi_2 \ell_t(s)\ell_t(i) + \pi_3]\, S_t I_t \tag{13}$$

where $c_t(h)$ and $\ell_t(h)$ are consumption and labor, resp., by the representative consumers.

We add an international economic channel to this transmission mechanism, taking into account that the consumption of imports leads to cross-border contacts that are potentially contagious. Typical examples of such imports of country k would be the delivery and installation of goods and equipment in k by producers from country $j \neq k$, tourists from country k in j, or services provided by j-firms in k. In Section A.3 in the Appendix we provide a microfounded analysis of such an international transmission mechanism, which yields the following generalization of (13):

$$\begin{aligned} T_t^k &= \left[\pi_1 \left(c_{k,t}^k(s)c_{k,t}^k(i) + c_{-k,t}^k(s)c_{-k,t}^k(i)\right) + \pi_2 \ell_t^k(s)\ell_t^k(i) + \pi_3\right] I_t^k S_t^k \\ &+ \pi_4 \left[c_{k,t}^k(s)c_{k,t}^{-k}(i) + c_{-k,t}^k(s)c_{-k,t}^{-k}(i)\right] I_t^{-k} S_t^k \end{aligned} \tag{14}$$

As in (13), the first three terms capture infections from domestic contacts arising during consumption, work, and all other local activity, respectively. The fourth term describes infections arising from contacts with foreigners while importing or exporting.[3] This is the international disease transmission mechanism at the heart of our analysis, of which the single country case (13) is a special case obtained by setting $c_{-k}^k = 0$, for $k = A, B$.

As in standard epidemiological models, the evolution of the transmission in any country is now given by

$$S_{t+1} = S_t - T_t \tag{15}$$

$$I_{t+1} = I_t + T_t - (p_r + p_d)I_t \tag{16}$$

$$R_{t+1} = R_t + p_r I_t \tag{17}$$

$$D_{t+1} = D_t + p_d I_t \tag{18}$$

where p_r and p_d are the fractions of infected individuals that recover or die, respectively, during the period. Here, the transition probabilities p_r and p_d are in principle functions of I_t, because the functioning of the national health system depends on its use.[4] For computational simplicity we work with constant probabilities for now.

Note that the system (15)–(18) is deterministic, and the overall population, $N_t = S_t + I_t + R_t$, decreases by $p_d I_t$ each period. We normalize the initial population in each country to $N_1^k = 1$. As is commonly assumed in much of the epidemiological literature at the moment, we assume that recovered individuals remain in that category for sure (i.e. acquire at least temporary immunity).[5] Importantly, by (14), the epidemiological evolution in each country depends on that of the other.

We denote the current state of the disease by

$$\Theta_t = \left(S_t^A, I_t^A, R_t^A, S_t^B, I_t^B, R_t^B\right) \tag{19}$$

---

[3] In order to simplify the model and the calibration, we do not include an international spillover-term from labor, as in π_2, which would be particularly relevant for the import and export of services. We have experimented with such a more general model, and our results would become stronger.

[4] The role of such "congestion externalities" has been emphasized and modelled in the work on optimal containment policies, e.g. by Brotherhood et al. (2020), Kaplan, Moll and Violante (2020), Favero (2020), and Assenza et al. (2020).

[5] At the time of this writing, there is some uncertainty about this claim, see (see e.g. Long et al., 2020).

and consider a situation in which initially,

$$S_1^A = 1-\varepsilon, I_1^A = \varepsilon, R_1^A = 0 \tag{20}$$

$$S_1^B = 1, I_1^B = R_1^B = 0 \tag{21}$$

where $\varepsilon > 0$ is a small number. Hence, the pandemic begins with a small number of infections in country A and then spreads endogenously to country B.

1.3 The role of government

As noted above, in the current simple model there is no role for redistributive policies $g_t(h)$. Policy therefore consists in setting the domestic containment policy μ_t^k that controls overall consumption and the tariff frictions ν_t^k that control imports. Once these are fixed, government spending g_t is given by the government budget constraint (12) and (10). The tariff can be used to achieve the following, partially conflicting goals of trade and health policy. First, of course, tariffs raise money that can be distributed directly to households. Second, as usual, tariffs manipulate the terms of trade in favor of domestic goods and thus higher domestic labor income. Third, high tariffs (or related frictions) reduce infections through foreign contacts. And fourth, tariffs can be used to influence the infection dynamics by attempting to shift production internationally to where infection rates are lower.

Since the international infection dynamic (14) is deterministic, the interaction between the two governments is an infinite-horizon, deterministic multi-stage game with observed actions (see Fudenberg and Tirole, 1991). In a single-agent framework, conditioning on the state of nature (here: the aggregate infection state) would therefore not be necessary, and every open-loop optimal path can be implemented by closed-loop strategies (i.e. strategies that depend on time t and the state) and vice versa. In a multi-agent framework, on the other hand, conditioning on the state of nature (i.e. considering Markov Nash equilibria) usually increases the set of equilibria. Here, for computational reasons we restrict attention to open-loop strategies, i.e. strategies that only depend on time t and not on the state. Hence, governments set their policy path initially once and for all.[6] To further simplify the computation, we assume that a vaccine or other cure is known to exist in a fixed, finite time T in the future. Hence, after date T there are no more infections and the economies operate without any SIR-dynamics.[7]

As discussed, households maximize their expected discounted utility, given government

---

[6] Uniqueness of equilibrium is, of course, an issue. We have conducted extensive computational searches for other equilibria from different starting values, but always found the single Nash equilibrium reported in Section 4.1 below.

[7] In fact, for the parametrizations we have studied, the pandemic has run its course at T and both countries have reached herd immunity. So this restriction is not binding.

policy and the evolution of the disease. Let

$$u_t^k(h_t) = v(x_t^k(h_t)) - \frac{1}{2}\kappa \ell_t^k(h_t)^2 \tag{22}$$

denote the flow utility of households of health status h_t in country k at the household's optimum, and

$$V_t^k(h_t) = \mathbb{E}_t \sum_{\tau=t}^{\infty} \beta^{\tau-t} u_\tau^k(h_\tau) \tag{23}$$

the corresponding value functions. By symmetry, we assume that the government of country k maximizes the utilitarian welfare function

$$V^k = S_1^k V_1^k(s) + I_1^k V_1^k(i) + R_1^k V_1^k(r) \tag{24}$$

Uncoordinated Policy: Without coordination, we assume that the two governments play a non-cooperative game, where each chooses open-loop policy paths as described, such as to

$$\max_{\{\mu_t^k, \nu_t^k\}_t} V^k$$

taking the other government's policy path $\{\mu_t^{-k}, \nu_t^{-k}\}_t$ as given. A Nash equilibrium consists of two policy paths that are each optimal responses to each other.

Coordinated Policy: Alternatively, we consider the benchmark of a single social planner who makes the containment and tariff decisions for both countries in order to maximize the sum of the two countries' welfare:

$$\max_{\{\mu_t^k, \nu_t^k, \mu_t^{-k}, \nu_t^{-k}\}_t} V^A + V^B \tag{25}$$

2 Equilibrium Analysis

Given government policy μ_t^k, ν_t^k, and g_t^k in each country, firms maximize profits and households expected utility taking prices and the economic and epidemiological constraints as given.

2.1 Firm behavior

Because of the constant-returns-to-scale structure (1) firms make zero profits in equilibrium and hire as much labor as is supplied by households. Hence, in equilibrium, aggregate output in each country is

$$Y_t = z\left(S_t \ell_t(s) + \phi I_t \ell_t(i) + R_t \ell_t(r)\right) \tag{26}$$

wages are

$$w_t(h) = \begin{cases} \overline{w}_t & \text{for } h = s, r \\ \phi \overline{w}_t & \text{for } h = i \end{cases} \tag{27}$$

$$\overline{w}_t = p_t z \tag{28}$$

and firm profits are $v_t = 0$.

2.2 Household behavior

Households of each country at each date maximize expected utility U_t given by (3) subject to the budget constraint (11). Dropping the country superscript k, they choose their levels of domestic consumption $c_{k,t} = c_{k,t}(h)$, foreign consumption $c_{-k,t} = c_{-k,t}(h)$, and labor $\ell_t = \ell_t(h)$. They know their own health status h,[8] and the current state of the disease Θ_t, given by (19).

Using (23), in recursive terms, households thus choose current labor and consumption to maximize

$$v(x_t) - \frac{1}{2}\kappa \ell_t^2 + \beta \mathbb{E}_t V_{t+1}(h_{t+1}; \Theta_{t+1}) \tag{29}$$

where the expectation operator refers to the distribution of personal health h_{t+1} next period.

Susceptible Households. For a susceptible individual there are only two possible future health states - either she remains in s or she gets infected and transits to i. Given (14), there are four possibilities to get infected. First, she may get infected from local contacts while consuming (shopping, eating out, etc.). This probability is increasing with her own time spent on that activity and the total time infected domestic or foreign individuals do the same. This corresponds to the first part of the π_1-term and of the π_4-term in (14), respectively. Second, she may get infected at work with a similar logic, which corresponds to the π_2-term. Third, she may get infected in general encounters with infected people locally, not related to consumption or work, summarized by the π_3-term. Fourth, she may get infected during the consumption of goods and services abroad or coming from abroad, which is summarized by the second part of the π_1- and of the π_4-term. While the first three terms refer to infections from domestic households, the fourth explicitly highlights the consumption risk from imports and exports and the associated interaction with foreigners.

As shown in Section A.3 in the Appendix, when choosing $(c_k^k(s), c_{-k}^k(s), \ell^k(s)) \geq 0$, and thus the consumption basket $x^k(s)$ at time t, a susceptible will transit to the infectious state

---

[8] Hence, we ignore the problem of asymptomatic or presymptomatic infections. See, for example, von Thadden (2020) for a detailed discussion.

with a probability that is approximately equal to

$$\begin{aligned} & \tau(c_k^k(s), c_{-k}^k(s), \ell^k(s); c_k^k(i), c_{-k}^k(i), c_k^{-k}(i), c_{-k}^{-k}(i), \ell^k(i)) \\ = & \left[\pi_1\left(c_k^k(s)c_k^k(i) + c_{-k}^k(s)c_{-k}^k(i)\right) + \pi_2\ell^k(s)\ell^k(i) + \pi_3\right] I^k \\ + & \pi_4\left[c_k^k(s)c_k^{-k}(i) + c_{-k}^k(s)c_{-k}^{-k}(i)\right] I^{-k} \end{aligned} \tag{30}$$

where $c_k^k(i), c_{-k}^k(i), c_k^{-k}(i), c_{-k}^{-k}(i), \ell^k(i)$ are the equilibrium decisions by domestic and foreign infected households. We assume that susceptible households take this probability into account when making their decision, and use the linear approximation (30) in the remainder of our analysis.

Bringing back the time index, at time t the s-household therefore has the following problem:

$$V_t^k(s) = \max_{c_{k,t}^k(s), c_{-k,t}^k(s), \ell_t^k(s)} v(x_t^k(s)) - \frac{1}{2}\kappa\left(\ell_t^k(s)\right)^2 + \beta\left[\tau_t^k(s)V_{t+1}^k(i) + (1-\tau_t^k(s))V_{t+1}^k(s)\right]$$

subject to

$$x_t^k(s) = q(c_{k,t}^k(s), c_{-k,t}^k(s)) \tag{31}$$

$$\widehat{p}_{k,t}^k c_{k,t}^k(s) + \widehat{p}_{-k,t}^k c_{-k,t}^k(s) = \overline{w}_t^k \ell_t^k(s) + g_t^k \tag{32}$$

where $\tau_t^k(s) = \tau(c_{k,t}^k(s), c_{-k,t}^k(s), \ell_t^k(s))$. Here, (31) describes the household's consumption basket according to (2) and (32) is its budget constraint.

If λ_t^{ks} is the Lagrange multiplier of the budget contraint (32), the first-order conditions for the consumption of the domestic good, the consumption of the imported good, and labor are

$$\begin{aligned} x_t^k(s)^{-\rho}\frac{\partial x_t^k(s)}{\partial c_{k,t}^k(s)} + \beta\left(\pi_1 c_{k,t}^k(i)I_t^k + \pi_4 c_{k,t}^{-k}(i)I_t^{-k}\right)\left(V_{t+1}^k(i) - V_{t+1}^k(s)\right) &= \lambda_t^{ks}\widehat{p}_{k,t}^k \\ x_t^k(s)^{-\rho}\frac{\partial x_t^k(s)}{\partial c_{-k,t}^k(s)} + \beta\left(\pi_1 c_{-k,t}^k(i)I_t^k + \pi_4 c_{-k,t}^{-k}(i)I_t^{-k}\right)\left(V_{t+1}^k(i) - V_{t+1}^k(s)\right) &= \lambda_t^{ks}\widehat{p}_{-k,t}^k \\ \kappa\ell_t^k(s) - \beta\pi_2\ell_t^k(i)I_t^k\left(V_{t+1}^k(i) - V_{t+1}^k(s)\right) &= \lambda_t^{ks}\overline{w}_t^k \end{aligned}$$

where the second terms in each equation reflect the fact that consuming foreign goods and services increases the chances of getting infected through contacts with foreigners. Eliminating λ_t^{ks} and simplifying yields the following two first-order conditions for the optimal choices of susceptible individuals:

$$
\begin{aligned}
& \overline{w}_t^k \left[\alpha x_t^k(s)^{\frac{1}{\sigma}-\rho} c_{k,t}^k(s)^{-\frac{1}{\sigma}} + \beta \left(\pi_1 c_{k,t}^k(i) I_t^k + \pi_4 c_{k,t}^{-k}(i) I_t^{-k}\right) \left(V_{t+1}^k(i) - V_{t+1}^k(s)\right)\right] \\
= & \left[\kappa \ell_t^k(s) - \beta \pi_2 \ell_t^k(i) I_t^k \left(V_{t+1}^k(i) - V_{t+1}^k(s)\right)\right] \widehat{p}_{k,t}^k \qquad (33) \\
& \overline{w}_t^k \left[(1-\alpha) x_t^k(s)^{\frac{1}{\sigma}-\rho} c_{-k,t}^k(s)^{-\frac{1}{\sigma}} + \beta \left(\pi_1 c_{-k,t}^k(i) I_t^k + \pi_4 c_{-k,t}^{-k}(i) I_t^{-k}\right) \left(V_{t+1}^k(i) - V_{t+1}^k(s)\right)\right] \\
= & \left[\kappa \ell_t^k(s) - \beta \pi_2 \ell_t^k(i) I_t^k \left(V_{t+1}^k(i) - V_{t+1}^k(s)\right)\right] \widehat{p}_{-k,t}^k \qquad (34)
\end{aligned}
$$

Together with the aggregation condition (31) and the budget constraint (32), (33)–(34) determine the behavior of s-individuals as a function of current prices, the state of the pandemic, the current choices of infected agents and the policy parameters g_t^k and μ^k, ν^k (which are inherent in the consumer prices $\widehat{p}_{k,t}^k, \widehat{p}_{-k,t}^k$).

Infected Households. The behavior of infected households is simpler. Their behavior has no consequences for their future health, which is exogenously given by either recovery, with probability p_r, or death, with probability p_d.

A type i household at time t therefore chooses $(c_{k,t}^k(i), c_{-k,t}^k(i), \ell_t^k(i)) \geq 0$ such as to optimize the static decision problem

$$
\begin{aligned}
V_t^k(i) \quad = \quad & \max v(x_t^k(i)) - \frac{1}{2}\kappa \left(\ell_t^k(i)\right)^2 + \beta \left[(1 - p_r - p_d) V_{t+1}^k(i) + p_r V_{t+1}^k(r) + p_d V_{t+1}^k(d)\right] \\
\text{subject} \quad & \text{to} \\
& x_t^k(i) = q(c_{k,t}^k(i), c_{-k,t}^k(i)) \qquad (35) \\
& \widehat{p}_{k,t}^k c_{k,t}^k(i) + \widehat{p}_{-k,t}^k c_{-k,t}^k(i) = \phi \overline{w}_t^k \ell_t^k(i) + g_t^k \qquad (36)
\end{aligned}
$$

Letting λ_t^{ki} denote the multiplier of the budget constraint, the problem yields the first-order conditions

$$
\begin{aligned}
x_t^k(i)^{-\rho} \frac{\partial x_t^k(i)}{\partial c_{k,t}^k(i)} &= \lambda_t^{ki} \widehat{p}_{k,t}^k \\
x_t^k(i)^{-\rho} \frac{\partial x_t^k(i)}{\partial c_{-k,t}^k(i)} &= \lambda_t^{ki} \widehat{p}_{-k,t}^k \\
\kappa \ell_t^k(i) &= \lambda_t^{ki} \phi \overline{w}_t^k
\end{aligned}
$$

These conditions can be further simplified and even solved explicitly for $\rho = 1$, which we do in Appendix Section A.2. Together with the aggregation condition (35) and the budget constraint (36), they determine the behavior of i-individuals as a function of current prices and the policy parameters g_t^k and μ^k, ν^k.

Recovered Households. Similarly, when recovered, a type r household at time t chooses $(c^k_{k,t}(r), c^k_{-k,t}(r), \ell^k_t(r)) \geq 0$ such as to optimize the static decision problem

$$\begin{aligned} V^k_t(r) = \quad & \max v(x^k_t(r)) - \frac{1}{2}\kappa\left(\ell^k_t(r)\right)^2 + \beta V^k_{t+1}(r) \\ \text{subject} \quad & \text{to} \\ & x^k_t(r) = q(c^k_{k,t}(r), c^k_{-k,t}(r)) \qquad (37) \\ & \widehat{p}^k_{k,t} c^k_{k,t}(r) + \widehat{p}^k_{-k,t} c^k_{-k,t}(r) = \overline{w}^k_t \ell^k_t(r) + g^k_t(r) \qquad (38) \end{aligned}$$

Letting λ^{kr}_t denote the multiplier of the budget constraint, the first-order conditions are

$$\begin{aligned} x^k_t(r)^{-\rho}\frac{\partial x^k_t(r)}{\partial c^k_{k,t}(r)} &= \lambda^{kr}_t \widehat{p}^k_{k,t} \\ x^k_t(r)^{-\rho}\frac{\partial x^k_t(r)}{\partial c^k_{-k,t}(r)} &= \lambda^{kr}_t \widehat{p}^k_{-k,t} \\ \kappa \ell^k_t(r) &= \lambda^{kr}_t \overline{w}^k_t \end{aligned}$$

As before, these conditions can be further simplified and even solved explicitly for $\rho = 1$, which we do in Appendix Section A.2. Together with the aggregation condition (37) and the budget constraint (38), they determine the behavior of r-individuals as a function of current prices and the policy parameters.

2.3 The macroeconomic synthesis

Each period, the following endogenous economic variables are determined in equilibrium:

- Households: 18 variables $c^k_{k,t}(h), c^k_{-k,t}(h), \ell^k_t(h)$, for $h = s, i, r$ and $k = A, B$
- Markets: 4 variables $p_{k,t}$, $\overline{w}^k_t$ for $k = A, B$, where prices, consumer prices, and government policy are linked by (8)–(9).
- Government expenditures: 2 variables g^k_t, $k = A, B$. In the absence of health dependent transfers $g_t(h)$, fiscal policy therefore is reduced to the balanced-budget rule (12).

As argued above, given the linear production technologies, the firm variables are trivial and follow automatically from the household decisions.

The governments or the common social planner set the epidemiological policy consisting of the 4 variables μ^k_t, ν^k_t, $k = A, B$, which are exogenous from the point of view of market participants. These variables are implicit in the consumer prices $\widehat{p}^k_{k,t}, \widehat{p}^k_{-k,t}$.

Counting equations, we have

- Labor markets: 2 equations in (28)

- Households: in each country 9 equations
    - for s: (32)–(34),
    - for i: (50), (51), and (47), with $w = \phi \overline{w}_t^k$, appropriately indexed.
    - for r: (50), (51), and (47), with $w = \overline{w}_t^k$, appropriately indexed.
- Goods markets: 2 equations

$$Y_t^k = H_t^k + M_t^{-k} \tag{39}$$

for $k = A, B$, where output Y_t^k is given by (26), domestic consumption H_t^k by (6) and imports M_t^{-k} by (7).

There are 6 value functions to be solved, $V_t^k(s), V_t^k(i), V_t^k(r)$, for $k = A, B$. As usual, we normalize the value function $V_t^k(d) = 0$, assuming that the cost of death is the lost utility of life.

To help interpret the results, we define the terms of trade as the relative price of the output of country A to that of country B, before taxes and tariffs:

$$e = \frac{p^A}{p^B} \tag{40}$$

Finally, we define the aggregate consumption in each country as the population weighted sum of the consumption baskets of all health groups

$$X_t^k = S_t^k x^k(s) + I_t^k x^k(i) + R_t^k x^k(r) \tag{41}$$

3 Parameterization

Our parameterization builds on Eichenbaum, Rebelo and Trabandt (2020). Each period in the model is a week. To save on computational costs in our very complex environment, we assume log utility from consumption in the baseline model, i.e., we set $\rho = 1$, because this yields simple closed-form solutions to some expressions (see Appendix Section A.2).[9] We set $\beta = .96^{(1/52)}$ such that the value of life in autarky is approximately \$10 million.[10] Furthermore, we let $\phi = .8$, such that the productivity loss for infected individuals is 20%, and we set productivity $z = 39.835$ and $\kappa = 0.001275$ so that in the pre-pandemic steady state each person works 28 hours per week and earns $58,000$ per year, consistent with average data from the U.S. Bureau of Economic Analysis and the Bureau of Labor Statistics in 2018. Initial populations are normalized to 1. In the pre-pandemic steady state the countries are symmetric.

---

[9] Noting that ρ is also the inverse of the marginal rate of intertemporal substitution, Kaplan, Moll and Violante (2020) argue that also empirically $\rho = 1$ is a reasonable assumption.

[10] See, e.g., Hall, Jones and Klenow (2020) for a discussion.

We follow Costinot and Rodríguez-Clare (2014) and set $\sigma = 6$. The home bias parameter α is chosen such that the pre-pandemic steady-state domestic consumption share is 66%.

To fix ideas we assume that the infection originates in country A with an initial infected population of 0.001 (0.1%). It then spreads to country B via international trade, at a speed that is endogenous to each country's policy. To parameterize our disease transmission we choose π_1, π_2, and π_3 such that in a closed economy 1/6 of transmission would occur through consumption, 1/6 of transmission through production, and the remaining 2/3 of transmission through other activities. We then choose π_4 such that without government intervention the peak of the infection in country B occurs approximately 6 months after the peak of the infection in country A where the disease originates. Moreover, we calibrate the transition probability p_r and p_d so that the mortality rate is 0.5% for the infected and it takes on average 18 days to either recover or die from infection.[11]

For our benchmark results we focus on a case where the pandemic ends definitively in 3 years from its beginning. While stylized, this case illustrates many of the key tradeoffs we are interested in this paper. Since estimates of the likely arrival time of the vaccine and the time to its global delivery, both measured from onset of the pandemic, were in the range of 18 months to 48 months, we take the "end" of the pandemic in our computation to be 3 years as a reasonable mid-point. If in our simulations we take 2 years instead of 3, the results are qualitatively unchanged.

We provide further details about the computation algorithm in Appendix Section A.4.

4 Results

4.1 Health and Economic Outcomes with No Government Policy

As a benchmark, Figure 2 illustrates the SIR dynamics and economic outcomes when there are no containment policies or tariffs. Starting with an initial infection rate of $I_0 = 0.001$ in country A, the pandemic quickly takes off in country A and slowly spreads to country B, where it begins to take off after around week 25. The share of infected households in country A peaks at 5.2% in week 34 and declines thereafter. Around week 50, infections in country B overtake those in A and peak at 5.2% in week 60. After week 91 the disease has run its course in country A, and after week 115 in country B, when both countries have reached herd immunity. Eventually, 53% of the population in both countries becomes infected, and a mortality rate of 0.5% implies that around 0.27% of the population in both countries dies.

---

[11] Our calibration of the case fatality rate is at the lower end of the early estimates that we are aware of (see, for example, Fernandez-Villaverde and Jones (2020) or Verity et al. (2020)). These early estimates reflect high uncertainty, but also lack of experience with the treatment of severe cases.

The economic outcomes track local infection rates closely. When the first wave of infection hits country A, its consumption and labor decline quickly by almost 10 percent, while the values for country B.stay constant or even increase slightly. Similarly for country B, when the pandemic hits there. The decline in consumption is greater in magnitude than the additional leisure from lower labor, which leads to declines in the country-level utility during the peak of domestic infection. Here, aggregate utility of country k is the weighted sum of the flow utilities (22). Interestingly, during both peaks, i.e. when the domestic infection rates are either much higher or much lower than the foreign ones, domestic households increase foreign consumption. This is to reduce the exposure to domestic infection or to profit form foreigners not wanting to consume their home production. These shifts in consumption shares only have a small impact on the terms of trade expressed by the relative prices of both goods (which change by at most 1 percent).

4.2 Government Policy by a Coordinated Planner, the case $\delta_\mu = 1$

Next, we consider the optimal policy by a coordinated planner who maximizes the sum of the welfare of both countries' households where the welfare of each country is calculated as the weighted average of utilities of its health groups. At time 0, this planner determines both countries' domestic containment policies and tariffs from week 1 to 156 until the vaccine arrives.

Figure 3 reports the equilibrium outcomes for the case of $\delta_\mu^k = 1$, i.e. the case in which containment policies are not very costly economically as they raise tax revenue. As in Figure 2, the pandemic quickly takes off in country A and slowly spreads to country B, where it begins to take off after around week 25. The share of infected households in country A peaks at 3.2% in week 35, almost the same time as in the unfettered outbreak, and declines thereafter. This peak is about 1/3 lower than in the case of an unfettered outbreak, shown in the benchmark in Figure 2. After around week 50, infections in country B overtake those in A and peak at 3.2% in week 63. Hence, the coordinated planner slows the spread of the disease from A to B, but not significantly. After week 122 the disease has run its course in country A, and after week 149 in country B. Eventually, 43% of the population in both countries become infected, which is significantly lower than that in the laissez-faire case in Figure 2 and leads to a lower death rate.

The economic outcomes react both to the infection rates and the domestic containment and tariff policies. When the first wave of infection hits country A, its consumption and labor decline much more than under laisser-faire. Differently from the laisser-faire case, also the consumption basket in country B decreases, while labor and production in B stay moreless constant. Only when the second wave of infection hits country B, its consumption and labor decline significantly. The decline in both consumption and labor is much more drastic than the laissez-faire case in Figure 2, which reflects the planner's tradeoff between economic welfare and health outcomes. The early reduction of aggregate consumption X_t in country B when the pandemic begins in country A is a remarkable sign of foresight intended to limit infections from imports.

The coordinated planner achieves these health and economic outcomes with a combination of domestic containment measures and tariffs. The severity of containment measures in each country roughly tracks the level of infection rates in the country, and its peaks at a tax rate of 67%. On the other hand, tariffs have a different pattern across time that is symmetric between the two countries. When the infection peaks in country A around week 34, the coordinated planner responds by raising a positive tariff of 8% in country A, while imposing a negative tariff of -11% in country B.

These tariffs are intriguing at a first pass because they encourage both countries to consume more of country A's goods, which transmits the pandemic via consumption- and labor-induced interactions in country A and via imports to country B. However, these health costs are dominated by the economic benefits — as the tariffs raise the terms of trade for country A during the peak of the infection, its households have higher income and enjoy a higher level of consumption. The tariffs act as an international transfer mechanism to smooth out the economic outcomes during the pandemic. Similarly, when the second wave of infection hits country B, the coordinated planner reverses the tariffs in both countries, leading to a more favorable terms of trade for country B and raising its households' consumption. Note that the terms of trade rise by more than 13 percent for country A during the peak of its pandemic, i.e. more than ten times the change under laisser-faire. This drastic swing of the terms of trade brought about by boosting tariffs allows risk-sharing between the two countries due to the asynchronous feature of the pandemic.

4.3 Government Policy in Nash Equilibrium, the case $\delta_\mu = 1$

We next consider the case where each country's government determines its own domestic containment and tariff policies in order to maximize the welfare of their domestic households, defined as the weighted average of their lifetime utilities. More precisely, at time 0, the governments determine the domestic containment policy and tariff from week 1 to 156 until the vaccine arrives, in a non-cooperative game where the equilibrium policies are best responses to each other.

Figure 4 reports the outcomes of the Nash equilibrium for the case of $\delta_\mu^k = 1$, i.e. the case in which containment policies raise tax revenue. The share of infected households in country A peaks at around 3.5% in week 33, whereas the share of infected households in country B

peaks at 3.5% in week 62. Hence, infections peak more strongly and earlier under Nash than under coordinated planning. The disease is over after week 118 in country A, and after week 151 in country B.

The governments fight the disease by raising the containment tax on consumption, and its levels again track the levels of infection closely. The tax level peaks around 74% during the peak of infection in each country. In this aspect, the coordinated planner and the Nash governments engage in similar domestic containment measures, but the Nash players choose significantly stricter measures than the planner.

In contrast, the governments' tariff policies are very different between the uncoordinated and the coordinated cases. In the Nash game, both governments impose tariffs of up to 30%, as is typical in models of trade wars. In fact, in the current calibration, tariffs of around 23 percent would be set in the equilibrium of a stationary trade game without a pandemic. As in standard trade wars, both governments attempt to manipulate the terms of trade and tilt the consumption share towards domestic goods - actions that offset each other. But in the case of the pandemic, as country A approaches the peak of infection, the government in country A lowers its import tariff to 2%, in order to encourage its domestic households to consume more foreign goods that expose them less to infection. Compared to the social planner, who raises tariffs up to 8 percent, government A does too much too late. On the other hand, the government in country B raises its import tariff to 30% during A's peak infection, in order to minimize the international transmission of the pandemic through the imports from country A. When the disease hits country B, the same happens with reversed roles, but, interestingly with an additional delay. 7 weeks after country B hits the peak of infection, in week 68, tariffs in country A reach their maximum, but at a level below the maximum of country B previously, because the marginal benefit is smaller since a large share of the population in country A has already gone through an infection and recovered.

4.4 Comparing the Policies, the case $\delta_\mu = 1$

Figure 5 compares the equilibrium government policies and pandemic dynamics in the three cases discussed above, for the case of $\delta_\mu^k = 1$. Both the Nash case and the Planner case feature similar paths of domestic containment policies, with higher peaks in the Nash case. In contrast, the Nash case has large swings in tariffs that drop with domestic infections and rise with foreign infections, just the opposite of what the planner would impose optimally. As discussed above, the Nash tariffs try to adjust the trade war logic that inefficiently attempts to benefit the domestic households at the expense of the foreign households, whereas the coordinated planner's tariffs act as international risk-sharing mechanisms.

In both cases, coordinated planning and Nash behavior, the combination of private demand reactions to the pandemic and government containment policies and tariffs induces severe economic recessions in both countries. In both cases, aggregate labor and production decline by more than 26 percent until the peak of the pandemic in each country. But in addition, in the Nash case, as the domestic government lowers tariffs during the peak of domestic infection while the foreign government raises tariffs, the demand for the domestic goods in the infected country collapses and magnifies the variation in the terms of trade that is induced by the precautionary motive of households discussed in Section 4.1. As Figure 6 shows, this leads to a highly unbalanced consumption basket in terms of domestic goods and imports, such that the domestic consumption basket X_t at the peak of the infection under Nash decreases more than under coordinated planning, and the weekly flow utility, which measures the consumption-leisure tradeoff, drops much more than in the coordinated solution.

Interestingly, the Nash players do not do much worse than the Planner compared to the benchmark in terms of health outcomes when $\delta_\mu^k = 1$ (the coordinated planner reduces the ultimate death toll by 18.8%, while the Nash governments reduce it by 15.8% compared to laisser-faire). The reason is that domestic containment is less costly in economic terms and can thus be used to make up for the deficiencies in tariff policies, so that the Nash competitors “get it approximately right for the wrong reasons", as their aggressive trade policies limit the international spread of the infection. As discussed above, the real difference is the unbalanced shift in imports and thus the consumption baskets, which reduces economic welfare. The coordinated planner achieves a slightly better health outcome by using the policy instruments very differently, but much of her efficiency gain is reflected in the better economic outcomes.

These results highlight the contrast between health and economic externalities. Health externalities arise from the possibility that a country does too little to shut down its production and consumption activities, thus spreading the pandemic. Economic externalities arise from the possibility that a country will reduce its consumption of foreign goods in order to promote the interests of its own workers and firms. The coordinated planner fully internalizes this economic externality and uses tariffs to control the pandemic and smooth out its impact on both countries’ economies. In this way, international trade can lead to better risk-sharing and facilitates global health diversification. Importantly, the two externalities interact. When the disease hits one country the demand for its good collapses for health reasons, leading to a collapse of its price. This, however, triggers a demand effect in the less affected country, where the risk of infection is overall lower, and thus provides a countervailing stimulus that is absent in the affected country. The government in that country reacts by increasing tariffs to contain that stimulus and at the same time benefit from domestic financial gain of tariffs. This leads to the apparently paradoxical situation, exhibited in the second row of Figure 6, that in Nash equilibrium imports in one country can peak when tariffs are highest.

The above comparison is made explicit in the decomposition of the overall policy effect in Table 1, which considers the case of revenue-generating containment measures $\delta_\mu^k = 1$. Table (a) reports the welfare of the full benchmark case with pandemic and government policy. We decompose the households' utility loss in each country relative to the pre-pandemic level into two components: the welfare loss due to economic recession, and the welfare loss due to death. The former is the present value of the utility change in the consumption and labor of living households, from period 1 to the infinite future; the latter is the present value of the foregone utility due to death. Their sum is the total utility loss relative to the alternative world with no pandemic and no government tax and tariff.

Trivially, the coordinated outcome is better than that of no policy. More precisely, the planner lowers the utility loss due to death by partially shutting down the economy and causing a welfare loss due to economic recession relative to the no policy regime. In both countries, the economic loss is greater than under laisser faire, the loss of lives is smaller, and the sum of both losses is smaller. Clearly, the social planner implements a different consumption-work-health tradeoff than that resulting from laisser-faire, with more emphasis on health.

In contrast, the Nash equilibrium outcome is worse than laisser-faire, due to the damaging effect of high tariffs. To put this in perspective, Table 1(b) reports the welfare calculation in a world with no pandemic, where the welfare loss from tariffs is 25.23 units. In the world with the pandemic, the welfare loss due to economic recession is even greater due to the governments' containment policies and households' precaution. As noted earlier, the welfare loss due to death in Nash equilibrium is also greater than that in the coordinated case: Since the households have lower life-time utility due to high tariffs, a domestic government that weighs current losses against future gains also has less incentive to save lives. As we discuss below, this tradeoff depends on the relative economic costs and benefits of tariffs and is not present in a world with no tariffs ($\nu \equiv 0$).

4.5 Domestic Containment Policies with no Monetary Benefit: The Case $\delta_\mu^k = 0$

In this section we consider the case, in which domestic containment measures do not generate revenue, $\delta_\mu^k = 0$. The government budget (10) therefore only consists of tariff receipts, and domestic containment measures μ^k are pure frictions reducing economic activity, such as stay-at-home orders, social distancing rules, special hygiene prescriptions, etc. that discourage consumption but do not generate revenue.

Figures 7 and 8 report the coordinated and the Nash equilibrium outcomes. They differ from the case $\delta_\mu^k = 1$ in one striking dimension. Because domestic containment measures now are highly inefficient in economic terms, both governments do not use them under either scenario. This is remarkable as these measures would be saving lives. But the economic cost of using them is too high. As a consequence, infections peak much higher, and the ultimate death toll in the coordinated outcome is 2.7 deaths per 1000, 24% higher than in the case where domestic containment measures generate revenenues for the government. This outcome is a result of our simplifying assumption in (18) that death rates are independent of the health situation. If instead we assume that the probability of dying from an infection, p_d, increases in the number of infected I_t, i.e. if there are health congestions, then this picture changes, and domestic containment measures become more important.

A notable consequence of this reduced relative value of domestic containment measures is that in the case $\delta_\mu^k = 0$ the Nash outcome is clearly inferior to the coordinated one in terms of health. In fact, Figure 7 shows that the Nash outcome now has more than 6 percent more deaths than under coordinated planning. Hence, the superiority of coordination over non-coordination in both, the economic and the health, dimensions is more pronounced in the case $\delta_\mu^k = 0$ than if $\delta_\mu^k = 1$.

Furthermore, tariff policies in both cases are very similar to those in our benchmark specification in Figure 5: tariffs in the coordinated case facilitate international resource transfer by managing the terms of trade, while tariffs in the uncoordinated case are high on average, exhibiting exactly the same destructive dynamics as in the case $\delta_\mu^k = 1$ discussed above.

This setting also exhibits another feature of the interaction between health and economic externalities made above more clearly. In the uncoordinated case, governments attempt to improve their domestic welfares at the expense of the foreign welfares by raising import tariffs and enhancing their terms of trade. As shown in Figure 8, these tariffs lead to high consumption shares of domestic goods: While the consumption home bias c_A^A / c_B^A under coordination is approximately 2:1, it is fluctuating between 7:1 and 4:1 in Nash equilibrium, where the third row of Figure 8 shows a double dip reflecting the attempts of domestic governments to react to the infection peaks in each country, as discussed above.

In fact, the high consumption home bias aggravates the health outcomes. When the infection rate peaks in country A around week 30, even though country A lowers the tariff to encourage its domestic households to consume foreign goods, the consumption home bias is still 4:1. Domestic households are thus stuck at consuming the domestic goods, which fasten the spread of the pandemic. As a result, the uncoordinated case has a higher cumulative infection rate and a higher death rate compared with the coordinated case. Again, the lack of international trade coordination leads to worse infection dynamics during a global pandemic.

4.6 Containment Without Tariffs: The Case $\nu \equiv 0$

An interest variant of our model obtains if we rule out tariffs, i.e. set $\nu \equiv 0$. This case certainly is realistic, as tariffs and other trade barriers are internationally regulated by trade agreements and cannot be changed flexibly in crises. Furthermore, in many parts of the world, most notably the European Union, tariffs have been abolished altogether.

We report the health and economic dynamics in this case for $\delta_{\mu}^{k} = 1$ in Figures 9 and 10, and again compare laisser-faire, Nash equilibrium, and coordination. In this case, and different from the case $\nu > 0$, the domestic containment policies adopted by the coordinated planner and the Nash governments are qualitatively very similar, and so are the outcomes. In particular, governments in Nash equilibrium now cannot use tariffs to counteract the risk-shifting policies that are optimal under coordination. Therefore, key variables such as terms of trade or imports now move very much alike under coordination and non-coordination. Thus, in terms of the observed dynamics, “Nash equilibrium broadly gets it right". However, this obervation masks important differences between the coordinated and the uncoordinated outcome. Most importantly, on the health front, total deaths are lower in Nash equilibrium than under optimal policy coordination. Table 2(a) reports the welfare comparison in this case and disaggregates it into its economic and health component as described above. The coordination failure in Nash equilibrium now lets each government adopt too stringent domestic containment measures, and since there are no international transfers via tariffs possible to offset this (partially and inefficiently), Nash is inefficiently aggressive on the health front and does not use the international risk-sharing through trade as well as a social planner would do during a pandemic.

5 Conclusion

In this paper, we have developed a model of epidemiology and international trade to study how international coordination and the lack thereof influences the impact of government policies on health and economic outcomes. By studying Nash equilibria over high-dimensional strategies that determine dynamic macroeconomic equilibria, the model introduces a relatively complex tool to study this complex and important question. This benefit comes at the price of simplifying each of the modelling components as much as possible. This relates to the notion of Nash equilibrium, where we restrict attention to open-loop equilibria, to the modelling of health policy, where we restrict attention to simple two-dimensional pairs of “containment taxes" and tariffs, to the role of aggregate risk, which, in line with much of the literature, we currently assume away, and to the macroeconomic dynamics, where we ignore important intertemporal linkages such as private savings or government debt. In ongoing work, we are undertaking a thorough sensitivity analysis to different model features and model parameterizations to enrich our understanding of the gains from coordination that we find in this paper. This includes analyzing the role of the finite horizon due to the arrival of a vaccine, the relative importance of transmission via consumption and labor, and the impact of the magnitude of household risk-aversion. In future work we plan to generalize the model to address the broader questions along the dimensions sketched above. We hope that our analysis will ultimately be able to shed light on the important general question of the costs and benefits of coordination of local health and economic policies, be it between different sovereign governments, between states in a federal country, or within the European Union.

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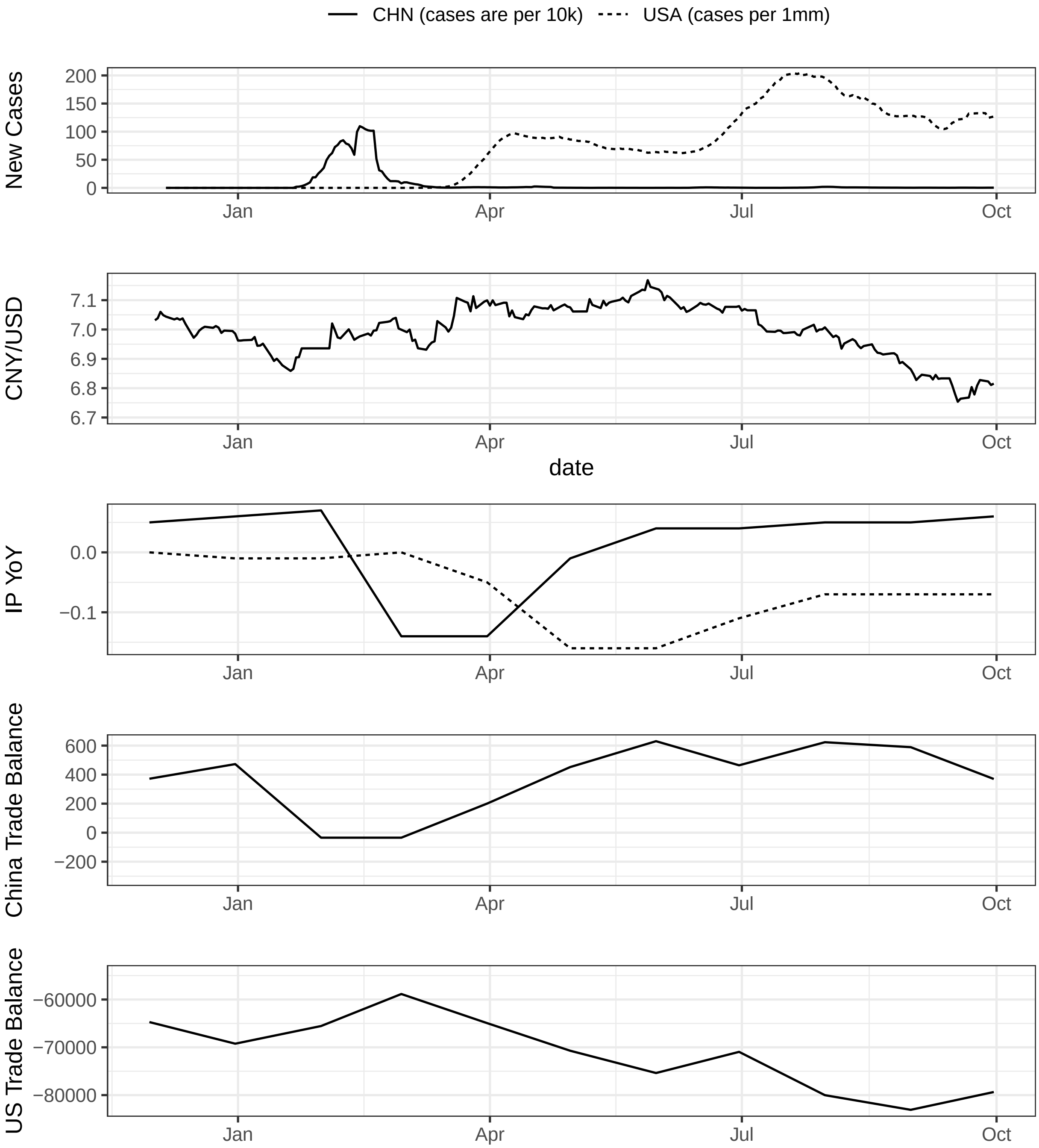
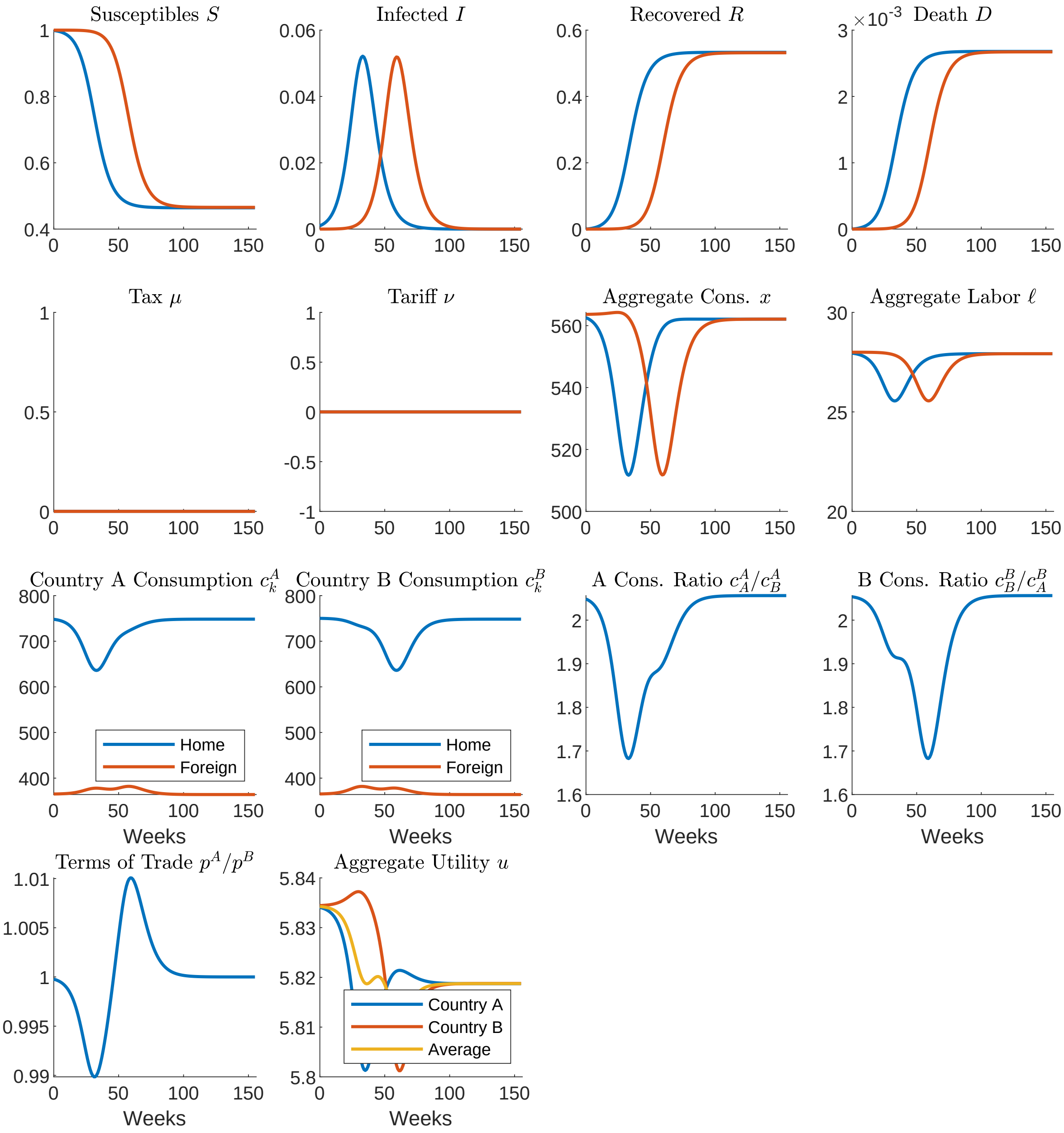
Figure 1: Pandemic and Economic Outcomes in China and the U.S.



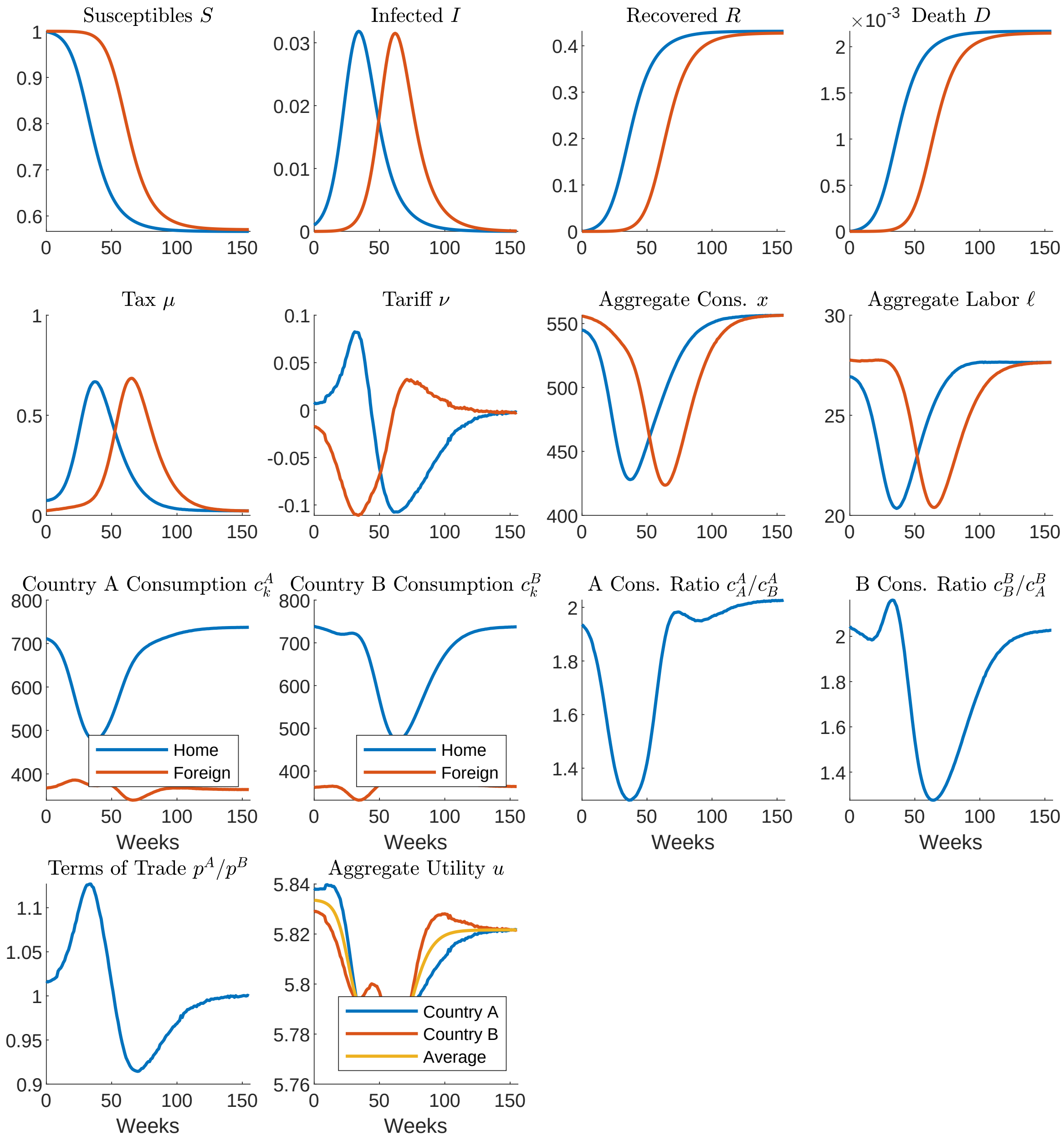
Note: Health and economic outcomes in China and the United States during the 2020 pandemic. Daily new cases for China are per 10,000 people and per 1,000,000 for the United States. Industrial production is measured year-over-year. Trade balance is total exports minus total imports.

Figure 2: Benchmark SIR Dynamics



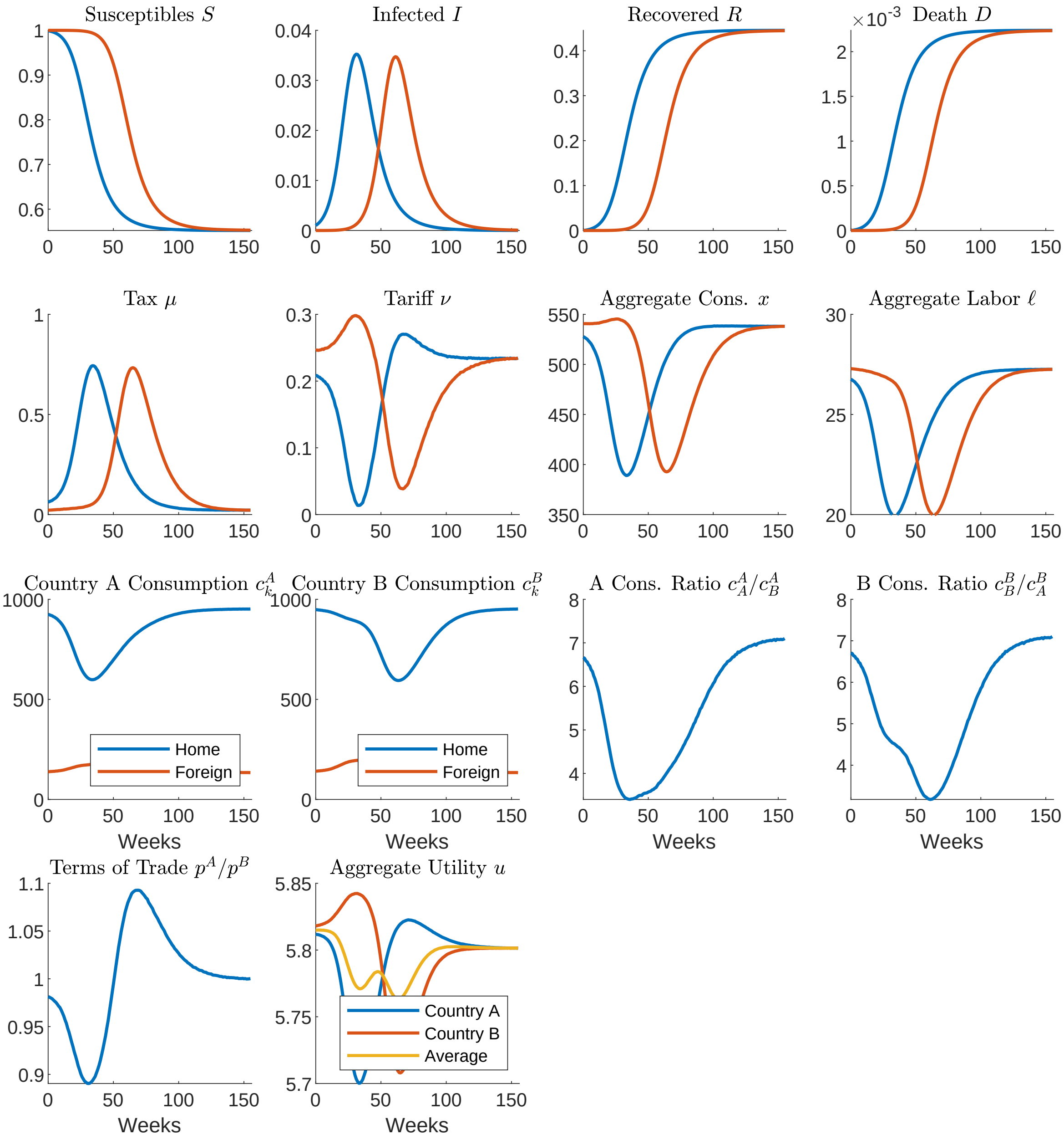
Note: Benchmark model with international transmission of pandemic. No government domestic containment policies or tariffs.

Figure 3: Coordinated Planning Equilibrium Outcomes, $\delta_\mu = 1$



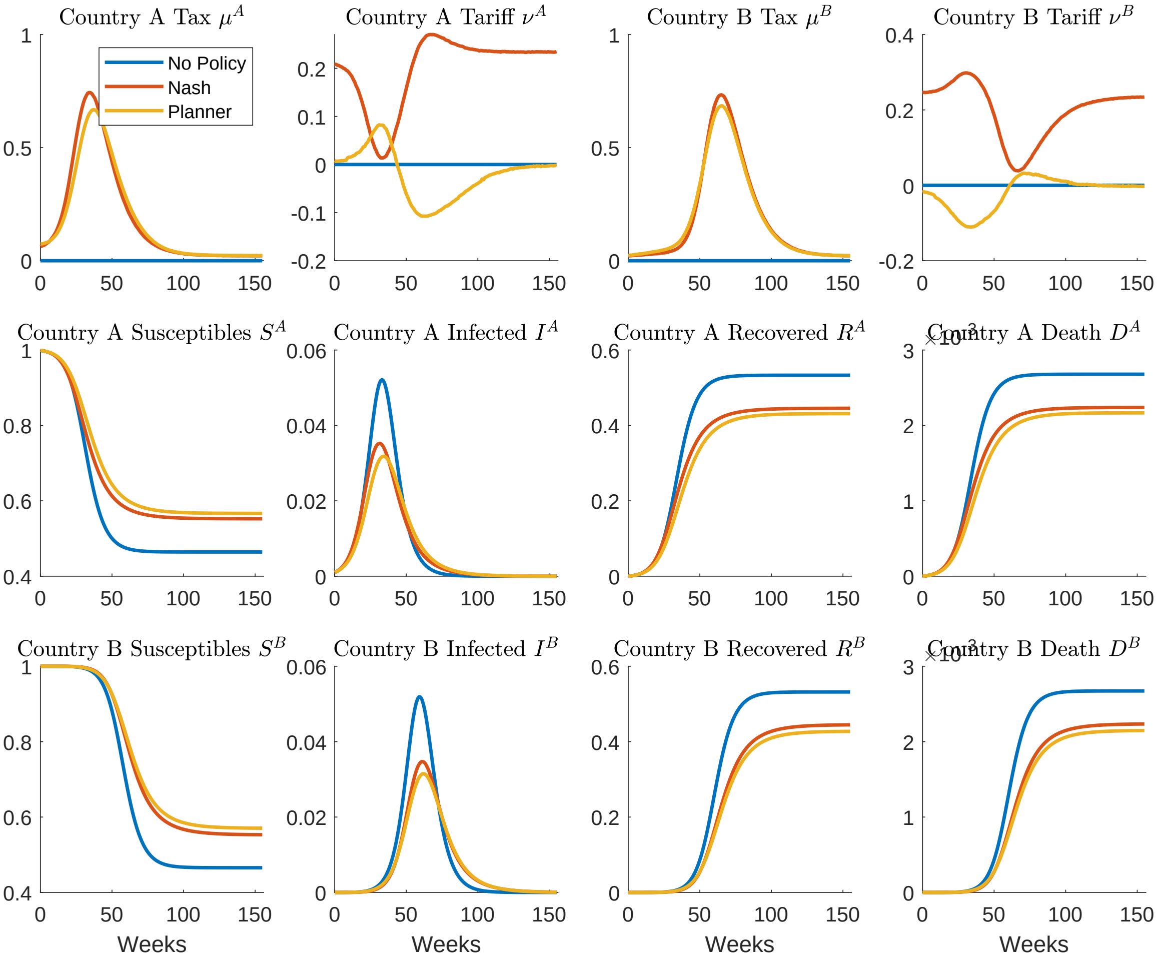
Note: Benchmark model with international transmission of pandemic. Equilbirium domestic containment policies and tariffs are determined by a global social planner that maximizes the sum of both countries' welfare.

Figure 4: Nash Equilibrium Outcomes, $\delta_\mu = 1$



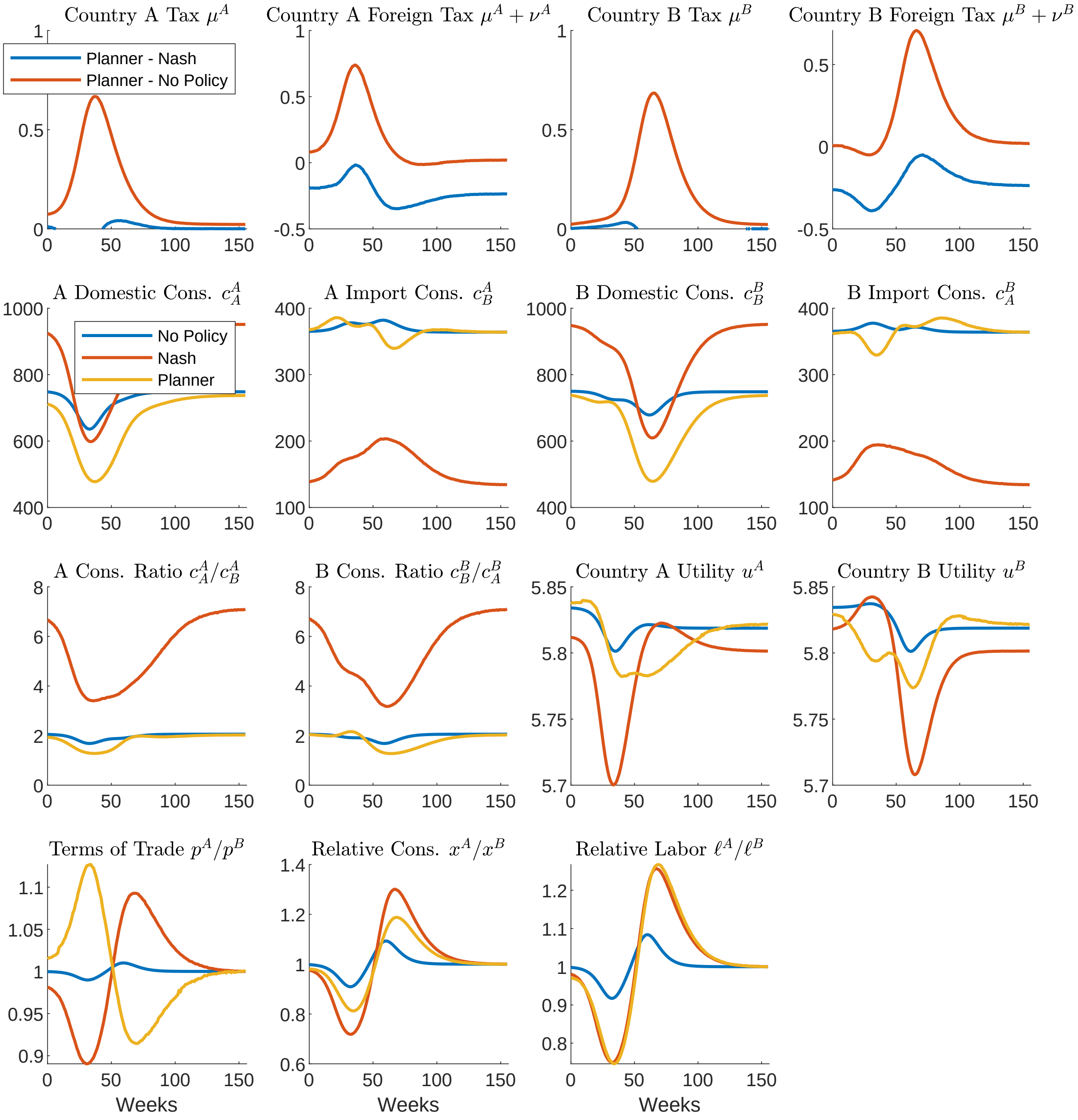
Note: Benchmark model with international transmission of pandemic. Equilbirium domestic containment policies and tariffs are the outcome of a Nash game between the two countries.

Figure 5: Equilibrium Policy and SIR Dynamics, $\delta_\mu = 1$



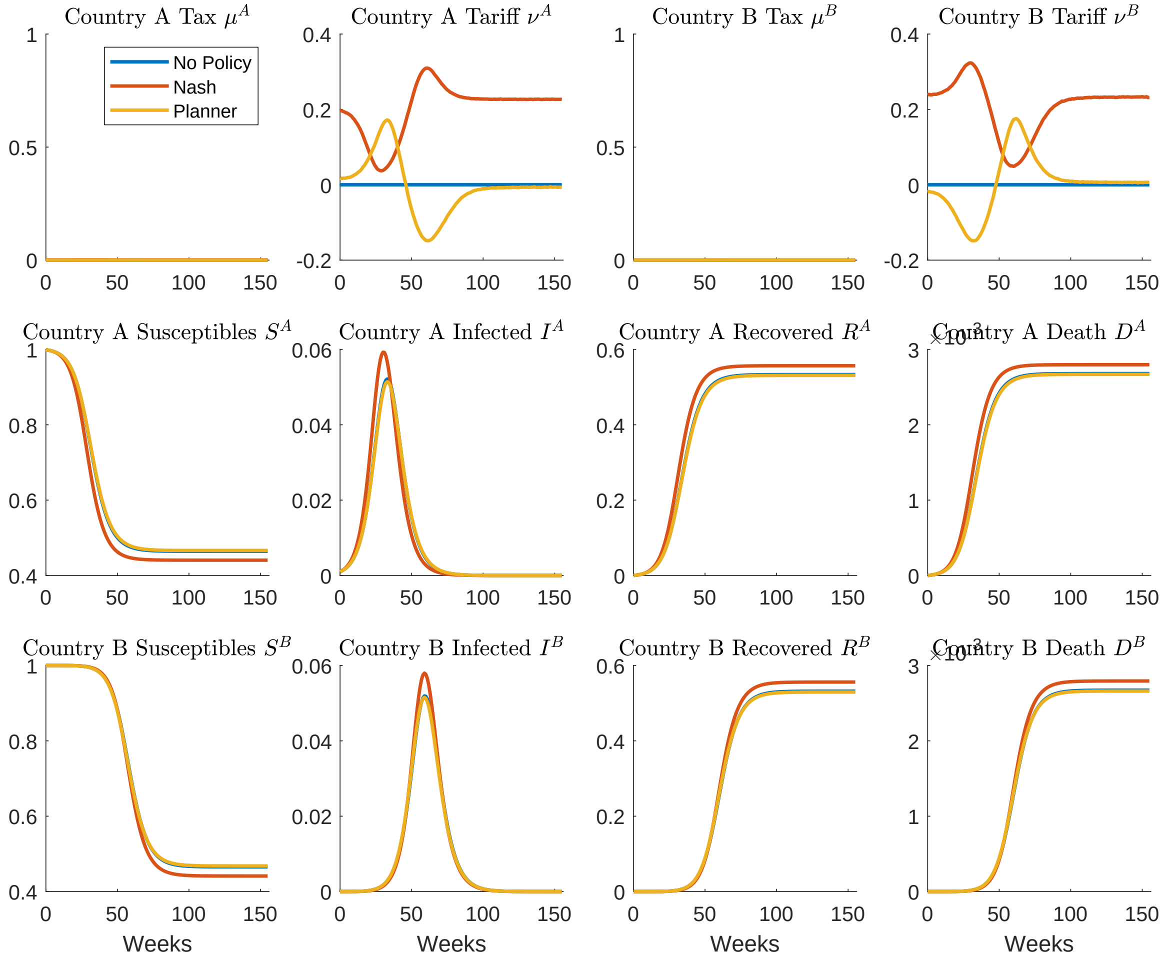
Note: Comparison of domestic containment policies and SIR dynamics in three cases: benchmark, Nash, and Planner. In the no policy case there are no domestic containment policies. In the Nash case, equilibrium domestic containment policies and tariffs are the outcome of a Nash game between the two countries. In the planner case, equilibrium domestic containment policies and tariffs are determined by a global social planner that maximizes the sum of both countries welfare.

Figure 6: Equilibrium Policy and Economic Outcomes, $\delta_{\mu} = 1$



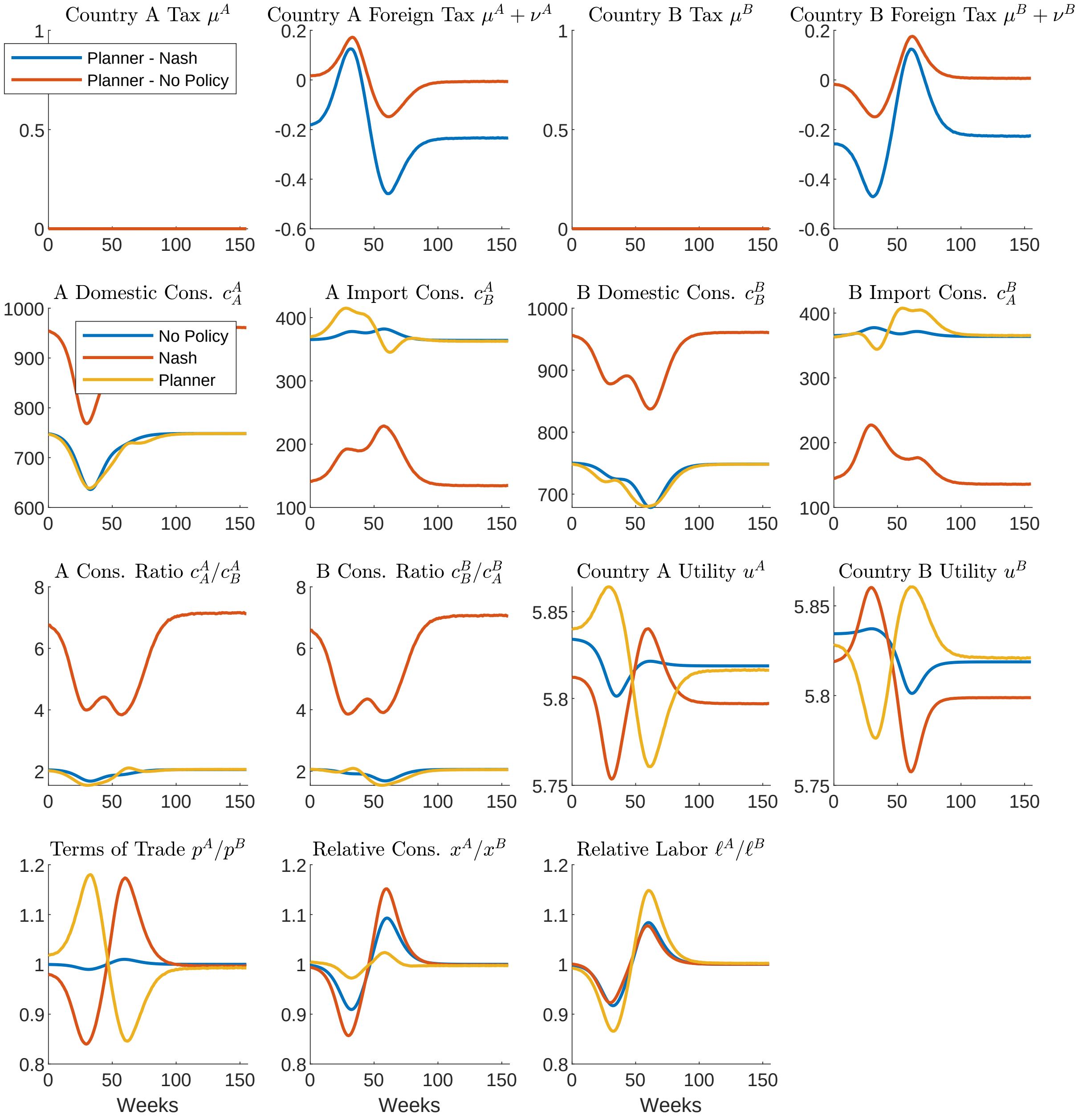
Note: Comparison of equilibrium outcomes and SIR dynamics for three cases: benchmark, Nash, and Planner. In the no policy case there are no domestic containment policies. In the Nash case, equilibrium domestic containment policies and tariffs are the outcome of a Nash game between the two countries. In the planner case, equilibrium domestic containment policies and tariffs are determined by a global social planner that maximizes the sum of both countries welfare.

Figure 7: Equilibrium Policy and SIR Dynamics, $\delta_\mu = 0$



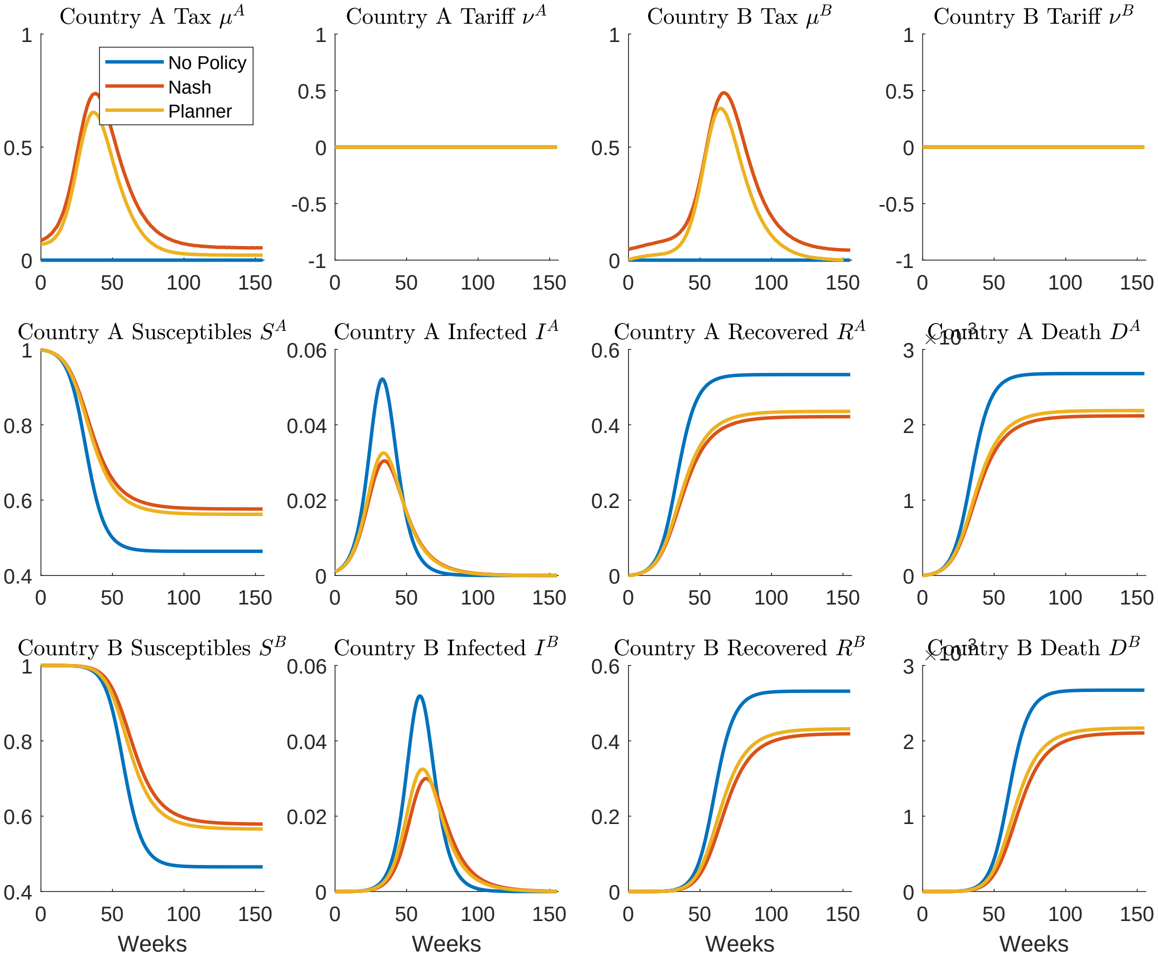
Note: Equilibrium outcomes in a model in which containment policy collects no revenue for the government.

Figure 8: Equilibrium Policy and Economic Outcomes, $\delta_\mu = 0$



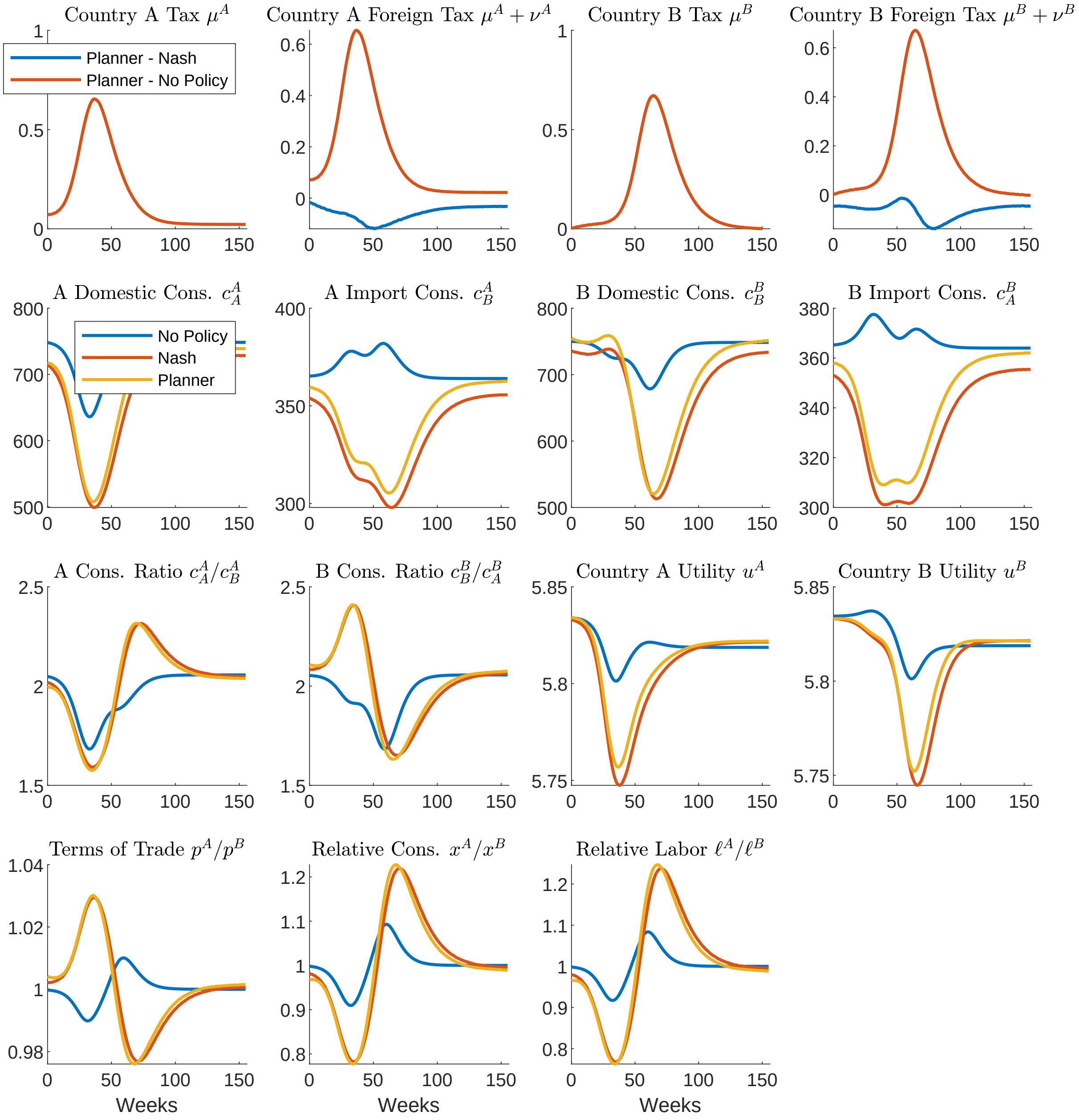
Note: Equilibrium outcomes in a model in which containment policy collects no revenue for the government.

Figure 9: Equilibrium Policy and SIR Dynamics, $\nu \equiv 0$



Note: Equilibrium outcomes in a model with domestic containment policy but no tariff.

Figure 10: Equilibrium Policy and Economic Outcomes, $\nu \equiv 0$



Note: Equilibrium outcomes in a model with domestic containment policy but no tariff.

Table 1: Welfare Decomposition

We report the welfare loss relative to the steady−state level without pandemic and policy. We decompose the welfare loss in each country into two components. The *economy* loss is the present value of the utility loss of living households due to changes in consumption and labor during the pandemic episode, and the *death* loss is the present value of the foregone utility due to death.

Panel (a): With Pandemic and Domestic Containment Policy/Tariff

	Country A			Country B		
	Total	Economy	Death	Total	Economy	Death
No Policy	-19.85	-0.48	-19.37	-19.41	-0.47	-18.93
Nash	-43.29	-27.18	-16.11	-42.74	-27.03	-15.71
Planner	-17.96	-2.34	-15.62	-17.50	-2.36	-15.14
Planner - Nash	25.33	24.83	0.50	25.24	24.67	0.57

Panel (b): With No Pandemic

	Country A			Country B		
	Total	Economy	Death	Total	Economy	Death
No Policy	0.00	0.00	0.00	0.00	0.00	0.00
Nash	-25.18	-25.18	0.00	-25.18	-25.18	0.00
Planner	0.00	0.00	0.00	0.00	0.00	0.00
Planner - Nash	25.18	25.18	0.00	25.18	25.18	0.00

Table 2: Welfare Decomposition: Different Specifications

We report the welfare loss relative to the steady−state level without pandemic and policy. We consider two additional cases. In Panel (a), we report the case in which governments cannot impose tariff. In Panel (b), we report the case in which governments can impose domestic containment policy but cannot remit the revenue on consumption of domestic goods back to the households.

Panel (a): No Tariff

	Country A			Country B		
	Total	Economy	Death	Total	Economy	Death
No Policy	-19.85	-0.48	-19.37	-19.41	-0.47	-18.93
Nash	-18.16	-2.90	-15.26	-17.70	-2.88	-14.82
Planner	-18.04	-2.26	-15.77	-17.63	-2.32	-15.31
Planner - Nash	0.12	0.64	-0.52	0.07	0.57	-0.49

Panel (b): Dissipative Domestic Containment Policy on Consumption of Domestic Goods

	Country A			Country B		
	Total	Economy	Death	Total	Economy	Death
No Policy	-19.85	-0.48	-19.37	-19.41	-0.47	-18.93
Nash	-45.51	-25.31	-20.21	-44.69	-24.95	-19.73
Planner	-19.99	-0.69	-19.30	-19.21	-0.36	-18.85
Planner - Nash	25.53	24.62	0.91	25.48	24.60	0.88

A Model Appendix

A.1 Insights from a Two-Period Model

First, we illustrate our key ideas in a simple model with two periods $t \in \{0, 1\}$. There are two countries $k = A, B$. Variables describing consumption, production, or government activity in country $k \in \{A, B\}$ have the superscript k. When discussing a single country, the superscript $-k$ denotes the other country. Each country has a unit mass of agents, with health status s for susceptible and i for infected. Let S^k denote the share of susceptible agents.

Each country has a distinct which we index with subscripts $j = A, B$. Let $c_j^k(h)$ denote the consumption of the good produced in country j by the agent in country k with health status h. We use τ^k to denote the transmission likelihood of country k's susceptible agents. We assume

$$\tau^k(\{c\}) \quad = \quad \pi_1[c_k^k(s)c_k^k(i) + c_{-k}^k(s)c_{-k}^k(i)](1 - S^k) + \pi_4[c_k^k(s)c_k^{-k}(i) + c_{-k}^k(s)c_{-k}^{-k}(i)](1 - S^{-k});$$

this transmission equation implies that the disease is transmitted both domestically and internationally, in proportion to the product between the susceptible agents' consumption and the infected agents' consumption, as well as to the share of infected agents $1 - S^k$.

We use U^k to denote the utility of country k's agent at time 0. At time 1, susceptible agents have utility $\overline{U}_s^k$ and infected agents have utility $\overline{U}_i^k$.

Government Consider first the centralized problem solved by the government of country k. The objective function is

$$\begin{aligned}\max_{\{c_k^k(h), c_{-k}^k(h)\}} \quad & S^k[U^k(c_k^k(s), c_{-k}^k(s)) + \beta(1 - \tau^k)\overline{U}_s^k + \beta\tau^k\overline{U}_i^k] + (1 - S^k)[U^k(c_k^k(i), c_{-k}^k(i)) + \beta\overline{U}_i^k] \\ + \quad & p_k(S^{-k}c_k^{-k}(s) + (1 - S^{-k})c_k^{-k}(i)) - p_{-k}(S^k c_{-k}^k(s) + (1 - S^k)c_{-k}^k(i))\end{aligned}$$

where the good price p_k and p_{-k} are taken as given.

We model the international trade in a simplified setting. From the perspective of a planner in country k, the production cost of domestic goods is 0, but it costs p_{-k} to purchase a unit of the foreign good. Therefore, the optimization problem is equivalent to

$$\begin{aligned}\max_{\{c_k^k(h), c_{-k}^k(h)\}} \quad & S^k[U^k(c_k^k(s), c_{-k}^k(s)) + \beta(1 - \tau^k)\Delta\overline{U}^k - p_{-k}c_{-k}^k(s)] \\ & +(1 - S^k)[U^k(c_k^k(i), c_{-k}^k(i)) - p_{-k}c_{-k}^k(i)]\end{aligned}$$

where $\Delta\overline{U}^k = \overline{U}_s^k - \overline{U}_i^k > 0$. Now we assume $U(c_1, c_2) = \alpha \log c_1 + (1 - \alpha) \log c_2$. The first-order conditions imply

$$\begin{aligned}
c_k^k(s) &= \frac{\alpha}{\beta(\pi_1 c_k^k(i)(1-S^k) + \pi_4 c_k^{-k}(i)(1-S^{-k}))\Delta\overline{U}^k} \\
c_{-k}^k(s) &= \frac{(1-\alpha)}{\beta(\pi_1 c_{-k}^k(i)(1-S^k) + \pi_4 c_{-k}^{-k}(i)(1-S^{-k}))\Delta\overline{U}^k + p_{-k}} \\
c_k^k(i) &= \frac{\alpha}{\beta(\pi_1 c_k^k(s)S^k)\Delta\overline{U}^k} \\
c_{-k}^k(i) &= \frac{(1-\alpha)}{\beta(\pi_1 c_{-k}^k(s)S^k)\Delta\overline{U}^k + p_{-k}}
\end{aligned}$$

Social Planner Next, we consider the first best from the perspective of a global planner. Let $\hat{c}$ denote the equilibrium allocation:

$$\begin{aligned}
\max_{\{\hat{c}_A^A(h),\hat{c}_B^A(h),\hat{c}_B^B(h),\hat{c}_A^B(h)\}} \quad & S^A[U^A(\hat{c}_A^A(s),\hat{c}_B^A(s)) + \beta(1-\tau^A)\overline{U}_s^A + \beta\tau^A\overline{U}_i^A] \\
& +(1-S^A)[U^A(\hat{c}_A^A(i),\hat{c}_B^A(i)) + \beta\overline{U}_i^A] \\
& +S^B[U^B(\hat{c}_B^B(s),\hat{c}_A^B(s)) + \beta(1-\tau^B)\overline{U}_s^B + \beta\tau^B\overline{U}_i^B] \\
& +(1-S^B)[U^B(\hat{c}_B^B(i),\hat{c}_A^B(i)) + \beta\overline{U}_i^B]
\end{aligned}$$

The first-order conditions imply

$$\begin{aligned}
\hat{c}_k^k(s) &= \frac{\alpha}{\beta(\pi_1 \hat{c}_k^k(i)(1-S^k) + \pi_4 \hat{c}_k^{-k}(i)(1-S^{-k}))\Delta\overline{U}^k} \\
\hat{c}_{-k}^k(s) &= \frac{(1-\alpha)}{\beta(\pi_1 \hat{c}_{-k}^k(i)(1-S^k) + \pi_4 \hat{c}_{-k}^{-k}(i)(1-S^{-k}))\Delta\overline{U}^k} \\
\hat{c}_k^k(i) &= \frac{\alpha}{\beta(\pi_1 \hat{c}_k^k(s)S^k)\Delta\overline{U}^k + \beta(\pi_4 \hat{c}_k^{-k}(s)S^{-k})\Delta\overline{U}^{-k}} \\
\hat{c}_{-k}^k(i) &= \frac{(1-\alpha)}{\beta(\pi_1 \hat{c}_{-k}^k(s)S^k)\Delta\overline{U}^k + \beta(\pi_4 \hat{c}_{-k}^{-k}(s)S^{-k})\Delta\overline{U}^{-k}}
\end{aligned}$$

The difference between the global planner and the local government planner's solutions illustrates two key insights. First, the global planner addresses the externality of international transmission of the pandemic. As a result, the infected agents' consumption has an additional term $\beta(\pi_4 \hat{c}_k^{-k}(s)S^{-k})\Delta\overline{U}^{-k}$ in its denominator. This term lowers the infected agents' consumption, in order to account for its effect to the susceptible agents in country k>

Second, the global planner recognizes that the export price p_{-k} is just a cross-country transfer. This unnecessarily depresses the consumption of foreign goods, and will therefore be set to 0 using differential tariffs at the optimal global allocation.

A.2 The Static Model

Without pandemics, the model boils down to an essentially static two-country macro model. This is because, in order to focus on the epidemiological dynamics, in (11) we have ruled out economic dynamics. As a benchmark we now provide the basic properties of this simple static model. This analysis is also useful because it directly applies to the choice problems of the infected and the recovered households in the full model, who structurally solve the same static decision problems. The only truly dynamic decisions are made by susceptible households, whose choices influence their future health status.

To simplify notation, we drop country superscripts and time subscripts for the static analysis of households of country k. Denote the wage by w.

The representative consumer of country k (who is not concerned with health) chooses per-period consumption and labor $(c_k, c_{-k}, \ell) \geq 0$ in order to

$$\begin{aligned} & \max v(x) - \frac{1}{2}\kappa\ell^2 \\ \text{subject to} \quad & x = q(c_k, c_{-k}) && (42) \\ & \widehat{p}_k c_k + \widehat{p}_{-k} c_{-k} = w\ell + g && (43) \end{aligned}$$

where $\widehat{p}_j$ are consumer prices and g is the public transfer. Let λ denote the Lagrange multiplier of the budget constraint. Importantly, λ measures the pre-epidemic willingness to pay for utility, i.e. the “exchange rate between utils and dollars", which is needed to calibrate the model. As noted in Section 2, the solution is characterized by the following first-order constraints:

$$\begin{aligned} x^{-\rho}\frac{\partial x}{\partial c_k} &= \lambda \widehat{p}_k && (44) \\ x^{-\rho}\frac{\partial x}{\partial c_{-k}} &= \lambda \widehat{p}_{-k} && (45) \\ \kappa\ell &= \lambda w && (46) \end{aligned}$$

Dividing (44) by (45) yields

$$c_{-k} = \left(\frac{1-\alpha}{\alpha}\right)^{\sigma} \left(\frac{\widehat{p}_k}{\widehat{p}_{-k}}\right)^{\sigma} c_k \qquad (47)$$

Hence, unsurprisingly, c_k and c_{-k} are linear functions of each other.

Inserting (47) into (42) yields

$$x = \psi^{\frac{\sigma}{\sigma-1}} \left(\alpha \widehat{p}_{-k}\right)^{-\sigma} c_k \qquad (48)$$

where

$$\psi = \alpha^{\sigma} \widehat{p}_{-k}^{\sigma-1} + (1-\alpha)^{\sigma} \widehat{p}_{k}^{\sigma-1}$$

Inserting (48) into (44), using (46), yields

$$w\psi^{-\frac{\sigma\rho-1}{\sigma-1}} \left(\alpha\widehat{p}_{-k}\right)^{\sigma\rho} c_{k}^{-\rho} = \kappa \widehat{p}_{k} \widehat{p}_{-k} \ell \tag{49}$$

By straightworward calculations, the three equations (43), (47), and (49) yield the following solutions for the three unknowns (c_k, c_{-k}, ℓ). Labor ℓ is given by

$$\ell \left(w\ell + g\right)^{\rho} = \frac{w}{\kappa} \psi^{\frac{1-\rho}{\sigma-1}} \left(\widehat{p}_{k}\widehat{p}_{-k}\right)^{\rho-1} \tag{50}$$

home consumption c_k by

$$\psi \left(\widehat{p}_{k}\widehat{p}_{-k}\right)^{2} c_{k}^{\rho+1} - \widehat{p}_{k}\widehat{p}_{-k} \left(\alpha\widehat{p}_{-k}\right)^{\sigma} g c_{k}^{\rho} = \frac{w^{2}}{\kappa} \psi^{-\frac{\sigma\rho-1}{\sigma-1}} \left(\alpha\widehat{p}_{-k}\right)^{\sigma(\rho+1)} \tag{51}$$

and foreign consumption by (47). It is easy to see that (50) and (51) each have a unique positive root. Hence, the household problem has a unique solution.

For the case $\rho = 1$, which we use in the numerical calibration, things are particular simple, as both equations are quadratic. In particular, we have

$$\ell = -\frac{g}{2w} + \frac{1}{2w}\sqrt{g^{2} + \frac{4w^{2}}{\kappa}} \tag{52}$$

which yields the multiplier λ, the “price of utility", by (46), as $\lambda = \frac{\kappa}{w}\ell$.

Optimal domestic consumption is

$$c_{k} = \frac{g\left(\alpha\widehat{p}_{-k}\right)^{\sigma}}{2\psi\widehat{p}_{k}\widehat{p}_{-k}} + \frac{\left(\alpha\widehat{p}_{-k}\right)^{\sigma}}{2\psi\widehat{p}_{k}\widehat{p}_{-k}}\sqrt{g^{2} + \frac{4w^{2}}{\kappa}} \tag{53}$$

and foreign consumption correspondingly.

The above analysis describes the demand side of each of the two economies in the absence of health concerns.

A.2.1 No-Pandemic Equilibria

We re-introduce country superscripts to describe market clearing in economies with no health concerns, be it pre-pandemic or after the arrival of a vaccine. The conditions are

$$\begin{aligned} w^{k} &= p_{k} z^{k} && (54) \\ z^{k}\ell^{k} &= c_{k}^{k} + c_{k}^{-k} && (55) \end{aligned}$$

$k = A, B$, for labor market and product market clearing, respectively.

Social Planner Under a benevolent social planner, government policy in each country will be $(\mu^k, \nu^k) = (0, 0)$: levying taxes on domestic or foreign goods is welfare reducing. Hence, the government collects no taxes, and by the budget constraint (12) transfers are $g = 0$. Consumer prices are undistorted,

$$\widehat{p}^k_k = p_k, \widehat{p}^k_{-k} = p_{-k}$$

and the 4 equations (54) and (55) to are sufficient to determine the 4 prices w^k, p_k, $k = A, B$, by using the solutions of (50), (51), and (47) obtained above. Of course, prices are determined only up to one degree of freedom, and by Walras' Law one of the above equilibrium relations is redundant.

Nash In Nash Equilibrium, $\mu^k = 0$ in each country. Yet, tariffs can be positive, for the standard economic reasons of trade wars discussed more broadly in the main text. Hence, consumer prices are

$$\begin{aligned} \widehat{p}^k_k &= p_k \\ \widehat{p}^k_{-k} &= (1 + \upsilon^k) p_{-k} \end{aligned}$$

Public transfers are therefore endogenous even in the static setting,

$$g^k = \nu^k p_{-k} c^k_{-k} \tag{56}$$

Now, for given government policies (ν^A, ν^B), we have the 6 equations (54), (55), and (56) to determine the 6 endogenous variables w^k, p_k, g^k, $k = A, B$.

A.2.2 Demand by Infected or Recovered Households

As noted above, the demand of infected and of recovered households in the full model in Section 2 derives from an essentially static optimization problem. Hence, by letting $w = \phi \overline{w}^k_t$ for the infected households of country k at date t, the household optimization conditions of the full model yield the conditions (50), (51), and (47), appropriately indexed for the i households. Similarly, by letting $w = \overline{w}^k_t$ for the recovered households, the household optimization conditions of the full model lead to (50), (51), and (47), appropriately indexed for the r households.

A.3 Disease Transmission

This subsection provides a microfoundation for the disease transmission dynamics (14) in Section 1.2.

In the basic SIR model (without economic choices) transmission occurs according to

$$T_t = \eta S_t I_t \tag{57}$$

This has the following logic. Let N be size of a given population. Let $N = S + I + R$, where I is the number of infectious, and S that of susceptibles. Let φN be the rate of contacts of a single individual during which the disease can potentially be transmitted.[12] The assumption is that individuals spend a fixed proportion of their time outside the home, where they can transmit or contract the virus. Letting θ denote the probability that a contact leads to an infection,[13] equation (57) can now be derived as follows.[14] One susceptible individual outside his home, per unit of time, on average has φN contacts. This leads to $\varphi N(I/N) = \varphi I$ contacts with infectious individuals. The probability of getting infected in these $k = \varphi I$ contacts is

$$\overline{\tau} = 1 - (1-\theta)^k = \theta \sum_{m=0}^{k-1} \binom{k}{m+1} (-\theta)^m \tag{58}$$

for $k > 0$, and the expected total number of transmissions per unit of time is $\overline{\tau} S$. $\overline{\tau}$ as a function of θ is a polynomial of degree k and strictly concave for $k > 1$. Hence, for small θ (which seems to be the case for Covid-19 under social distancing) $\overline{\tau}$ is smaller than, but approximately equal to $k\theta$. In this case, letting $\eta = \theta\varphi$, the average rate of transmission is approximately equal to

$$\theta k S = \theta \varphi I S = \eta I S$$

as stated in (57). If N is large or the population fragmented (so mass incidence in the form described above is not reasonable), the argument holds by adding up local populations.

A.3.1 The Macro-SIR Model

Eichenbaum et al. (2020) have proposed a particularly simple framework to incorporate economic activity into the above model, by distinguishing transmissions while consuming, at

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[12] This is the so-called “mass incidence" model which is relevant for Covid-19 (differently from, say, HIV, as analyzed in Greenwood et al. (2019)): one infectious individual can infect a whole (sub-)group, no need for bilateral interaction.

[13] θ clearly depends on the country and its policies. At least in richer countries, θ has decreased dramatically since February 2020.

[14] This is the perspective of susceptibles, which is most relevant for economic incentives. Usually, the derivation takes the perspective of infectious. See standard textbooks such as Brauer (2008).

work, and during other activities outside the home. This model does not distinguish between foreign and domestic consumption goods.

To make that precise, dropping the time index for convenience, suppose that individuals spend a fixed fraction $f < 1$ of their time outside neither at work nor consuming. All durations are in terms of the unit of time chosen (which is scaled by φ).[15] To simplify, and different from Brotherhood et al. (2020), we do not distinguish between utility from different types of leisure. Hence, individuals do not derive specific utility from leisure outside the home, and we therefore assume this fraction to be constant.[16] Suppose that individuals of health status h spend a fraction $\ell(h) < 1$ of their time at work, and a fraction $\gamma c(h) < 1$ consuming (shopping, dining, ...), the assumption being that the time spent on consumption is proportional to the quantity bought. We assume that $f + \ell(h) + \gamma c(h) < 1$, the remaining time being leisure alone at home.[17] Then, using the linear approximation of the infection probability $\overline{\tau}$, we have the following infection probabilities for susceptibles and aggregate average transmission rates:

1. During non-work-non-consumption time outside the home,
   - individual proba of becoming infected: $f\eta I$
   - expected total number of transmissions: $f\eta IS$
2. During work,
   - average rate of susceptible contacts with infected: $\varphi L(\ell(i)I/L)$
   - individual proba of becoming infected when working: $\ell(s)\eta\ell(i)I$
   - expected total number of transmissions at work: $\ell(s)\eta\ell(i)IS$
3. During consumption,
   - average rate of contacts with infected: $\varphi\gamma C(\gamma c(i)I/\gamma C)$
   - individual proba of becoming infected when consuming $c(s)$: $c(s)\eta\gamma^2 c(i)I$
   - expected total number of transmissions from consumption: $\eta\gamma^2 c(s)c(i)IS$

Here,

$$C_t = S_t c_t(s) + I_t c_t(i) + R_t c_t(r)$$

is total consumption, and

$$L_t = S_t \ell_t(s) + I_t \ell_t(i) + R_t \ell_t(r)$$

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[15] If this unit is a week and a day has 16 useful hours (e.g. McGrattan, Rogerson et al., 2004), then the individual has $112f$ hours of non-shopping leisure per week outside the home.

[16] See Garibaldi et al. (2020) for work that endogenizes f in a model of occupational choice, abstracting from the work-consumption choice considered here.

[17] We calibrate the parameter values such that the individual time constraints are satisfied in our simulations. Hence, we can ignore the time constraint in the household's optimization problem of (29).

total labor (hours worked) in the economy.

Hence, an s individual faces the following transition probability to the infected state, if she chooses individual consumption $c(s)$ and labor supply $\ell(s)$:

$$\begin{aligned} \tau(c(s),\ell(s)) &= f\eta I + \ell(s)\eta\ell(i)I + c(s)\eta\gamma^2 c(i)I && (59)\\ &= \eta\left[\gamma^2 c(s)c(i) + \ell(s)\ell(i) + f\right] I && (60)\end{aligned}$$

This yields the expected total number of transmissions from all activities, now with time indices:

$$\begin{aligned} T_t &= \eta\left(\gamma^2 c_t(s)c_t(i) + \ell_t(s)\ell_t(i) + f\right) I_t S_t && (61)\\ &= \left[\pi_1 c_t(s)c_t(i) + \pi_2\ell_t(s)\ell_t(i) + \pi_3\right] I_t S_t && (62)\end{aligned}$$

where

$$\pi_1 = \eta\gamma^2, \pi_2 = \eta, \pi_3 = \eta f$$

A.3.2 International transmission

Again dropping the time index for convenience, we denote individual consumption of good $j = A, B$ in country $k = A, B$ by $c_j^k = c_j^k(h)$. Aggregate consumption of good j in country k is

$$C_j^k = Sc_j^k(s) + Ic_j^k(i) + Rc_j^k(r) \qquad (63)$$

In terms of the notation of (6) and (7) in the main text, we have $C_k^k = H^k$ and $C_{-k}^k = M^k$. As before, suppose individuals of country k and health status h spend a fraction $\ell^k(h)$ of their time at work, a fraction $\gamma c_k^k(h)$ of their time consuming the domestic good, a fraction $\gamma c_{-k}^k(h)$ consuming the foreign good, and a fraction f out of their home for other reasons. When "shopping", an individual is directly exposed to home residents and foreigners. Since the contact intensity for foreign and domestic consumption is likely to differ we assume that the consumer has a contact rate $\varphi^d\gamma(C_k^k + C_{-k}^k)$ with domestic residents and a contact rate $\varphi^f\gamma(C_k^{-k} + C_{-k}^{-k})$ with foreigners. In fact, when consuming the domestic good, an individual in country k meets foreign consumers who consume her domestic good, which leads to a number of contacts per unit of time of $\varphi^f\gamma C_k^{-k}$. And when consuming the foreign good, she meets foreign consumers who consume this good, i.e. their domestic good, which leads to a number of contacts per unit of time of $\varphi^f\gamma C_{-k}^{-k}$. Since the consumption of foreign goods is often intermediated by specialized import/export agents and thus likely to involve fewer direct contacts, we expect $\varphi^f < \varphi^d$.[18]

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[18] An important exception to this logic is tourism. Remember that consumption includes tourism, which is a large

We assume for simplicity that there are no international encounters in non-work-non-consumption situations, and we also ignore those at the workplace. Hence, the transmission dynamics is unchanged from the previous subsection as regards these two types of encounters, and only changes with respect to the transmission related to consumption. For a susceptible consuming the bundle $(c_k^k(s), c_{-k}^k(s))$, we have:

- average rate of contacts: $\gamma(\varphi^d C_k^k + \varphi^f C_k^{-k}) + \gamma(\varphi^d C_{-k}^k + \varphi^f C_{-k}^{-k})$
- average rate of contacts with infected: $\gamma\varphi^d(c_k^k(i)+c_{-k}^k(i))I^k+\gamma\varphi^f(c_k^{-k}(i)+c_{-k}^{-k}(i))I^{-k}$
- individual proba of becoming infected:
  $c_k^k(s)\theta\gamma^2\left[\varphi^d c_k^k(i)I^k + \varphi^f c_k^{-k}(i)I^{-k}\right] + c_{-k}^k(s)\theta\gamma^2\left[\varphi^d c_{-k}^k(i)I^k + \varphi^f c_{-k}^{-k}(i)I^{-k}\right]$

Adding the infection probabilities shows that a susceptible in country k who chooses $\ell^k(s)$, $c_k^k(s)$, and $c_{-k}^k(s)$ transits to the infectious state with probability

$$\begin{aligned}
& \tau(c_k^k(s), c_{-k}^k(s), \ell^k(s)) \\
= & \left[\theta\gamma^2\varphi^d\left(c_k^k(s)c_k^k(i) + c_{-k}^k(s)c_{-k}^k(i)\right) + \theta\varphi^d\ell^k(s)\ell^k(i) + \theta\varphi^d f\right] I^k \qquad (64) \\
& \quad +\theta\gamma^2\varphi^f\left[c_k^k(s)c_k^{-k}(i) + c_{-k}^k(s)c_{-k}^{-k}(i)\right] I^{-k}
\end{aligned}$$

This yields the expected total number of transmissions from all activities in country k, now with time indices, as used in Section 1.2:

$$\begin{aligned}
T_t^k &= \left[\pi_1(c_{kt}^k(s)c_{kt}^k(i) + c_{-kt}^k(s)c_{-kt}^k(i)) + \pi_2\ell_t^k(s)\ell_t^k(i) + \pi_3\right] I_t^k S_t^k && (65) \\
&\quad +\pi_4\left[c_{kt}^k(s)c_{kt}^{-k}(i) + c_{-kt}^k(s)c_{-kt}^{-k}(i)\right] I_t^{-k} S_t^k && (66)
\end{aligned}$$

where

$$\begin{aligned}
\pi_1 &= \theta\gamma^2\varphi^d && (67) \\
\pi_2 &= \theta\varphi^d && (68) \\
\pi_3 &= \theta\varphi^d f && (69) \\
\pi_4 &= \theta\gamma^2\varphi^f && (70)
\end{aligned}$$

The transmission dynamics (65)-(66) generalize those of the single good case (61) - (62). The new terms reflect the transmissions through consumption interactions in exports $(c_{kt}^{-k}(i))$

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component of international trade in several countries (see, e.g., Culiuc, 2014). As in standard foreign trade statistics, holidays abroad therefore count as the domestic purchase of a foreign consumption good. It is likely that this type of import is very contact intensive. Also tourism is not subject to the usual logic of import tariffs. A more general model (not presented here) therefore distinguishes between tourism and other imports/exports.

and imports $(c^{k}_{-kt}(i))$ and therefore also involve foreign consumption abroad $(c^{-k}_{-kt}(i)$ in the π_4-term).

A.4 Computation Details

The numerical algorithm for solving our model proceeds in a number of steps. We first detail the solution to the model for fixed containment policies and then detail the solution for the optimal coordinated and uncoordinated policies.

Solution for fixed policies. To solve the model for a fixed set of containment taxes, we begin with guesses for the susceptible households' labor and consumption choices in each country and period as well as the relative price of country B's good in each period. Note that we normalize country A prices to 1. Given these guesses, we calculate the implied government tax as well as the labor and consumption of all other household types. We then iterate forward on the SIR equations until the final period of the model, at which point consumption and labor return to their steady state values due to the vaccine's arrival. Next, we iterate backward to derive the present value of lifetime utility for each agent. We then use gradient-based methods to adjust our initial guesses until the susceptible agents' first-order conditions, market clearing conditions, and government budget constraints hold. In this way, we confirm all equilibrium conditions are satisfied.

Social planner solution. To solve for optimal containment policies from the perspective of a social planner, we nest the solution for fixed policies within another gradient-based optimizer. In this outer loop, we solve for containment policies and tariffs which maximize the present value of total time-0 utility, equally weighted across both countries.

Nash equilibrium solution. To solve for the Nash Equilibrium containment policies we begin with a guess for containment policies and tariffs across both countries. Given a fixed policy for a given country, we use a gradient-based optimizer to find the optimal policy response of the other country that maximizes the welfare of its own households. We then take this policy as fixed and find the optimal policy response of the other country. We iterate on this procedure until both countries' policies are the best responses to each other. We experiment with many different starting values but do not find any differences in the final result, which makes us believe that the identified Nash equilibrium is unique.