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International Comovement in the Global Production Network

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This article provides a general framework to study the role of production networks in international GDP comovement. We first derive an additive decomposition of bilateral GDP comovement into components capturing shock transmission and shock correlation. We quantify this decomposition in a parsimonious multi-country, multi-sector dynamic network propagation model, using data for the G7 countries over the period 1978–2007. Our main finding is that while the network transmission of shocks is quantitatively important, it accounts for a minority of observed comovement under the estimated range of structural elasticities. Contemporaneous responses to correlated shocks in the production network are more successful at generating comovement than intertemporal propagation through capital accumulation. Extensions with multiple shocks, nominal rigidities, and international financial integration leave our main result unchanged. A combination of TFP and labour supply shocks is quantitatively successful at reproducing the observed international business cycle.

Key words: Production networks, International comovement

JEL codes: F41, F44

1. INTRODUCTION

Production networks play an important role in transmitting shocks within countries and amplifying aggregate fluctuations.[1] Since input networks increasingly cross national borders, a natural conjecture is that they may also help explain the positive correlation of real GDP growth across

1. The closed-economy literature on the micro origins of aggregate fluctuations and on shock propagation via input linkages goes back to Long and Plosser (1983) and has been modernized recently following the seminal contribution by Acemoglu *et al*. (2012).

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countries. Although there is a growing body of work on the international propagation of disaggregate shocks through interconnected sectors and firms (*e.g.* di Giovanni *et al*., 2018; Boehm *et al*., 2019), we still lack a comprehensive theoretical and quantitative account of the role of production networks in international GDP synchronization.

This article develops and quantifies a general framework to study international comovement in the presence of global production networks. We first derive an additive decomposition of bilateral GDP comovement into components capturing shock transmission and shock correlation. We then set up a parsimonious and tractable multi-country, multi-sector dynamic network propagation model that can be implemented using widely available data. Using this framework, we quantify the relative importance of correlated shocks versus shock transmission in generating GDP comovement. In the model, shocks transmit internationally and generate positive comovement, consistent with micro evidence. However, the transmission of shocks through the input network accounts for a minority of observed comovement under the estimated values of structural elasticities. Fully reproducing observed comovement requires correlated shocks.

Section 2 sets up a simple accounting framework that clarifies the mechanisms at play and objects of interest for measurement. Two countries can experience positive comovement if shocks in one country influence the other country's GDP through trade and production linkages. Comovement also arises if influential sectors in the two economies have correlated shocks. The GDP correlation between two countries can be expressed as a function of the primitive shock covariances and a global influence matrix. The latter collects the general equilibrium elasticities of GDP in each country with respect to all sector-country-specific shocks worldwide, and thus translates the variances and covariances of the primitive shocks into comovements of GDP. We show that the GDP correlation between two countries can always be written as a sum of two terms, respectively capturing correlated shocks and transmission.

The accounting framework provides a roadmap for quantification and measurement. First, as the global influence matrix will always be model-dependent, we must impose sufficient structure and bring sufficient data on the international production network linkages to build the global influence matrix. Second, we must recover some underlying shocks to determine the extent of their correlation across countries. This will allow us to establish both how the influence matrix interacts with the shock correlation, and how it produces transmission.

Section 3 sets up a dynamic multi-country, multi-sector, multi-factor model of the world economy. Countries trade both intermediate and final goods. Each sector uses labour, capital, and intermediate inputs that can come from any sector and country in the world. Sector-specific supply shocks propagate through the production network both domestically and internationally. In response to both domestic and foreign shocks, capital can be accumulated in each sector subject to a time-to-build lag. We provide a first-order analytical solution for the contemporaneous GDP impact of a global vector of shocks in the multi-country dynamic general equilibrium. This analytical solution expresses the response to shocks in terms of observables that can be measured and a set of structural elasticities.

Our baseline framework generalizes the canonical network propagation model (*e.g.* Acemoglu *et al*., 2012) in three dimensions. First, our solution applies in the international setting. We write the change in GDP of a single country as an inner product of the vector of shocks to all countries and sectors in the world and the country-specific influence vector that collects the elasticities of that country's GDP to every sectoral shock in the world. Second, the model features endogenous factor supply. This is important for analysing business cycle transmission to measured GDP. In the canonical network model factor supply is fixed, and thus measured GDP by construction does not respond to foreign shocks. Third, our analytical solution for the contemporaneous change in GDP applies in a dynamic setting where shocks also propagate intertemporally. Our analysis thus integrates the static network literature that follows

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Acemoglu *et al*. (2012) and the dynamic international business cycle literature (*e.g.* Backus *et al*., 1992). We can cleanly separate the intratemporal propagation analysed in the former and the delayed responses to shocks emphasized by the latter.

Section 4 quantifies the model using sector-level data for the G7 countries over the period 1978–2007. Implementing the decomposition of the overall comovement into the correlated shocks and transmission components from Section 2 requires the model solution (most importantly the influence matrix) and a time series for the vector of shocks. The model solution in turn requires two sets of objects: the input network (final and intermediate expenditure shares) and structural elasticities (of labour supply and substitution). The global input network comes from a standard source, the World Input–Output Database (WIOD). We use the model-implied relationships to structurally estimate the key elasticities. An important byproduct of this step is that it also yields confidence intervals for the values of these elasticities, that we use in the sensitivity analysis to provide a range of likely outcomes.

We then use the fully calibrated quantitative framework as a means to recover the shocks. As the global influence matrix translates sector-country specific shocks to equilibrium changes in output, it can also be inverted to infer supply shocks that rationalize the observed output changes. By construction, when these shocks are fed back into the model, they reproduce each country's GDP, and hence observed international GDP correlations exactly.[2]

Our main finding is that the shocks required to rationalize observed output growth are correlated across countries. In our preferred calibration, the transmission component accounts for about one-fifth of the total GDP correlation, with the shock correlation responsible for the remaining four-fifths. Thus, while network linkages do propagate shocks across borders, the internal transmission mechanisms in global production network models cannot generate all of the observed comovement. We also decompose overall GDP correlation into the components due to the contemporaneous change in GDPs due to a vector of shock innovations, and the infinite sum of responses to all the past innovations. Quantitatively, the intertemporal propagation through capital accumulation is much less important for comovement than the contemporaneous responses to shocks in the production network.

We next investigate the roles of the structural elasticities and the input network in generating this baseline result. The model requires three elasticities: the Frisch elasticity of labour supply, and substitution elasticities between inputs and final goods. The substitution elasticities govern both the direction and the magnitude of the demand shift experienced by the home economy following a foreign productivity shock. A higher Frisch elasticity implies a larger response of labour inputs to a given shift in demand, and hence a larger real GDP response. Lower substitution elasticities and higher Frisch elasticities thus lead to a greater share of transmission in total comovement.

We use our econometric estimates to obtain a three-dimensional empirical distribution over the three elasticities. We re-do the shock recovery procedure and calculate the share of overall

2. Foerster *et al*. (2011) perform a related exercise in the closed economy. An advantage of our approach is that the model plus these shocks match the GDP data perfectly, which permits a decomposition of the observed GDP correlations into the different components. The disadvantage is that the resulting recovered shocks have a broad interpretation. In our framework, TFP and factor supply shocks have the same effect on the global vector of output changes, up to a scaling factor. Thus, inverting the global influence matrix yields a composite supply shock, which is sufficient to answer the main question posed in Section 4. As discussed in detail in Section 5.2, many "demand" shocks such as monetary policy or sentiments manifest themselves in reduced form as factor supply shifts, and would thus be picked up in our composite sectoral supply shocks. Section 5.2 separates out several distinct types of shocks. Doing so leaves the main conclusion about the relative importance of correlated shocks versus transmission in overall comovement virtually unchanged. An alternative use of our framework would be to feed in externally specified shocks for any subset of countries and sectors, which is appropriate in some applications (see *e.g.* Bonadio *et al*., 2021).

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comovement due to transmission and correlated shocks for each candidate set of elasticities. The result is an estimation-based distribution of the shares of transmission and correlated shocks in total comovement. By construction, the procedure matches the data on the overall GDP correlations under each set of elasticities, but the fraction of comovement attributed to transmission varies with these parameters. Most of the mass is in the range where shock correlation accounts for over 70% of the total comovement. Thus, our main result that shock transmission cannot generate nearly the observed level of comovement is robust to reasonable statistical parameter uncertainty.

Next, we investigate the role of international trade by comparing the baseline economy to one in which countries are in autarky. We write the difference in GDP comovement between the trade and autarky equilibria as a sum of two terms: the international transmission of shocks; and the change in contribution of correlated domestic shocks. The second term is the aggregation of the changes in the influence of the domestic shocks times the covariances of those shocks. As expected, international transmission is positive in the trade equilibrium and increases comovement relative to autarky. On the other hand, the second term tends to be negative and quantitatively important, reducing G7 GDP correlations by 0.05–0.1 on average. This effect has not to our knowledge been previously pointed out. It occurs because opening to trade makes economies less susceptible to domestic shocks, reducing their influence on domestic GDP growth. Intuitively, when a country sources a significant share of expenditure abroad, domestic conditions matter less and domestic shocks propagate less to GDP. As a result, it matters less that domestic shocks are positively correlated across countries. Of course, this is a *ceteris paribus* effect. Domestic influence is replaced by foreign influence when countries open to trade, and comovement increases overall. But, it increases by less than naive reasoning would imply.

Section 5 presents several extensions. First, we perform the analysis in a static model that is an international extension of Acemoglu *et al*. (2012). One advantage of the static approach is lower data requirements. Since to implement the static model we do not need to take a stand on forward-looking decisions, we do not need to estimate the joint stochastic process for the shocks in all countries and sectors. Thus, the static model can be implemented even on relatively short time series, and we can expand the analysis to include 29 countries available in KLEMS from 1995. The conclusion of the static analysis regarding the share of transmission in overall comovement is similar to the dynamic model implemented on the G7 countries.

The baseline analysis is based on a parsimonious framework with one composite supply shock. By construction, is not especially informative on the underlying drivers of business cycles in general, and of international comovement in particular. In the second extension we enrich the model to feature four shocks: TFP, labour, capital/investment, and intermediate input. We recover these four shocks to match the data on output, labour, capital, and intermediate inputs. The relative importance of correlated shocks versus transmission is unchanged when we move to the 4-shock model. We simulate the model conditional on subsets of shocks to understand which ones are most important for comovement. No single shock has a dominant role in international comovement. Individually, the labour and the TFP shocks appear most promising.[3] A model that combines labour and TFP shocks strikes a good balance between parsimony and fit to the data. The two shocks together generate 80% of the observed international correlation, and produce behaviour of GDP quite similar to the data. This specification is parsimonious both in the sense

3. Our labour supply shock can be viewed as a generalization of the "labour wedge" (*e.g.* Chari *et al*., 2007) to the sector level. Though reduced-form, it has a variety of "demand shock" microfoundations, such as sentiment shocks (*e.g.* Angeletos and La'O, 2013; Huo and Takayama, 2015), monetary policy shocks under sticky wages (Galí *et al*., 2007; Chari *et al*., 2007), or shocks to working capital constraints (*e.g.* Neumeyer and Perri, 2005; Mendoza, 2010).

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that it relies on only two shocks, as well as in the sense that these shocks themselves are relatively simple, and would work in the same way in a variety of models.

Finally, we develop further extensions incorporating wage rigidities and international financial integration. We provide an analytical characterization of how the parameter governing the extent of wage rigidity affects the impact response of the world economy to a vector of shocks. In our framework, greater wage rigidity acts like a higher Frisch elasticity, amplifying the economy's response to a given size shock, and thus the importance of transmission. However, even for quite high levels of wage rigidity transmission accounts for a minority of the overall comovement. We next implement a complete markets version of the model. If anything, introducing international risk sharing weakens international transmission of shocks to GDP, as it further decouples consumption from labour supply (and hence output). All in all, while these extensions do not overturn the main quantitative conclusions, introducing wage rigidities does increase the importance of transmission in international comovement, and thus should be explored in depth in future research.

1.1. *Related literature*

Our article draws from, and contributes to two literatures. The first is the active recent research agenda on shock propagation in production networks. A number of closed-economy papers following the seminal contributions of Carvalho (2010) and Acemoglu *et al.* (2012) enrich the theory, provide econometric evidence, and estimate key structural parameters (see, among others, Foerster *et al.*, 2011; Acemoglu *et al.*, 2016; Barrot and Sauvagnat, 2016; Atalay, 2017; Grassi, 2017; Baqaee, 2018; Baqaee and Farhi, 2019a, 2019b; Boehm *et al.*, 2019; Adao *et al.*, 2020; Allen *et al.*, 2020; Bigio and La'O, 2020; Carvalho *et al.*, 2020; Ferrari, 2022; Foerster *et al.*, 2022; vom Lehn and Winberry, 2022). We apply the insights and tools developed by this body of work to the study of international GDP comovement. The notion that international input trade is a key feature of the global economy goes back to Hummels *et al.* (2001) and Yi (2003) and has more recently been documented and quantified in a series of contributions by Johnson and Noguera (2012, 2017) and Caliendo and Parro (2015).[4]

The second is the research program in international macro that studies business cycle comovement using dynamic IRBC models featuring simple production structures. A large literature builds models in which fluctuations are driven by productivity shocks, and asks under what conditions those models can generate observed international comovement (see, among many others, Backus *et al.*, 1992; Heathcote and Perri, 2002). A smaller set of contributions adds non-technology shocks (Stockman and Tesar, 1995; Wen, 2007; Bai and Ríos-Rull, 2015).[5] More recently, Ho *et al.* (2022) study the propagation of various idiosyncratic country shocks in a global New Keynesian model with both trade linkages and nominal rigidities and extend the analysis to inflation comovement.

4. In the international trade literature, contemporaneous work by Baqaee and Farhi (2024) and subsequent work by Kleinman *et al.* (2020, 2023) also derives analytical first-order solutions to international network models. While these frameworks focus on long-run comparative statics such as gains from trade or foreign productivity growth, they cannot be used to study international transmission of business cycle shocks (and related applications). Because these papers feature fixed factor supply, measured real GDP is not responsive to foreign shocks, and thus international transmission (to real GDP) is nonexistent by construction.

5. A number of papers are dedicated to documenting international correlations in productivity shocks and factor inputs (*e.g.* Imbs, 1999; Kose *et al.*, 2003; Ambler *et al.*, 2004). Also related is the body of work that identifies technology and demand shocks in a VAR setting and examines their international propagation (*e.g.* Canova, 2005; Corsetti *et al.*, 2014; Levchenko and Pandalai-Nayar, 2020).

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Our framework nests the rich static production network models, the canonical IRBC models, as well as more recent frameworks (such as Burstein *et al*., 2008; Johnson, 2014; Eaton *et al*., 2016a, 2016b) that combine dynamics with simplified input–output structures. Note that the accounting decompositions of transmission versus shock correlation and the static versus dynamic components developed in Section 2 also apply to all of these. While all papers on international business cycle comovement must take a stand on the relative importance of correlated shocks versus transmission, we provide a method to cleanly separate these two potential sources of comovement that can be applied across models. We further contribute to this research agenda by deriving a set of analytical results that help quantify the relative importance of transmission and correlated shocks, measuring the shocks, and expanding the scope of quantification to more countries and sectors.[6,7]

2. ACCOUNTING

Consider an economy comprised of J sectors indexed by j and i, and N countries indexed by n and m. Gross output in sector j of country n at time t aggregates a primary factor input bundle $\mathcal{I}_{nj,t} \in \mathbb{R}_+$ (for instance, capital and labour) and materials inputs $X_{nj,t} \in \mathbb{R}_+$:

$$Y_{nj,t} = F_{nj}\left(\mathcal{I}_{nj,t}(\boldsymbol{\theta}), X_{nj,t}(\boldsymbol{\theta}); \boldsymbol{\theta}\right).$$

The bundle of inputs $X_{nj,t}$ can include foreign imported intermediates. The sectoral output is affected by a generic array of current and past shocks $\boldsymbol{\theta}$.[8] For concreteness, one can think of productivity shocks. A productivity shock $\theta_{nj,t}$ to sector j in country n at time t will directly affect output in that sector. Because the economy is interconnected through trade, output in every sector and country is in principle a function of all the history of shocks anywhere in the world, hence the dependence of $Y_{nj,t}$ on the full array $\boldsymbol{\theta}$ across countries, sectors, and time up to t. The array $\boldsymbol{\theta}$ can include multiple types of shocks (such as technology and non-technology). The next section completely specifies the shocks, and the nature of output's dependence on those shocks in the context of a particular model.

Following national accounting conventions, real GDP of country n at time t is defined as value added evaluated at the prices of some base year b:

$$G_{n,t} = \sum_{j=1}^{J}\left(P_{nj,b}Y_{nj,t}(\boldsymbol{\theta}) - P^X_{nj,b}X_{nj,t}(\boldsymbol{\theta})\right), \tag{2.1}$$

where $P_{nj,b}$ is the price of gross output and $P^X_{nj,b}$ is the price of the input bundle in the base year b.

6. Also related is the large empirical and quantitative literature on the positive association between international trade and comovement (*e.g.* Frankel and Rose, 1998; Imbs, 2004; Kose and Yi, 2006; di Giovanni and Levchenko, 2010; Ng, 2010; Liao and Santacreu, 2015; di Giovanni *et al*., 2018; de Soyres and Gaillard, 2019; Drozd *et al*., 2021). While these papers focus on the slope of the trade-correlation relationship in a cross-section of countries, we broaden the scope to provide a complete treatment of international comovement. Supplementary Appendix D.5 explores the connection between the "trade-comovement" regressions and our analysis.

7. Following the network propagation literature, our analysis captures the shock transmission through the market for inputs. It leaves open the possibility that the presence of input trade endogenously leads to correlated shocks, for instance through coordination of monetary policy, flow of information/sentiments, or transmission of productivity shocks within multinationals, among others. Microfounding shock correlation is outside the scope of our analysis but remains a fruitful avenue for future research.

8. The shock $\boldsymbol{\theta} \in (\ell^2)^{NJ}$ as we allow $\boldsymbol{\theta}$ to have an infinite history for each country sector.

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Let $\theta_{mi,t}$ be a scalar-valued shock affecting sector i in country m at time t. A first-order approximation to the log change in real GDP of country n can be written as:[9]

$$d\ln G_{n,t} = \sum_{k=0}^{\infty}\sum_{m}\sum_{i} s_{mni,k}\theta_{mi,t-k}, \tag{2.2}$$

where $s_{mni,k}$ are the elements of the global influence matrix, that give the elasticity of the GDP of country n with respect to shocks in sector i, country m, k periods in the past: $s_{mni,k} \equiv d\ln G_{n,t}/d\theta_{mi,t-k}$. Notice that these elasticities capture the full impact of a shock through direct and indirect input–output links and general equilibrium effects.

To highlight the sources of international GDP comovement, write real GDP growth as

$$d\ln G_{n,t} = \underbrace{\sum_{k=0}^{\infty}\sum_{j} s_{nnj,k}\theta_{nj,t-k}}_{\mathcal{D}_{n,t}} + \underbrace{\sum_{k=0}^{\infty}\sum_{j} s_{mnj,k}\theta_{mj,t-k}}_{\mathcal{P}_{n,t}} + \underbrace{\sum_{k=0}^{\infty}\sum_{n'\neq n,m}\sum_{j} s_{n'nj,k}\theta_{n'j,t-k}}_{\mathcal{T}_{n,t}}. \tag{2.3}$$

This equation simply breaks out the triple sum in (2.2) into the component due to country n's own shocks ($\mathcal{D}_{n,t}$), the component due to a particular trading partner m's shocks ($\mathcal{P}_{n,t}$), and the impact of "third" countries that are neither n nor m ($\mathcal{T}_{n,t}$).[10]

We assume that the world is stationary, and thus the moments of the GDP distributions do not depend on calendar time t. We interpret the $\theta_{nj,t}$'s as the innovations to the stochastic process for the exogenous states of the economy and assume that these innovations have a covariance matrix $\mathbf{\Sigma}$ across country-sectors but are uncorrelated across time.[11] Then, the GDP correlation between country n and country m is:

$$\varrho_{nm} = \underbrace{\frac{\mathrm{Cov}(\mathcal{D}_n,\mathcal{D}_m)}{\sigma_n\sigma_m}}_{\text{Shock Correlation}} + \underbrace{\frac{\mathrm{Cov}(\mathcal{D}_n,\mathcal{P}_m)+\mathrm{Cov}(\mathcal{P}_n,\mathcal{D}_m)+\mathrm{Cov}(\mathcal{P}_n,\mathcal{P}_m)}{\sigma_n\sigma_m}}_{\text{Bilateral Transmission}}$$
$$+ \underbrace{\frac{\mathrm{Cov}(\mathcal{D}_n+\mathcal{P}_n+\mathcal{T}_n,\mathcal{T}_m)+\mathrm{Cov}(\mathcal{T}_n,\mathcal{D}_m+\mathcal{P}_m)}{\sigma_n\sigma_m}}_{\text{Multilateral Transmission}}, \tag{2.4}$$

where σ_n is the standard deviation of country n's GDP growth.

This expression underscores the sources of international comovement. The first term captures the fact that economies might be correlated even in the absence of trade if the underlying shocks themselves are correlated, especially in sectors influential in the two economies. The numerator

9. The first-order approximation converges to the exact change for infinitesimally small shocks. To streamline notation, we use the equal sign instead of "≈" throughout the article even when describing first-order model solutions. The extension to vector-valued $\theta_{mi,t}$ is straightforward, *i.e.* each sector can experience multiple shocks simultaneously.

10. To be fully precise, $\mathcal{P}_{n,t}$ and $\mathcal{T}_{n,t}$ also depend on trading partner m. To avoid cluttering notation, we do not index these objects by m. This omission does not create an ambiguity in this section, as we only consider the correlation between n and m.

11. That is, $\mathrm{Cov}(\theta_{mi,t},\theta_{nj,t'}) = 0\ \forall t' \neq t$. This is without much loss of generality. Assuming that the shock innovations are uncorrelated across time still allows for a rich autocorrelation structure in the vector of exogenous states. For instance, if $\theta_{mi,t}$ is the innovation in the stochastic process for TFP growth, the global productivity vector can still follow an AR(p) process, with autoregressive coefficients on both the own sector's lagged TFP growth as well as spillover coefficients from other sectors' lagged TFP. The effects of persistent states are encoded in the elements of the influence matrix $s_{mnj,k}$.

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of the Shock Correlation term can be written as:

$$\text{Cov}(\mathcal{D}_n, \mathcal{D}_m) = \sum_{k=0}^{\infty} \sum_{j} \sum_{i} s_{nnj,k} s_{mmi,k} \text{Cov}(\theta_{nj}, \theta_{mi}).$$

The second term captures bilateral or direct transmission. If the GDP of country n has an elasticity with respect to the shocks occurring in country m ($s_{mni,k} > 0$), that would contribute to comovement as well. Taking one of the components of the Bilateral Transmission component:

$$\begin{aligned}\text{Cov}(\mathcal{D}_n, \mathcal{P}_m) &= \sum_{k=0}^{\infty} \sum_{j} \sum_{i} s_{nnj,k} s_{nmi,k} \text{Cov}(\theta_{nj}, \theta_{ni}) \\ &= \sum_{k=0}^{\infty} \boldsymbol{s}'_{nn,k} \boldsymbol{\Sigma}_n \boldsymbol{s}_{nm,k},\end{aligned}$$

where $\boldsymbol{\Sigma}_n$ is the $J \times J$ covariance matrix of shocks in country n, and $\boldsymbol{s}_{nm,k}$ is the $J \times 1$ influence vector collecting the impact of k-period lagged shocks in n on GDP in m. This expression underscores that one source of comovement is that under trade, both country n and country m will be affected by shocks in n.

Finally, the Multilateral Transmission term collects all the other sources of comovement between n and m that do not come from shocks to either n or m, such as shocks in other countries.

The overall comovement also admits an additive decomposition into the contributions of contemporaneous and past shocks. The GDP correlation between countries n and m can be written as:

$$\varrho_{nm} = \sum_{k=0}^{\infty} \frac{\boldsymbol{s}'_{n,k} \boldsymbol{\Sigma} \boldsymbol{s}_{m,k}}{\sigma_n \sigma_m}, \tag{2.5}$$

where $\boldsymbol{s}_{n,k}$ is the $NJ \times 1$ influence vector collecting the impact of all worldwide innovations k periods ago on country n. This leads to the following decomposition:

$$\varrho_{nm} = \sum_{k=0}^{\infty} \omega_{nm,k} \; \varrho_{nm,k}, \tag{2.6}$$

where

$$\varrho_{nm,k} = \frac{\boldsymbol{s}_{n,k} \boldsymbol{\Sigma} \boldsymbol{s}'_{m,k}}{\sqrt{\boldsymbol{s}_{n,k} \boldsymbol{\Sigma} \boldsymbol{s}'_{n,k}} \sqrt{\boldsymbol{s}_{m,k} \boldsymbol{\Sigma} \boldsymbol{s}'_{m,k}}} \quad \text{and} \quad \omega_{nm,k} = \frac{\sqrt{\boldsymbol{s}_{n,k} \boldsymbol{\Sigma} \boldsymbol{s}'_{n,k}} \sqrt{\boldsymbol{s}_{m,k} \boldsymbol{\Sigma} \boldsymbol{s}'_{m,k}}}{\sqrt{\sum_{k'=0}^{\infty} \boldsymbol{s}_{n,k'} \boldsymbol{\Sigma} \boldsymbol{s}'_{n,k'}} \sqrt{\sum_{k'=0}^{\infty} \boldsymbol{s}_{m,k'} \boldsymbol{\Sigma} \boldsymbol{s}'_{m,k'}}}.$$

In words, $\varrho_{nm,k}$ is the GDP correlation that would obtain due exclusively to shocks k periods ago. The weight $\omega_{nm,k}$ is the standard deviation of GDP only due to shocks k periods ago divided by the actual standard deviation of GDP (due to shocks at all lags).

Thus, the overall GDP correlation is additive in the component due to the contemporaneous shock innovations $\omega_{nm,0}\varrho_{nm,0}$ and the dynamic propagation of past shocks. In a static model, or more broadly any model without delayed propagation of shocks, the actual GDP correlation coincides with the contemporaneous component: $\varrho_{nm} = \varrho_{nm,0}$. Given a quantifiable model of delayed shock propagation, (2.6) gives a transparent answer to the question of how much comovement occurs due to contemporaneous versus delayed effects of the shocks. We will quantify this decomposition below.

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To summarize, in order to provide an account of international comovement, we must (i) recover shocks in order to understand their comovement properties; and (ii) assess how the global production and trade network (the distribution of $s_{nnj,k}$'s) translates sectoral comovement of the primitive shocks into GDP comovement. Finally, (iii) we must discipline the persistence of both the shocks and equilibrium adjustments over time in order to quantify the relative importance of contemporaneous versus intertemporal correlation.

3. THEORY

The decompositions above are general and would apply in any production economy. However, any measurement of the elements of the influence matrix and of shocks requires additional theoretical structure. This section introduces a parsimonious dynamic multi-country production network model and derives a number of analytical results. Section 4 uses it to quantify the contributions of correlated shocks and transmission to GDP comovement.

3.1. *Setup*

3.1.1. Households. Each country n is populated by an infinitely lived representative household. The household consumes the final good available in country n and supplies labour and capital to firms. It solves

$$\max_{C_{n,t},\{I_{nj,t}\},\{H_{nj,t}\}} \mathbb{E}_0 \sum_{t=0}^{\infty} \beta^t \, \mathcal{U}\left(C_{n,t} - \sum_j H_{nj,t}^{1+\frac{1}{\psi}}\right) \tag{3.1}$$

subject to

$$P_{n,t}\left(C_{n,t} + \sum_j I_{nj,t}\right) = \sum_j W_{nj,t} H_{nj,t} + \sum_j R_{nj,t} K_{nj,t} \tag{3.2}$$

$$K_{nj,t+1} = (1-\delta_j) K_{nj,t} + I_{nj,t} \qquad \forall j, \tag{3.3}$$

where $C_{n,t}$ is consumption of final goods, $H_{nj,t}$ is the total labour hours supplied to sector j, and $K_{nj,t}$ is the amount of installed capital in sector j. Labour collects a sector-specific wage $W_{nj,t}$, and capital is rented at the price $R_{nj,t}$. As is customary, it takes one period for investment to become capital, and thus the capital stock in each sector is predetermined by one period.

Our formulation of the disutility of the labour supply is based on the Greenwood *et al.* (1988) preferences. The GHH preferences mute the interest rate effects and income effects on the labour supply, which helps to study the properties of the intratemporal equilibrium where the amount of capital is treated as predetermined. Labour and capital are differentiated by sector, as the household supplies factors to each sector separately. In this formulation, labour is neither fixed to each sector nor fully flexible, and its responsiveness is determined by the Frisch elasticity ψ.[12]

Our benchmark model assumes financial autarky, for two main reasons. First, as highlighted by Heathcote and Perri (2002), among others, models with financial autarky perform well in

12. The specification of labour supply bears an affinity to the "Roy-Frechet" models common in international trade (*e.g.* Galle *et al.*, 2022), in the sense that the relative supply of hours to two different sectors is isoelastic in the relative wages in the two sectors. The difference is that in most existing Roy-Frechet implementations, aggregate labour supply is fixed and only sectoral shares vary, whereas in our analysis total economywide labour supply shifts as well.

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accounting for business cycle comovement.[13] Second, under financial autarky there is an analytical solution for the contemporaneous response of output to shocks (Proposition 3.1), that requires only observed export and import shares, the elasticities of substitution among intermediate and final goods, and the Frisch elasticity. Adding endogenous capital flows would come at a cost of both tractability and transparency. Supplementary Section D.6 presents an extension with complete markets.

The final use in the economy, denoted $\mathcal{F}_{n,t} = C_{n,t} + \sum_j I_{nj,t}$, is an Armington aggregate across countries and sectors. Trade is subject to iceberg costs τ_{mnj} to ship good j from country m to country n (throughout, we adopt the convention that the first subscript denotes source, and the second destination). The functional form and its associated price index are given by

$$\mathcal{F}_{n,t} = \prod_j \left[\sum_m \vartheta_{mnj}^{\frac{1}{\rho}} \mathcal{F}_{mnj,t}^{\frac{\rho-1}{\rho}} \right]^{\nu_{nj}\frac{\rho}{\rho-1}}, \quad P_{n,t} = \prod_j \left[\sum_m \vartheta_{mnj} \left(\frac{P_{mnj,t}}{\nu_{nj}} \right)^{1-\rho} \right]^{\frac{\nu_{nj}}{1-\rho}}, \tag{3.4}$$

where $\mathcal{F}_{mnj,t}$ is final use in n of sector j goods coming from country m, and $P_{mnj,t}$ is the price of $\mathcal{F}_{mnj,t}$. That is, the final bundle is Cobb–Douglas over sectoral bundles, and sectoral bundles are Armington aggregates across source countries. The expenditure shares on final good j imported form country m within sector j and across all goods are given by

$$\pi^c_{mnj,t} = \frac{\vartheta_{mnj} P_{mnj,t}^{1-\rho}}{\sum_k \vartheta_{knj} P_{knj,t}^{1-\rho}}, \quad \text{and} \quad \pi^f_{mnj,t} = \nu_{nj} \pi^c_{mnj,t}. \tag{3.5}$$

The labour supply curves are isoelastic in the wages relative to the consumption price index, and given by (up to a normalization constant):

$$H_{nj,t}^{\frac{1}{\psi}} = \frac{W_{nj,t}}{P_{n,t}}. \tag{3.6}$$

The Euler equations governing investment in each sector j are:

$$U'_{n,t} = \beta \mathbb{E}_t \left[\left(\frac{R_{nj,t+1}}{P_{n,t+1}} + (1-\delta) \right) U'_{n,t+1} \right].$$

3.1.2. Firms. Sector j in country n is populated by competitive firms that operate a CRS production function

$$Y_{nj,t} = Z_{nj,t} \left(K_{nj,t}^{1-\alpha_j} H_{nj,t}^{\alpha_j} \right)^{\eta_j} X_{nj,t}^{1-\eta_j}, \tag{3.7}$$

13. We can easily accommodate a sequence of exogenous trade imbalances as in Dekle *et al.* (2008), without much change in the results. The financial autarky assumption is also adopted in Corsetti *et al.* (2008), Ruhl (2008), and many others. Kose and Yi (2006) show that when it comes to accounting for the trade-comovement relationship, the benchmarks of complete markets and financial autarky deliver similar results. We acknowledge that the financial autarky assumption excludes transmission mechanisms that operate through international capital flows. While this article focuses on shock transmission through goods trade and production linkages, we leave the evaluation of other transmission mechanisms for future research.

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where $Z_{nj,t}$ is the total factor productivity, and the intermediate input usage $X_{nj,t}$ is an aggregate of inputs from potentially all countries and sectors:

$$X_{nj,t} \equiv \left(\sum_i \sum_m \mu_{mi,nj}^{\frac{1}{\varepsilon}} X_{mi,nj,t}^{\frac{\varepsilon-1}{\varepsilon}} \right)^{\frac{\varepsilon}{\varepsilon-1}},$$

where $X_{mi,nj,t}$ is the usage of inputs coming from sector i in country m in production of sector j in country n, and $\mu_{mi,nj}$ is a taste shifter.[14]

Let $P_{mi,t}$ denote the price of output produced by sector i in country m, and let $P_{mi,nj,t}$ be the price paid in country-sector (n, j) for inputs from (m, i). No arbitrage in shipping implies that the price "at the factory gate" and the price at the time of final or intermediate usage are related by:

$$P_{mi,nj,t} = P_{mni,t} = \tau_{mni} P_{mi,t}.$$

Cost minimization implies that the payments to primary factors and intermediate inputs are:

$$\begin{aligned} R_{nj,t} K_{nj,t} &= (1-\alpha_j)\eta_j P_{nj,t} Y_{nj,t} \\ W_{nj,t} H_{nj,t} &= \alpha_j \eta_j P_{nj,t} Y_{nj,t} \qquad (3.8) \\ P_{mi,nj,t} X_{mi,nj,t} &= \pi^x_{mi,nj} \left(1-\eta_j\right) P_{nj,t} Y_{nj,t}, \qquad (3.9) \end{aligned}$$

where $\pi^x_{mi,nj,t}$ is the share of intermediates from country m sector i in total intermediate spending by n, j, given by:

$$\pi^x_{mi,nj,t} = \frac{\mu_{mi,nj} \left(\tau_{mni} P_{mi,t}\right)^{1-\varepsilon}}{\sum_{k,\ell} \mu_{k\ell,nj} \left(\tau_{knl} P_{k\ell,t}\right)^{1-\varepsilon}}. \qquad (3.10)$$

3.1.3. Equilibrium. An equilibrium in this economy is a set of sequences of goods and factor prices $\{P_{nj,t}, W_{nj,t}, R_{nj,t}\}_{t=0}^{\infty}$, factor allocations $\{K_{nj,t}, H_{nj,t}\}_{t=0}^{\infty}$, and goods allocations $\{Y_{nj,t}\}_{t=0}^{\infty}$, $\{\mathcal{F}_{mnj,t}, X_{mi,nj,t}\}_{t=0}^{\infty}$ for all countries and sectors such that (i) households maximize utility; (ii) firms maximize profits; and (iii) all markets clear. The following market clearing condition has to hold for each country n sector j:

$$P_{nj,t} Y_{nj,t} = \sum_m P_{m,t} \mathcal{F}_{m,t} \pi^f_{nmj,t} + \sum_m \sum_i (1-\eta_i) P_{mi,t} Y_{mi,t} \pi^x_{nj,mi,t}. \qquad (3.11)$$

Meanwhile, trade balance implies that each country's final expenditure equals the sum of value added across domestic sectors

$$P_{m,t} \mathcal{F}_{m,t} = \sum_i \eta_i P_{mi,t} Y_{mi,t}. \qquad (3.12)$$

Note that once we know the share of value added in production η_j, the expenditure shares $\pi^f_{nmj,t}$ and $\pi^x_{nj,mi,t}$ for all n, m, i, j, we can compute the nominal output $P_{nj,t} Y_{nj,t}$ for all country-sectors

14. Liao and Santacreu (2015) show that in the presence of profits, international input trade will synchronize TFPs across countries, as measured by the Solow residual. A model with profits affecting the measured Solow residual is observationally equivalent to a model with decreasing returns to scale (see, *e.g.* Ruzic and Ho, 2023, for a discussion). In related work (Huo *et al.*, 2023), we extend our framework to estimate returns to scale and find them to be quite close to constant. Thus, in this article, we abstract from the role of profits in GDP synchronization.

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(n, j) after choosing a numeraire good. There is no need to specify further details of the model, and we will utilize this property to derive the influence matrix.

3.2. *Impact response*

Under the maintained assumptions, our model has the property that the contemporaneous response of output to a worldwide vector of productivity shocks can be obtained by solving the set of intratemporal optimality and market clearing conditions. Furthermore, we can solve for the contemporaneous response of output to a productivity shock analytically to first order. The following proposition summarizes this discussion and states the analytical solution. Denote by "ln" the log-deviation from steady state/pre-shock equilibrium. Let the vectors $\ln \mathbf{Z}_t$, $\ln \mathbf{K}_t$, and $\ln \mathbf{Y}_t$ of length NJ collect the worldwide sectoral productivity, capital, and output log changes.

Proposition 3.1. *The response of worldwide output* $\ln \mathbf{Y}_t$ *to the global vector of supply shocks* $\ln \mathbf{Z}_t$ *and changes in capital* $\ln \mathbf{K}_t$ *is to a first order approximation given by*

$$\ln \mathbf{Y}_t = \mathbf{\Lambda} \left(\ln \mathbf{Z}_t + \boldsymbol{\eta} (\mathbf{I} - \boldsymbol{\alpha}) \ln \mathbf{K}_t \right), \tag{3.13}$$

where

$$\mathbf{\Lambda} = \left(\mathbf{I} - \frac{\psi}{1+\psi} \boldsymbol{\alpha} \boldsymbol{\eta} \left(\mathbf{I} + \left(\mathbf{I} - \mathbf{\Pi}^f \right) \mathcal{P} \right) - (\mathbf{I} - \boldsymbol{\eta}) \left(\mathbf{I} + \left(\mathbf{I} - \mathbf{\Pi}^x \right) \mathcal{P} \right) \right)^{-1}, \tag{3.14}$$

$\boldsymbol{\eta}$ and $\boldsymbol{\alpha}$ are matrices of output elasticities, $\mathbf{\Pi}^f$ and $\mathbf{\Pi}^x$ are matrices of the pre-shock final consumption and intermediate shares, respectively, and $\mathcal{P}$ is a matrix that combines both structural elasticities and pre-shock spending shares.[15]

Proof. See Supplementary Appendix B. □

Since the capital is predetermined at time t, equations (3.13)–(3.14) illustrate that all we need to understand the contemporaneous response of worldwide output $\ln \mathbf{Y}_t$ to various sector-country productivity shocks in this quantitative framework are measures of steady state final goods consumption and production shares, as well as model elasticities. The matrix $\mathbf{\Lambda}$ is the impact influence matrix. It encodes the contemporaneous general equilibrium response of output in every sector-country to shocks in every sector-country, taking into account the full model structure and all direct and indirect links between the countries and sectors.

The influence matrix (3.13)–(3.14) resembles the typical solution of a network model, that writes the equilibrium change in output as a product of the Leontief inverse and the vector of shocks. Our expression also features a vector of shocks, and an inverse of a matrix that is more complicated due to the multi-country structure of our model combined with elastic factor supply and non-unitary elasticities of substitution.

The proof proceeds by manipulating the equilibrium conditions of the model. To highlight the nature of general equilibrium effects captured by the influence matrix, linearize the market

15. The $NJ \times NJ$ diagonal matrices $\boldsymbol{\eta}$ and $\boldsymbol{\alpha}$ collect the η_j's and α_j's. A typical element of $\mathbf{\Pi}^f$ is π^f_{mnj} and a typical element of $\mathbf{\Pi}^x$ is $\pi^x_{mi,nj}$. All of the matrices in Proposition 3.1 are defined precisely in Supplementary Appendix B.

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clearing conditions (3.11) to obtain

$$\ln \mathbf{P}_t + \ln \mathbf{Y}_t = \underbrace{\left(\boldsymbol{\Psi}^f \boldsymbol{\Upsilon} + \boldsymbol{\Psi}^x\right)(\ln \mathbf{P}_t + \ln \mathbf{Y}_t)}_{\text{destination country output variation}} + \underbrace{(1-\rho)\left(\operatorname{diag}\left(\boldsymbol{\Psi}^f \mathbf{1}\right) - \boldsymbol{\Psi}^f \boldsymbol{\Pi}^c\right)\ln \mathbf{P}_t}_{\text{consumption goods relative price variation}} + \underbrace{(1-\varepsilon)\left(\operatorname{diag}\left(\boldsymbol{\Psi}^x \mathbf{1}\right) - \boldsymbol{\Psi}^x \boldsymbol{\Pi}^x\right)\ln \mathbf{P}_t}_{\text{intermediate goods relative price variation}} \tag{3.15}$$

where the vector $\ln \mathbf{P}_t$ collects sector-level log-deviations in prices, $\boldsymbol{\Psi}^x$ and $\boldsymbol{\Psi}^f$ are matrices containing the steady-state export shares of intermediate and final goods, $\boldsymbol{\Pi}^c$ is a matrix of final consumption share for the inner layer of CES, and $\boldsymbol{\Upsilon}$ is a matrix of value added shares.[16] The first term contains the response of nominal output that arises from output changes in every country and sector following a shock. The second term contains the relative price changes of final goods and the final term the relative price changes of intermediate inputs. Equation (3.15) implies that we can solve for the vector of country-sector price changes as a function of output changes and a matrix $\mathcal{P}$ that depends only on spending shares and structural elasticities:

$$\ln \mathbf{P}_t = \mathcal{P} \ln \mathbf{Y}_t. \tag{3.16}$$

The matrix $\mathcal{P}$ is then an input into the influence matrix. Combining (3.16) with linearized versions of the production function (3.7), labour market clearing, and the demand for intermediate goods leads to the model solution (3.13).

3.2.1. GDP change and shock transmission. Proposition 3.1 states the change in gross output, whereas GDP is value added. The following proposition describes the GDP changes.

Proposition 3.2. *The real GDP change in any country n is given by*

$$\ln G_{n,t} = \sum_{j=1} \omega_{nj} \left(\ln Z_{nj,t} + \alpha_j \eta_j \ln H_{nj,t} + (1-\alpha_j)\eta_j \ln K_{nj,t}\right), \tag{3.17}$$

where $\omega_{nj} \equiv \frac{P_{nj} Y_{nj}}{G_n}$ *is the steady-state Domar weight, and the global vector of changes in hours is given by:*

$$\ln \mathbf{H}_t \equiv \boldsymbol{\mathcal{H}}\left(\ln \mathbf{Z}_t + (\boldsymbol{\eta} - \boldsymbol{\alpha}\boldsymbol{\eta}) \ln \mathbf{K}_t\right), \quad \boldsymbol{\mathcal{H}} = \frac{\psi}{1+\psi}\left(\mathbf{I} + \left(\mathbf{I} - \boldsymbol{\Pi}^f\right)\boldsymbol{\mathcal{P}}\right)\boldsymbol{\Lambda}. \tag{3.18}$$

Proof. See Supplementary Appendix B. □

To construct GDP, we need to aggregate the changes of sector-country real value added, as in (2.1). The first term in equation (3.17) captures the impact of domestic TFP changes on GDP. Note that there is no direct dependence of country n's GDP on foreign TFP changes. The second term in (3.17) captures the changes in hours. Equation (3.18) underscores that hours in every country and sector depend on the entire vector of TFP changes worldwide.

16. A typical element of $\boldsymbol{\Psi}^f$ is $\frac{P_m \mathcal{F}_m v_j \pi^f_{nmj}}{P_{nj} Y_{nj}}$, a typical element of $\boldsymbol{\Psi}^x$ is $\frac{P_{mi} Y_{mi} \pi^x_{nj,mi}}{P_{nj} Y_{nj}}$, a typical element of $\boldsymbol{\Pi}^c$ is π^c_{mnj}, and a typical element of $\boldsymbol{\Upsilon}$ is $\frac{\eta_i P_{mi} Y_{mi}}{P_m \mathcal{F}_m}$. See the proof of Proposition 3.1 in Supplementary Appendix B for the detailed definitions.

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The international transmission mechanism in our model is thus the endogenous factor supply responses to foreign shocks. This is the main transmission mechanism in the international macro literature going back to its origins (*e.g.* Backus *et al*., 1992), that has been used to study shock transmission through production networks (*e.g.* Kose and Yi, 2006; Burstein *et al*., 2008; Johnson, 2014). Our contribution here is to provide a transparent analytical solution to a larger-scale international input network model, that enables a simple decomposition of the overall comovement into the transmission and shock correlation terms.[17]

Proposition 3.2 connects to the accounting decomposition (2.4) of comovement into shock correlation and transmission components. Mapping to the notation of Section 2, the contemporaneous GDP impact of a domestic TFP shock in sector j is equal to $s_{nnj,0} = \omega_{nj} + \sum_i \alpha_i \eta_i \omega_{ni} \mathcal{H}_{ni,nj}$, where $\mathcal{H}_{ni,nj}$ is the (ni, nj)th element of the hours influence matrix. The contemporaneous GDP impact of a shock to sector j in a foreign country m is given by $s_{mnj,0} = \sum_i \alpha_i \eta_i \omega_{ni} \mathcal{H}_{ni,mj}$. Thus, the direct effect of own TFP changes (the first term in (3.17)) plus the block-diagonal elements of $\mathcal{H}$ together make up $\mathcal{D}_n$—the influence of domestic shocks on GDP, and thus determine the shock correlation term. The off-diagonal elements of $\mathcal{H}$ capture the influence of foreign shocks on a country's GDP, and thus make up the transmission terms.

3.2.2. Intuition. To better understand the forces shaping the influence matrix, consider the following special case.

Corollary 3.3. *With unitary elasticities of substitution, the influence matrix for the impact response of hours is*

$$\begin{aligned}\mathcal{H} &= \frac{\psi}{1+\psi}\mathbf{\Pi}^f\left(\mathbf{I} - \frac{\psi}{1+\psi}\boldsymbol{\eta}\boldsymbol{\alpha}\mathbf{\Pi}^f - (\mathbf{I}-\boldsymbol{\eta})\mathbf{\Pi}^x\right)^{-1} \\ &= \frac{\psi}{1+\psi}\mathbf{\Pi}^f\sum_{k=0}^{\infty}\left(\frac{\psi}{1+\psi}\boldsymbol{\eta}\boldsymbol{\alpha}\mathbf{\Pi}^f + (\mathbf{I}-\boldsymbol{\eta})\mathbf{\Pi}^x\right)^k, \end{aligned} \tag{3.19}$$

and thus all the elements of $\mathcal{H}$ are non-negative.

Proof. See Supplementary Appendix B. □

According to (3.19), the response of hours $\mathcal{H}$ can be built directly using the observed expenditure shares. Importantly, since all the elements in the final goods and intermediate input expenditure shares are non-negative, it follows that all the elements in $\mathcal{H}$ are positive. Combined with Proposition 3.2, this implies that under unitary elasticities the transmission terms are positive: a country's GDP increases following a positive foreign shock. Relatedly, if countries use foreign goods more intensively ($\mathbf{\Pi}^f$ or $\mathbf{\Pi}^x$ contain larger off-diagonal elements), the off-diagonal elements of $\mathcal{H}$ become larger and the international transmission channels more potent. Finally, this special case makes it transparent that a higher Frisch elasticity amplifies the off-diagonal elements in $\mathcal{H}$, resulting in greater international transmission.

17. Proposition 3.2 highlights the difference between our analytical results and the contemporaneous work by Baqaee and Farhi (2024) that considers the case of exogenous factor supplies. Proposition 3.2 under the assumption that $\ln H_{nj,t}$ and $\ln K_{nj,t}$ are exogenous is essentially Theorem 1 in that paper (and the earlier result in Kehoe and Ruhl, 2008). By contrast, we obtain an analytical solution when factor supplies are endogenous to shocks, and show that in this case a country's real GDP does respond to foreign shocks. Obviously, this property is essential to make the analysis of international shock transmission non-trivial. When factor supply is exogenous as in Baqaee and Farhi (2024), international shock transmission to real GDP is ruled out by construction, and the entirety of international GDP comovement is trivially accounted for by shock correlation.

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The second line of equation (3.19) writes the hours response as an infinite summation of the share matrices, reflecting first-, second-, etc. round effects propagating via relative price changes through the input and factor markets. This infinite propagation reflects the general-equilibrium (GE) forces, through which each sector's hours are generically a function of the entire global vector of productivity shocks. The term $\frac{\psi}{1+\psi}\boldsymbol{\eta}\boldsymbol{\alpha}\boldsymbol{\Pi}^{f}$ captures the GE multiplier due to the endogenous labour response, and the term $(\mathbf{I}-\boldsymbol{\eta})\boldsymbol{\Pi}^{x}$ captures the GE multiplier due to the adjustments of material inputs.[18]

3.2.3. Static network models. An active literature, initiated by Carvalho (2010) and Acemoglu *et al.* (2012), explores shock propagation in static production network models. It turns out that the contemporaneous output and GDP response to shocks in our fully dynamic model coincides with the response of a static network economy to the same shock.[19] This claim follows immediately from the proof of Proposition 3.1. The influence matrix $\boldsymbol{\Lambda}$ is obtained solely from the intratemporal optimality and market clearing conditions (3.6), (3.8)–(3.9), and (3.11)–(3.12) and thus requires no forward-looking equations or expectations. Thus, to understand today's response of output to today's shock, we do not need to take a stand on the future evolution of the economy following this shock, or evaluate agents' expectations over the future variables. The later periods' GDP response to today's shock will depend on the properties of the stochastic process for shocks and the capital accumulation decisions, which are not encoded in $\boldsymbol{\Lambda}$ (but can be evaluated numerically).

Our analysis thus integrates the static network propagation literature that follows Acemoglu *et al.* (2012) and the dynamic international business cycle literature. We can cleanly separate the instantaneous propagation analysed in the former and the delayed responses to shocks emphasized by the latter. We will use this property in the analysis below. First, implementing the dynamic model requires observing a long time series of shocks, as we need to estimate the shock process in order to give it to the agents to form expectations. On the other hand, the static model does not require us to estimate the shock process, and so it can be implemented on any length time series. We only have long time series for a small number of countries, but data for 1995–2007 are available for 29 countries. Thus, in addition to reporting the dynamic model results for a small set of countries, we will also report the results under the static network model for a large sample of countries. For the subset of countries for which both the dynamic and static models can be implemented, they deliver very similar results, lending credibility to the static network model.

Second, we can compute the exact nonlinear static model solution using the Dekle *et al.* (2008) exact hat algebra and evaluate the quality of the first-order approximation deployed throughout the article. Supplementary Appendix B.3 presents the details of the exact solution,

18. The general versions of these terms are $\frac{\psi}{1+\psi}\boldsymbol{\alpha}\boldsymbol{\eta}(\mathbf{I}+(\mathbf{I}-\boldsymbol{\Pi}^{f})\mathcal{P})$ and $(\mathbf{I}-\boldsymbol{\eta})(\mathbf{I}+(\mathbf{I}-\boldsymbol{\Pi}^{x})\mathcal{P})$, respectively.

19. This statement is of course holding fixed the vector of capital stocks and all the expenditure shares that enter the influence matrix. The static network model is characterized by the equations in Section 3.1, with (3.1) replaced by static optimization $\max_{C_{n,t},\{H_{nj,t}\}} \mathcal{U}\left(C_{n,t}-\sum_{j} H_{nj,t}^{1+\frac{1}{\psi}}\right)$, setting $I_{nj,t}=0$ in (3.2) with $K_{nj,t}$ exogenously given, and dropping the capital accumulation equation (3.3). While the impact response of GDP and sectoral output coincide in the two models, trivially the responses of consumption and investment do not, as in the dynamic model the agents split final output into consumption and investment, whereas in the static model all final output is consumed.

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and compares the GDP growth rates implied by the two approaches. The exact and first-order approximation solutions are very close to each other, as shown by Supplementary Figure A3.[20]

3.3. *Dynamics*

With endogenous capital accumulation, the current output in a location not only depends on current global shocks but also the past global shocks. The following proposition states the general form of this type of dependence.

Proposition 3.4. *When the vector of supply shocks follows a first-order auto-regressive process, the equilibrium law of motion of capital obeys*

$$\ln \mathbf{K}_{t+1} = (\mathbf{I} - \mathbf{M}\,\mathbb{L})^{-1}\mathbf{\Gamma} \ln \mathbf{Z}_t,$$

where $\mathbb{L}$ *is the lag operator, and the matrices* $\mathbf{M}$ *and* $\mathbf{\Gamma}$ *depend on steady-state shares, elasticities of substitution, the discount factor, and the depreciation rates, and* $\mathbf{\Gamma}$ *also depends on the shock processes.*

Proof. See Supplementary Appendix B. □

Propositions 3.1 and 3.4 imply that the entire history of global shocks matters for the current GDP and therefore international comovement. However, the impact of past shocks will fade away compared with the contemporaneous ones. In Section 4, we will quantify the contribution of this dynamic effect. In addition, the parsimonious structure discussed in Proposition 3.1 largely extends to the dynamic setting. There is no need to specify additional model details other than the depreciation rates, the discount factor, and the processes for the productivity shocks.

To further build intuition, we consider a special case where capital accumulation is subject to full depreciation ($\delta_j = 1\ \forall j$). In this case, the economy features constant saving rates with respect to the country's total income, which is a generalization of the textbook growth model result to an international economy with trade. The resulting dynamics of GDP changes can be summarized as follows.

Proposition 3.5. *When* $\delta_j = 1$, $\alpha_j = \alpha$, *and* $U(\cdot) = \ln(\cdot)$, *the GDP changes are given by*

$$\ln G_{n,t} = \sum_j \omega_{nj} \Bigg(\ln Z_{nj,t} + (1-\alpha_j)\eta_j \ln G_{n,t-1} + \alpha_j \eta_j \sum_{m,i} \mathcal{H}_{nj,mi} \left(\ln Z_{mi,t} + \eta_i (1-\alpha_i) \ln G_{m,t-1} \right) \Bigg).$$

Proof. See Supplementary Appendix B. □

The first two terms in the parentheses are the GDP responses to a country's own TFP shock and to their own past GDP changes. The term involving $\ln G_{n,t-1}$ simply captures the direct dependence of today's capital stock on last period's domestic capital decisions. The last term encodes the transmission of current and past shocks in other countries to country n's GDP. This system of N equations depicts the entire dynamics of global GDP changes.

20. Supplementary Appendix B.3 also explores the difference between the exact and linearized models for varying shock sizes and shock correlations, and illustrates that in the quantitatively relevant range of shocks, the linear approximation is a very good fit.

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With partial depreciation, the GDP dynamics are more involved and we explore their quantitative properties in the next section.

4. QUANTIFICATION

This section quantifies the dynamic global network model laid out in the previous section to explore the nature of international GDP comovement.

4.1. *Data and calibration*

To quantify the model, we require data on the (i) growth of real value added and hours worked for a panel of countries, sectors, and years and (ii) global input-output linkages. The dataset with the broadest coverage for real value added is KLEMS 2009 (O'Mahony and Timmer, 2009).[21] It contains gross output, value added, labour and capital inputs, as well as output and input deflators. The database covers all sectors of the economy at a level slightly more aggregated than the 2-digit ISIC revision 3, yielding, after harmonization, 30 sectors listed in Supplementary Appendix Table A1. In a limited number of instances, we supplemented KLEMS with data from the WIOD Socioeconomic Accounts, which contains similar variables. The core of the analysis is carried out on the G7 countries for which we have a balanced panel over 1978–2007, and an aggregate of other countries into a "rest of the world." Sections 4.2 and 5.1 utilize a broader sample of 29 economies, for which data are available from the mid-1990s. Supplementary Appendix Table A2 lists the countries.

Constructing the influence matrix (3.14) requires expenditure and sales shares $\mathbf{\Pi}^f$, $\mathbf{\Pi}^x$, $\mathbf{\Psi}^f$, and $\mathbf{\Psi}^x$, Cobb–Douglas shares α_j and η_j, and three elasticities: the two substitution elasticities ρ and ε, and the labour supply elasticity ψ. The data on input linkages at the country-sector-pair level, as well as on final goods trade come from the 2013 WIOD database (Timmer *et al.*, 2015), which contains the global input–output matrix. The expenditure and sales shares $\mathbf{\Pi}^f$, $\mathbf{\Pi}^x$, and $\mathbf{\Psi}^f$ can be computed directly from WIOD. Capital shares in total output α_j and value added shares in gross output η_j come from KLEMS. We time-average the expenditure and sales share matrices, and average α_j and η_j in each sector across countries and time to reduce noise. The model period is a year. We set the discount rate to $\beta = 0.96$, and the depreciation rates δ_j are set to match sector-specific depreciation rates obtained from the BEA for 2001.[22] The period utility is $U(\cdot) = \ln(\cdot)$.

4.2. *Elasticity estimation*

The elasticities ρ, ε, and ψ are estimated structurally by fitting model-implied relationships to data on expenditure shares, prices, and hours worked. This section summarizes the procedures briefly. Supplementary Appendix C contains the detailed discussion.

To estimate ρ and ε, we log-difference the CES expenditure shares (3.5) and (3.10) with respect to $t-1$ and a reference country m'. This yields the following relationships between

21. This is not the latest vintage of KLEMS, as there is a version released in 2016. Unfortunately, the 2016 version has a shorter available time series, as the data start in 1995 and also has many fewer countries. A consistent concordance between the two vintages is not feasible without substantial aggregation.

22. The BEA provides depreciation rates for 1995–2007 that can be mapped to NAICS codes. We concord these to the sectors in the WIOD. As the depreciation rates are relatively stable over time, we use the depreciation rates of 2001.

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shares and prices:

$$\ln\left(\frac{\widehat{\pi}^{f}_{mnj,t}}{\widehat{\pi}^{f}_{m'nj,t}}\right) = (1-\rho)\ln\left(\frac{\widehat{P}_{mj,t}}{\widehat{P}_{m'j,t}}\right) + \ln\left(\frac{\widehat{\vartheta}_{mnj,t}\widehat{\tau}^{1-\rho}_{mnj,t}}{\widehat{\vartheta}_{m'nj,t}\widehat{\tau}^{1-\rho}_{m'nj,t}}\right)$$

and

$$\ln\left(\frac{\widehat{\pi}^{x}_{mj,ni,t}}{\widehat{\pi}^{x}_{m'j,ni,t}}\right) = (1-\varepsilon)\ln\left(\frac{\widehat{P}_{mj,t}}{\widehat{P}_{m'j,t}}\right) + \ln\left(\frac{\widehat{\mu}_{mj,ni,t}\widehat{\tau}^{1-\varepsilon}_{mnj,t}}{\widehat{\mu}_{m'j,ni,t}\widehat{\tau}^{1-\varepsilon}_{m'nj,t}}\right),$$

where the "hat" refers to the *gross* proportional change in any variable between time t and $t-1$. The structural error term is then the stochastic component of iceberg trade costs, final consumer taste shocks, and input share shocks, as well as any measurement error.

As the expenditure share changes $\widehat{\pi}$ are relative to a reference country m', the estimation amounts to regressing double-differenced expenditure share changes on relative price changes. A threat to identification would be that relative source country price changes are affected by destination country demand shocks (*e.g.* $\widehat{\vartheta}_{mnjt}$), and thus correlated with the residual. We address endogeneity in three ways. First, we include source-destination-reference country-time ($n \times m \times m' \times t$) fixed effects, which absorb many confounders including any common components occurring at the country 3-tuple-time level, such as exchange rate changes and other taste and transport cost changes. Thus, the coefficient is estimated from the variation in the relative sectoral price indices and relative sectoral share movements within that cell. Second, our estimates are based on the subsample in which destination countries are all non-G7, and the source and reference countries are all G7 countries. Therefore, it is unlikely that taste shocks in the (smaller) destination countries will affect relative price changes in the larger G7 source countries. Third, we use foreign Solow residual shocks as instruments for changes in relative prices. The exclusion restriction is that the Solow technology shocks in source countries are uncorrelated with taste and trade cost shocks in the destination countries in the relevant sample and conditional on the fixed effects.[23]

Our preferred estimates are $\rho = 1.43$ and $\varepsilon = 0.89$. These values for annual frequency elasticities are sensible in light of existing estimates (Atalay, 2017; Boehm *et al.*, 2019, 2023). Supplementary Appendix Table A4 contains the full battery of results, including extensive robustness checks, discussed in the text in Supplementary Appendix C.1.

To estimate ψ, we use the responses of labour hours to shocks in a theory-consistent way. The starting point are the responses of hours to productivity shocks given by Proposition 3.2. However, because the Proposition states the general-equilibrium relationship, the vector of shocks $\ln \mathbf{Z}_t$ act as both labour demand shifters through their effect on $\ln \mathbf{Y}_t$, but also as labour supply and demand shifters through their effects on equilibrium final goods prices $\mathbf{\Pi}^{f} \ln \mathbf{P}_t$ and firm intermediate goods prices $\ln \mathbf{P}_t$. This is a threat to identification, as estimating the labour supply elasticity ψ requires isolating shocks that shift the labour demand curve but hold the labour supply curve approximately constant. An additional threat to identification is other shocks to labour supply. As a result, as is well known in the literature estimating the Frisch elasticity, we cannot simply estimate ψ by regressing hours on either observed or model-implied wages. In fact, if TFP shocks in some sectors increase using sector labour demand and also decrease the

23. Huo *et al.* (2023) find that the Solow residual is virtually uncorrelated across countries. Note that the Solow residual is not the same as the composite shock $\ln \mathbf{Z}_t$ in our model. As discussed above, the composite shock will include true TFP shocks as well as shocks to factor supply.

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TABLE 1
Parameter values

Param.	Value	Source	Related to
ρ	1.43	Supplementary Appendix C.1	Final substitution elasticity
ε	0.89	Supplementary Appendix C.1	Intermediate substitution elasticity
ψ	0.72	Supplementary Appendix C.2	Frisch elasticity
β	0.96	Standard	Discount rate
δ_j	[0.07, 0.13]	BEA	Depreciation rates
α_j	[0.40, 0.79]	KLEMS	Labour and capital shares
η_j	[0.31, 0.67]	KLEMS	Intermediate input shares
ν_{nj}	–	WIOD	Final use sectoral expenditure shares
π^f_{mnj}	–	WIOD	Final use trade shares
$\pi^x_{mi,nj}$	–	WIOD	Intermediate use trade shares

Notes: This table summarizes the parameters and data targets used in the quantitative model, and their sources. For α_j, δ_j, and η_j, the table reports the 10th and 90th percentiles of the range of these parameters.

final goods price index for consumers, thereby decreasing labour supply, we would expect the estimate of ψ from regressing hours growth on wage changes to be biased towards zero.

To address this issue, we use a plausibly exogenous set of $\ln \mathbf{Z}_t$ shocks, that are likely to shift sectoral labour demand but not sectoral labour supply, and use them to estimate the labour supply elasticity. The procedure, detailed in Supplementary Appendix C.2, is broadly based on Shea (1993a, 1993b). Briefly, a shock to (m, i) is assumed to be a plausibly exogenous shifter for the labour demand in (n, j) if (m, i) is an important intermediate input ($\pi^x_{mi,nj}$ is large), but not an important final consumption good (π^f_{mnj} is small). The model-consistent estimation of ψ is conditional on the parameters ρ and ε estimated above. Further, because $\mathbf{\Lambda}$ is a function of ψ, the estimating equation is nonlinear, and so we utilize nonlinear least squares. Our baseline estimate of ψ is 0.72, close to the value of 0.75 recommended by Chetty *et al.* (2011) for use in macro models.

Table 1 summarizes the baseline parameters for the network model and data sources. Section 4.6 performs a systematic sensitivity analysis with respect to the values of ρ, ε and ψ. These are the key source of uncertainty in the quantification; the other model inputs, such as expenditure shares and production function parameters, are directly available in the data. Our estimation procedure yields the joint distribution of ρ, ε and ψ. In other words, we do not treat the uncertainty over these three parameters as independent. We instead estimate the joint likelihood of the different combinations of these three parameters.

4.3. *Recovering shocks*

The core quantification exercise of the article is a decomposition (2.4) of the overall GDP correlation into the shock correlation and transmission terms. The exercise is at its most informative when the model can replicate the observed GDP correlations. Thus, we invert the model to recover the global vector of supply shocks $Z_{nj,t}$ in such a way as to match actual value added growth in every country and sector (and therefore actual GDP growth in every country).

Let the vector $\ln \mathbf{V}_t$ of length NJ collect sectoral value added in log deviations from steady state. Similar to Proposition 3.2, sectoral value added can also be expressed as a function of shocks and changes in primary inputs (derivation in Supplementary Appendix B):

$$\begin{aligned}\ln \mathbf{V}_t &= \ln \mathbf{Z}_t + \boldsymbol{\alpha}\boldsymbol{\eta} \ln \mathbf{H}_t + (\mathbf{I} - \boldsymbol{\alpha})\boldsymbol{\eta} \ln \mathbf{K}_t \\ &= (\mathbf{I} + \boldsymbol{\alpha}\boldsymbol{\eta}\boldsymbol{\mathcal{H}}) \ln \mathbf{Z}_t + (\mathbf{I} + \boldsymbol{\alpha}\boldsymbol{\eta}\boldsymbol{\mathcal{H}})(\mathbf{I} - \boldsymbol{\alpha})\boldsymbol{\eta}(\mathbf{I} - \mathbf{M}\mathbb{L})^{-1}\mathbf{\Gamma} \ln \mathbf{Z}_{t-1}. \end{aligned} \tag{4.1}$$

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Thus, the structure of the model world economy and the observed/measured objects can be used to recover the history of the global vector of supply shocks $\{\ln \mathbf{Z}_{t-\tau}\}_{\tau=0}^{\infty}$ that rationalizes the observed real value added growth rates in each country-sector and year. Note that the interdependence between country-sectors through input linkages implies that the entire global vector $\{\ln \mathbf{Z}_{t-\tau}\}_{\tau=0}^{\infty}$ must be solved for jointly.

With fixed exogenous capital, as in a static network model, the procedure would be especially simple: (4.1) is inverted to get $\ln \mathbf{Z}_t = (\mathbf{I} + \boldsymbol{\alpha}\boldsymbol{\eta}\boldsymbol{\mathcal{H}})^{-1} \ln \mathbf{V}_t$.[24] The presence of endogenous capital accumulation makes this procedure more challenging as the matrices $\mathbf{M}$ and $\boldsymbol{\Gamma}$ depend on the shock processes. However, the shock processes can only be estimated when the shock realizations are available. Therefore, recovering the shocks requires finding a fixed point.

To proceed, we assume that the country-sector shocks follow a vector autoregressive process. Due to the large number of countries and sectors, it is not feasible to estimate a fully unrestricted VAR. We therefore impose parsimonious functional forms on the shock processes:

$$\ln Z_{nj,t} = \rho_{nj} \ln Z_{nj,t-1} + \zeta_n \mathbf{1}\,(m = n, k \neq j) \ln Z_{mk,t-1} + \theta_{nj,t}. \tag{4.2}$$

These processes allow for own autocorrelation and within-country lagged spillovers of sectoral shocks. In addition, innovations $\theta_{nj,t}$ can have an arbitrary contemporaneous cross-border and cross-sector covariance structure. On the other hand, (4.2) does not allow for lagged cross-border spillovers.

Computationally, we adopt an iterative procedure. We start with a guess for the shock process, which allows us to compute the implied shock series. We then estimate the VAR processes (4.2), which leads to updated shock processes. We iterate these two steps to convergence. The procedure ensures that the perceived laws of motion are consistent with the actual ones.[25] The result is consistent with rational expectations, which imposes the cross-equation restriction that perceived shock processes need to coincide with actual shock processes.

At a formal level, the only shock in this world economy is the TFP shock $Z_{nj,t}$. From the perspective of this shock recovery procedure and the quantification that follows, $Z_{nj,t}$ should be interpreted broadly as a composite supply shock, encompassing both technology and primary factors. In the model, labour supply is upward-sloping in real wages, but shifts in the labour supply curve are isomorphic to TFP shocks in their effect on the global vector of output changes, up to a scaling factor. The dynamic model predicts a change in the next period's capital stock as a function of the history of shocks. If in the data, part of the reason for a high value added in the next period is a higher capital stock than what is implied by the model, the shock inversion will attribute this to a higher TFP. (Note that this procedure targets value added, not the capital stock series.) Thus, inverting the global influence matrix recovers a composite supply shock, which is sufficient to answer the main question posed in this section. Section 5.2 formally separates technology, labour supply, and capital supply shocks.

4.4. *Impulse responses*

We start with a "test drive" of the propagation mechanism by computing the world economy's response to some simple hypothetical shocks (i) a 1% U.S. shock in all sectors; and (ii) a 1%

24. We verify this matrix is invertible in our data.

25. Further details of the estimation are in Supplementary Appendix C.3. Supplementary Appendix Table A5 summarizes the estimated shock processes. We have also experimented with shock processes that include lagged within-sector cross-border spillovers, and the quantitative results remain similar. We make the assumption that the shocks before the first available observation of value added are zero.

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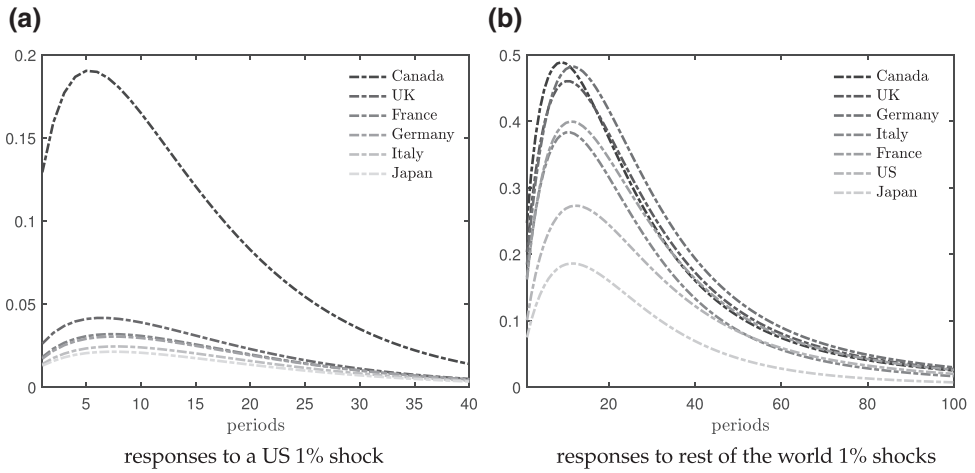


FIGURE 1
Impulse responses to U.S. and rest-of-world shocks

Notes: (a) displays the change in log real GDP of every other country in the sample when the United States experiences a supply shock of 0.01 in every sector. (b) displays the change in log real GDP of every country in the sample when the rest of the world excluding the country experiences a supply shock of 0.01 in every sector.

rest-of-the-world shock in all sectors from the perspective of each country. The rest-of-the-world exercise assumes that the country in question is not shocked, but all other possible countries and sectors are, and thus has to be conducted country by country.

The left panel of Figure 1 displays the change in real GDP in every other country in the world following a 1% U.S. shock in each sector. The results show that the observed trade linkages do result in transmission. The smaller economy with the largest trade linkages to the U.S.—Canada—is most strongly affected by the U.S. shocks. The mean response of foreign GDP at the peak is 0.05%, and the maximum response—Canada—is about 0.16%.

Next, we simulate the real GDP responses of each country n in the sample when all other countries (excluding n) experience a 1% technology shock. This exercise answers the question, if there is a 1% world shock outside of the country, how much of that shock will manifest itself in the country's GDP? The right panel of Figure 1 displays the results. In response to a 1% outside world shock, the mean country's GDP increases by 0.34% at the peak, with the impact ranging from around 0.16% in Japan to around 0.43% in Canada. Not surprisingly, smaller and more open countries are more affected by shocks in their trade partners. All in all, these exercises suggest that outside world shocks have a significant impact on most countries.

4.5. *Decomposing GDP correlations*

Table 2 implements the decomposition (2.4) of the overall GDP comovement into the shock correlation and transmission terms, using the shocks recovered in Section 4.3 to match the observed value added growth. The core sample of countries is the G7 over the period 1978–2007. These countries have sufficiently long time series data in KLEMS so that the dynamic model can be implemented. The first row reports the GDP growth correlations in the data, the second row in the model.[26] The rest of the table reports the results of the decomposition (2.4). The correlation

26. Our procedure matches the sectoral value added growth rates in the data. The small discrepancy in GDP correlations between the data and the model is due to the fact that the model Domar weights are slightly different from the data. This is because in the model we must ensure trade balance, whereas in the data trade is unbalanced. The

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TABLE 2
Correlated shocks versus transmission decomposition: G7 countries

	Mean	Median	25th pctile (N. obs. = 21)	75th pctile
Data	0.358	0.333	0.122	0.552
Dynamic model	0.350	0.356	0.124	0.558
Decomposition in simulated model				
Shock correlation	0.290	0.303	0.097	0.467
Bilateral transmission	0.014	0.013	0.007	0.015
Multilateral transmission	0.045	0.044	0.026	0.067

Notes: This table presents the decomposition of the GDP correlations into the shock correlation, the direct transmission, and the multilateral transmission terms as in equation (2.4).

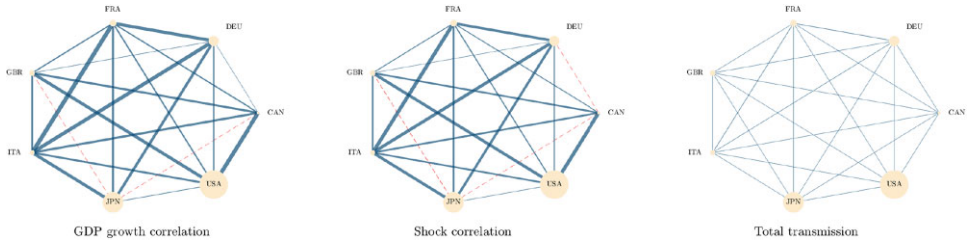


FIGURE 2
Total correlation, shock correlation, and transmission, G7 countries

Notes: This figure displays the network of GDP correlations (far left), decomposing it into the shock correlation (middle) and transmission (far right) components. Thicker lines denote higher values. Solid (blue) displays positive values, dashed (red) negative values. Larger nodes (countries) displayed with bigger dots.

of shocks is responsible for over four-fifths of the total comovement. Nonetheless, the bilateral and multilateral transmission terms have a non-negligible contribution to the overall correlation, accounting for the remaining one-fifth.

Figure 2 displays the heterogeneity in the correlation and transmission terms in a network graph for the G7 countries. The left panel depicts all the bilateral correlations among those countries, with thicker lines denoting larger values, and blue (resp. red) depicting positive (resp. negative) correlations. The middle panel displays the same for the shock correlation component, and the left panel the combined transmission. The scale (thickness of the lines) is the same in all three panels. It is clear that the differences in the shock correlation component are responsible for both the bulk of the overall correlation, as well as the variation across countries. For instance, none of the transmission components are negative, and thus all the negative actual correlations are due to the negative correlations of the shocks.

4.5.1. Influence matrix and shock correlation. The top panel of Figure 3 displays two heat maps. In each, both rows and columns are broken into country-sectors, though due to space constraints sectors are too numerous to be labelled. In the top left is the influence matrix.

discrepancy introduced by this divergence between the model and the data is small (see also Supplementary Figure A7). Note we assume constant Domar weights in these aggregations. Bonadio *et al.* (2023) study the role of changing Domar weights over time. Throughout the quantitative analysis, we report correlations of growth rates. Supplementary Appendix Table A6 shows that the properties of GDP growth rates to HP-filtered series for the G7 countries are quite similar.

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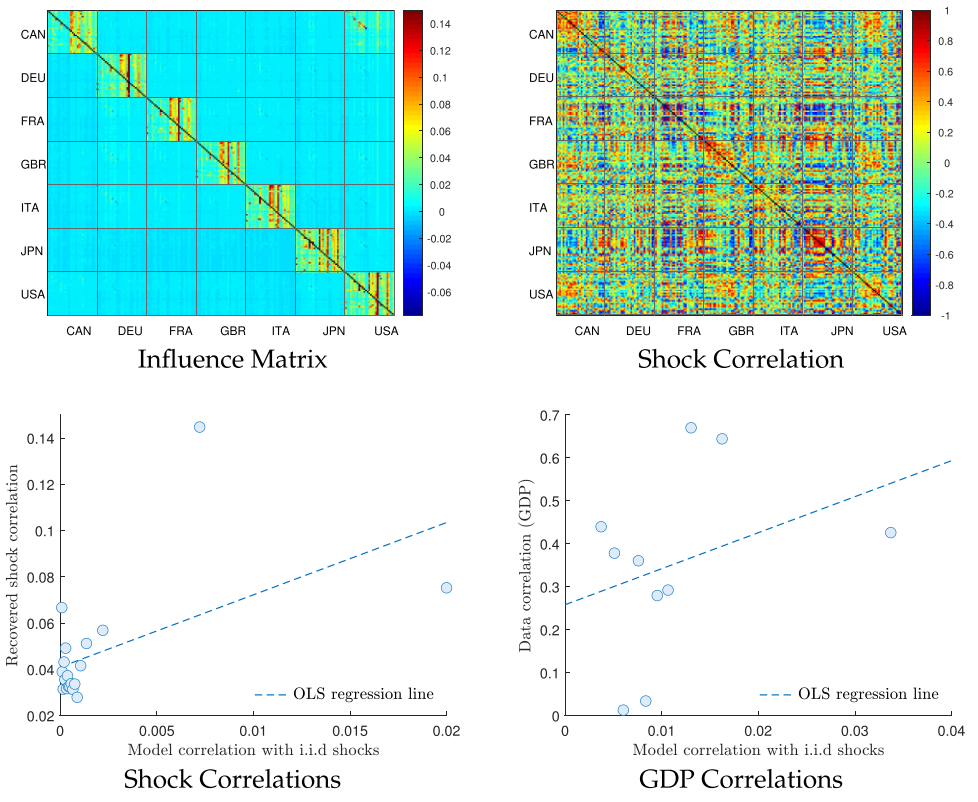


FIGURE 3

Input, influence, and correlation heat maps, G7

Notes: This figure displays the heat maps of the influence matrix (top left), the bilateral shock correlations (top right), the binscatter of the sector-pair correlations in the inferred shocks for 1978–2007 (y-axis) against correlations in value added in the model with i.i.d. shocks (x-axis) (bottom left), and the binscatter of the GDP correlations in the data (y-axis) against GDP correlations between country pairs in the model with i.i.d. shocks (x-axis) for the G7 countries (bottom right).

It shares some clear similarities with the raw input–output and final shares matrices (Supplementary Appendix Figure A2). Specifically, the largest positive entries tend to be domestic, and there are clear relationships between close trading partners like Canada and the U.S. (upper right corner). However, there is one important difference: entries of the influence matrix are sometimes negative. Visible negative values in this heatmap are darker blue lines running parallel to the diagonal. These correspond to the same industries in different countries: in our influence matrix, a positive supply shock to foreign producers in the same industry tends to have a negative impact on sectoral output. This is in spite of the fact that often, the input shares in those sectors are also relatively high (the lines parallel to the diagonal are also evident in the input–output heat map). This discussion illustrates that the influence matrix conveys information distinct from the IO matrix itself.

The top right panel depicts the heat map of shock correlations. There is little if any similarity between this panel and the influence heat map. Visually, it does not even appear to be the case that within-country shock correlations are that much higher than the cross-country ones. As the overall GDP correlation is built from the shock correlation and the influence matrices, these two panels convey the sources of variation in these two components and the relative importance of the two. In particular, whereas the off-block-diagonal (cross-country) elements of the influence

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matrix by and large are both small and display limited variation, there is a great deal of variation in the cross-border shock correlation.

In order to better understand where and why the shock recovery procedure assigns correlated shocks, the bottom left panel of Figure 3 displays a binscatter of the the correlation of inferred shocks at the sector level against the sectoral value added correlations that arise when the model is subjected to i.i.d. shocks. The model with i.i.d. shocks produces correlation purely through transmission, as the shock correlation term is zero by construction. There is if anything a mildly positive relationship: the procedure assigns more positively correlated shocks in places where the model also generates the most transmission. However, the relationship is weak and driven mostly by the upper tail. Aggregating up to GDP, the bottom right panel displays a binscatter of the GDP correlations in the data on the y-axis against GDP correlations in the model subjected to i.i.d. shocks. According to Corollary 3.3, when the elasticities of substitution are around unity, the GDP correlation predicted by the model is positive. With our calibrated parameters, the implied relationship is also positive, but the model with i.i.d shocks does not generate the level of correlations observed in the data. Thus, the shock recovery procedure assigns a positive correlation to shocks because the internal propagation mechanisms are not sufficiently powerful to generate the observed levels of comovement. At the same time, the propagation mechanisms in the model go in the right direction in predicting comovement in the cross-section of sectors and countries. Thus, it is not the case that the assignment of shock correlations has to "compensate" for the wrong predictions of the model regarding where higher and lower correlations should be.

4.5.2. Contemporaneous versus delayed propagation. We next explore the quantitative importance of the intertemporal propagation relative to the contemporaneous response for international comovement. As emphasized in Section 2, in the dynamic model the GDP growth rate can be expressed as a function of current and past shocks (equation (2.2)). Thus, the total GDP correlation is the weighted sum of the correlations of the responses to shocks at different horizons (equation (2.6)).

The solid line in Figure 4(a) plots $\varrho_{nm,k}\omega_{nm,k}$ across horizons k, averaging over country pairs. The correlation of contemporaneous responses corresponds to $k = 0$. It turns out that the contemporaneous component is dominant, accounting for over 95% of the total correlation. That is, adding dynamics does not substantially raise the GDP correlations.[27]

The model features rich intertemporal propagation patterns, as evidenced by Figure 1. The small contribution of dynamics to overall comovement is mainly due to the fact that the timing of the response to the same shock is not sufficiently similar across countries to induce substantial delayed correlation. To illustrate this pattern, Figure 4(b) compares the response of U.S. GDP to its own and rest-of-the-world shocks. While the country responds positively and persistently to positive foreign shocks, both the shape and the magnitude of the responses are different. The response to its own shock is high on impact, and gradually dies out. In contrast, the response to other countries' shocks continues to build slowly and peaks after over twenty periods. In addition, the response to a country's own shock is far larger than the response to other countries' shocks, both on impact and at most horizons.

27. The overall correlation in Figure 4 is somewhat lower than the correlation reported in Table 2. To implement the decomposition (2.2), we must use the shock processes (4.2) and the analytical model solution rather than sequences of shock realizations over 1978–2007 as we do in Table 2. It turns out that the finite sample correlation over 1978–2007 is somewhat higher than the long-run correlation implied by the estimated shock processes.

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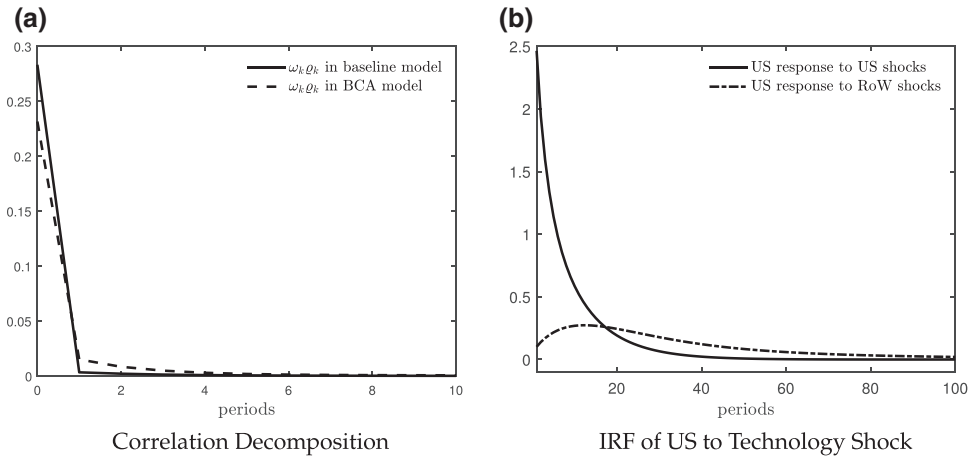


FIGURE 4
Dynamic correlation decomposition

Notes: (a) displays the elements of the dynamic decomposition of the overall correlation into the components accounted for by elements at horizon k, as in equation (2.6). The solid line displays the results for the baseline model in Section 4.5. The dashed line displays the results for the business cycle accounting model in Section 5.2. (b) displays the impulse responses of U.S. GDP following 1% shocks in all sectors in U.S. (solid line), and following 1% shocks in the rest of the world excluding the U.S. (dashed line).

One reason why the model delivers so little delayed propagation is that the composite shocks $\ln Z_{nj,t}$ are not intertemporal. Looking ahead, Section 5.2 implements a business cycle accounting exercise with four shocks, one of which is intertemporal, acting on next period's capital. The dashed line in Figure 4 plots the dynamic decomposition in that model. Indeed, the role of delayed propagation in comovement is visibly greater in the presence of an intertemporal shock. However, it is still the case that the large majority of the total comovement comes from the impact responses.

4.5.3. The sectoral dimension. Supplementary Appendix D.2 implements a decomposition similar to Section 2 at the sector level to complement this analysis and assess whether any sectors are especially influential in overall comovement. It turns out that services sectors such as real estate and wholesale trade sectors are the most prominent ones in contributing to comovement. Supplementary Appendix D.3 fits some factor models to examine whether the recovered shocks exhibit a strong factor structure. While country and sector components are detectable in the panel of shocks, most of the variation is idiosyncratic.

4.6. *Understanding model mechanisms*

The analytical solution (3.13)–(3.14) makes it transparent that model quantification requires two sets of objects: (i) the input network (final and intermediate expenditure shares) and (ii) elasticities (of labour supply and substitution). To better understand the headline result, we perform exercises that highlight the roles of each of these.

4.6.1. The role of elasticities. The model requires three elasticities: the Frisch elasticity of labour supply ψ, and substitution elasticities between inputs ε and final goods ρ. These elasticities govern the strength of the economy's response to foreign shocks, and therefore the extent of international shock transmission.

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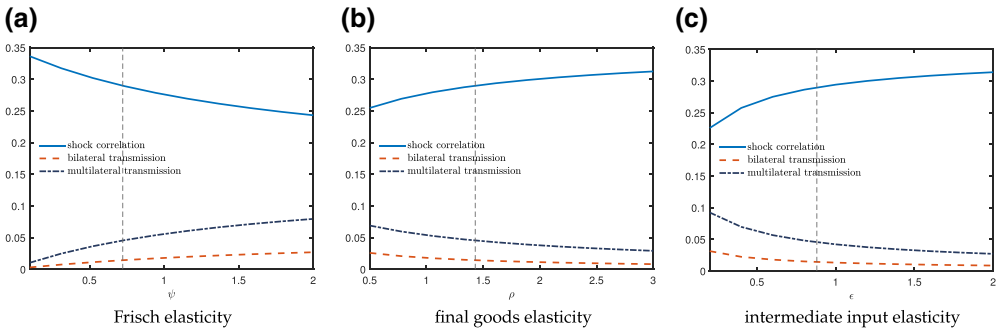


FIGURE 5
Correlated shocks and transmission, alternative elasticities

Notes: This figure displays the average contributions of correlated shocks and transmission in alternative calibrations of the baseline model. For each alternative parameter combination, we re-recover the shocks to match the observed sectoral value added. The vertical dashed line is the baseline calibrated value of that parameter. Panel (a), (b), and (c) vary ψ, ρ, and ϵ, respectively.

Intuitively, how much the domestic economy responds to a foreign shock depends on both demand for and supply of domestic value added. From the perspective of the domestic economy, a foreign productivity shock is a demand shock for its value added. The elasticity of substitution between domestic and foreign goods governs both the direction and the magnitude of the demand shift experienced by the home economy following a foreign productivity shock. The lower the elasticity, the more positive is the shift in demand for domestic goods. This is because with low elasticities, a fall in the price of one intermediate input strongly increases not just the quantity demanded of that input, but also quantity demanded of other inputs. The Leontief limit is particularly clear: when the price of a Leontief input falls, the using firm increases its demand for all inputs by the same proportional amount. When the elasticity of substitution goes above 1, demand for other inputs falls when an input becomes cheaper. The role of the low Armington elasticity in generating positive cross-country propagation has been highlighted since the early IRBC papers (Backus *et al.*, 1992, 1995) and has been a consistent thread in the international macro literature since then (Heathcote and Perri, 2002; Kose and Yi, 2006; Burstein *et al.*, 2008; Corsetti *et al.*, 2008; Johnson, 2014, among many others).

Given a shift in demand, the Frisch elasticity then governs the magnitude of the domestic supply response. When the Frisch elasticity is low, factor inputs do not respond much to the shift in demand, muting the measured real GDP response. (The limiting case of perfectly inelastic factor supply is particularly clear, as a foreign productivity shock has no impact on domestic real GDP—there is no international transmission, see *e.g.* Kehoe and Ruhl, 2008.) Higher Frisch elasticities imply a larger GDP response.

Figure 5 illustrates this discussion. The three panels plot the shares of shock correlation and of transmission in the total GDP comovement as a function of the three elasticities. In these figures, we re-do the shock extraction for each ψ, ε, and ρ. By construction, the procedure matches the data on the overall GDP correlations under each set of elasticities. However, since the shock extraction procedure itself relies on these elasticities, the fraction of comovement attributed to transmission varies with these parameters. Lower substitution elasticities and higher Frisch elasticities imply a higher share of transmission in total comovement, consistent with the intuition above.

Figure 5 makes it clear that the ultimate conclusion about the share of transmission in comovement depends on these parameters. As we estimate ε, ρ, and ψ, we can be explicit about the uncertainty surrounding these parameter values. Furthermore, estimation of ψ uses the values

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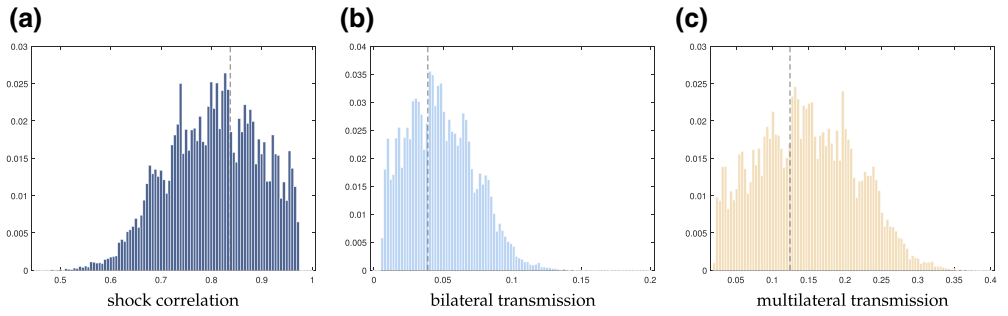


FIGURE 6
Distribution of shares of shock correlation and transmission

Notes: This figure displays the distributions of the shares of shock correlation (panel a), bilateral transmission (panel b) and multilateral transmission (panel c) in average GDP correlations in the G7 countries. The elasticities of substitution ρ and ϵ are drawn from normal distributions with means/standard deviations corresponding to the point estimates/standard errors for ρ and ε in column 3 of Supplementary Table A4, and the Frisch elasticity ψ is reestimated for each draw of a pair of ρ and ε.

of ε and ρ, and thus is in that sense conditional on those. To provide a range of likely outcomes, we undertake the following simulation exercise. We draw ε and ρ from 1-standard-error intervals around their estimated values, and for each draw of a pair of (ε, ρ), we re-estimate ψ. Using the resulting triplet of elasticities, we then compute the shares of correlated shocks and transmission in the overall comovement. Repeating this simulation 1,000 times gives us a distribution of these shares. Figure 6 reports the results as histograms of the shares of each component in overall comovement. The vertical dashed lines display the values under the point estimates. The simulation yields a range of outcomes. While some of the most extreme values imply that the share of transmission can be as high as 50%, those combinations of elasticities are unlikely. Most of the mass is in the range where shock correlation accounts for over 70% of the total comovement.[28]

4.6.2. The role of the input network. To illustrate the role of the input network in generating the observed comovement, we compare the correlations in the baseline model to correlations that would obtain in an autarky counterfactual. Using the setup from Section 2, we can write the difference in GDP correlations between autarky and trade as a sum of two terms:

$$\Delta\rho_{nm} = \underbrace{\sum_{k=0}^{\infty}\sum_{j}\sum_{i}\left(\frac{s_{nnj,k}s_{mmi,k}}{\sigma_n\sigma_m} - \frac{s^A_{nj,k}s^A_{mi,k}}{\sigma^A_n\sigma^A_m}\right)\mathrm{Cov}(\theta_{nj},\theta_{mi})}_{\Delta\ \text{Shock Correlation}} + \text{Bilateral Transmission} + \text{Multilateral Transmission}, \tag{4.3}$$

where $s^A_{mi,k}$ are the elements of the influence vectors in autarky, and σ^A_n is the standard deviation of GDP growth in autarky.

28. While our estimation strategy for ε and ρ is conventional and well-tested, estimating ψ in a quantitative international macro model is less common. Furthermore, the procedure uses the full structure of the model. As an alternative, we can draw from the distribution of ε and ρ, but treat ψ as a fixed ("calibrated") parameter, setting it to $\psi = 0.75$ as advocated by Chetty *et al.* (2011). Supplementary Appendix Figure A6 displays the results. Not surprisingly, without variability in ψ the range of outcomes is narrower, with very few draws implying a share of transmission in total comovement of more than 20%.

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Equation (4.3) shows that trade opening can affect the GDP correlation in two ways. First, it will make countries sensitive to foreign shocks, as captured by the Bilateral and Multilateral Transmission terms. Second, and more subtly, opening to trade will affect the economies' responses to their own domestic shocks: the domestic elements of the influence vectors will change. This is captured by the Δ Shock Correlation term. It will differ from zero when the shocks have some correlation, $\text{Cov}(\theta_{nj}, \theta_{mi}) \neq 0$.[29]

Thus, in order to understand the contribution of international trade to international comovement, we must capture how going from autarky to trade changes the composition of the economy (and consequently the differences between $s_{nnj,k}$ and $s^A_{nj,k}$). We construct an autarkic economy by reassigning all final and intermediate expenditure shares on foreign goods to the same-sector domestically produced goods. This is the most intuitive and parsimonious approach to construct autarky expenditure shares.[30] Using the resulting input and final consumption shares, we build the autarky influence matrix according to the same model solution (Section 3). We then apply the baseline shocks recovered in Section 4.3 to the autarky influence matrix to compute GDP growth rates in all countries and the resulting GDP correlations.

Figure 7(a) displays the mean difference between the trade and the autarky correlations for each country, and decomposes it into the Δ Shock Correlation and transmission terms as in equation (4.3). Not surprisingly, moving from autarky to trade tends to increase the overall correlations (the blue bars), and the transmission terms contribute positively to this increase in comovement (yellow bars). Less expected, Δ Shock Correlation is actually negative for all countries. All else equal, when countries move from autarky to trade, their susceptibility to domestic shocks changes in such a way as to reduce overall comovement.

To understand this effect, Figure 7(b) plots the average changes in the domestic elements of the influence vectors when moving from autarky to trade, $s_{nnj,k} - s^A_{nj,k}$. On average, under trade $s_{nnj,k}$'s are lower than in autarky: economies are less susceptible to domestic shocks in an open economy compared to the closed one. The shrinking of influence is most pronounced in tradeable sectors: six of the top seven largest average reductions in influence are in manufacturing and mining. Intuitively, when a country sources a significant share of its sectoral expenditure abroad, domestic sectoral conditions matter less and domestic shocks propagate less to GDP. As a result, it matters less that domestic shocks are positively correlated across countries. Of course, this is a *ceteris paribus* effect. Domestic influence is replaced by foreign influence when countries open to trade, and comovement increases overall. But it increases by less than partial equilibrium reasoning would imply.

All in all, this exercise shows that in counterfactual exercises with respect to the role of international trade, we must keep track of the entire reshuffling of the production network, including importantly the domestic linkages. This lesson is relevant, for example, in analysing the effects of renationalizing supply chains as in Bonadio *et al.* (2021). Supplementary Appendix D.4 presents the results of two intermediate counterfactuals, in which we shut down intermediate input and final goods trade one at a time. As expected, intermediate input trade has a

29. Because we are working with correlations, changes in the standard deviation of GDP between autarky and trade, σ^A_n versus σ_n, also appear in this expression, but this is not a large effect in practice.

30. A natural way to construct autarky would be to set the trade costs to infinity. Because the substitution elasticity between inputs ε is less than 1, raising τ_{mni} will actually *increase* expenditure shares on imports. This value of ε is meant to govern the short-run responses of the economy to shocks, and is estimated from year-to-year variation. It is clearly not the right elasticity to apply to "long-run" structural changes in the economy like opening to trade (see Boehm *et al.*, 2023, for empirical evidence that long-run elasticities are larger than short-run elasticities). Our autarky counterfactual can be conceived as a limiting case as all $\tau_{mnj} \to \infty$ while the substitution elasticity between inputs approaches 1 from above: $\varepsilon \downarrow 1$.

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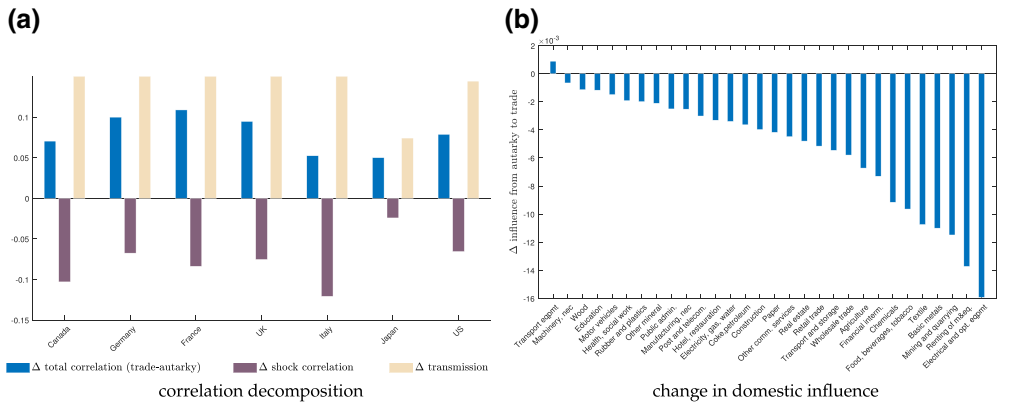


FIGURE 7
Change in GDP correlation between trade and autarky: decomposition

Notes: (a) displays the mean change in the GDP correlation going from autarky to trade (left/blue bars), decomposing it into the mean ΔShock Correlation$_{mn}$ (middle/brown bars) and transmission terms (right/yellow bars). (b) displays the mean change, by sector, in the domestic terms of the influence vector under trade relative to autarky, $s_{nnj,k} - s^{A}_{nj,k}$.

stronger synchronizing impact than final goods trade. Supplementary Appendix D.5 relates our results to the well-known trade-comovement regressions. It shows that much of the overall trade-comovement slope is in fact due to the positive relationship between the Shock Correlation term and trade intensity, echoing Imbs (2004).

5. EXTENSIONS

5.1. *Full country sample and the static network model*

For all the 29 countries in the sample, we lack sufficient time series data to estimate the stochastic process for the shocks required to implement the dynamic model. However, we can still work with a static network version of the model, described in Section 3.2. In this model, the shock recovery procedure is a matrix inversion that takes place in one step, as discussed in Section 4.3. Table 3 reports the results. The top panel summarizes the G7 correlations, to be compared with Table 2. The middle panel reports the results for all countries. Two conclusions emerge. First, for the G7 the static and dynamic models give essentially the same answers on the share of overall comovement accounted for by the different components. Second, in the full sample correlations are lower on average, but the share accounted for by transmission is very similar to the G7.

5.2. *Multiple shocks*

The composite sectoral shock extracted in Section 4 subsumes changes in productivity, as well as changes in labour and capital inputs that the model cannot produce endogenously. This composite shock has two potential limitations. The first is that it is by construction not especially informative on the deeper underlying drivers of business cycles in general, and of international comovement in particular. Second, at a more technical level, only the intratemporal shocks to primary factor supplies can be made isomorphic to TFP, $\mathbf{Z}_t$. Intertemporal shocks cannot be extracted using this approach. Shocks to frictions in the intermediate input market are also not

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TABLE 3
Correlated shocks versus transmission decomposition, extensions

	Mean	Median	25th pctile	75th pctile
Static network model, G-7 countries (N. obs. = 21)				
Data	0.358	0.333	0.122	0.552
Static network model	0.350	0.356	0.124	0.558
Decomposition				
Shock correlation	0.293	0.298	0.102	0.499
Bilateral transmission	0.014	0.011	0.006	0.016
Multilateral transmission	0.043	0.047	0.022	0.056
Static network model, all countries (N. obs. = 406)				
Data	0.187	0.183	−0.110	0.500
Static network model	0.193	0.198	−0.104	0.498
Decomposition				
Shock correlation	0.149	0.179	−0.122	0.431
Bilateral transmission	0.005	0.003	0.001	0.006
Multilateral transmission	0.039	0.029	0.011	0.066
Four-shock model, G-7 countries (N. obs. = 21)				
Data	0.358	0.333	0.122	0.552
4-shock dynamic model	0.350	0.356	0.124	0.558
Decomposition				
Shock correlation	0.290	0.290	0.106	0.472
Bilateral transmission	0.050	0.045	0.033	0.057
Multilateral transmission	0.010	0.007	−0.017	0.039

Notes: This table presents the decomposition of the GDP correlations into the shock correlation, the direct transmission, and the multilateral transmission terms as in equation (2.4) in the static network model for G7 and all countries, and in the dynamic model with four shocks.

isomorphic to TFP. Thus, if shocks to the intermediate input market are non-trivial, the procedure in Section 4.3 would recover a supply shock that is in part a linear combination of all countries' and sectors' intermediate input market shocks.

This section enriches the model to allow for several distinct shocks. One benefit of this extension is that we can now perfectly match multiple series: value added, labour, capital, and intermediate inputs. We accommodate intertemporal as well as intratemporal shocks, and thus we can quantify their relative importance.

The household problem is now subject to two shocks: labour ξ^H_{njt} and investment ξ^I_{njt}, which we interpret as distortive taxes following Chari *et al*. (2007).[31] The budget constraint becomes:

$$P_{n,t}\left(C_{n,t}+\sum_j\left(1+\xi^I_{nj,t}\right)I_{nj,t}\right)=\sum_j\left(1-\xi^H_{nj,t}\right)W_{nj,t}H_{nj,t}+\sum_j R_{nj,t}K_{nj,t}+T_{n,t},$$

31. Note that modelling these wedges as shocks to preferences and technologies or distortive taxes does not matter for accounting purposes or the primary question in this article, but will have different welfare implications (Chari *et al*., 2009).

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where $T_{n,t}$ is a lump-sum transfer that rebates to the households all the within-country taxes. The labour supply and Euler equations now read:[32]

$$H_{nj,t}^{\frac{1}{\psi}} = \left(1 - \xi_{nj,t}^{H}\right) \frac{W_{nj,t}}{P_{n,t}}, \tag{5.1}$$

and

$$U'_{n,t}\left(1 + \xi_{nj,t}^{I}\right) = \beta \mathbb{E}_t \left[U'_{n,t+1} \left(\frac{R_{nj,t+1}}{P_{n,t+1}} + (1-\delta)\left(1 + \xi_{nj,t+1}^{I}\right) \right) \right].$$

While capital accumulation does not feature explicit adjustment costs, Chari *et al.* (2007) point out that the investment shock plays much the same role as adjustment costs.

Production is subject to a TFP shock, which we relabel $\xi_{nj,t}^{Z}$ in this section,[33] and a shock to the intermediate input market $\xi_{nj,t}^{X}$. The firm thus solves:

$$\max \left\{ P_{nj,t} Y_{nj,t} - W_{nj,t} H_{nj,t} - R_{nj,t} K_{nj,t} - (1 + \xi_{nj,t}^{X}) P_{nj,t}^{x} X_{nj,t} \right\},$$

where

$$Y_{nj,t} = \xi_{nj,t}^{Z} \left(K_{nj,t}^{1-\alpha_j} H_{nj,t}^{\alpha_j} \right)^{\eta_j} X_{nj,t}^{1-\eta_j}. \tag{5.2}$$

The intermediate goods shock affects the input choice decision:

$$(1 - \eta_j) P_{nj,t} Y_{nj,t} = (1 + \xi_{nj,t}^{X}) P_{nj,t}^{X} X_{nj,t}. \tag{5.3}$$

The market clearing conditions are unchanged, and still given by (3.11).

5.2.1. Recovering shocks. As mentioned above, with four shocks instead of one, we match multiple data series: value added, labour input, capital input, and intermediate input. Three of the four shocks can be recovered by applying data for $Y_{nj,t}$, $H_{nj,t}$, $K_{nj,t}$, and $X_{nj,t}$ to intratemporal optimality conditions and thus do not rely on the dynamic structure of the model. The TFP shock is read simply as the Solow residual from (5.2). The labour shock is recovered from the labour supply (5.1), after expressing $W_{nj,t}$ and $P_{n,t}$ as functions of $Y_{nj,t}$ and model parameters. The intermediate shock $\xi_{nj,t}^{X}$ comes from (5.3), after expressing the prices as functions of $Y_{nj,t}$.

The TFP shock is the least reliant on model parameters, as it needs information only on factor shares α_j and η_j. The intermediate market shock requires in addition substitution elasticities ρ and ε, plus the global matrix of input and final good shares. Recovery of the labour shocks relies on all of those plus the Frisch elasticity.

The investment shock $\xi_{nj,t}^{I}$ enters the Euler equation and thus requires solving the full dynamic model. To do that requires specifying the stochastic processes for all four shocks, as

32. The labour shocks can have a literal interpretation as exogenous shifts in intratemporal factor supply curves. Alternatively, news shocks (*e.g.* Beaudry and Portier, 2006), or sentiment shocks (*e.g.* Angeletos and La'O, 2013; Huo and Takayama, 2015) would manifest themselves as shocks to $\xi_{nj,t}^{H}$, as agents react to a positive innovation in sentiment by supplying more labour. Straightforward manipulation shows that $\xi_{nj,t}^{H}$ can also be viewed as a shifter in the optimality condition for factor usage. The literature has explored the aggregate labour version of this shifter, labelling it alternatively a "preference shifter" (Hall, 1997), "inefficiency gap" (Galí *et al.*, 2007), or "labour wedge" (Chari *et al.*, 2007). While this object is treated as a reduced-form residual in much of this literature, we know that monetary policy shocks under sticky wages (Galí *et al.*, 2007; Chari *et al.*, 2007), or shocks to working capital constraints (*e.g.* Neumeyer and Perri, 2005; Mendoza, 2010) manifest themselves as shocks to $\xi_{nj,t}^{H}$.

33. The $\xi_{nj,t}^{Z}$ match the measured Solow residual, and differ from the Z shock recovered in Section 4.

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policy functions depend on the perceived stochastic shock processes. In exercises similar to ours, Chari *et al*. (2007) and Ohanian *et al*. (2018) use maximum likelihood and Bayesian estimation respectively to obtain the shock processes. However, the number of parameters to be estimated in our exercise is an order of magnitude larger because all shocks are at the sectoral level, which makes either maximum likelihood or Bayesian estimation intractable. Instead, we follow an approach similar to the composite shock recovery procedure in Section 4.3. We impose parsimonious functional forms on the shock processes:

$$\ln \xi^x_{nj,t} = \rho^x_{nj} \ln \xi^x_{nj,t-1} + \zeta^x_n \mathbf{1}\,(m = n, k \neq j) \ln \xi^x_{mk,t-1} + \theta^x_{nj,t} \tag{5.4}$$

for $x = Z, X, H, I$. We then apply an iterative procedure to recover the shock processes. Given some perceived shock processes, we compute the policy functions. Under these candidate policy functions, we can recover the time series for the realizations of shocks that rationalize the data. These candidate shock realizations can in turn be used to estimate the stochastic shock processes, which become the perceived processes in the next iteration. We iterate until the perceived and estimated shock processes coincide. Supplementary Appendix Table A5 summarizes the parameter estimates for the processes. The estimated processes are persistent, with mean own-lag parameter estimates ranging from 0.85 for $\ln \xi^X_{nj,t}$ to 0.95 for $\ln \xi^I_{nj,t}$. Lagged cross-sector within-country spillovers are very small and close to zero on average for all series.

The bottom panel of Table 3 reports the main decomposition (2.4) of the overall comovement into correlated shocks and transmission. The extension of the decomposition to four shocks is straightforward. The main result on the relative importance of correlated shocks versus transmission is virtually the same in the 4-shock model compared to the baseline.

5.2.2. The role of individual shocks. A well-known feature of this type of business cycle accounting exercise is that the four extracted shocks are not mutually uncorrelated (see, among others, Chari *et al*., 2007; Eaton *et al*., 2016b). Thus, part of the GDP correlation will come from cross-shock covariance terms, for instance comovement driven by correlation of TFP in country j with the labour shock in country i.[34]

We proceed by presenting two polar exercises. In the first, we take out one shock at a time, keeping the other three. In terms of shock correlation, removing a shock gets rid of both the correlations of that shock with the same shock in other countries (*e.g.* TFP in country j with TFP in country i), and the correlation of that shock with other shocks in other countries (*e.g.* TFP in country j with labour in country i). In the second exercise, we feed in one shock at a time. This exercise generates comovement only through correlation of a shock with the same shock abroad (in addition to transmission). Needless to say, in both types of exercises, the transmission terms change as well. Note that shocks can have a negative correlation, and thus it is not necessarily the case that the first exercise leads to a larger contribution of a single shock to comovement compared to the second exercise.

Table 4 reports the resulting correlations. The first two rows present the data and the correlations conditional on all four shocks, which by definition match the data. The next four rows

34. As in other business cycle accounting analyses, different types shocks within the same country are correlated among themselves. With a small number of aggregate shocks in a single country, one can in principle orthogonalize them. Our object is international correlations, and there are four shocks in each sector in each country. There is no practical way to transform them in such a way that a given type of shocks in one country is only correlated with the same type of shocks in the other countries, but orthogonal to all other categories of foreign shocks.

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TABLE 4
GDP growth correlations conditional on subsets of shocks

	Cross-country correlation			
	Mean	Median	St. dev. (GDP)	Corr w/data
Data	0.358	0.333	1.667	1.000
All shocks	0.350	0.356	1.663	1.000
No TFP shock	0.357	0.337	1.297	0.530
No labour shock	0.142	0.169	1.560	0.830
No intermediate input shock	0.371	0.353	1.689	0.977
No investment shock	0.403	0.376	0.703	0.478
Only TFP shock	0.103	0.090	1.528	0.663
Only labour shock	0.235	0.197	0.914	0.399
Only intermediate input shock	0.283	0.184	0.367	0.028
Only investment shock	0.599	0.574	0.711	0.539
TFP and labour	0.273	0.333	1.492	0.901

Notes: This table presents the summary statistics of the correlations of $d \ln G_{n,t}$ in the sample of G7 countries driven by various shocks.

remove one shock at a time. The largest impact on correlation is due to the labour shock: removing it lowers the mean correlation by nearly 60%. Removing the other shocks has much less impact, conditional on the other shocks operating.

The bottom four rows report instead the correlations conditional on a single shock. The correlation generated by the labour shock, 0.24, is more than double the 0.11 correlation generated by the TFP shocks. Interestingly, the intermediate input shocks and especially the investment shocks by themselves itself generates the highest correlations. The two rightmost columns of Table 4 report two additional diagnostics on the alternative shock models: the standard deviation of GDP growth, and the correlation between GDP growth generated by each subset of shocks and the data GDP growth. The intermediate and investment shocks do not generate sufficient volatility. Alone, the intermediate input and investment shocks produce standard deviations of GDP growth that are only 20 and 40% of the data values, respectively. GDP growth driven by intermediate input shock is uncorrelated with the data. By contrast, while the TFP shock by itself does not produce a lot of international comovement, the GDP growth rates generated by TFP are the most correlated with the data compared to those generated by other shocks, as evidenced by the last column of Table 4.

It may appear puzzling that the labour shock comes out as the most important in the first exercise, but less so in the second one. The discrepancy in the conclusions from the two exercises is resolved by the fact that the labour shock is positively correlated with other shocks abroad, whereas the investment and intermediate shocks are negatively correlated with other shocks abroad. Table 5 illustrates this by reporting the mean GDP correlations when GDP in country j is driven by a shock in the row of the table, and GDP in country i is driven by a shock in the column. The labour shock-driven GDP is positively correlated with the TFP-driven GDP (0.126), and with the investment shock-driven GDP (0.242). By contrast, the investment and intermediate shock-driven GDP has negative correlations with other shocks.

When shocks are mutually correlated, one way to decompose the overall comovement into the contributions of individual shocks is the Shapley (1953) value approach. Essentially, the Shapley value averages the contribution to the overall comovement of each shock across all the possible permutations of the four shocks. It answers the question of how much comovement increases on average when a shock gets added to the model. Expressed as shares of the total comovement, the contributions of all four shocks add up to one. One challenge with this exercise

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TABLE 5
Correlations among GDP growth rates driven by single shocks

	TFP	Labour	Intermediate	Investment	Shapley value (share of total)
TFP	0.103	0.025	0.196	−0.055	0.271
Labour	0.124	0.235	−0.069	0.250	0.429
Intermediate	0.093	−0.047	0.283	−0.189	−0.042
Investment	−0.023	0.284	−0.130	0.599	0.342

Notes: The first four columns of this table reports the average GDP correlations that result when GDP growth in one country is driven by the shock in the row of the table, and the GDP growth in the other country is driven by the shock in the column. The last column reports the Shapley value of each shock, expressed as a share of the total comovement, in contributing to the average GDP covariance in the data.

is that different shocks produce very different business cycle volatilities (Table 4). As a result, the GDP correlations they yield are not necessarily directly comparable. Thus, we carry out the Shapley value decomposition on the average covariances instead of correlations. The last column of Table 5 reports the results. The labour shock is the single most important shock according to this metric, followed by the investment and the TFP shocks that are of roughly equal importance. The intermediate shock's Shapley value is close to zero.[35]

We synthesize these results as follows. First, no single shock has a dominant role in international comovement. Individually, the labour and the TFP shocks appear most promising, but for different reasons. The labour shock has the highest synchronizing impact, with the qualification that much of its overall effect appears to come from its correlation with other shocks rather than with itself. Taken alone, the TFP shocks generate less GDP comovement, but they produce GDP series closer to the data, as measured by both standard deviation and correlation. On the face of it, intermediate and investment shocks generate the most correlation alone, but that comes in part due to their negative correlations with other shocks. As a result, the GDP series generated by these shocks alone do not look much like the data.

Second, a model that combines labour and TFP shocks strikes a good balance between parsimony and fit to the data. The bottom row of Table 4 reports the statistics for the model performance with these two shocks. The two shocks together generate 80% of the observed international correlation. At the same time, they reproduce the observed GDP volatility and generate a GDP series with an 0.90 correlation with the data. The model is parsimonious both in the sense that it relies on only two shocks, and in the sense that these shocks themselves are relatively simple, and would work in the same way in both static and dynamic models.

Third, the next shock in order of importance is the investment shock. Adding it to TFP and labour essentially reproduces the data (see row "No intermediate input shock" in Table 4). However, adding this shock comes at a cost of parsimony, especially because both extracting and using this shock requires solving and iterating on the full dynamic model. While the baseline model abstracts from modelling financial shocks explicitly, as shown by Chari *et al*. (2007) some types of financial frictions will manifest themselves as investment shocks. Our results can be viewed as suggestive that financial shocks may play a non-trivial role in international comovement, but perhaps a less important one than the TFP and labour shocks.

Finally, the intermediate input shock is the least successful, either by itself or in conjunction with other shocks. A quantification is not missing much by omitting it.

35. To further illustrate the properties of the different shocks, Supplementary Appendix D.7 projects the extracted shocks on a vector of shocks identified elsewhere in the literature, and presents a historical narrative that attributes changes in international GDP correlations to changes in the realizations of different shocks over time.

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5.3. *Rigidities in labour markets*

The baseline analysis is carried out under flexible goods and factor prices. We do not consider goods price stickiness, as that would require a departure from perfect competition in the goods markets. This subsection extends the baseline one-shock model from Sections 3–4 to incorporate wage rigidities, which are pervasive and persistent in the data (Schmitt-Grohé and Uribe, 2016; Grigsby *et al.*, 2021).

To make the analysis more comparable with our baseline framework and to avoid specifying the monetary policy rules in multiple countries, we assume that wages are rigid in real terms. Denote by $w_{nj,t} \equiv \frac{W_{nj,t}}{P_{n,t}}$ the real wage in country n and sector j. We make two assumptions. First, the law of motion (in percentage deviations from the steady state) is given by

$$\ln w_{nj,t} = (1-\lambda)\ln w^*_{nj,t} + \lambda w_{nj,t-1}, \tag{5.5}$$

where $w^*_{nj,t}$ is the real wage in the absence of wage rigidities, and λ parameterizes the degree of wage stickiness. When $\lambda = 0$, we return to the baseline model in Section 3. This specification captures the partial dependence on past wage levels and is similar in spirit to the modelling of non-optimizing backward-looking firms in Fuhrer and Moore (1995) and Galí and Gertler (1999). Compared with the wage Philips curve with Calvo-type wage rigidities, condition (5.5) abstracts from the forward-looking wage determinants. Second, such frictions necessarily prevent labour markets from clearing. Following the literature on business cycle models subject to nominal rigidities, we assume that the outcomes in the labour market are demand determined. That is, workers do not always operate on their intratemporal optimality conditions.

In this setting, following a higher productivity or lower intermediate goods prices, the lack of upward adjustment in wages results in a larger increase the quantity of labour demanded. This manifests itself in labour market outcomes being more responsive, which is as if workers had a higher Frisch elasticity in a model without nominal rigidities. The following proposition formalizes this argument.

Proposition 5.1. *When real wages are governed by* (5.5)*, the impact response of output to a vector of shocks* $\ln \mathbf{Z}_t$ *is*

$$\ln \mathbf{Y}_t = \mathbf{\Lambda}(\infty)\left[\mathbf{\Lambda}\left(\frac{\psi+1-\lambda}{\lambda}\right)\right]^{-1}\mathbf{\Lambda}(\psi)\ln \mathbf{Z}_t,$$

where $\mathbf{\Lambda}(x)$ *is the impact response of the flexible-wage* ($\lambda = 0$) *economy with Frisch elasticity* x.

Proof. See Supplementary Appendix B. □

Note that when λ approaches zero, the influence matrix returns to $\mathbf{\Lambda}(\psi)$ which is the baseline case in the absence of wage rigidities. When λ approaches one, the influence matrix becomes $\mathbf{\Lambda}(\infty)$, implying that the sticky wage model with $\lambda = 1$ is isomorphic to the baseline model with an infinitely high Frisch elasticity. This proposition illustrates that as the wage rigidity becomes more severe, the force of internal propagation strengthens and the bilateral and multilateral transmission are more important. This property is consistent with the findings of Ho *et al.* (2022) under price rigidity.

Figure 8 displays the international comovements decomposition (2.4) as a function of λ. Our baseline model ($\lambda = 0$) remains a good approximation for economies with the duration of real wages are less than 5 years ($\lambda \leq 0.2$). Even for values of λ as high as 0.5, shock correlation accounts for over 50% of overall comovement.

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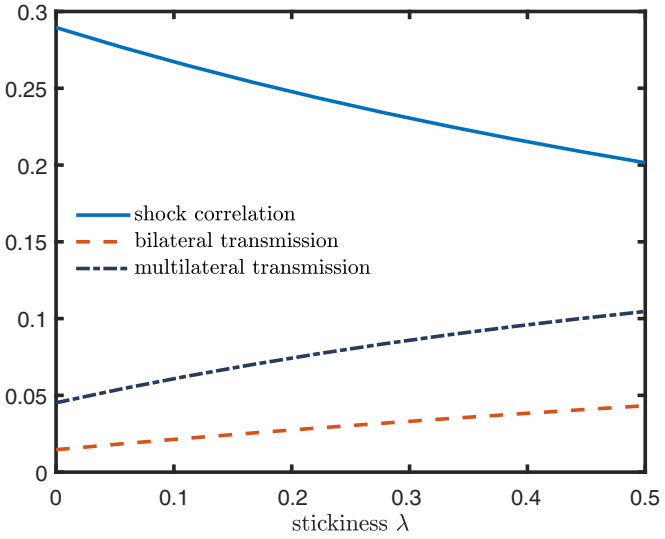


FIGURE 8
Correlated shocks and transmission with wage rigidity

Notes: This figure displays the average contributions of correlated shocks and transmission in models with different degrees of wage rigidities.

5.3.1. Financial integration. Supplementary Appendix D.6 extends the model to allow countries to trade a complete set of state-contingent securities. The main conclusions about the relative importance of correlated shocks versus transmission are robust to this extension.

6. CONCLUSION

We set out to provide a comprehensive account of international comovement in real GDP. Using a simple accounting framework, we decomposed the GDP covariance into additive components representing correlated shocks and cross-border transmission. The relative importance of these two terms is determined jointly by the correlations of the primitive shocks and the strength of domestic and international input–output linkages. The accounting framework also clarifies the role of dynamic propagation: the total GDP correlation is the sum of the correlation due to the instantaneous responses to shock innovations, and dynamic terms that capture the lagged responses to shocks.

While transmission of shocks has an economically meaningful role, most of the observed GDP comovement is accounted for by correlated shocks. The majority of the observed overall correlation is due to the instantaneous response of the economy to shocks, rather than dynamic propagation of past shocks. And finally, while no single shock is predominantly responsible for international comovement, a relatively parsimonious model with two shocks—TFP and labour—appears to generate the bulk of the observed GDP correlations.

Our results suggest that when searching for correlated shocks that synchronize GDP, Solow residual shocks are not sufficient, and that we should instead focus on non-technology shocks that have a labour wedge representation in a prototype model. Structural estimates of various candidate shocks that might explain the correlation in these "labour wedges" across countries are not yet available, and identifying them is a promising avenue for future research. Bui *et al.* (2024) take a step in this direction by modelling and measuring informational frictions in the global value chains, that can give rise to international sentiment shocks. A related finding is that

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introducing wage rigidities increases the relative importance of transmission in international comovement. Thus, the role of rigidities should also be explored in future research (*e.g.* Ho *et al.*, 2022).

Beyond the specific substantive focus of this article, we have provided a conceptual and quantitative framework to study international shock transmission through input networks. This framework remains tractable under a variety of extensions and can readily be used in a variety of further applications by future researchers.

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Supplementary Data

Supplementary data are available at *Review of Economic Studies* online.

Data Availability Statement

The data underlying this article are available in Zenodo at https://dx.doi.org/10.5281/zenodo.10475647.

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