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JEL Classification: E44, E52, F3, E58, F42

Keywords: monetary policy spillovers, monetary policy shocks, International Transmission

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12 April 2021

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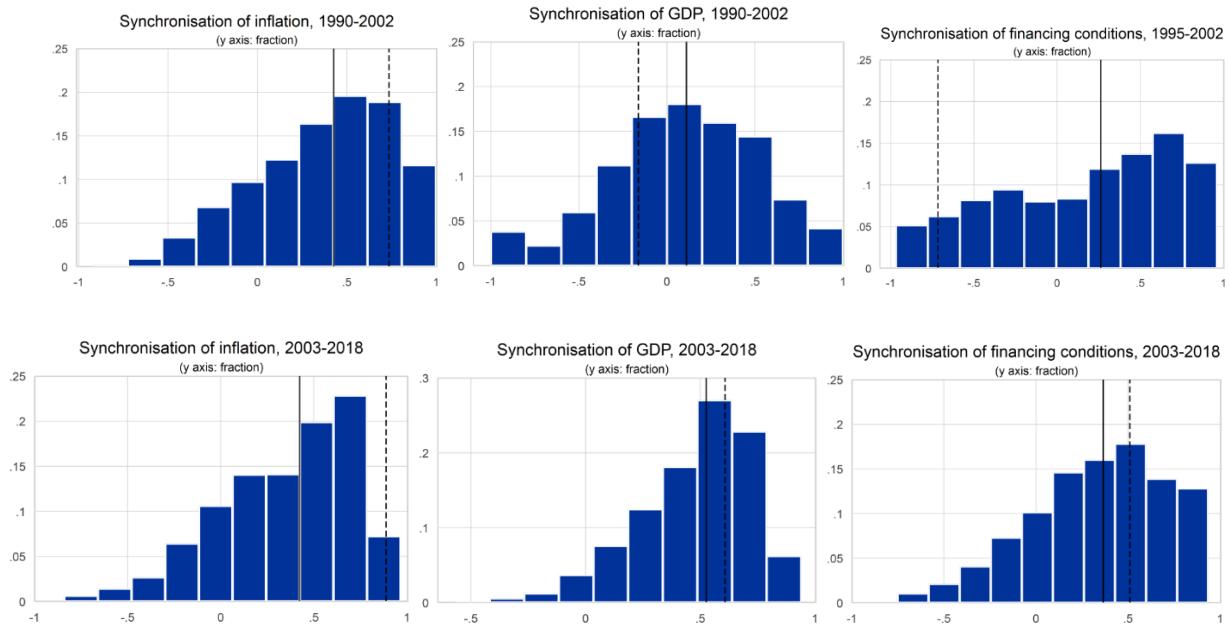
1. Introduction

The Global Financial Crisis and the recourse to unconventional monetary policy measures it entailed have created renewed interest in the international dimension of monetary policy. Events since then have triggered an intense debate about the potential of monetary policy in systemic economies to propagate to the rest of the world (Mantega, 2010).[1] A related discussion has revolved around the question of whether a "global financial cycle" also fuelled by monetary policy in systemic economies is undermining the ability of central banks in the rest of the world to impact domestic financial conditions and eventually control prices, real activity and financial stability (Rajan, 2013; Rey, 2016).

Figure 1: Distribution of pairwise cross-country correlations of inflation, GDP growth and financing conditions



Source: World Bank (World Development Indicators) and IMF Global Financial Stability Report.
Note: The solid line indicates the median correlation and the dashed line the correlation between the United States and the euro area. The data covers 53 advanced and emerging economies at annual frequency for GDP and inflation. Financing conditions indices are calculated by ECB staff extending the IMF Global Financial Stability Report (April 2017) methodology using a set of nine financial variables.

Indeed, the increasing international co-movement of key macroeconomic and financial variables over the recent decades points to closer international linkages that may underpin growing monetary policy spillovers (Figure 1). Splitting the period between 1990 and 2018 in two halves, the distributions of

[1] See Draghi (2016).

bilateral cross-country correlations between inflation, real GDP growth and financing conditions have become more skewed to the right. For the euro area-US country pair, the correlations have increased substantially for real GDP growth and financing conditions. Especially striking is the switch in the sign of the correlation between euro area and US financing conditions across the two periods. Some explanation for this could be the larger and more frequent common shocks in the later period, but the greater spillovers from country-specific shocks and the associated systematic responses by central banks in systemic economies could play a non-trivial role as well.

While a large and growing literature has explored spillovers from monetary policy in the main systemic economies – namely by the Fed and ECB – there remain gaps in our understanding. One of these relates to assessing the differences across spillovers from Fed and ECB monetary policy. Existing work has typically explored Fed *or* ECB monetary policy spillovers individually, but not together in a consistent and unified methodological framework evaluating both their bilateral and global impact. As a result, a comparison of Fed and ECB monetary policy spillovers across existing studies is generally problematic, as findings are based on rather different methodological approaches and data. Specifically, it remains unclear whether differences in the existing evidence on Fed and ECB monetary policy spillovers reflect a feature of the world or simply sampling and model uncertainty.

The main contribution of this paper is to document and compare spillovers from Fed and ECB monetary policy using a consistent and unified methodological framework. In particular, we estimate spillovers from Fed and ECB monetary policy using identical vector-autoregressive (VAR) models, identification approaches and data samples. We estimate Bayesian VAR models with the same set of US and euro area endogenous variables, employ high-frequency interest rate surprises around Federal Open Market Committee and ECB Governing Council meetings to identify monetary policy shocks (Jarociński and Karadi, 2020), and consider data for the same countries over the time period from 1999 to 2016. We first analyse the domestic effects and transatlantic spillovers between the US and the euro area elicited by Fed and ECB monetary policy, respectively, and then spillovers to the rest of the world with a focus on emerging market economies (EMEs).

Three key findings improve our understanding of the domestic and international effects of Fed and ECB monetary policy. First, our results document that even in a highly globalised economy both Fed and ECB monetary policy have a sizable impact on domestic financial conditions, real activity, and inflation. An exogenous ECB and Fed monetary policy tightening raises domestic risk-free rates and corporate bond yields, depresses domestic equity markets, is followed by an appreciation of the domestic currency, slows real activity and reduces inflation.

Second, we document a stark asymmetry in transatlantic spillovers, with the Fed having a much more encompassing impact on the euro area economy than the ECB on the US economy. The largest spillover from Fed monetary policy materialises in euro area financial markets; the spillover to euro area real activity is more subdued and on euro area inflation very short lived. The impact of ECB monetary policy on US economic variables is instead small in all dimensions, including on US financial markets, real

activity and inflation. Hence, while deeper transatlantic goods and financial market integration has entailed a greater role of Fed monetary policy for the euro area economy, the role of ECB monetary policy for the US economy remains limited. Overall, even though in some cases spillovers from US monetary policies matter more, our results suggest that both the ECB and the Fed can achieve their inflation mandates even in a highly globalised world.

Third, we document that there is a "hierarchy" in Fed and ECB monetary policy spillovers to EMEs. Consistently with the dominant role of the US dollar in the international monetary and trade system, Fed monetary policy elicits large spillovers to financial conditions and real activity in EMEs. By contrast, spillovers from ECB monetary policy are largely confined to trade (and, perhaps surprisingly, commodity prices).

Our paper is related to and contributes to existing literature. A very large and still growing literature has explored the spillovers from Fed monetary policy (for a subset of recent work see Passari and Rey, 2015; Ammer et al., 2016; Georgiadis, 2016; Dedola et al., 2017; Gerko and Rey, 2017; Dées and Galesi, 2019; Iacoviello and Navarro, 2019; Degasperi et al., 2020). Another – much smaller – literature explores the spillovers from ECB monetary policy (Babecká-Kucharčuková et al., 2016; Bluwstein and Canova, 2016; Potjagailo, 2017; Moder, 2019; Feldkircher et al., 2020; ter Ellen et al., 2020). In general, the results in this literature suggest that spillovers from Fed monetary policy to the rest of the world – in particular to EMEs – are large, while those from ECB monetary policy are confined to Europe and neighbouring regions. Comparing the findings for Fed and ECB spillovers is however not generally feasible due to differences in identification assumptions, the choice of time and country samples, and model specifications. Moreover, none of the existing work zooms in on bilateral spillovers between the US and the euro area.

A third – even smaller – literature has estimated spillovers from both Fed and ECB monetary policy, but with a more limited scope than in our study and different methodologies. Rogers et al. (2014), Curcuru et al. (2018a,b) as well as Kearns et al. (2018) focus on short-term spillovers from monetary policy surprises to financial markets. Chen et al. (2017) examine spillovers from Fed and ECB unconventional monetary policy in a global VAR model with sign restrictions. Hajek and Horvath (2018) also consider a global VAR model, but only explore generalised impulse responses rather than identified monetary policy shocks. Walerych and Wesolowski (2020) consider Bayesian panel VAR models with Taylor-rule residuals as monetary policy shocks. In general, these papers find that Fed monetary policy elicits larger spillovers than ECB monetary policy at the global level but don't discuss bilateral spillovers between the US and the euro area. Moreover, several of these papers do not examine the response of macroeconomic variables but focus on the impact on financial variables. And none of these papers purges interest rate shocks from central bank information effects, which has been shown to be empirically important (Jarocinski and Karadi, 2020).[2] Finally, Miranda-Agrippino et al. (2020) estimate

[2] A related paper by Jarocinski (2020) focuses instead on the transatlantic spillovers of the information effects.

Bayesian VAR models to estimate the spillovers from US and China's monetary policy. However, they use different identification approaches – namely high-frequency interest rate surprises for the US and recursiveness assumptions for China – and do not consider bilateral spillovers.

The rest of the paper proceeds as follows. Section 2 briefly reviews the main international transmission channels for monetary policy to set the stage on the importance of the financial channel in a highly globalised world. Section 3 introduces our empirical methodological framework and why it is helpful in isolating interest rate surprises. In Section 4 we present our empirical findings concerning the domestic and transatlantic effects of Fed and ECB monetary policy. The international effects of ECB and Fed monetary policy on EMEs are considered in Section 5. In Section 6 we conclude.

2. Transmission channels of monetary policy spillovers

To set the stage for our empirical analysis we briefly review how monetary policy spillovers propagate via the aggregate demand, the expenditure-switching, and a multi-faceted financial channel.

To the extent that a contractionary monetary policy action curbs home consumption and investment, it also reduces the demand for imported goods, and thus for exports of the economy's trading partners. As a result, spillovers through the *aggregate demand channel* reduce output in trading partners. The magnitude of the monetary policy spillover through the aggregate demand channel rises with the weight of the home economy in its trading partners' overall trade. Therefore, monetary policy of economies with a large weight in the global economy should have a commensurately large effect on aggregate demand worldwide.

Monetary policy affects the exchange rate, which in turn alters the relative price of imported and domestically produced goods, which then gives rise to an *expenditure switching channel*. How a nominal appreciation of the home currency affects the relative price between domestically produced goods and imports depends on the degree of exchange rate pass-through (ERPT) to import prices and the ensuing expenditure switching. A key determinant of ERPT over shorter horizons is the currency in which export and import prices are sticky. First, under producer-currency pricing (PCP), traded goods prices are sticky in the currency of the producer, ERPT is complete, and an appreciation of the home currency improves the terms-of-trade, inducing expenditure switching away from domestically produced goods towards goods produced in the rest of the world at home and abroad. Second, under local-currency pricing (LCP), all export prices are sticky in the currency of the importer, and ERPT and expenditure switching are muted.[3] Third, under dominant-currency pricing (DCP), all export (and import) prices worldwide are sticky in a just a few major currencies, and expenditure switching depends on the source of the shock and on the specific bilateral trade relationship in question.[4] The US dollar is currently the dominant invoicing currency in global trade (Boz et al., 2020), so that DCP should be particularly relevant for the

[3] See Betts and Devereux (1996, 2000) as well as Devereux and Engel (2003).
[4] See Gopinath et al. (2020).

global transmission of Fed monetary policy. Especially EMEs invoice the bulk of their imports and exports in US dollars regardless of the destination. For the euro area, in contrast a substantial fraction of non-US imports and exports are invoiced in euro rather than in dollar; the share of euro area countries' total imports and exports invoiced in euro amounts to 71% and 74%, respectively (see Boz et al., 2020). For example, under DCP an appreciation of the US dollar is inconsequential in terms of expenditure switching in the US as its import and export prices are sticky in US dollar. In contrast, in all countries in the rest of the world a multilateral appreciation of the US dollar entails a widespread rise in import prices, which induces expenditure switching away from imports towards domestically produced goods. Moreover, because imports in economies in the rest of the world decline regardless of the source, rest-of-the-world exports decline commensurately. In contrast, a multilateral appreciation of a non-US dollar currency (like the euro) would have only limited expenditure switching effects under DCP. In the non-US economy expenditure switching in this case affects only imports, but not exports. Trade in the rest of the world that does not involve this non-US economy is entirely unaffected by the multilateral appreciation of its currency.[5]

The role of the *financial channel* is particularly important in view of the strong international integration of financial markets. In a financially integrated world, monetary policy in a large currency area may affect financial conditions and thereby aggregate demand in the rest of the world. First, when a country supplies a global safe asset its monetary policy can have a direct effect on aggregate demand abroad: a home monetary policy tightening increases the global demand for home assets and thus directly reduces global aggregate demand.

Second, exchange rate valuation effects in cross-border assets and liabilities change the value of foreign-currency denominated collateral, and thereby borrowing and leverage.[6] For example, when a firm borrows in foreign currency, home currency depreciation tightens borrowing constraints and reduces the firm's borrowing capacity. Third, a monetary policy tightening depresses the value of domestic assets via a higher discount factor and lower expected cash flows. Some holders of these assets are leveraged investors, including financial intermediaries. The decline in asset values tightens their balance sheet constraints and raises their borrowing costs. This domestic balance sheet channel propagates across borders via asset price equalisation and the synchronisation of credit spreads and borrowing costs of leveraged cross-border investors (see e.g. Dedola and Lombardo, 2012, and Devereux and Yetman, 2010). The US dollar is the dominant currency in global financial markets, and hence US

[5] An additional transmission channel for monetary policy spillovers from the dominant-currency issuing economy to the rest of the world operates through the endogenous response of monetary policy: as all import prices in the rest of the world are sticky in the dominant currency – regardless of their source – a multilateral appreciation of the dominant currency raises local currency import prices and thereby consumer price inflation. Depending on the degree of openness, this might induce local monetary policy to tighten, putting downward pressure on production (see Mukhin, 2018, and Zhang, 2018; Corsetti et al., 2021). Georgiadis and Schumann (2019) discuss export-import US dollar invoicing share differentials under partial DCP as another conduit for output spillovers from US monetary policy.

[6] Bruno and Shin (2015) describe the consequences of the co-movement of US dollar exchange rates and the leverage of global banks. They refer to this relationship between domestic and global financial conditions as the "risk-taking channel of [local] currency appreciation". See Kearns and Patel (2016), Hofmann et al. (2017) and Avdjiev et al. (2019) for empirical evidence.

monetary policy has a disproportionate impact on global financial conditions (Rey, 2016; Gourinchas et al., 2019; Obstfeld, 2020, Miranda-Agrippino and Rey (2021)).

3. Empirical framework

3.1 Identification of monetary policy surprises

We construct exogenous interest rate surprises from asset price movements over narrow time windows around monetary policy announcements. The basic idea of this identification approach is that in a sufficiently narrow time window it is unlikely that financial markets are driven by events other than the monetary policy announcement. Therefore, movements in interest rates over the narrow time window represent exclusively the financial market effect of the monetary policy announcement. Moreover, such abrupt movements in interest rates represent a surprise: If financial markets had anticipated a change in the monetary policy stance, e.g. as a systematic reaction of monetary policy to the state of the economy, it would have already been priced in and interest rates would not have moved over the narrow time window.

However, interest rate surprises might not coincide with monetary policy surprises. In particular, the interest rate surprises might be contaminated by a central bank information effect. Central banks may move financial markets not only by surprises in their monetary policy stance for a given state of the economy, but also by affecting financial market beliefs about the state of the economy. For example, financial markets may interpret an unexpected interest rate cut as the central bank having a more pessimistic view about the state of the economy; in this case, financial markets could revise downwards their own beliefs about the state of the economy. This central bank information effect is different from a monetary policy shock, both conceptually as well as in terms of its macroeconomic effects (Romer and Romer, 2000; Melosi, 2017; Nakamura and Steinsson, 2018; Cieslak and Schrimpf, 2018; Miranda-Agrippino and Ricco, forthcoming). Jarociński and Karadi (2020) document that central bank information effects can distort the estimation of the effects of monetary policy, in particular for the persistence of the interest rate response and the magnitude of the price level response.

We follow Jarociński and Karadi (2020) and purge interest rate surprises from central bank information effects using changes in stock prices in the same narrow window around the monetary policy announcement. Specifically, if stock prices move in the same direction as interest rates around the time of the announcement, we label the interest rate surprise a central bank information effect. If, by contrast, stock prices and interest rates move in opposite directions, we classify this as a monetary policy shock. This corresponds to the "poor man's" identification approach of Jarociński and Karadi (2020).

The "poor-man's" approach makes the simplifying assumption that the total interest rate surprise is either entirely a monetary policy shock or entirely a central bank information effect. We also consider

the "rotational sign restrictions" approach of Jarociński and Karadi (2020), under which the total interest rate surprise that we observe is assumed to be a combination of both types of shocks in each month, i.e. in a typical month both shocks contribute to the overall interest rate surprise. It turns out that the monetary policy surprises based on the "poor man's" approach represent a better instrument for ECB monetary policy in our setup. Since our results are not very sensitive to this choice, for the sake of comparability we consider the "poor's man" approach to construct both ECB and Fed monetary policy surprises. Nevertheless, we discuss the results from "rotational sign restrictions" for the Fed whenever the results diverge in important ways.[7]

3.2 Data and sample

Our dataset consists of 168 Fed and 296 ECB monetary policy announcements between 1999 and 2018. The changes in interest rates and stock prices are measured in the time window starting 10 minutes before and ending 20 minutes after a central bank announcement. In the case of the Fed, the timing of the announcement typically coincides with that of the press release. In the case of the ECB, the time window is generally longer, starting 10 minutes before the press release and ending 20 minutes after the end of the press conference. In these windows we define the Fed interest rate surprise as the first principal component of the changes in Federal Funds futures and Eurodollar futures with remaining maturities from one month up to one year. Similarly, we define ECB interest rate surprises as the first principal component of the changes in EONIA swaps with maturities from one month up to one year. By including maturities of up to one year, these surprises capture not just changes in current policy rates but also the expectations for interest rates up to one year in the future, reflecting forward guidance and other non-standard monetary policy measures.[8]

Our ECB and Fed monetary policy surprises are uncorrelated. The systematic components of ECB and Fed monetary policy of course both respond endogenously to the state of the economy and hence also to synchronised business cycles more generally (Belke and Gros, 2005). As a result, the observed ECB and Fed monetary policy stance is correlated over time. But the exogenous, unsystematic surprise components of ECB and Fed monetary policy are uncorrelated. Therefore, any co-movement between euro area and US variables that we may estimate in response to an ECB or Fed monetary policy shock must represent monetary policy spillovers rather than the effects of common shocks.

[7] Jarociński and Karadi (2020) discuss the merits of the two identification approaches.

[8] The Fed surprises come from the updated dataset of Gürkaynak et al. (2005) and the ECB surprises from the dataset of Jarociński and Karadi (2020). Similar monetary policy surprises are used in a large body of literature that includes e.g. Kuttner (2001), Gürkaynak et al. (2005), Bernanke and Kuttner (2005) and many others. For robustness checks we also consider longer-term rates. Extracting ECB monetary policy surprises from movements in three-year overnight index swaps during the effective lower bound period increases the magnitude, but not the time-series pattern, of monetary policy surprises, and therefore our results remain unchanged.

3.3 A Bayesian VAR model with monetary policy surprises

We estimate the impact of ECB and Fed monetary policy based on a series of separate Bayesian VAR models. In each case, the VAR model includes the one-year government bond yield, stock prices, the corporate bond spread, industrial production and the consumer price index (CPI/HICP). We add the monetary policy surprises to the VAR model as the first endogenous variable. We restrict the coefficients of the first equation to zero, reflecting the assumption that the monetary policy shock is independently and identically distributed over time. After estimating the VAR models with a standard Minnesota prior, we compute the impulse responses to a shock to the first equation, assuming a recursive structure. Note that this is less restrictive than in a VAR model in which a shock to a monetary policy indicator such as the Federal Funds rate is used. In particular, in our specification the variable in the VAR that is assumed to not respond contemporaneously – and in fact not at all due to the zero constraints on all coefficients – is the temporally aggregated high-frequency interest rate surprise on monetary policy announcement days cleansed from central bank information effects. The set of endogenous variables and the estimation of the VAR model in the baseline are the same as in Jarociński and Karadi (2020).[9]

We compute the transatlantic spillovers from Fed monetary policy shocks by entering the Fed shocks in the euro area VAR model. Analogously, for the domestic effects we enter the Fed shocks in the US VAR model. The effects of the ECB shocks are obtained analogously. The responses of other variables, which are not part of the baseline VAR model, are computed by adding them one by one as last variable to the respective baseline VAR model.

Several variables we consider have a bilateral nature, for example the exchange rate or the spread between US and euro area bond yields. In these cases, we use a bilateral VAR model to estimate their impulse responses. The bilateral VAR model includes the exchange rate, the spread between US Treasuries and one-year Bund yields, the corporate bond spread of the country experiencing the shock, and, separately for the US and the euro area, industrial production and consumer price indices.[10] Monetary policy shocks are typically found to account only for a small fraction of the total variation of the observed monetary policy stance in the data. In the case of policy rates, the typical (exogenous) shock in an average month is only of about 2 or 3 basis points.

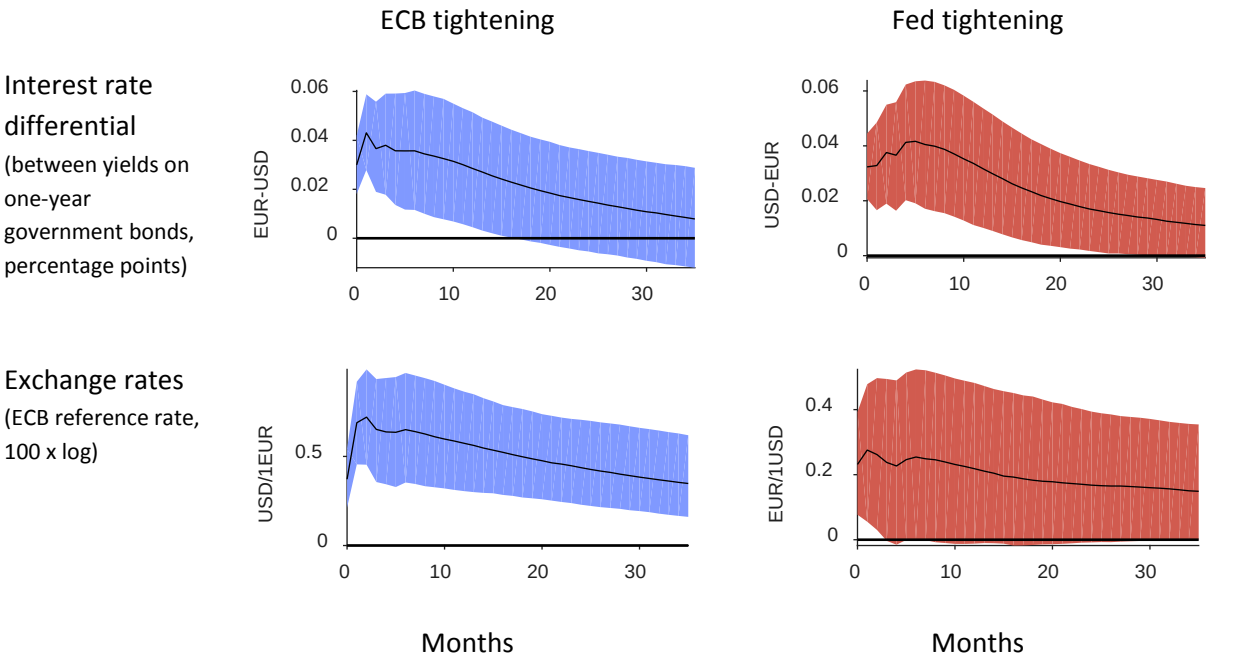
[9] Jarociński and Karadi (2020) also provide details on the rotational sign restrictions approach, which yields a similarly good instrument for Fed monetary policy shocks, but a weaker one for ECB shocks.

[10] Appendix A1 provides further details on the specification of the Bayesian VAR models. The online appendix summarises the definitions of the response variables.

4. Domestic and bilateral effect of US and euro area monetary policy

In the following we report the responses to an exogenous monetary policy tightening of one standard deviation, which corresponds to a contemporaneous increase in domestic one-year bond yields by almost 2.8 basis points for the ECB and close to 2.0 basis points for the Fed.[11] In Figure 2 and in the following figures we show how key domestic and foreign variables are estimated to respond in the 36 months following a tightening by the ECB (left column) and the Fed (right column). The point estimate of the impulse response is plotted as a solid line, surrounded by the 68% confidence band as shaded area (blue for euro area variables and red for US variables). The responses reflect the general equilibrium effects of the exogenous monetary policy tightening, and hence include the effects of the endogenous policy responses on the other side of the Atlantic.

Figure 2: Responses of the bilateral interest rate differential and exchange rate to an exogenous ECB and Fed monetary policy tightening (bilateral model)



Notes: The solid line plots the median impulse response, surrounded by the 68% confidence band. The left-hand column shows the responses to an ECB tightening and the right-hand column responses to a Fed tightening. The quantities in the right-hand column are the inverse of the quantities in the left-hand column. The first row shows the yield differential between a one-year US Treasury and the one-year German Bund.

[11] The ECB and Fed monetary policy shocks studied here have thus a similar, but not identical, impact on one-year bond yields. To compare monetary policy shocks with a (counterfactually) identical impact, the quantities in the following figures can be rescaled. Such rescaling reduces the relative magnitude of the effect of ECB policy versus Fed policy shocks but does by construction not affect significance. Because the model is linear the impulse responses to a monetary policy loosening can be obtained by flipping the sign of the responses.

4.1. Effect on interest rate differentials and bilateral exchange rates

The evidence in the first row of Figure 2 highlights that after both an ECB and an exogenous Fed tightening the interest rate differential between the two regions (defined as home minus foreign government bond rate) widens significantly. The magnitude and persistence of the responses of the interest rate differential for one-year bonds is very similar across the ECB and the Fed shocks.[12] The impulse responses in the second row of the figure document that, in line with uncovered interest rate parity, the domestic currency appreciates both in case of ECB and Fed shocks as domestic interest rates increase relative to foreign rates. After an ECB monetary policy tightening the euro appreciates particularly sharply against the US dollar. Likewise, after a Fed monetary policy tightening the US dollar appreciates as well, but the effect is smaller and less persistent.[13]

4.2. Effect on real activity and prices at home and abroad

Figure 3 shows the domestic effect of an exogenous monetary policy tightening by the ECB (left column) and by the Fed (right column), together with the corresponding spillover. Domestic effects are reported as a dotted line; they are marked by diamonds instead of the dots whenever the one standard error (68%) band around the domestic response excludes zero. Spillovers are shown as a solid line surrounded by the one standard error (68%) confidence band as shaded area (blue for euro area variables and red for US variables as before).

The two columns in Figure 3 confirm that both ECB and Fed monetary policy shocks have a substantial impact on domestic consumer prices and real activity, in line with the results in Jarociński and Karadi (2020). After an ECB tightening, euro area consumer prices drop immediately, statistically significantly, and persistently. The effect of a Fed tightening on US consumer prices is not statistically significant in our baseline. Under the more general "rotational sign restrictions" approach, however, the effect of Fed monetary policy on US consumer prices is comparable in size to that of ECB monetary policy on euro area consumer prices. The fall in real activity is statistically significant both in case of an ECB and a Fed tightening. Domestic unemployment (in the bottom row) also rises in response to an ECB and Fed tightening, even if the effect is statistically significant in the latter case only. The more limited impact of ECB monetary policy on euro area unemployment is consistent with the more comprehensive employment protection compared with the US.

Turning to spillovers, Figure 3 suggests that the cross-border effects of ECB and Fed monetary policy on consumer prices are small and short-lived. An ECB tightening is followed by a marginal decline in US consumer prices on impact, which however turns insignificant very quickly. The spillover from an ECB

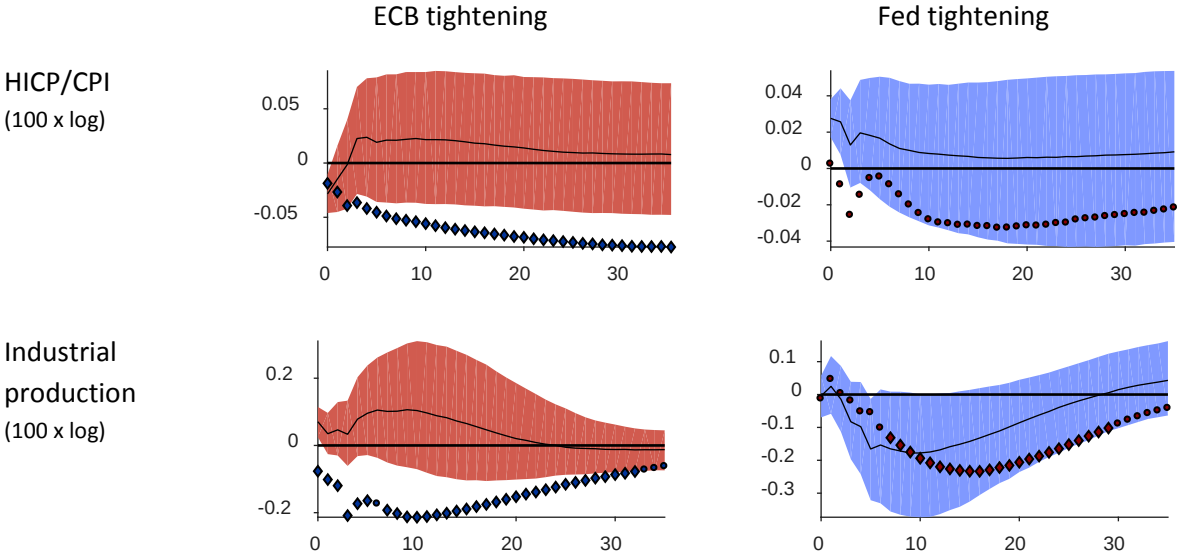
[12] The effect on interbank lending rates on impact is considerably stronger after a Fed monetary policy shock. Over a one-year horizon, however, the effects from the two monetary policy sources are very similar, as shown in the online appendix.

[13] Under the "rotational sign restrictions" described in Jarociński and Karadi (2020) the US dollar appreciation is persistently statistically significant, but even then, it remains smaller for at least one year than the euro appreciation after an ECB tightening.

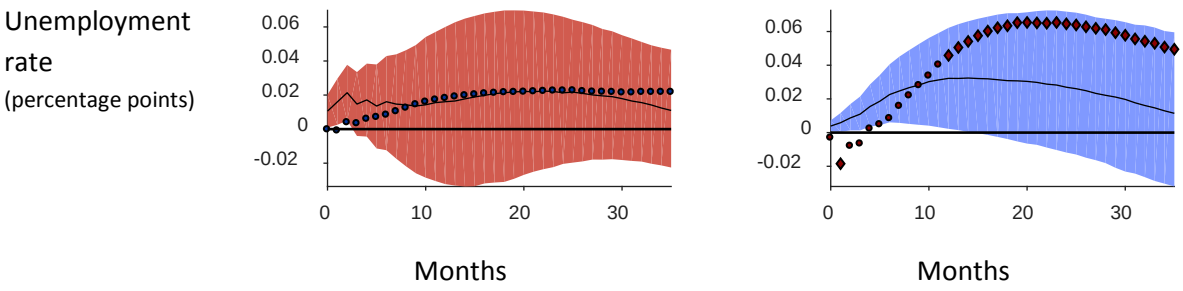
tightening to US consumer prices is thus very small compared with the sizeable domestic effect of a Fed tightening. Against the background of the discussion in Section 2, this evidence is consistent with the absence of a quantitatively significant aggregate demand effect on the one hand (as shown in the middle and bottom rows), and the large share of US imports from/exports to the euro area being invoiced in US dollar and hence immune to exchange rate variation on the other hand.

A Fed tightening has a somewhat stronger impact on euro area consumer prices in the short term. There is a small but statistically significant increase in euro area consumer prices for about one quarter in response to the Fed tightening. The upward pressure on euro area consumer prices may be due to an increase in import prices due to the appreciation of the dollar. Indeed, the euro area GDP deflator, which is not directly exposed to exchange rate changes, responds negatively, though not significantly, to a Fed monetary policy shock.[14] The finding of a statistically significant rise in euro area consumer prices in the absence of a corresponding increase in the GDP deflator is consistent with a non-trivial share of euro area imports, not only from the US, being invoiced in US dollars as discussed in Section 2 under the DCP case; for example, while on average only about 4% of euro area countries' total imports are sourced from the US, about 24% are invoiced in dollars (see Boz et al., 2020).

Figure 3: Bilateral spillovers from ECB and Fed exogenous monetary policy tightening to real activity and consumer prices



[14] Please refer to the online appendix for this and more impulse responses.



Notes: The solid line plots the median impulse response surrounded by the 68% confidence band. In the left-hand column these are the responses to an ECB tightening, in the right-hand column responses to a Fed tightening. Quantities for the US are plotted in red, quantities for the euro area in blue. The dotted lines plot the responses of the corresponding domestic variables, with diamonds symbolising significance at the 68% level. In the left-hand column these are the responses of euro area variables, in the right-hand column the responses of US variables.

Turning to real activity, we find that there are no spillovers to unemployment and industrial production from an ECB tightening. In contrast, real activity spillovers from a Fed tightening are large. The impact of an ECB shock on US unemployment is not statistically significant beyond one quarter, while the impact on US industrial production is even slightly expansionary. An expansionary spillover from an ECB tightening to US industrial production may in theory occur as US exporters temporarily gain competitiveness relative to their local competitors in the euro area. However, looking beyond the one-month horizon, spillovers to US industrial production are short-lived and statistically insignificant. The impact of a Fed tightening on real activity in the euro area is sizeable and much more long-lasting. Euro area unemployment and industrial production respond by at least as much as their US counterparts over the course of an entire year, and initially the spillover is even larger than the domestic effect in the US.[15] After one year the increase in the unemployment rate in the euro area is still close to one-half of the domestic increase in the US. In the next two subsections we delve into the transmission channels of US spillovers, looking at the responses of trade and financial conditions.

4.3. Effect on trade

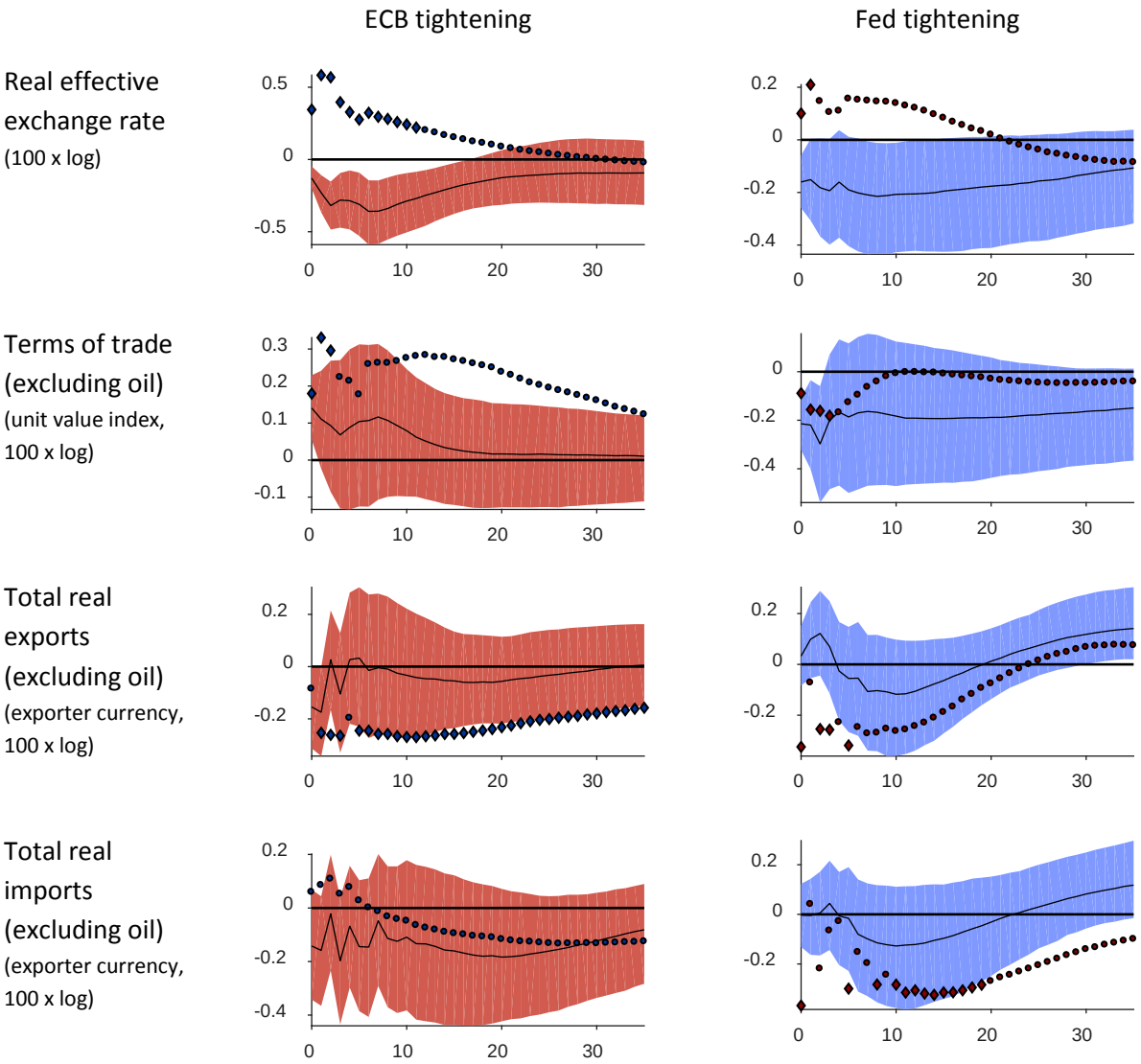
The main international transmission channel of monetary policy in textbook models operates via the effect of exchange rates on exports (e.g. Mundell, 1963). In this subsection we explore the relative importance of the aggregate demand and expenditure-switching effects in transmitting spillovers from monetary policy tightening.

Figure 4 shows that a tightening by both the ECB and the Fed induces an appreciation (i.e. an increase in the dotted lines in the first row of Figure 4) of the respective real effective exchange rate (REER). The larger appreciation of the euro REER is in line with our estimates suggesting that the effect of an ECB

[15] The estimated spillover from Fed shocks to the euro area based on "rotational sign restrictions", which – as noted – capture US monetary policy shocks better, are larger.

tightening on the euro-dollar exchange rate is larger than that of a Fed tightening.[16] Because of the substantial trade links between the euro area and the US, both central banks also affect each other's REER. A Fed tightening triggers a persistent and marginally statistically significant depreciation of the euro REER (a decrease in the solid line in the right column). An ECB tightening leads to a depreciation of the US dollar REER for more than one year. Of course, these results are at least in part due to the large weight each currency has in the effective exchange rate of the other.

Figure 4: Response of euro area and US trade to an exogenous monetary policy tightening



[16] The response of exchange rates to Fed monetary policy shocks is also weaker under "rotational sign restrictions".

Months Months

Notes: The left-hand column shows the responses to an ECB tightening, and the right-hand column the responses to a Fed tightening. Quantities for the US are plotted in red, quantities for the euro area in blue. The dotted lines are the responses of the domestic variables, with diamonds symbolising significance at the 68% level. In the left-hand column these are the responses of euro area variables, in the right-hand column the responses of US variables. The solid line shows the median impulse response of the corresponding spillover with a 68% confidence band. The real effective exchange rate is the number of trade-weighted foreign currency units per home currency unit. Within any given graph, the dotted line and the solid line therefore differ in their denominator.

The responses of the US ex-oil terms-of-trade, i.e. the (log) difference between export and import prices excluding oil, to an ECB and Fed tightening, shown in the second row of Figure 4, are consistent with limited ERPT to import and export prices. That the US terms-of-trade vis-à-vis the rest of the world, after worsening (i.e. falling) on impact, barely respond to a Fed tightening as shown by the dotted line in the right column, is consistent with DCP, under which US export and import prices are sticky in US dollars.[17] Notice that under PCP, i.e. when all export prices are sticky in the currency of the producer, a Fed monetary tightening that leads to a US dollar appreciation would improve (i.e. raise) the US terms of trade because US dollar import prices would fall and US dollar export prices would remain unchanged in the short term. The US terms of trade are also relatively stable following an ECB tightening, except for a very small improvement on impact shown in the left column.

In contrast with the muted response of the terms of trade, a Fed tightening has a large contractionary effect on both US exports and US imports. On the one hand, in addition to the aggregate demand channel that dampens real activity abroad, the decline in US real exports is also consistent with the expenditure-switching channel when prices of US exports to the rest of the world are sticky in US dollars (consistent with DCP): a Fed tightening that leads to an appreciation in the US dollar reduces the competitiveness of US exports. On the other hand, the contemporaneous drop in imports is driven by a fall in the domestic aggregate demand: As US real activity slows down, demand for imports falls. Moreover, under DCP import prices are sticky in US dollars, and there is no expenditure switching that could mitigate the effect of declining demand for imports.[18] Interestingly, there is no statistically significant impact on euro area trade from a Fed monetary policy shock, which may be because the share of total euro area trade directly absorbed by the US (about 6% of total euro area countries' exports), or whose prices are sticky in US dollar (about 20% of total euro area countries' exports, see Boz et al., 2020), is not too large.

The estimated effects on euro area trade prices and quantities are consistent with the predictions of a limited ERPT of euro-denominated export prices, and a higher degree of ERPT of euro-denominated import prices – consistent with PCP or, alternatively, US dollar DCP for (a share of) euro area imports. An

[17] From the perspective of the US, DCP is equivalent to PCP in exports and LCP in imports.

[18] The decline in US imports also contributes to the decline of trade volumes in EMEs after a dollar appreciation (Boz et al. 2020).

ECB tightening improves (i.e. raises) the euro area 's terms of trade statistically significantly and persistently, as shown in the second row of the left column of Figure 4. This is what PCP predicts, as import prices expressed in euro would fall given the appreciation of the euro, while export prices expressed in euro would remain unchanged. However, this finding is also consistent with a share of euro area import prices being sticky in US dollar (as stated above, this amounts to about 24% of euro area countries' total imports). After a Fed tightening, euro area terms-of-trade deteriorate for several months. This finding is again consistent with low ERPT in euro area export prices sticky in euro and a higher ERPT in euro import prices. In the data, a large share of euro area countries' total imports and exports are invoiced in euro, namely about 71% and 74%, respectively (see Boz et al., 2020).

An ECB tightening strongly affects euro area exports, but not imports, as shown in the last two rows of the left column of Figure 4, euro area exports decline statistically significantly and persistently after an ECB tightening. Such drop is consistent with their prices to a large degree being sticky in euro, and hence with the above evidence on euro area terms of trade. That euro area imports do not respond much is consistent with either the expenditure switching and aggregate demand channels offsetting each other, and/or the notion that euro area import prices are to a large extent also sticky in euro (though this would be in contrast with the improvement in the terms-of-trade). There is also no significant impact of ECB monetary policy on US trade, which is again consistent with DCP in US trade.

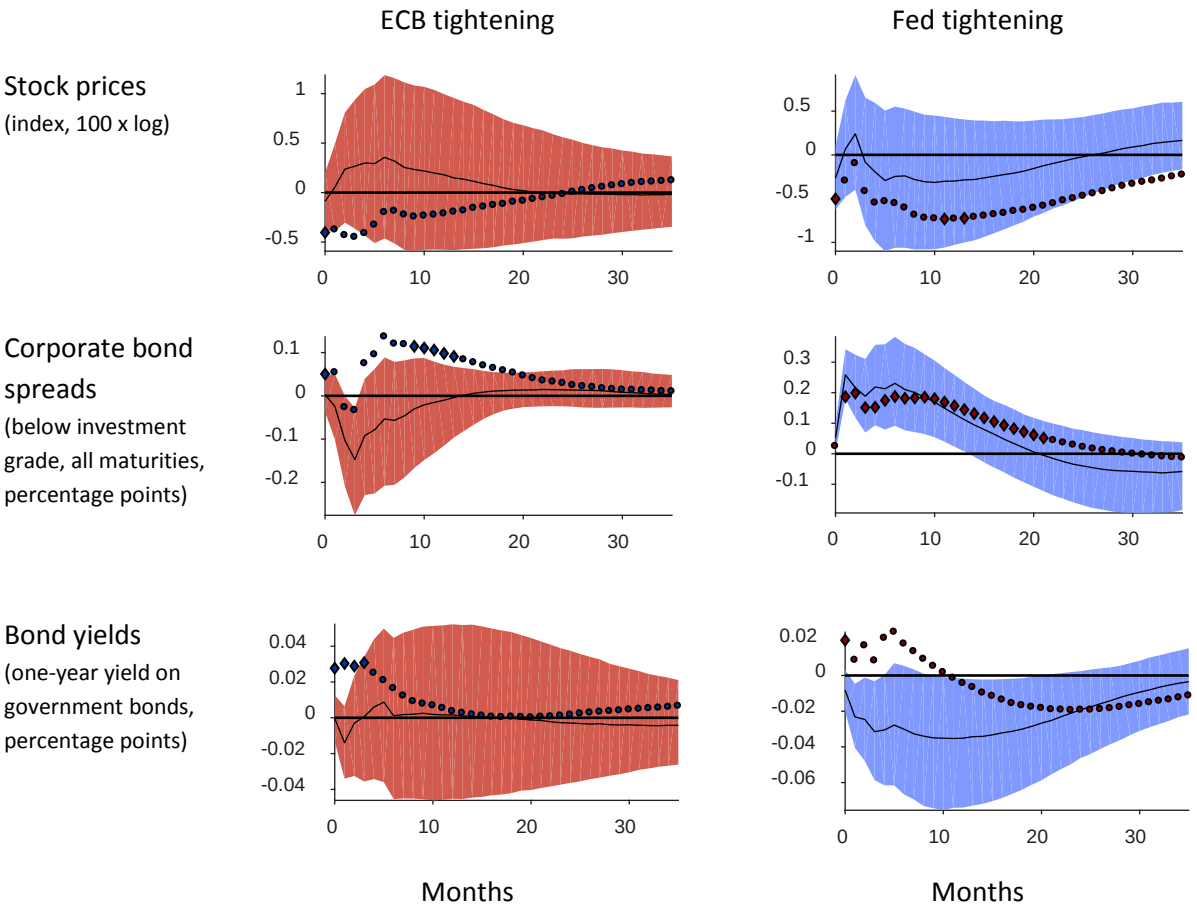
Overall, despite their effect on exchange rates, there are no notable spillovers from ECB monetary policy to US trade and from Fed monetary policy to euro area trade. However, given the evidence for US dollar DCP in global exports (excluding most of those of the euro area), the results so far suggest that Fed monetary policy may have a large impact on trade of other economies, a question we investigate in Section 5 below.

4.4. Effect on financial conditions

The comparable size of the real economies of the euro area and the US contrasts sharply with the unequal global importance of their financial sectors and currencies. The global dominance of US financial markets and the US dollar renders the financial channel between the US and the euro area almost unidirectional, and accounts for the spillovers from US monetary policy on euro area real activity.

Our findings suggest that financial spillovers from ECB and Fed monetary policy are asymmetric. Figure 5 shows the spillovers to three financial variables: stock prices, spreads of speculative-grade corporate bonds, and sovereign bond yields. For stocks, as shown in the top row of the figure, even though both ECB and Fed tightening reduce domestic prices on impact, bilateral spillovers are not statistically significant. Note that this evidence is not inconsistent with a very short-lived positive correlation between euro area and US stock markets after a monetary policy shock over a couple of days that is no longer detectable at monthly frequency.

Figure 5: Financial spillovers of an exogenous monetary policy tightening



Notes: The left-hand column shows the responses to an ECB tightening, and the right-hand column the responses to a Fed tightening. Quantities for the US are plotted in red, quantities of the euro area in blue. The dotted lines are the responses of the domestic variables, with diamonds symbolising significance at the 68% level. In the left-hand column these are the responses of euro area variables, in the right column the responses of US variables. The solid line shows the median impulse response of the corresponding spillover with a 68% confidence band. The stock index shown for the euro area is the Euro Stoxx 50, the index for the US the S&P 500. The corporate bond spread is the option-adjusted spread between a corporate bond with BBB or below investment grade rating and a government bond. The government bonds used are Bunds for the euro area and Treasuries for the US.

At the same time, we find that Fed monetary policy strongly affects interest rates and financing conditions in the euro area. The middle row of Figure 5 shows the spread between a basket of corporate bonds below investment grade (i.e. rated BBB or below, with interest rates adjusted for any included option value) and government bonds. After a Fed tightening, there is a statistically significant and persistent increase in the spread of euro area speculative-grade corporate bonds.[19] In fact this financial

[19] These corporate bonds were not part of the ECB's asset purchase programme. It is conceivable that in recent years they have been more isolated from Fed monetary policy shocks, but this period is too short to significantly dampen the estimated spillover from monetary policy shocks. The impulse responses show the average spillover over 20 years.

spillover is as large as the response of domestic (US) corporate bond spreads, shown by the red dotted line in the right column. The bottom row shows that one-year Bund yields decline after a Fed tightening,[20] pointing to some (systematic) offsetting response by the ECB to mitigate at least some of the effects of Fed monetary policy shocks on the euro area economy.[21] Clearly, financial spillovers are much smaller in case of an ECB tightening compared to a Fed tightening, as responses of US variables in the left column of the figure are small and never statistically significant. A corollary of this finding is that the (unconditional) co-movement between euro area and US bond yields typically observed in the data mostly stems from common shocks or – more generally – synchronised business cycles which induce similar systematic monetary policy responses (Belke and Gros, 2005). In particular, such co-movement in the data could reflect spillovers from central bank information effects. Our findings thus suggest that monetary policy spillovers do not significantly contribute to the observed co-movement between euro area and US financial variables such as stock prices and sovereign rates.[22]

In contrast, an ECB monetary policy tightening does not have a comparable effect on US financial conditions. US corporate bond spreads – unlike euro area corporate bond spreads – do not increase after an ECB tightening. And although one-year government bond yields in the euro area respond significantly to the ECB monetary policy shock, there are no discernible spillovers to US bond yields.[23]

In summary, a Fed tightening tightens financial conditions in the euro area as captured by corporate bond spreads, while an ECB tightening does not affect financial conditions in the US.

5. International effects of ECB and Fed monetary policy

This section explores whether the asymmetry found in the previous section is specific to the euro area - US bilateral links, or whether it can be extended to the global economy.

5.1. Effect on global financial markets

Figure 6 presents the effects of ECB and Fed monetary policy on global financial markets. The right column documents that a Fed tightening contracts borrowing denominated in US dollars worldwide. A

[20] Under "rotational sign restrictions", after a Fed tightening euro area one-year interest rate swaps decline significantly as well.

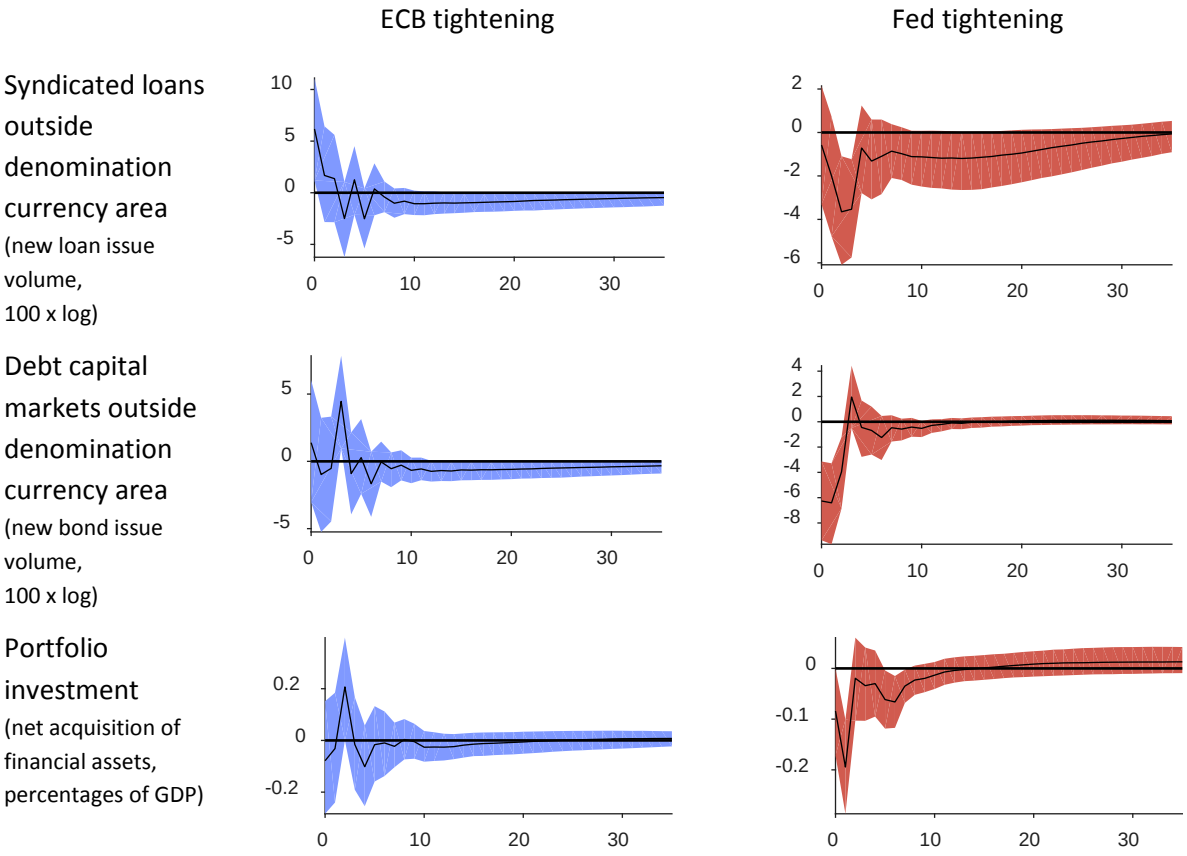
[21] Recall that all euro area impulse responses are net of the effect of any systematic ECB policy response.

[22] Because the effects shown are long-term averages, they are robust to isolated spillover episodes, e.g. in the context of unconventional monetary policy. The period of unconventional monetary policies in the euro area is too short to confirm or reject a possible change in spillovers from the ECB to the US in recent years. Using a different approach, Curcuru et al. (2018b) find that between the euro area and the US spillovers of conventional monetary policy (as measured by changes in expected interest rates) on ten-year yields were not significantly different from spillovers of unconventional monetary policy (as measured by changes in term premia).

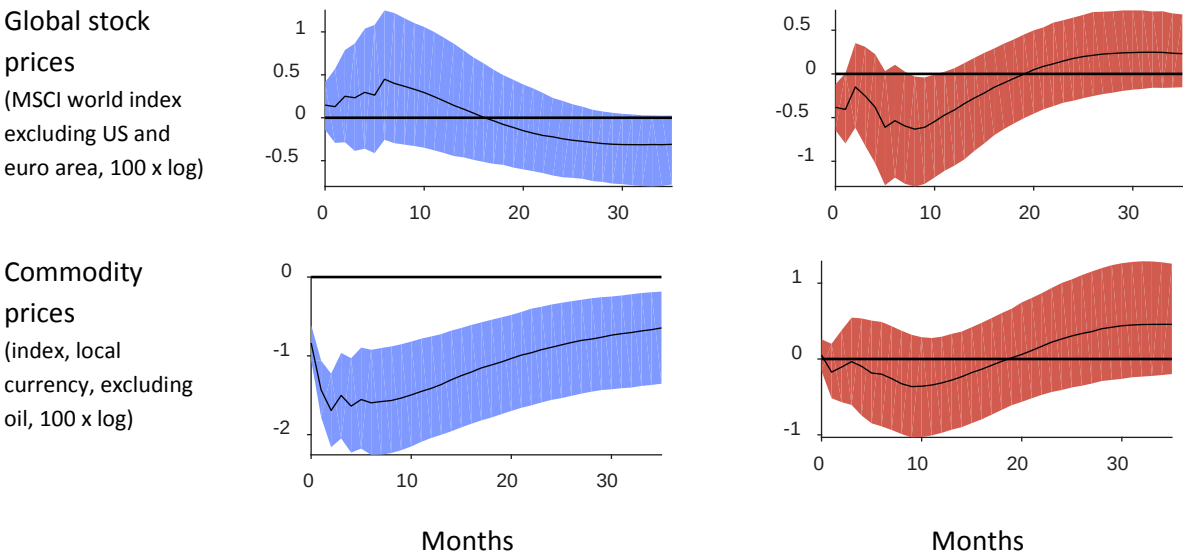
[23] After both ECB and Fed tightening the respective domestic bond yields respond very similarly on impact. During the first half year after the shock a considerable term spread opens up, as shown in the online appendix. Only thereafter do longer maturities follow short-term rates, as noted by Hanson and Stein (2015).

prominent example is new debt issued by borrowers whose business activity is mostly located outside of the US (and other countries which use the US dollar as their official currency). After a Fed tightening, new issuance of dollar-denominated syndicated loans outside the US drops by up to 4%, and new dollar-denominated debt capital, which includes all sectors (government, financial and non-financial), drops by even more (first and second row of Figure 6, respectively). One might conjecture that this drop is mainly due to the financial sector, but this is not the case. Non-financial corporations outside the US reduce their issuance of US dollar debt by just as much.[24] This reveals a direct link between US monetary policy and investment activity in the rest of the world, i.e. a powerful financial spillover channel from Fed monetary policy to the rest of the world.

Figure 6: Effects of an exogenous monetary policy tightening on global financial markets



[24] Please refer to the online appendix for this and further impulse responses.



Notes: The solid line shows the median impulse response surrounded by the 68% confidence band. In the left-hand column these are the responses to an ECB tightening, in the right-hand column the responses to a Fed tightening. Quantities related to the euro area are plotted in blue, quantities related to the US in red.

In contrast, the effect of an ECB tightening on borrowing in euro outside the euro area, shown in the left column of the figure, is not contractionary and barely statistically significant. Euro-denominated borrowing outside the euro area is less common than US dollar-denominated borrowing outside the US.[25] But even in relative terms the effect of ECB monetary policy on foreign euro borrowing is much smaller and insignificant.

Likewise, US international net portfolio investment drops significantly after a Fed tightening. As shown in the third row of Figure 6, after a Fed tightening, US residents acquire a significantly smaller amount of foreign financial assets, i.e. claims against non-US residents, in net terms. Since US liabilities in net terms drop simultaneously, cross-border financial investment positions shrink, consistent with the hypothesis of Fed monetary policy greatly affecting the global financial cycle (Miranda-Agrippino and Rey, 2021). Again, the analogous effects of ECB tightening have the opposite sign and are not statistically significant.

Next, a Fed tightening also depresses global stock markets, while an ECB tightening is inconsequential. Global stock prices, summarised by the MSCI index excluding both US and euro area stocks in the fourth row of Figure 6, fall on impact and a few months after a Fed tightening, but are unchanged after an ECB tightening. It is also worth noting that global stock prices respond more strongly to the Fed's monetary policy than the euro area stock prices presented earlier in Section 4.4.

[25] Since 1999 on average about 31% of US dollar-denominated syndicated loans and about 22% of debt capital have been issued outside the US, whereas of the corresponding euro-denominated assets only about 4% and 7% respectively have been issued outside the euro area. The volume in these foreign euro-denominated markets over the same period was about one-sixth of that in foreign US dollar-denominated markets for syndicated loans, and one-third in the case of debt capital.

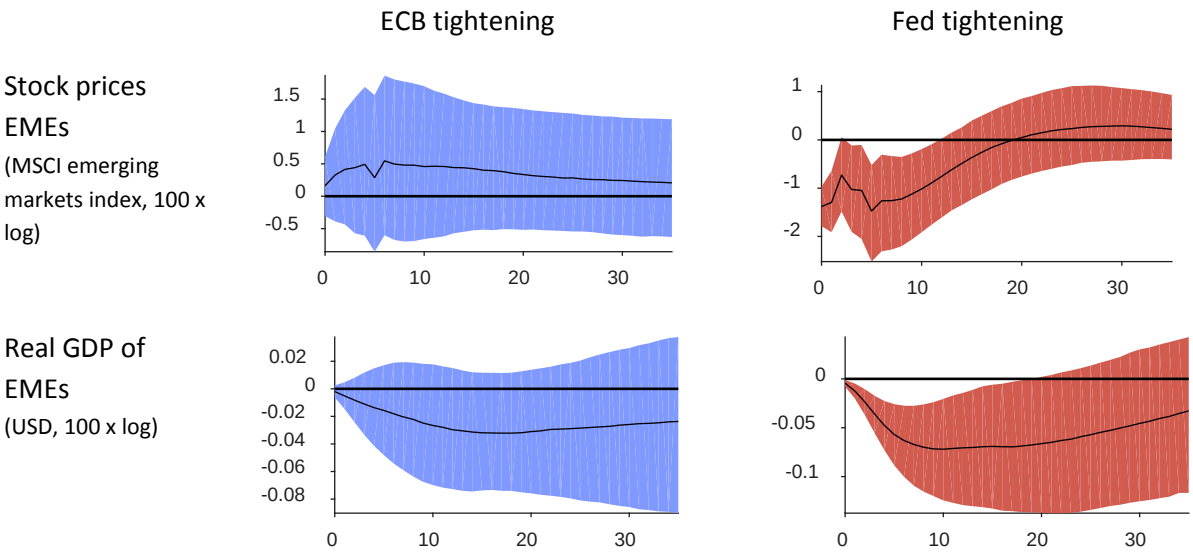
An ECB tightening has a statistically significant impact on non-oil commodity prices, however. Although the spillovers from ECB monetary policy via financial conditions are negligible, there seems to be an indirect impact via the euro area business cycle. An ECB tightening leads to a drop in non-oil commodity prices quoted in US dollars and, in combination with the euro appreciation, to an even larger drop in commodity prices quoted in euros. The effect of a Fed tightening is statistically significant only under the "rotational sign restrictions".

5.2. Effect on EMEs

The first row of Figure 7 shows that financial spillovers to EMEs from Fed monetary policy are much more consequential than those from ECB monetary policy. After a Fed tightening, the statistically significant drop in EME stock prices is larger than that in both euro area and global stock prices shown in Figures 5 and 6; after an ECB tightening, EME stock prices barely move. This mirrors the strong spillovers from Fed tightening to financial markets of EMEs found by Hoek et al. (2020).[26]

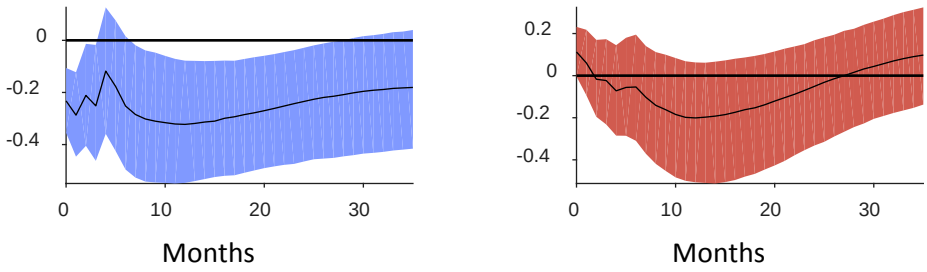
The evidence for asymmetric effects of Fed and ECB monetary policy on EMEs extends to real activity (Avdjiev et al., 2019). Monetary policy tightening by both the ECB and the Fed reduces real GDP in EMEs, but the effect is statistically significant only in case of a Fed tightening.

Figure 7: Effects of an exogenous monetary policy tightening on EMEs



[26] Hoek et al. (2020) consider identification of the drivers of Fed tightening based on high frequency moves in US Treasury yields and stock prices around FOMC announcements and US employment report releases. They interpret positive co-movements between stocks and interest rates around these events as growth shocks and – as we do in this paper – negative co-movements as monetary shocks.

Export volume of EMEs
(index, 100 x log)



Notes: The solid line shows the median impulse response surrounded by the 68% confidence band. In the left-hand column these are the responses to an ECB tightening, in the right-hand column the responses to a Fed tightening.

Both the ECB and the Fed affect EMEs' trade. After an ECB tightening, exports (including energy) decline persistently, but with only a limited impact on overall GDP. Exports similarly fall after a Fed tightening although statistically significant only under the "rotational sign restrictions" approach.[27] This suggests that Fed monetary policy impacts EME real activity beyond trade.

To better understand the transmission channels of monetary policy we focus on non-oil trade, which however requires narrowing the analysis to a smaller set of countries.[28] We focus on spillovers to Brazil, Russia, India, China and South Africa, often referred to as "BRICS" countries. After an ECB and Fed tightening, non-oil exports from, respectively, the euro area and the United States to BRICS countries decline persistently. Imports from BRICS countries decline with a delay, but this is only statistically significant in case of the Fed tightening. Overall, the effects on trade with the BRICS countries are similar for both Fed and ECB tightening. The demand effects that dampen imports from BRICS countries about half a year after the tightening are, however, more pronounced in case of the Fed, in line with the stronger impact of Fed monetary policy on e.g. US unemployment and the weaker appreciation of the US dollar (see Figures 2 and 3).

5.3. A hierarchy of spillovers from monetary policy

The comparison of the effects of ECB and Fed monetary policy in a unified and coherent framework suggests a pronounced asymmetry in their spillovers. Overall, a hierarchy of monetary policy spillovers emerges, which places the Fed ahead of the ECB in terms of the global impact of its monetary policy. Financial spillovers from Fed monetary policy spread to the euro area and other countries, affecting real activity. Trade spillovers from ECB monetary policy barely affect the US but spread to other countries. Finally, significant spillovers from ECB and Fed monetary policy may imply policy trade-offs in EMEs.

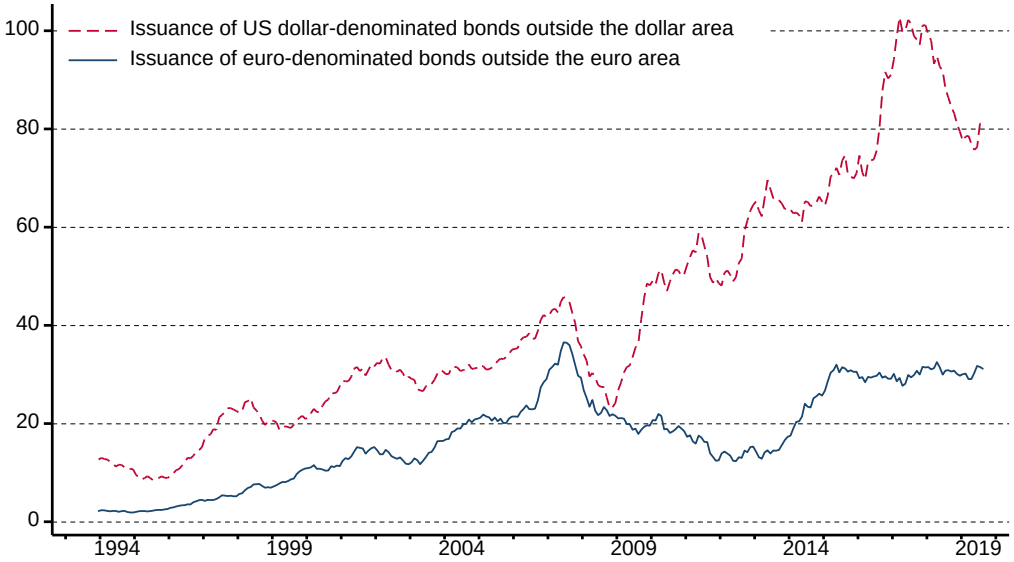
The asymmetry of monetary policy spillovers is most pronounced in financial channels. The importance of this channel of Fed monetary policy has been illustrated during the Covid-19 crisis, when aggressive

[27] Likewise, the remaining impulse responses to a Fed shock in the figure are statistically significant (or more precisely estimated) under the "rotational sign restrictions" approach.

[28] Please refer to the online appendix B for these impulse responses.

action by the Fed, especially in mid-March 2020 resulted in a normalization of financing conditions globally. At least three well-known factors contribute to the asymmetry of the international impact of ECB and Fed monetary policy: the central role of US financial markets, the dominant role of the US dollar, and the relatively low trade openness of the US, with respect to the euro area.

Figure 8: Issuance volume of bonds outside the home currency area



(EUR billions, 12-month moving average)

Sources: Dealogic and ECB calculations.

The first factor is the central role of US financial markets. US financial markets represent a global financial hub, whose size and global interconnectedness can be seen, for example, in the importance of the US dollar lending market. Figure 8 shows the issuance volume of bonds outside of their home currency area. Since 2009 the US dollar bond market has been about three times as large as the euro

bond market.[29] In fact, it has been argued in this vein that Fed monetary policy is a major driver of the global financial cycle (Miranda-Agrippino and Rey, 2020).[30]

A second factor is that the US dollar remains the globally dominant currency.[31] A dominant trade invoicing currency changes transmission via the expenditure switching channel. Our results suggest, however, that the central role of the US dollar in trade invoicing may be only one aspect of dollar dominance (Boz et al. 2017; Gopinath et al., 2020). More important is the US dollar's dominance in the pricing of financial assets, which amplifies the exchange rate effect of Fed monetary policy, affecting global financial conditions. As important financial assets are denominated in US dollars, dollar exchange rate fluctuations affect balance sheet positions worldwide. Thereby, Fed monetary policy can influence not only borrowing and lending in any currency, but also any capital-intensive economic activity, even global value chains (Bruno and Shin, 2015, 2020).

The third factor which helps explain the asymmetry across the two regions is the stronger importance of trade for the euro area than for US GDP. Indeed, trade openness measured in terms of imported goods and services relative to GDP is approximately 25% for the euro area and only 15% for the US. Figures 4 and 7 highlight the pronounced responsiveness of euro area trade to exchange rate movements caused by monetary policy shocks, especially in trade with EMEs.

The first two factors contribute to the potential special role of Fed monetary policy as a driver of the global financial cycle. The global effects of Fed monetary policy are strong, and are not limited to EMEs, but are seen also in the bilateral spillovers to the euro area (see e.g. Figure 3). Further adding to this might be other countries mimicking Fed monetary policy, which is, however, not separable in our analysis (Mukhin, 2018; Corsetti et al., 2021; Georgiadis and Zhu, 2021).

[29] This difference re-emerged after the sovereign bond crisis. Since then, the euro's relevance in bond markets has been falling behind that of the US dollar, enforcing the dominant role of the United States in global financial conditions. In the period up to the year 2007, both euro and dollar bond markets grew rapidly. The euro market grew disproportionally strongly, boosted by the strong euro appreciation, so that by 2007-08 it had largely caught up with the dollar bond market. But after the sovereign bond crisis, the euro bond market only recovered to pre-crisis levels, whereas the dollar bond market kept growing at a constant rate.

[30] For international capital flows, Fed monetary policy may be less important than financial shocks. Habib and Venditti (2019) find that changes in global risk caused by "pure" financial shocks have an even larger effect on capital flows than Fed monetary policy shocks.

[31] The dominant role of the US dollar is particularly sizeable in terms of foreign exchange rate holdings, issuance of international debt by international borrowers and international loans in foreign currency and foreign exchange turnover. Two other pieces of evidence confirm the persistent centrality of the US dollar in global financial markets during periods of high economic tensions. The first piece of evidence is the correlation between the effective exchange rate of the US dollar and global (non-US) stock markets during period of turbulence. The second piece of evidence is the positive correlation between the US dollar and the VIX index. The centrality of the US dollar is explained, besides historical reasons such as the importance of the dollar as an anchor currency, by the safety and liquidity of dollar-denominated assets in crisis periods (Maggiori et al., 2019) and by EME firms' incentives to issue dollar-denominated bonds (Bruno and Shin, 2017) in periods of favourable US dollar carry trades. The relative strength of the euro during the recent pandemic episode signals the relevance of the enhanced institutional architecture of the Economic and Monetary Union and of high-quality marketable euro-denominated assets in determining the future role of the euro (Ilzetzki et al., 2020).

The third factor helps explain why ECB spillovers tend to transmit mainly via trade channels. These spillovers via trade are stronger for other economies than bilaterally with the US. For trade partners other than the US, the euro area's import share of goods is about 90%, so that ECB monetary policy can spill over to smaller countries via, specifically, the demand and expenditure switching channels.

6. Concluding remarks

In this paper we estimate spillovers from Fed and ECB monetary policy in a unified and state-of-the-art econometric framework. We find that bilateral spillovers between the US and the euro area are generally small. Our finding of a small impact of ECB monetary policy on the US economy could be due to two reasons: First, it might reflect that the Fed has been able and determined to fully offset spillovers from ECB monetary policy; alternatively, it might reflect that ECB monetary policy spillovers to the US have been small in the first place. We also find that the Fed monetary policy spillovers to the euro area are generally small as well, they are statistically significant, at least for unemployment and there is evidence of a stronger responsiveness of euro area financial conditions to Fed monetary policy conditions. This finding could imply that the ECB faces trade-offs between price stability and stabilisation of output and/or financial conditions in the very short term. Notwithstanding this possibility, our estimates suggest the ECB has been successful in preserving price stability in the face of Fed monetary policy spillovers at least over the *medium term*. Overall, given our findings of limited size of transatlantic spillovers, the necessary pre-conditions that would justify more extensive forms of international monetary policy cooperation between the ECB and the Fed do not appear to be met.

Looking at spillovers from Fed and ECB monetary policy to EMEs, our findings suggest a key role for the trade and financial channels. Moreover, our findings point to a pronounced asymmetry across ECB and Fed monetary policy spillovers. The large spillovers from Fed monetary policy via financial channels are consistent with the central role of US financial markets and the US dollar, and the spillovers from ECB monetary policy through trade are consistent with the more limited integration of the US economy in world trade. The policy trade-offs in EMEs implied by our finding of non-trivial spillovers could be rooted in more pronounced and widespread frictions in these economies.

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Appendix

High-frequency identification of monetary policy shocks

As highlighted in Section 3, we use financial market reactions to monetary policy announcements in order to identify monetary policy shocks. The approach follows Jarociński and Karadi (2020).

The dataset consists of 248 Federal Reserve monetary policy announcements since 1990 and 283 ECB monetary policy announcements since 1999. Financial market reactions are measured in the time window starting 10 minutes before and ending 20 minutes after a central bank announcement. In the case of the Federal Reserve, the announcement time is typically the release time of the press release. In the case of the ECB, the time window is longer and ends 20 minutes after the end of the press conference (when there is one). In these windows we record interest rate surprises and stock price surprises. The Federal Reserve interest rate surprises are defined as the mean of the changes in federal funds futures and eurodollar futures with remaining maturities from one month up to one year. The ECB interest rate surprises defined as the mean of the changes in EONIA swaps with maturities from one month up to one year. By including maturities up to one year, these surprises capture not just the changes of the current policy rates but also of the expectations for interest rates up to one year into the future, reflecting forward guidance and non-standard policies. The Federal Reserve stock price surprises are measured as the change in the S&P 500 stock index and the ECB stock price surprises are measured as the change in the Euro Stoxx 50 stock index. We aggregate these surprises to monthly frequency.

In the next step we isolate the monetary policy shocks from among the interest rate surprises by purging the information effects from them. This is based on the sign restriction: interest rates and stock prices are assumed to co-move negatively after a monetary policy shock, as is implied by a wide range of models. Therefore, we treat as monetary policy shocks only those interest rate surprises which co-move negatively with stock prices in the respective month. A more sophisticated alternative is to decompose interest rate and stock price surprises into two orthogonal components and "rotate" them so that one is associated with a negative co-movement and the other with the positive co-movement of interest rate and stock price surprises. Jarociński and Karadi (2020) find that in the large sample for the United States the two approaches yield similar results, but in the euro area sample the former, simpler approach, dubbed "poor man's sign restrictions", yields a stronger instrument for monetary policy (i.e. is associated with a stronger increase in the one-year bond yield) than the more sophisticated sign restrictions approach. Therefore, we use this approach for both the United States and the euro area for comparability. The Federal Reserve monetary policy surprise in April 2001 is larger than six standard deviations of monetary policy shocks. We exclude this stark outlier from the analysis.

Estimation of the impulse responses

We track the responses of the economy to the identified shocks using a VAR. The baseline VAR for each country includes the one-year government bond yield, stock prices, the corporate bond spread, industrial production and the respective consumer price index (CPI/HICP). We add the identified shock

to this VAR as the first variable. We restrict the coefficients of the first equation to zero, reflecting the fact that the shock is independently and identically distributed. After estimating the VAR with the standard Minnesota prior, we compute the impulse responses to the first shock identified recursively. The variables and the estimation of the baseline VAR are the same as in Jarociński and Karadi (2020). This paper also provides details on the rotational sign restrictions approach, which yields a stronger instrument for Federal Reserve monetary policy shocks, but not for ECB shocks.

We compute the effect of the Federal Reserve policies on the euro area (plotted in the graphs as solid line) by combining the Federal Reserve shocks with the euro area variables in the VAR. Analogously, for the domestic effects of the Federal Reserve policies (plotted with dots) we combine Federal Reserve shocks with the US variables in the VAR. To obtain the effect of the ECB policies, the set-up is simply mirror-inverted: the domestic effect of ECB policies is based on the effect of ECB shocks on euro area variables; the spillover effect to the United States is based on the effect of ECB shocks on US variables. The responses of other variables, which are not part of the baseline VAR specification, are computed by adding them one by one as last variable to the respective baseline VAR.

Several variables that we study are bilateral: the exchange rate, the spread between the United States and the euro area bond, etc. In these cases, we use a bilateral VAR specification[32] to compute their impulse responses. The bilateral VAR includes the exchange rate, the spread between US Treasuries and one-year Bund yields, the corporate bond spread of the country experiencing the shock and, separately for the United States and the euro area, industrial production and consumer price indices.

[32] Georgiadis, Georgios (2017) compares the performance of bilateral VARs with multilateral (global) VARs.

Online Appendix to "Making waves: Monetary policy and its asymmetric transmission in a globalised world"

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A. Data

The monetary and central bank information shocks are part of the online appendix to Jarociński and Karadi (2020).

All series cover the period January 1999-December 2018, unless otherwise noted.

Table A1: Variable descriptions

Variable	Euro area	United States
Interest rate differential	Yield spread between the one-year Bund and the benchmark one-year Treasury as calculated by Thomson Reuters, end-of-month. Source: Thomson Reuters.	Yield spread between the benchmark one-year Treasury and the one-year Bund as calculated by Thomson Reuters, end-of-month. Source: Thomson Reuters.
Exchange rates	ECB reference USD/EUR exchange rate, rebased to EUR/USD, monthly average. Source: ECB Statistical Data Warehouse (SDW).	ECB USD/EUR reference exchange rate, monthly average. Source: SDW.
HICP/CPI	Harmonised Index of Consumer Prices (HICP) for the euro area in changing composition, working-day and seasonally adjusted, monthly. Source: SDW.	Consumer Price Index (CPI) for all urban customers: all Items, seasonally adjusted, monthly. Source: Federal Reserve Bank of St. Louis (FRED database).
Industrial production	Industrial production index, excluding construction, monthly. Source: SDW.	Industrial production index, excluding construction, monthly. Source: FRED.
Unemployment rate	Standardised unemployment rate for euro area in fixed composition (19 countries), seasonally but not working-day adjusted, monthly. Source: SDW.	Civilian unemployment rate, seasonally adjusted, monthly. Source: FRED.
Real effective exchange rate	Real broad effective exchange rate of the euro area, trade-weighted, deflated by relative consumer prices, as calculated by the Bank for International Settlements, monthly. Source: Haver Analytics	Real broad effective exchange rate of the United States, trade-weighted, deflated by relative consumer prices, as calculated by Bank for International Settlements, monthly. Source: Haver Analytics.
Terms of trade (excluding oil)	Export prices over import prices in euro, unit value index, monthly, sample: 2000-2018. Source: Haver Analytics.	Export prices over import prices in US dollars, unit value index, monthly, sample: 2000-2018. Source: Haver Analytics.

Total real exports (excluding oil)	Euro area trade data, deflated by price indicators, excluding oil trade, monthly, sample: 2000-2018. Sources: Haver Analytics, ECB calculations.	US trade data, deflated by price indicators, excluding oil trade, monthly, sample: 2000-2018. Sources: Haver Analytics, ECB calculations.
Total real imports (excluding oil)	Euro area trade data, deflated by price indicators, excluding oil trade, monthly, sample: 2000-2018. Sources: Haver Analytics, ECB calculations.	US trade data, deflated by price indicators, excluding oil trade, monthly, sample: 2000-2018. Sources: Haver Analytics, ECB calculations.
Stock prices	Dow Jones Euro Stoxx 50, historical close, end-of-month. Source: SDW.	S&P Dow Jones S&P 500 index, end-of-month. Source: SDW
Corporate bond spreads	Average spread between euro area corporate bonds and euro area government bonds; ICE BofAML Euro High Yield Index option-adjusted spread, basket of corporate bonds below investment grade (i.e. rated BBB or below), spreads averaged across maturities, monthly average. Source: FRED	Average spread between US corporate bonds and US government bonds; ICE BofAML US High Yield Master II option-adjusted spread, basket of corporate bonds below investment grade (i.e. rated BBB or below), spreads averaged across maturities, monthly average. Source: FRED.
Bond yields	Thomson Reuters benchmark one-year German government bond bid yield, end-of-month. Source: Thomson Reuters.	Thomson Reuters benchmark one-year Treasury bid yield, end-of-month. Source: Thomson Reuters.
Syndicated loans outside denomination currency area	Volume of syndicated loans denominated in euro (or the former currency of one of the 11 initial euro area countries) and newly issued outside of countries with the euro as official currency (pre-1999: outside of the 11 initial member countries), monthly, unit: euro. Sources: Dealogic, ECB calculations.	Volume of syndicated loans denominated in US dollars and newly issued outside of countries with the US dollar as official currency, unit: US dollar, monthly; Sources: Dealogic, ECB calculations.

Debt capital markets outside denomination currency area	Volume of newly issued debt capital denominated in euro (or the former currency of one of the 11 initial member countries) outside of countries with the euro as official currency (pre-1999: outside of the 11 initial member countries), unit: euro, monthly. Sources: Dealogic, ECB calculations.	Volume of newly issued debt capital denominated in US dollars outside of countries with the US dollar as official currency, unit: US dollar, monthly. Sources: Dealogic, ECB calculations.
Portfolio investment – financial assets	Net acquisition of financial assets, euro area in fixed composition (19 countries) vis-à-vis rest of the world, not seasonally adjusted, monthly, at market value. Source: SDW (balance of payments and international investment position).	Net purchases of foreign securities by US residents, not seasonally adjusted, monthly, at market value. Sources: Treasury International Capital (TIC) Data, Haver Analytics.
Global stock prices	Weighted average of MSCI country indices underlying the MSCI World and MSCI emerging markets indices excluding the United States and the euro area, local currency, all series rebased to 100 in January 2010, countries weighted by market capitalisation in US dollar, end-of-month. Source: Bloomberg, ECB calculations.	
Commodity prices in US dollars	Market prices of raw materials, excluding energy, in US dollars, monthly average. Source: OECD.	
Commodity prices in euro	Market prices of raw materials, excluding energy, in euro, monthly average. Source: OECD.	
Stock prices in emerging economies	MSCI emerging markets index, US dollar, end-of-month. Source: Bloomberg.	
Real GDP of emerging economies	GDP at prices and exchange rates in 2010, seasonally adjusted, in US dollars, cubic spline interpolation from quarterly data, sum of the following countries: Bolivia, Botswana, Brazil, Chile, China, Costa Rica, Ecuador, El Salvador, Hong Kong, India, Indonesia, Israel, Jordan, Kazakhstan, South Korea, Malaysia, Mexico, Paraguay, Peru, Philippines, Poland, Russia, Singapore, South Africa, Taiwan, Thailand, Turkey, Uruguay. Source: Haver Analytics.	
Export volume of emerging economies	Export volume index including energy, 43 countries, monthly. Sources: Haver Analytics and CPB Netherlands Bureau for Economic Policy Analysis World Trade Monitor.	

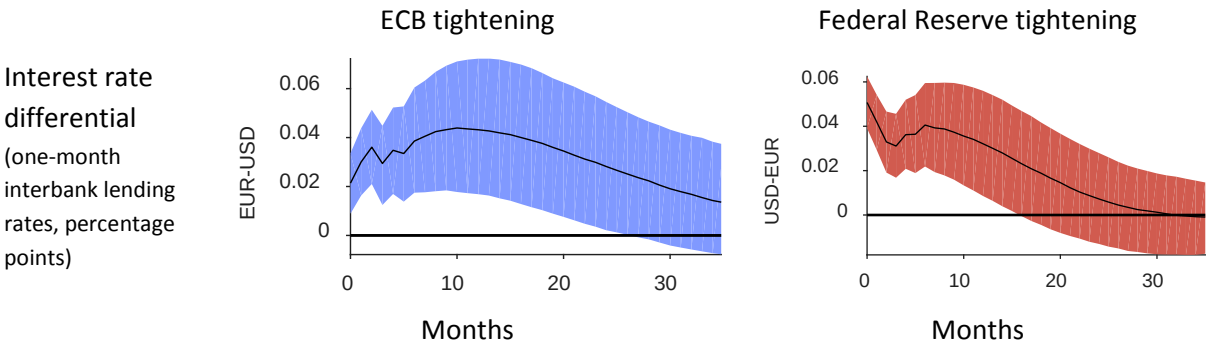
Table A2: Description of additional variables used in the online appendix

Variable	Euro area	United States
Interest rate differential	Spread between one-month EURIBOR and LIBOR, end-of-month. Source: SDW.	Spread between one-month LIBOR and EURIBOR, end-of-month. Source: FRED.
Core HICP/CPI	HICP for all items excluding energy and food, for euro area in changing composition, working-day and seasonally adjusted, monthly. Source: SDW.	CPI for all urban customers, all items less food and energy in US city average, seasonally adjusted, monthly. Source: FRED.
GDP deflator	GDP deflator interpolated from quarterly data, employing a similar strategy as for the United States. Source: SDW.	GDP deflator interpolated from quarterly data, following Stock and Watson (2010). Source: FRED.
Real GDP	Real GDP interpolated from quarterly data, employing a similar strategy as for the United States. Source: SDW.	Real GDP interpolated from quarterly data, following Stock and Watson (2010). Source: FRED.
Total real trade balance (excluding oil)	Euro area trade data, deflated by price indicators, excluding oil trade, monthly, sample: 2000-2018. Source: Haver Analytics, ECB calculations.	US trade data, deflated by price indicators, excluding oil trade, monthly, sample: 2000-2018. Source: Haver Analytics, ECB calculations.
Interest rate swaps	One-year interest rate swap based on six-month EURIBOR, monthly average. Source: Bloomberg.	One-year interest rate swap based on three-month LIBOR, monthly average. Source: Bloomberg.
Term spreads	Spread between ten and one-year yields based on the estimated German government debt yield curve, end-of-month. Source: Thomson Reuters.	Spread between ten and one-year Treasury constant maturity rates, end-of-month. Source: Thomson Reuters.

New issuance of bonds outside denomination currency area by non-financial corporations	Volume of debt capital denominated in euro (or the former currency of one of the 11 initial euro area countries) and newly issued outside of countries with the euro as official currency (pre-1999: outside of the initial member countries), non-financial corporations only, monthly, unit: euro. Sources: Dealogic, ECB calculations.	Volume of debt capital denominated in US dollars and newly issued outside of countries with the US dollar as official currency, non-financial corporations only, unit: US dollar, monthly. Sources: Dealogic, ECB calculations.
New issuance of bonds outside denomination currency area, low or junk rating	Volume of debt capital denominated in euro (or the former currency of one of the 11 initial euro area countries) and newly issued outside of countries with the euro as official currency (pre-1999: outside of the initial member countries), low or junk rating only, monthly, unit: euro. Sources: Dealogic, ECB calculations.	Volume of debt capital denominated in US dollars and newly issued outside of countries with the US dollar as official currency, low or junk rating only, monthly, unit: US dollars. Sources: Dealogic, ECB calculations.
Portfolio investment – financial liabilities	Net incurrence of financial liabilities, euro area in fixed composition (19 countries) vis-à-vis rest of the world, not seasonally adjusted, monthly, at market value. Source: SDW (balance of payments and international investment position).	Net foreign purchases of US securities, not seasonally adjusted, monthly, at market value. Sources: TIC data, Haver Analytics.
Oil price (in US dollars, in euro)	Spot price of West Texas Intermediate. Source: FRED.	
Real exports to BRICS (excluding oil)	Sum of real exports from euro area to all BRICS countries, deflated by price indicators, excluding oil, monthly, sample: 2000-2018. Sources: Haver Analytics, ECB calculations.	Sum of real exports from the United States to all BRICS countries, deflated by price indicators, excluding oil, monthly, sample: 2000-2018. Sources: Haver Analytics, ECB calculations.
Real imports from BRICS (excluding oil)	Sum of real imports by the euro area from all BRICS countries; see real exports to BRICS (excluding oil).	Sum of real imports by the United States from all BRICS countries; see real exports to BRICS (excluding oil).

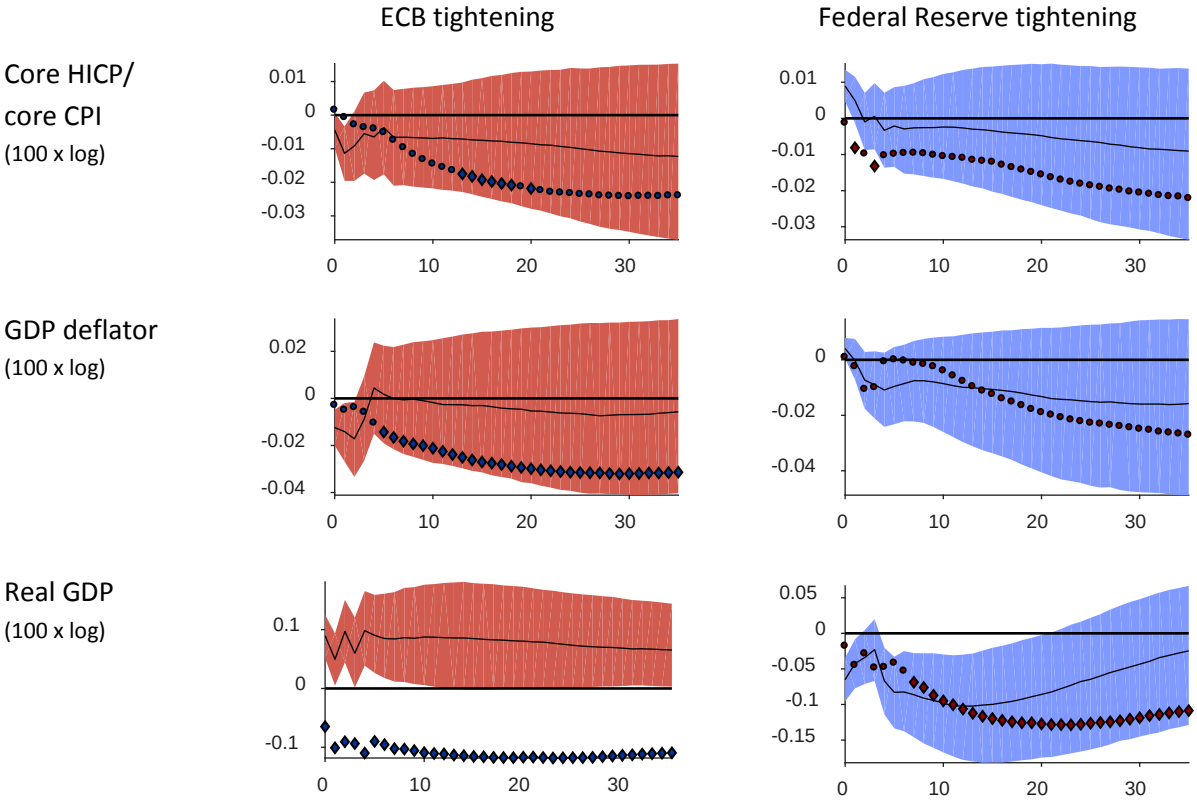
B. Additional impulse responses

Figure A1: Response to an exogenous monetary policy tightening (bilateral model)

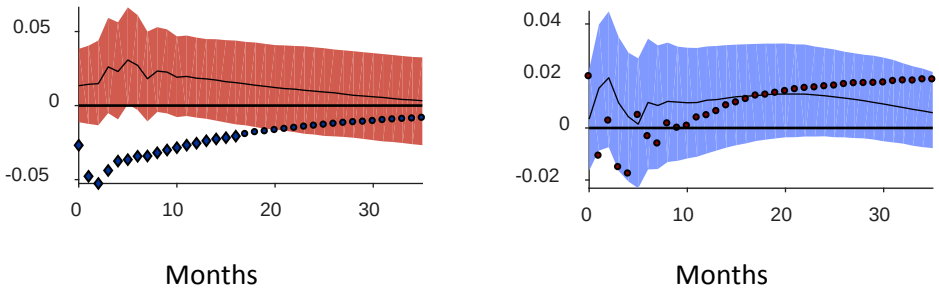


Notes: The solid line shows the median impulse response surrounded by the 68% confidence band based on the bilateral model.

Figure A2: Spillovers from an exogenous monetary policy tightening to real activity and prices



Total real trade balance (excluding oil)
(percentages of GDP)



Months Months

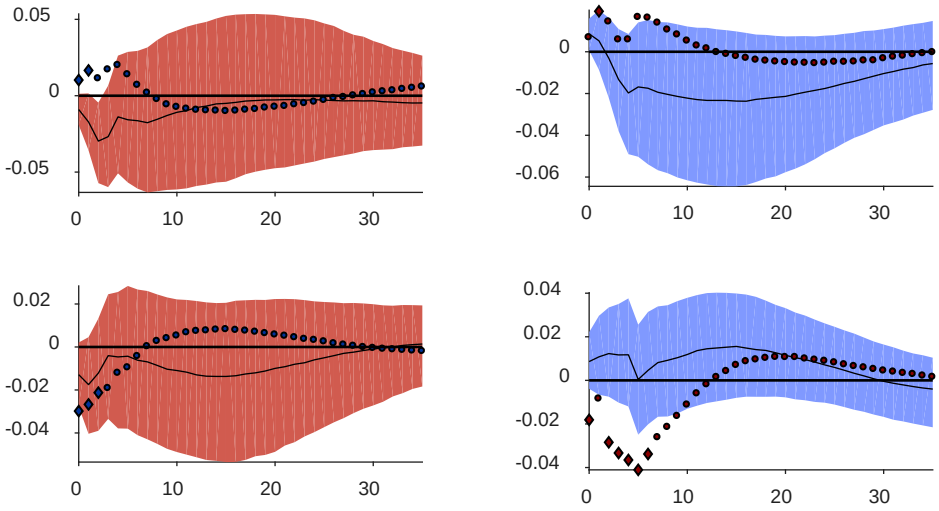
Notes: The solid line plots the median spillover surrounded by the 68% confidence band. In the left-hand column these are the responses to an ECB tightening, in the right-hand column the responses to a Federal Reserve tightening. Quantities for the United States are plotted in red, quantities of the euro area in blue. The dotted lines plot the responses of the corresponding domestic variables, with diamonds symbolising significance at the 68% level. In the left-hand column these are the responses of euro area variables, in the right-hand column the responses of US variables.

Figure A3: Spillovers from an exogenous monetary policy tightening to financial conditions

ECB tightening Federal Reserve tightening

Interest rate swaps
(one-year yield, percentage points)

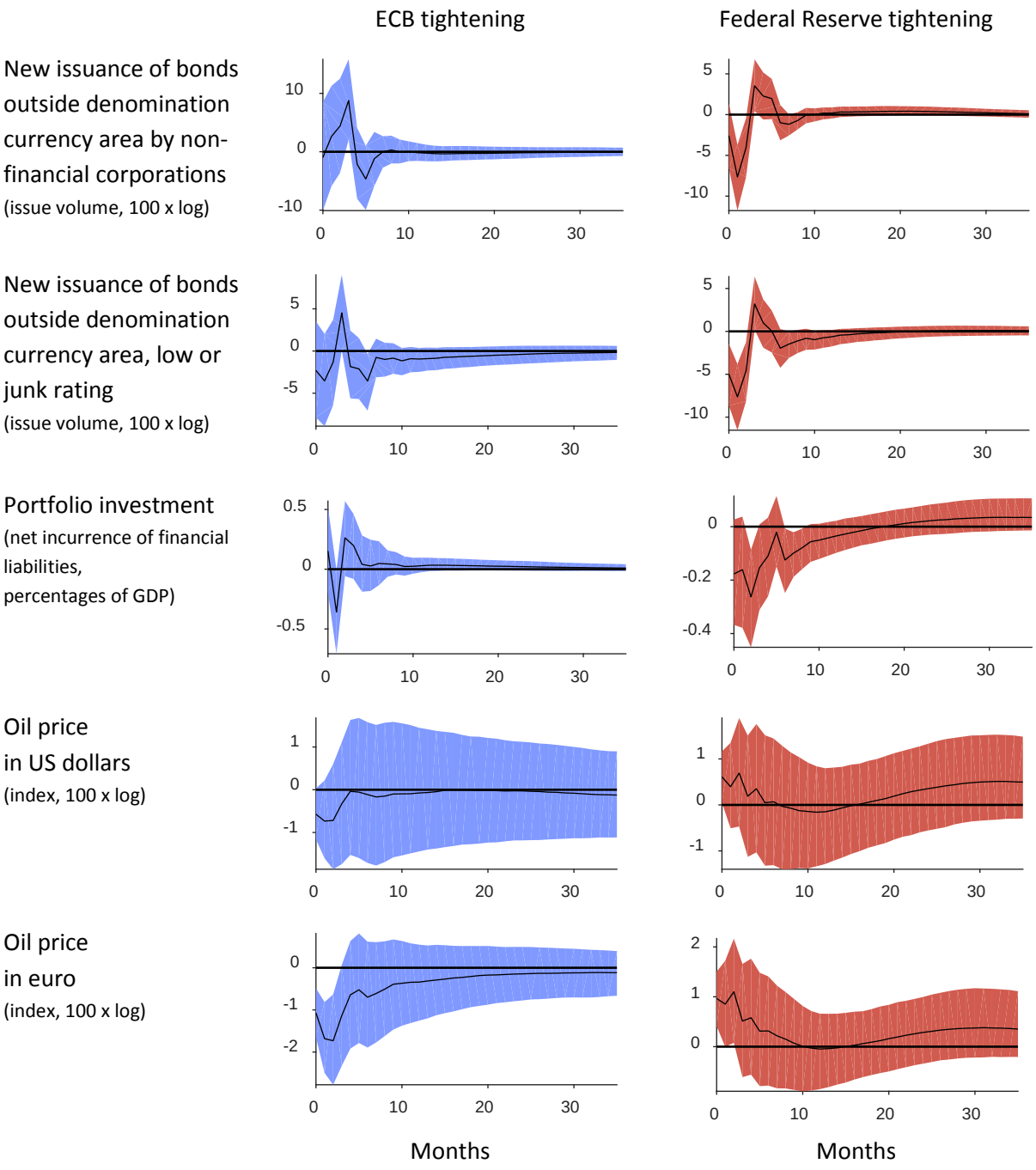
Term spreads
(ten-year-one-year government bond spreads, percentage points)



Months Months

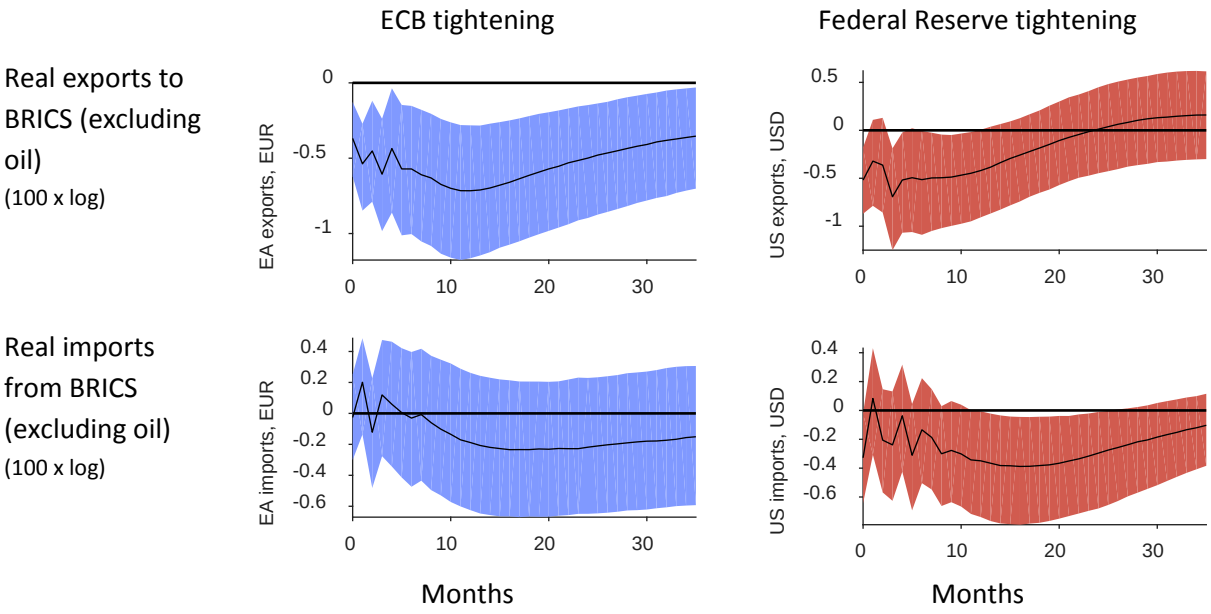
Notes: The solid line plots the median spillover surrounded by the 68% confidence band. In the left-hand column these are the responses to an ECB tightening, in the right-hand column to a Federal Reserve tightening. Quantities for the United States are plotted in red, quantities of the euro area in blue. The dotted lines plot the responses of the corresponding domestic variables, with diamonds symbolising significance at the 68% level. In the left-hand column these are the responses of euro area variables, in the right-hand column the responses of US variables. The government bonds used are the Bund for the euro area and the Treasury for the United States.

Figure A4: Effects of an exogenous monetary policy tightening on global financial markets



Notes: The solid line shows the median impulse response surrounded by the 68% confidence band. In the left-hand column these are the responses to an ECB tightening, in the right-hand column to a Federal Reserve tightening. Quantities related to the euro area are plotted in blue, quantities related to the United States in red.

Figure A5: Effects of an exogenous monetary policy tightening by the ECB or the Federal Reserve on emerging economies



Notes: The solid line shows the median impulse response surrounded by the 68% confidence band. In the left-hand column these are the responses to an ECB tightening, in the right-hand column the responses to a Federal Reserve tightening. (EA = euro area)