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Quantitative easing and sovereign bond yields: a global perspective

Dimitris Malliaropulos

Petros M. Migiakis

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BANK OF GREECE
Economic Analysis and Research Department – Special Studies Division
21, E. Venizelos Avenue
GR-102 50 Athens
Tel: +30210-320 3610
Fax: +30210-320 2432

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QUANTITATIVE EASING AND SOVEREIGN BOND YIELDS: A GLOBAL PERSPECTIVE

Dimitris Malliaropulos
Bank of Greece and University of Piraeus

Petros M. Migiakis
Bank of Greece

Abstract

We document the existence of a global monetary policy factor in sovereign bond yields in a panel consisting of both developed and emerging economies. This global factor is related to the size of the aggregate balance sheet of the four major central banks (Fed, ECB, Bank of Japan and Bank of England). Our estimates suggest that large-scale asset purchases and liquidity provision of major central banks following the Global Financial Crisis have contributed to a significant and *permanent* decline in long-term yields globally, ranging from 250 basis points for AAA rated sovereigns to 330 basis points for B rated sovereigns. Fiscally weaker Eurozone countries benefited most from Quantitative Easing, with their sovereign yields declining by 600-750 basis points, depending on the rating of their sovereigns. Our findings have important policy implications: normalizing monetary policy by scaling down the expanded balance sheets of major central banks to pre-crisis levels may lead to sharp increases in sovereign bond yields globally with severe consequences for financial stability, vulnerable sovereigns and the global economy.

Keywords: monetary policy; quantitative easing; sovereign bonds; interest rates; panel cointegration.

JEL classifications: E42; E43; G12; G15

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Correspondence:
Petros Migiakis
Bank of Greece
21 El. Venizelou avenue,
10250 Athens, Greece
tel: +302103203587
email: pmigiakis@bankofgreece.gr

1. Introduction

In the aftermath of the Global Financial Crisis of 2007-2008, major central banks resorted to unconventional monetary policy (UMP) measures such as ample liquidity provision to commercial banks and large-scale asset purchases, as short-term interest rates had hit the zero lower bound. The purpose of these measures (often called "Quantitative Easing" or "QE") was to improve the transmission of monetary policy and to lower long-term interest rates, thus supporting the real economy and avoiding a deflationary downward spiral.[1]

Numerous empirical papers have examined the effects of QE on financial market variables such as bond yields, equity returns and exchange rates at the national level.[2] There is indeed strong empirical evidence that the U.S. Federal Reserve's Large-Scale Asset Purchase (LSAP) programme lowered U.S. bond yields significantly.[3] Similar results have been obtained for the U.K. and the euro area.[4] Moreover, given that global financial markets are highly integrated, the implementation of such policies has affected sovereign bond yields globally as investors rebalanced their portfolios towards higher-yielding sovereign bonds and other assets outside the borders of the countries which employed these policies. In fact, a number of recent studies examine international spillover effects of QE.[5]

In this paper, we document the existence of a global monetary policy factor in sovereign bond yields in a panel consisting of both developed and emerging economies. This global factor is related to the size of the aggregate balance sheet of the four major central banks (Federal Reserve System, European Central

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[1] According to standard representative-agent models, QE should have no effects on the term structure and real economic variables due to Ricardian equivalence. This is not true, however, when the zero lower bound is binding and financial markets are segmented, see Cùrdia and Woodford (2011).

[2] For a survey of the early empirical literature on the effects of QE on bond yields and macroeconomic variables see Joyce et al. (2012).

[3] See, e.g., Doh (2010), Gagnon et al. (2011), D'Amico et al. (2012), D'Amico and King (2013), Wright (2011) and Bauer and Rudebusch (2011), Krishnamurthy and Vissing-Jorgenson (2011), Meaning and Zhu (2011) and Li and Wei (2013).

[4] For the U.K., see, e.g., Meier (2009), Joyce et al. (2011), Meaning and Zhu (2011), Breedon et al (2012), Christensen and Rudebusch (2012), McLaren et al. (2014) and Steeley (2015). For the euro area, see, e.g. Falagiarda and Reitz (2015) and De Santis (2016). For a review of the empirical literature, see Dell'Ariccia et al. 2018.

[5] See, e,g., Neely (2015), Moore et al. (2013), Rogers et al. (2016), Belke et al. (2017), MacDonald (2017), Fratzscher et al. (2012) and (2017).

Bank, Bank of Japan and Bank of England). We use a panel cointegration framework that accounts for the interaction between the level of sovereign risk, proxied by sovereign credit ratings, and the size of the aggregate balance sheet of the four major central banks. As a result, the effects of global QE differ across sovereigns with different credit ratings.

Our empirical framework allows distinguishing between permanent and temporary effects of unconventional monetary policies. This is an important issue from a policy perspective: If QE measures of central banks in the aftermath of the Global Financial Crisis have led to a permanent decline in global bond yields, long-term interest rates will likely remain low for a long time if central banks continue to keep their large balance sheets or reduce their size only gradually. On the flipside, if QE has led to a permanent decline in global bond yields, then reducing the stock of assets in central banks' portfolios too quickly could induce significant increases in long-term interest rates worldwide, leading to a sharp tightening of financial conditions with severe consequences on global economic activity and financial stability.

We find that, in the long run, sovereign bond yields are related to both sovereign ratings and the size of the aggregate balance sheet of the four major central banks, implying that QE is a global driver of bond yields. In terms of economic significance, our findings suggest that global QE policies over the period 2009-2017 have contributed to a permanent decline in sovereign bond yields, ranging from 250 basis points (bps) for AAA rated sovereigns to 330 bps for B rated sovereigns. Hence, while central banks have responded to the secular decline in the so-called "natural" short-term real interest rate[6] with unconventional monetary policies, these policies have eventually led to a permanent downward shift of the global sovereign yield curve.

[6] Laubach and Williams (2003) and Holston et al. (2017) document the secular decline in the natural rate, defined as the real short-term interest rate consistent with full employment and stable inflation. Williams (2016) and Constancio (2017) discuss the implications of the secular decline in the natural rate for monetary policy. Kiley (2018) and Kiley and Roberts (2017) present simulation results using a large-scale model (FRB/US), suggesting that QE can offset a significant portion of the adverse effects of the zero lower bound when the equilibrium real interest rate is low.

Our paper contributes to the literature on international spillover effects of QE. In contrast to previous papers in this strand of literature, which focus on international spillover effects of QE policies of a single central bank, we look at QE as a global phenomenon. In order to do so, we aggregate the QE measures of the four major central banks and examine their impact on global sovereign bond yields. By aggregating monetary policy measures across major central banks, we take the view that QE has acted as a global factor on sovereign bond markets, affecting their valuations. We provide extensive empirical evidence in support of this view.

Our motivation comes from a growing literature on the role of common factors in global financial prices. Pan and Singleton (2008) and Longstaff et al. (2011), among others, provide evidence that sovereign yield spreads are related to global factors. Malliaropulos and Migiakis (2018) show that most of the re-pricing of sovereign risk in global bond markets following the Global Financial Crisis is related to a common risk factor, which is driven by global variables such as investor confidence, volatility risk, the Fed's monetary base and the position and the slope of the Treasury yield curve in the US. Rey (2013) and Miranda-Agripino and Rey (2018) document the existence of a global financial cycle in asset prices which is largely driven by US monetary policy variables. The common factor accounts for about 60% of the variation of global asset prices and is negatively correlated with proxies of aggregate risk aversion and global volatility such as the CBOE VIX index. Kinateder and Wagner (2017) find that sovereign yield spreads in the euro area are driven by three unobservable common factors which explain about 70% of their variation over time.

[Insert Figure 1, around here]

We follow this strand of literature, but go beyond the usual approach of looking at the international spillover effects of national QE policies and look at QE as part of a global risk factor driving international sovereign yields. Figure 1 provides some preliminary evidence of our claim. The figure plots the aggregate balance sheet of the four major central banks as a share of the combined GDP of the four countries/economic areas along with the first principal component of all ten-year sovereign bond yields, that span all rating classes. The figure suggests that the increase in the size of the balance sheet of the four major central banks explains about 90% of the common variation of global bond yields over the period 2009-2017. As shown in Appendix II, the two series are cointegrated, i.e. they share a common stochastic trend, with causality in the long run running from the size of central banks' aggregate balance sheet to the trend component of sovereign bond yields.

From a monetary policy perspective, our paper also contributes to the ongoing debate about the "new normal" of monetary policy[7] and, in particular, the question whether central banks should keep appropriately large balance sheets in the future.[8] Proponents of this view point out that a large balance sheet could be a tool for enhancing financial stability, as it allows central banks to meet the increased demand of the private sector for safe, liquid assets, particularly during periods of financial crises. Caballero and Fahri (2014) discuss the emergence of a deflationary "safety trap" equilibrium due to a shortage of safe assets following the collapse of the ABS (Asset Backed Securities) and ABCP (Asset Backed Commercial Paper) markets during the Global Financial Crisis. As the authors document, there is a strong demand from the private sector for safe, liquid assets, as indicated by the fact that investors are willing to hold these assets at very low – even negative – yields.

The increased demand for safe assets can be met either by allowing the private sector to produce the equivalent supply through securitizations of loans, or in the form of bank reserves, provided by the central bank. Of course, the latter is a preferable strategy from the point of view of financial stability. However, in order for central banks to provide reserves in a quantitatively meaningful way, they would have to keep their balance sheets large (Greenwood et al. 2016). Boissay and Cooper (2014) highlight the role of external collateral for the normal functioning of the interbank market and discuss the emergence of a "collateral trap" and a collapse of secured lending when confidence in the interbank market declines. Reis (2017) shows that the size and the composition of the central bank's balance sheet can be powerful policy tools in a fiscal crisis as they allow the central bank to stabilize inflation by managing its sensitivity to fiscal shocks and to prevent a credit crunch by

[7] See, e.g., Bernanke (2017), Constancio (2016), Bayoumi et al. (2014), Ball et al (2016).
[8] See, e.g., Greenwood et al (2016), Bernanke (2016).

lowering the losses suffered by banks in the case of a sovereign default. Our paper adds to these arguments in favour of the view that central banks should keep their expanded balance sheets in the future by highlighting that, downsizing the balance sheets could lead to significant increases in global bond yields with serious implications for financial stability.

The rest of the paper is structured as follows: Section 2 briefly presents the QE measures of major central banks and the assessment of their effects on sovereign bond yields, provided by the extant empirical literature. Section 3 outlines the empirical model and describes our dataset. Section 4 presents the main findings of the empirical analysis. Section 5 tests for heterogeneity across different policies and country types. Section 6 concludes.

2. Quantitative easing and sovereign bond yields

2.1 Unconventional monetary policies of major central banks

Quantitative easing refers to policies that expand the central bank's balance sheet, mainly by (a) asset purchases that replace long-term holdings with short-term reserves in the balance sheets of the central bank's counterparties and (b) liquidity provision, i.e. provision of bank reserves against collateral. Tools employed by the Fed, the ECB, the Bank of England and the Bank of Japan were broadly similar in type, but differed with respect to their timing and on whether they were focused primarily on provision of liquidity or asset purchases. For instance, over the period 2008-2014, the ECB focused primarily on providing ample liquidity to the banking sector, while the Fed and the Bank of England proceeded to asset purchases as early as 2008 and 2009, respectively. Both liquidity provision and asset purchases are reflected in the expansion of the central banks' balance sheets.

[Insert Figure 2, around here]

As a result of QE, central banks ended up with large balance sheets. Figure 2 shows that the size of the aggregate balance sheet of the four major central banks quadrupled from USD 4 trillion in 2007 to about USD 16 trillion in 2017. This is equivalent to 45% of the combined GDP in the four countries/economic areas, up from about 10% of GDP in 2007.

LSAPs were first adopted by the Fed as nominal interest rates had hit the zero lower bound. The Fed's asset purchase program was implemented in three phases: QE1, beginning in autumn 2008, included government-sponsored enterprise debt and mortgage-backed securities; QE2, beginning in October 2010, included purchases of US Treasuries; and QE3, which began in September 2012, and included both purchases of mortgage-backed securities and US Treasuries. Overall, the Fed expanded its balance sheet by USD 3.5 trillion since end-2007 to around USD 4.5 trillion in December 2016 (23.6% of the US GDP).

The Bank of England adopted quantitative easing as a measure to stimulate the economy after it had sharply cut its basic policy rate to ½% in March 2009. Since then the Bank of England expand its balance sheet by around £450 billion. Gilts, i.e. UK sovereign bonds, formed the predominant proportion of this scheme (around £435 billion), the rest being corporate bonds and loans. In terms of liquidity provision, the Bank of England introduced the so-called *Indexed Long-Term Repo,* aiming at predictable liquidity needs, the *Discount Window Facility*, aiming at absorbing firm-specific or market-wide shocks on banks and the *Contingent Term Repo Facility*.[9]

The Bank of Japan introduced in April 2013 the Quantitative and Qualitative Monetary Easing (QQE), in order to fight deflation. The QQE program consisted mainly of two major components: an inflation-overshooting commitment and control of the yield curve.[10] The inflation-overshooting commitment aimed at changing economic agents' perceptions of inflation, through a significant expansion of the monetary base, in order to achieve the price stability target. The yield curve control target was served by expanding the monetary base, with asset purchases mainly of Japanese government bonds (JGBs); thus, until January 2017 the Bank of Japan expanded its balance sheet by ¥361 trillion to around ¥477 trillion (88.5% of Japanese GDP)[11].

[9] See Bank of England (2014).
[10] See, Kuroda (2016).
[11] Source: Bank of Japan, *Japanese government bonds held by the Bank of Japan* (May 2017).

Until the end of the third quarter of 2014, the ECB followed mainly a policy of ample liquidity provision to commercial banks, through Long Term Refinancing Operations (LTROs) and Targeted Long Term Refinancing Operations (TLTROs), see Figure 3. Finally, in autumn 2014, as part of a package of broader measures, the ECB started to implement purchases of securities issued by the private sector and, three months later, in January 2015, of euro-area government bonds. Until January 2018, the asset purchase program (APP) holdings of the ECB and the Eurosystem national central banks amounted to €2.3 trillion, out of which €1.9 trillion were sovereign bonds (including bonds of supranational entities).

2.2 The impact of QE policies on sovereign bond yields

A number of papers examine the impact of QE on financial prices using event study methods. Findings indicate that the announcement of the intention of the Fed to proceed to asset purchases resulted in a sizeable reduction of sovereign bond yields in the US. For example, Gagnon et al. (2011) find that the term premium declined by 30 to 100 bps, mainly as a result of portfolio balance effects, while the findings of Christensen and Rudesbusch (2012) for the effects of QE in the US and the UK are similar. Neely (2015) expands the analysis in order to account for signaling effects, which are found to have also played a significant role in the reduction of yields internationally.

Large-scale asset purchases of central banks affect bond yields largely through three channels: the signaling channel (e.g., Bauer and Rudebusch, 2014), the portfolio balance channel (e.g. Greenwood and Vayanos 2014), and the liquidity channel (Christensen and Gillan 2018). The signaling channel works by affecting expectations for future short-term interest rates, the portfolio balance channel works by lowering term premia, whereas the liquidity channel works through lowering liquidity premia.

Greenwood and Vayanos (2014) set up a preferred-habitat model of the term structure in which risk-averse arbitrageurs absorb shocks to the demand and supply of bonds at different maturities. The model captures the portfolio-balance effect and predicts that an increase in the supply of bonds raises bond yields and this effect is stronger for longer-maturity bonds. Empirical estimates of the effect of the maturity-weighted-debt-to-GDP ratio on bond yields support these predictions. Gagnon et al. (2011) argued that asset purchases are expected to affect the economy primarily through the reduction of the term premium. Central banks' purchases of sovereign bonds would push down the yields of these bonds, but also the yields of their substitutes, until a new equilibrium is reached. Krishnamurthy and Vissing-Jorgensen (2011) find that substitution across assets that belong to low default-risk classes and reduction of duration risks, by swapping across assets with different durations are the main elements with which the portfolio balance channel works.

Christensen and Rudebusch (2012) and Bauer and Rudebusch (2014) find that the signaling channel has more important effects than previously thought. Neely (2015) argues that the reduction in yields of US Treasuries, as well as of other bonds internationally, followed closely the announcements of the QE measures by the Fed. Similarly, a number of papers examining the effects of central banks' announcements point at the significance of the signaling channel for lowering bond yields (see, e.g., Gagnon et al., 2011; Falagiarda and Reitz, 2015; De Santis, 2016).

Finally, large-scale asset purchases also contribute to lower pricing frictions, by lowering liquidity risk premia. Christensen and Gillan (2018) suggest that QE improved market liquidity, thus reducing the liquidity premium of US Treasury inflation-protected securities.

It is worth pointing out that most of these papers focus on the domestic effects of LSAPs, using mostly U.S data (e.g., Gagnon et al., 2011; Thornton, 2014).[12] A number of studies focus on international spillover effects, particularly to emerging markets, which witnessed large capital inflows and currency appreciations (e.g., Neely, 2015; Rogers et al., 2016; MacDonald, 2017). Another strand of the literature focuses on the effect of ECB's asset purchases on euro-area sovereign bonds (e.g., Falagiarda and Reitz, 2015; De Santis, 2016).

In parallel to the literature on the effects of QE, a number of papers provide evidence that global monetary and financial conditions are interlinked. Asset prices

[12] Akram and Das (2014) examine the effects of asset purchases of the Bank of Japan on Japanese government bonds. Joyce et al. (2012) and Steeley (2015) study the effects of asset purchases of the Bank of England on Gilts.

worldwide seem to be driven by a common, global, factor (see, Rey 2013), which is related to monetary conditions in the US and global risk aversion. Miranda-Agripino and Rey (2018) claim that this global factor explains about 60% of the common variation of risky assets worldwide. Malliaropulos and Migiakis (2018) find that most of the re-pricing of sovereign bonds following the Global Financial Crisis was due to the increase in global risk, driven by investor confidence, volatility risk, central bank liquidity and the position and the slope of the US yield curve.

3. Data and empirical model

3.1 Data

Our data consist of monthly observations of ten-year sovereign bond yields for 45 government bonds from Thomson Reuters Datastream, covering the period from 2009:1 to 2017:1.

Our empirical analysis accounts for country-specific drivers of sovereign bond yields, such as sovereign default risk. This is important in order to disentangle the impact of QE on global bond yields from idiosyncratic factors affecting sovereign risk premia. Following previous literature, we proxy sovereign default risk with sovereign credit ratings.[13] We collected sovereign ratings of the three major credit rating agencies (Moody's, Standard and Poor's and Fitch) from Bloomberg for the same period. Ratings have been transformed from the alphanumeric scale (i.e. AAA, AA+/Aa1, AA/Aa, AA-/Aa3, …, B-/B3 and so on) to a numeric scale (i.e. AAA=1, AA+/Aa1=2, …, CCC=17). We use the 'second best rating' regulatory principle in order to mark ratings changes over time, meaning that we change the rating of a sovereign only if at least two rating agencies have changed their rating in the same direction.

We use monthly balance sheet data on UMP measures of the four major central banks (the Federal Reserve System, the European Central Bank, the Bank of England and the Bank of Japan), collected from their websites. By aggregating their balance sheets (all denominated in US dollars), we construct the variable "*total assets*", which measures the size of the combined balance sheets of the four central

[13] See, among others, Avramov et al. (2007), Afonso et al. (2012) and Malliaropulos and Migiakis (2018).

banks as a ratio to the combined annual GDP of the four countries/economic areas in US dollars.

In order to account for the short-term dynamics of sovereign bond yields, we use monthly changes of the fed funds rate (similar to Rey 2013 and Miranda-Agripino and Rey 2018) and the US term spread, measured as the yield differential between ten-year and two-year US Treasury bonds (similar to Malliaropulos and Migiakis 2018). The first variable is expected to reflect the effects of spot rates on sovereign bond yields globally and the second variable captures the effects of the expected path of interest rates in the US on global sovereign bond yields.

Finally, following Longstaff et al. (2011), we use the volatility risk premium to capture global market risk aversion. The volatility risk premium has been calculated as the difference between VIX, i.e. the S&P 500 implied volatility for the next 30 days, and the realized volatility of the S&P 500, measured as the standard deviation of daily returns for a rolling window of 30 calendar days. A detailed description of our data is provided in Table A.III.1 of Appendix III. Descriptive statistics of the variables are reported in Tables A.III.2 – A.III.4 of Appendix III.

3.2 Empirical model

Our analysis accounts for the fact that yields are formed in close connection to the default risk of the sovereign. The pricing of sovereign bonds that embed a non-negligible default risk premium is conceptualized in Duffie and Singleton (1999, 2012) and Lando (1998). In this context, the yield to maturity, $R_{it}^{n} = 1 + r_{it}^{n}$, of a defaultable bond of sovereign i takes the form of an exponential affine function of short-term interest rates and a default risk premium over the life of the bond:

$$R_{it}^{n} = \left(P(t,i,n)\right)^{-\frac{1}{n}} = E_t^{*}\left(e^{\frac{1}{n}\int_t^{t+n}[r(u)_i + s(u)_i]du}\right) \quad (1)$$

where $P(t,i,n)$ is the price of a bond of sovereign i with n years to maturity at time t, E_t^{*} is the risk-neutral expectations operator conditional on information available at time t, $r(.)_i$ is the short-term risk-free rate and $s(.)_i$ is the default risk premium. In order to obtain an econometrically tractable specification of equation (1), we assume that the default risk premium is related to the credit rating of the sovereign.[14] Then, taking logs of equation (1), we obtain (see Appendix I for details):

$$\ln(R_{it}^{n}) \simeq r_{it}^{n} = \alpha_{it} + \beta c_{it} + \varepsilon_{it} \qquad (2)$$

where α_{it} is a country-time fixed-effect term, related to the risk-free rate which varies across countries and time, β is the coefficient that links yields to the credit rating of the sovereign, denoted by c_{it}, and ε_{it} is the error term of the estimated equation.

As shown in Appendix I, the time t country fixed effect, a_{it}, in equation (2) is related to two factors: (a) current and expected short term interest rates of country i over the life of the bond and (b) the time t cross-sectional mean of the sovereign risk premium across countries. Both of these terms are likely related to global monetary policy. In particular, by providing large amounts of liquidity to the private sector and using forward guidance, major central banks may have affected both the level and expectations of global short-term interest rates. In addition, the coordinated actions of major central banks following the Global Financial Crisis may also have contributed to reducing sovereign risk premia worldwide, both directly through large-scale asset purchases, and indirectly (through forward guidance), by generating expectations in financial markets that central banks will provide insurance against downside risks. Hence, we decompose the time-country fixed effect a_{it} in equation (2) as $a_{it} = a_i + \beta_2 \left(\frac{total\ assets}{GDP}\right)_t + \beta_3 \left(\frac{total\ assets}{GDP}\right)_t \times c_{it}$, where $\left(\frac{total\ assets}{GDP}\right)_t$ is the size of the aggregate balance sheet of the four central banks as a ratio of GDP in the four countries/economic areas. Consequently, we estimate an expanded version of equation (2):

$$r_{it}^{n} = \alpha_i + \beta_1 c_{it} + \beta_2 \left(\frac{total\ assets}{GDP}\right)_t + \beta_3 \left(\frac{total\ assets}{GDP}\right)_t \times c_{it} + e_{it} \qquad (3)$$

Equation (3) specifies sovereign bond yields as a function of ratings, reflecting country-specific fundamentals, and a global monetary policy variable proxied by the

[14] See, among others, Bhatia (2002), Sy (2002), Correa et al. (2012), Aizenmann et al. (2013), Acharya et al. (2014) and Malliaropulos and Migiakis (2018). There is evidence that credit rating agencies had an important role both in the build-up of the crisis, by underestimating credit risks before the GFC and in its intensification, by overreacting to credit risks in its aftermath (see, among others, Gibson *et al*. 2017).

size of the balance sheet of the four major central banks. The interaction term $\left(\frac{total\ assets}{GDP}\right)_t \times c_{it}$ is included in order to capture heterogeneity of QE effects across sovereigns with different exposures to credit risk.

[Insert Table 1, around here]

Table 1 reports panel unit root tests of the bond yield series. The tests indicate that the unit root null cannot be rejected for our panel data. Country-specific unit root tests reported in Table 2 largely confirm this result. This allows us to use panel cointegration techniques to estimate the long-run effects of QE on sovereign bond yields.

[Insert Table 2, around here]

The cointegration framework for heterogeneous panel data is provided by Pedroni (1999 and 2000). The Pedroni tests allow for considerable heterogeneity in the individual series; the statistics of the tests are based on both the cross-section average of the autoregressive coefficient (the so-called 'within dimension' unit root statistics) and the weighted section-specific autoregressive coefficients (the so-called 'between dimension' unit root statistics).

Given the long-run relationship between yields, ratings and the size of central banks' balance sheet in equation (3), we estimate the short-run dynamics of sovereign bond yields as:

$$\begin{aligned}\Delta(r_{it}^{n}) = d_i + b\Delta(c)_{it} + \mu_1\Delta(Fed\ Funds\ rate)_t + \mu_2\Delta(Fed\ Funds\ rate)_t \times c_{it} \\ + \mu_3\Delta(US10y - US2y)_t + \mu_4\Delta(US10y - US2y)_t \times c_{it} \\ + \mu_5\Delta\left(\frac{total\ assets}{GDP}\right)_{t-1} + \mu_6\Delta\left(\frac{total\ assets}{GDP}\right)_{t-1} \times c_{it-1} \\ + \mu_7 vol_t + \mu_8 vol_t \times c_{it} + \delta e_{it-1} + u_{it} \qquad (4)\end{aligned}$$

where $\Delta(r_{it}^{n})$ is the first difference (monthly change) of the sovereign yield, $\Delta(Fed\ Funds\ rate)_t$ is the change in the Fed Funds rate, $\Delta(US10y - US2y)_t$ is the change in the US term premium, c_{it} is the rating of sovereign i, vol_t is the volatility risk premium of the VIX, e_{it-1} is the error correction term from equation (3) and d_i is the fixed-effects intercept. Finally, in order to assess the effects of different QE policies on yields, we decompose in a second step the change in the size of the balance sheet, $\Delta\left(\frac{total\ assets}{GDP}\right)_{t-1}$, into its three major components, i.e. purchases of government bonds, purchases of private debt and liquidity provision.

4. Empirical estimates

4.1. Long-run effects of QE on sovereign bond yields

First, we test the null of no cointegration between sovereign yields, ratings and total assets-to-GDP with the use of the Pedroni (1999) tests, which are suitable for heterogeneous panel datasets.[15] We examine three alternative specifications of the cointegration relationship: (i) no intercept or trend, (ii) individual intercepts and (iii) both individual intercepts and individual deterministic trends. Table 3 reports the results of the Pedroni cointegration tests between yields and ratings (Panel A), yields and total assets-to-GDP (Panel B) and yields and the interaction term of total assets-to-GDP with ratings (Panel C).

[Insert Table 3, around here]

The results reported in Table 3 suggest that the null of no cointegration between sovereign ratings and yields can be rejected by all four tests when individual intercepts or individual intercepts and individual trends are included in the cointegration space (2nd and 3rd specification of Table 3, Panel A). We obtain similar findings when we test for cointegration between yields and total assets, either interacted with ratings or not (Panel B and C of Table 3), suggesting that both ratings and central banks' total assets interacted with ratings belong to the cointegration space.

[Insert Table 4, around here]

[15] We provide results of tests for the 'between dimension' as well as for the 'within dimension' specifications; the difference of these two specifications is that the alternative hypothesis of cointegration in the between-dimension tests does not presume a common value in the autoregressive coefficients, as is the case under the within-dimension tests (Pedroni, 1999, p. 657-8). As a result, under the between dimension specification of the tests, the rejection of the null, i.e. the finding of a long-run cointegrating relationship in pairs, is not restricted by assumptions of common properties in the data.

Table 4 presents DOLS estimates of the cointegration relationship between sovereign yields, ratings and total assets-to-GDP, eq. (3). All estimates have the expected sign and are statistically significant at the 1% level. In terms of economic significance, our estimates suggest that yields of AAA rated sovereign bonds declined by 11 bps for every one percentage point rise of the total assets-to-GDP ratio, while, for comparison, B rated sovereign bond yields declined by 14 bps.

[Insert Figure 3, around here]

Based on the estimates of Table 4, one can run the counterfactual exercise of what would have happened to global sovereign yields, had central banks not expanded their balance sheets. Figure 3 visualizes the cumulative effect of QE between 2009 and 2017 on yields of sovereigns belonging to several rating categories, from AAA to B. The figure plots the fitted values of the estimated long-run regression, equation (3), in January 2009 (red line) across rating categories and the equivalent fitted values in January 2017 (blue line), keeping ratings at their January 2009 values, so as to capture only the effects of the cumulative change in the size of central banks' balance sheet on yields over the period January 2009 – January 2017. Given that total assets of the four central banks as a ratio of the combined GDP of their economies rose by about 24 percentage points (from 21.8% in January 2009 to 46% in January 2017), our estimates suggest that QE contributed to a permanent decline in AAA rated bond yields by 250 bps (=24*(-0.0011)+country fixed effect). Equivalently, for BBB bonds this decline is estimated at 297 bps and for B rated bonds the decline in yields is 330 bps.

Our results can be interpreted along the lines of the portfolio-balance model of Tobin (1958, 1969). Central bank purchases of long-term bonds from the private sector reduce the net supply of long-term bonds available to investors. Since investors now bear less duration risk in their portfolios, they are willing to absorb a lower net supply of long-term bonds at a lower yield relative to the short-term rate. To the extent that the reduction in the net supply of long-term bonds associated with the central bank purchases does not affect the position of the demand curve for the same bonds, QE leads to a permanent decline in the long-term yield.

4.2. Short-run adjustment of sovereign bond yields

Next, we examine the dynamic adjustment of bond yields to their long-run equilibrium, along with a set of control variables driving their short-term dynamics. The set of control variables includes changes in ratings, the volatility risk premium of the VIX index, changes in the Fed Funds rate and changes in the US term spread.

[Insert Table 5, around here]

The estimation results of the short-run model are reported in Table 5. Column (1) of the table reports estimates of the most basic specification. Column (2) includes interaction terms with the ratings variable, in order to capture effects specific for each rating category. In all specifications, the error-correction term is statistically significant with the expected negative sign. Interestingly, the estimated coefficient of the error-correction term is quite high, suggesting that deviations of yields from the level implied by their long-run relationship dissipate within nine to twelve months.

Our estimates suggest that changes in bond yields are positively related to ratings downgrades, increases in the Fed Funds rate, a steepening in the US Treasury yield curve and higher volatility risk (Column 1). With the exception of the Fed Funds rate, the interaction terms of these variables with ratings are significant, suggesting that changes in volatility risk and the US term spread have differential effects across different rating categories. In particular, we find that highly-rated sovereign bonds are affected more by increases in US term premia and volatility risk compared to lower-rated bonds (Column 2). Finally, changes in the total assets-to-GDP ratio are associated with lower bond yields of sovereigns rated higher than AA(-), whereas the effect becomes positive for lower-rated sovereigns (lower than A(+)).

5. Refinements

5.1. Do effects differ across types of QE policies?

In order to address the concern that the effects of QE on bond yields may have differed across different types of policy measures, we decompose the changes in the total assets-to-GDP ratio of the four central banks into three basic categories: (i) purchases of government bonds, (ii) purchases of private sector debt and (iii) liquidity provision.

So far the literature has focused on (i) and (ii) but less so on the effect of (iii), liquidity provision of central banks.[16] This is due to the inherent difficulty to distinguish between supply- and reserve-induced effects on bond yields because outright purchases of long-term securities by the central bank are financed through the creation of central bank reserves. Hence, asset purchases and liquidity creation act simultaneously, making it difficult to disentangle their effects on bond markets. Nevertheless, liquidity provision was an important tool of UMP during the initial phase of the Global Financial Crisis and later during the European sovereign debt crisis, when the ECB expanded its monetary base largely through long-term refinancing operations in order to provide ample liquidity to troubled banks. We measure liquidity provision by adding up all liquidity related programs of the four major central banks (see Figure 4).

[Insert Figure 4, around here]

We construct the following variables (all denominated in US dollars):

(a) "*GvtBonds*", which measures the aggregate value of sovereign bonds in central banks' balance sheets;
(b) "*Private*", which measures the purchases of private debt by the four central banks; and
(c) "*Liquidity*", which measures liquidity provision to the banking sector by the four central banks.[17]

All four variables are computed as ratios to the combined annual GDP of the four countries / economic areas in US dollars. Column 3 of Table 5 decomposes the effect of changes in the total assets-to-GDP ratio into the effects of liquidity

[16] One of the few exceptions is Christensen and Krogstrup (2016), who estimate the effects of the liquidity provision programme of the Swiss National Bank (SNB) in August 2011, where the expansion of reserves was achieved through purchases of short-term debt securities, repo operations and foreign exchange swaps. Also Fratzscher et al. (2018) distinguish between the effects of liquidity provision and asset purchases of the QE1 programme of the Fed.

[17] We proxy liquidity provision of central banks by the sum of volumes of the Fed's Term Auction Facility, Primary Dealer Credit Facility, Securities Lending Facility and the discount window, ECB's MROs, LTROs and TLTROs, BoE's sterling repos and BoJ's funds-supplying operations against pooled collateral.

provision, changes in government bond holdings and changes in holdings of privately issued debt, held by the four central banks. Our estimates suggest that central banks' purchases of government bonds and private debt are among the most effective policies in lowering bond yields both in the countries where these policies were implemented and abroad. Both policies lead to a decline in AAA bond yields by 10 bps in the short term for every one percentage point of GDP increase in central banks' asset purchases, whereas the equivalent decline in AAA bond yields of liquidity provision is 4.5 bps.

Interestingly, however, we find that, among the two policies of asset purchases, the most effective one from a global perspective is central banks' purchases of private debt, since they lower yields for all sovereigns independent of their rating. In contrast, increases in central banks' holdings of government bonds lower predominantly yields of higher-rated bonds but have weaker effects on yields of lower-rated bonds.[18] This result is in line with existing theory and empirical evidence. Caballero and Fahri (2014) show that in a safety trap equilibrium where short-term interest rates hit the zero lower bound, the most powerful policies are those that help the private sector substitute some of their risky assets with safe ones. Hence, QE policies that help the private sector implement this swap are the most effective. An example of such QE policies is the Large-Scale Asset Purchase programme of the Fed, which concentrated on purchases of risky private debt such as GSE debt, agency debt and mortgage-backed securities.

Finally, our estimates indicate that – similar to government bond purchases – the effects of liquidity provision are asymmetric across bonds with different ratings. In particular, accounting for the interaction of liquidity provision with ratings, we find that for sovereign bonds rated lower than AA-/Aa3, liquidity provision is associated with higher rather than lower bond yields. A possible explanation for this finding is that, following the global financial crisis, the provision of ample liquidity by central banks has led to a substitution in investors' portfolios from lower-rated sovereign bonds towards higher-rated ones ("flight to quality"), contributing to an increase in

[18] In particular, an increase in central banks' holdings of government bonds by one percentage point of GDP is related to a short-term decline in yields of AAA-rated bonds by 10 basis points but has no effect on yields of B-rated bonds.

the yields of the former and a decrease in the yields of the latter. This substitution effect may be related to incentives of commercial banks for holding highly rated bonds and pledge them as collateral in bilateral repos as this reduces the total cost of two-way credit risk (Ewerhart and Tapking 2008). It may also be related to collateral frameworks of central banks.[19] For example, the ECB and the BoE implement investment-grade rating thresholds for accepting collateral in their monetary policy operations and market values of bonds pledged as collateral are subject to haircuts that relate to their ratings.

5.2 Do effects differ across types of countries?

The effects of global QE on sovereign bond yields may have been stronger for countries whose bonds had been included in the asset purchase programmes of central banks compared to other countries, whose bond yields were affected only through spillover effects. For example, German Bunds may have benefitted from both direct asset purchases of the ECB and, indirectly, through spillover effects of purchases of US Treasuries by the Fed, as investors rebalanced their portfolios towards German Bunds. In contrast, Norwegian government bonds, for example, are likely to have benefitted less from global QE as they have been affected only by spillover effects. In order to address this concern, we split our sample in two groups, one group of countries whose bonds were in the list of assets purchased by any of the four central banks, and, hence, were affected by both direct and spillover effects of global QE (Group A); and a second group, consisting of countries whose bonds were not directly affected by central bank purchases (Group B).[20] Group A consists of thirteen countries (US, UK, JP plus ten Eurozone countries) whereas group B consists of the remaining thirty two countries in our sample.

[Insert Tables 6 and 7, around here]

Estimation results of equation (3) for the two groups of countries are presented in Tables 6 and 7, respectively. As expected, our estimates suggest that global QE had stronger effects on sovereign yields of countries belonging to group A,

[19] For a discussion of the impact of central bank collateral frameworks on financial markets see Nyborg (2017).

[20] We include Greece in the second group of countries since it did not participate in the Asset Purchase Programme of the ECB.

compared to countries belonging to group B. In particular, the cumulated effect of global QE over the period 2009 to 2017 on bond yields of countries of group A ranges from -290 bps for AAA rated bonds to -600 bps for A rated bonds and -750 bps for BBB rated bonds. In contrast, spillover effects of global QE on bond yields of countries of group B are estimated at -250 bps on average for all sovereigns, independent of their credit rating. Overall, our results suggest that global QE has mostly benefitted countries which were directly affected by central banks' asset purchase programmes with the effect being particularly strong for countries in this group with relatively low credit ratings. The latter group of countries consists of Eurozone members, such as Portugal, Ireland, Spain and Italy, which have been mostly affected by the sovereign credit crisis.

6. Concluding remarks

We examine the effects of QE measures adopted by the four major central banks (Fed, ECB, BoJ and BoE) following the Global Financial Crisis in a panel data set of ten-year sovereign bond yields from 45 governments that includes both emerging markets and developed economies. We employ cointegration techniques for heterogeneous panels in order to account for unit roots in the data.

Our analysis provides support for the effectiveness of QE in reducing the cost of funding of sovereign debt for the global economy. We find that the increase in the size of central banks' balance sheet, either due to asset purchases or due to liquidity provision, has led to a significant and permanent decline in global sovereign yields, ranging between 250 bps for AAA rated sovereign bonds and 330 bps for B rated sovereign bonds. These effects are both statistically and economically significant. Interestingly, the speed of adjustment of bond yields towards their long-run equilibrium level implied by ratings and central banks' total asset purchases is high, suggesting that the effects of QE have been transmitted quickly to global bond markets.

Furthermore, our estimates of the short-term adjustment of bond yields suggest that the effects differ both across major types of monetary policy operations and across sovereigns. In particular, we find that purchases of government bonds and liquidity provision by central banks reduced bond yields of higher-rated sovereigns relatively more than those of lower-rated ones, likely due to substitution effects in investors' portfolios. Furthermore, we find that, from a global perspective, the most effective QE policies were central banks' purchases of private debt, as they seem to have lowered yields for all sovereigns independent of their rating.

Our findings have important policy implications: if QE policies on aggregate had sizeable and permanent effects on global bond yields, scaling down the size of central banks' balance sheets in the future is likely to lead to significant increases in sovereign bond yields across the globe. Consequently, central banks should be cautious in tightening their monetary policy stance, as it may have significant implications for the global economy and financial markets. Of course, a caveat attached to this is that unwinding QE will not necessarily have symmetric effects on long-term interest rates. Since QE policies were introduced during a period of severe financial market frictions and zero interest rates, it is far from obvious that global yields will increase symmetrically when central banks unwind their balance sheets in the future. Nonetheless, our results are consistent with the view that central banks should keep appropriately large balance sheets in the future as a backstop for financial stability.

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Appendix I: Derivation of econometric model

In order to derive an econometrically tractable specification of eq. (1), we assume that the conditional sovereign risk premium is linearly related to the credit rating of the sovereign: $E_t^* e^{\frac{1}{n}\cdot\int_t^{t+n} s_i(u)du} = e^{\beta c_{it}}$, where c_{it} is the rating of sovereign i and β is a coefficient which reflects the pricing of credit risk in bond markets. Hence, the yield spread can be expressed as:

$$R_{it}^n = A_{it} \cdot e^{\beta c_{it}} \tag{A1}$$

where $e^{\beta c_{it}}$ reflects the sovereign risk as proxied by the rating and $A_{it} = E_t^* e^{\frac{1}{n}\cdot\int_t^{t+n} r_i(u)du}$ is an idiosyncratic factor which captures expectations about risk-free rates of country i.

In a final step, we log-linearize eq. (A1) using a first-order Taylor series expansion around the time *t* cross-sectional, unconditional mean of the sovereign risk premium, $e^{\beta E(c_{.t})}$:

$$r_{it}^n = \alpha_{it} + \beta c_{it} + \varepsilon_{it} \tag{A2}$$

where the country-time fixed effect is now
$\alpha_{it} = E_t^* \frac{1}{n} \cdot \int_t^{t+n} r_i(u)du - \ln\left(1 - e^{\beta E(c_{.t})}\right) \frac{e^{\beta E(c_{.t})}}{1-e^{\beta E(c_{.t})}} \beta E(c_{.t})$ and we have added an error term, ε_{it} ,with zero mean and constant variance. Equation (A2) is equation (2) in the text.

Appendix II: Cointegration analysis between assets-to-GDP ratio and common component of yields

The tests for a unit root in the total assets-to-GDP ratio and the common component of yields, reported in Table A.II.1, indicate the presence of a unit root in both series.

Table A.II.1 Unit and near-unit-root tests

	Common component of yields			
	ADF	DF-GLS	PP	PP-GLS
Series with constant	-1.336	-0.561	-1.362	-0.489
Series with constant and trend	-1.303	-1.579	-1.515	-1.524
	Total Assets-to-GDP			
	ADF	DF-GLS	PP	PP-GLS
Series with constant	-0.001	2.125	0.013	2.322
Series with constant and trend	-1.845	-1.847	-1.982	-1.786

Note: ADF and PP are the standard Augmented Dickey Fuller and Philips Perron tests. DF-GLS and PP-GLS are the GLS-modified versions of these tests for a series with near-unit-root properties. Critical values for the tests with constant at the 5% significance level are: ADF & PP: -2.89, DF-GLS: -1.94 and PP-GLS: -1.98. Critical values for the tests with constant and trend at the 5% significance level are: ADF & PP: -3.45, DF-GLS: -3.04 and PP-GLS: -2.91.

Table A.II.2 reports estimates of the cointegrating relationship between the two series. The ADF test and the PP test both reject the null of a unit root in the residuals, suggesting that the two series are cointegrated. The Wald test suggests long-run causality from total assets-to-GDP to yields.

Table A.II.2 Estimates of cointegration between the common component of yields and total assets-to-GDP ratio

	Coefficients	
constant	0.126** (0.008)	
Total assets-to-gdp	-0.003** ($2.15x10^{-4}$)	
Adj. R-squared	87.1%	
ADF test of the residuals	-2.847** [0.000]	
PP test of the residuals	-2.891** [0.000]	
	Total Assets-to-GDP -> Yields	Yields -> Total Assets-to-GDP
Long run causality (Wald test, F-stat)	4.194* [0.046]	0.047 [0.829]

Note: The table reports estimates of the cointegration relationship between the first principal component of yields and the total assets-to-gdp ratio, based on Dynamic Ordinary Least Squares, with optimal lag selection based on the Akaike Information Criterion. Figures in brackets [.] are p-values and standard errors are reported in parentheses (.). Asterisks (*,**) indicate significance (at the 5%, 1% level).

Appendix III: Data and descriptive statistics

Table A.III.1 Description of data set

Variable	Details of the data	Transformation
Yields	**Definition:** 10-year government bond yields; **Source:** Thomson Reuters, Datastream; **Period:** 2009:1-2017:1; **Frequency:** monthly; **Economies:** Albania; Austria; Australia; Belgium; Brazil; Bulgaria; Canada; China; Colombia; Croatia; Czech; Denmark; Finland; France; Germany; Greece; Hong Kong, China; Hungary; Iceland; India; Indonesia; Ireland; Italy; Japan; Korea; Lithuania; Malaysia; Mexico; New Zealand; Netherlands; Norway; Philippines; Poland; Portugal; Russia; Singapore; Slovakia; Spain; South Africa; Sweden; Switzerland; Taiwan, China; Thailand; United Kingdom; United States.	We take logarithmic values: $\log(1+yield_{it})$.
Ratings	**Definition:** foreign currency long-term issuer credit ratings from Fitch, Moody's and Standard and Poor's; **Source:** Bloomberg LP; Period: 2009:1-2017:1; **Frequency:** monthly; **Economies:** As listed above.	Rating scales transformed from alphanumeric to numeric values: AAA=1, AA+/Aa1=2, AA/Aa2=3, AA-/Aa3=4, A+/A1=5, A/A2=6, A-/A3=7, BBB+/Baa1=8, BBB/Baa2=9, BBB-/Baa3=10, BB+/Ba1=11, BB/Ba2=12, BB-/Ba3=13, B+/B1=14, B/B2=15, B-/B3=16, CCC/Caa1/CCC+=17, CCC/Caa2=18, CCC-/Caa3=19, CC/Ca and lower=20.
Total assets-to-gdp	**Definition:** Total assets of the balance sheets of the Fed Reserve System, the European Central Bank, Bank of England and Bank of Japan; **Sources:** SDW-ECB, FRED, BoE and BoJ; **Period:** 2009:1 to 2017:1; **Frequency:** monthly.	Data have been transformed from local currency to US dollars. Then we calculate the ratio of aggregate liquidity provision to the aggregate GDP of the four countries/areas.
Continued		

(Table A.III.1 continued)

Liquidity-to-GDP	**Definition:** Provision of liquidity from the Fed, the ECB, BoE and BoJ to the banking sector; **Sources:** SDW-ECB, FRED, BoE and BoJ; **Period:** 2009:1 to 2017:1; **Frequency:** monthly; **Description:** Aggregate amounts of liquidity provided by Fed's Term Auction Facility, Primary Dealer Credit Facility, Securities Lending Facility and the discount window, ECB's MROs and LTROs and TLTROs, BoE's repos and BoJ's "funds-supplying operations against pooled collateral".	Data have been transformed from local currency to US dollars. Then we calculate the ratio of aggregate liquidity provision to the aggregate GDP of the four countries/areas.
Government bond purchases-to-GDP	**Definition:** total holdings of domestic gvt-bonds as a ratio of the combined GDP of the US, the euro area, UK and Japan; **Sources:** SDW-ECB, FRED, BoE and BoJ; **Period:** 2009:1 to 2017:1; **Frequency:** monthly; **Description:** Total purchases of domestic government bonds by the Fed, ECB, BoE and BoJ; GDP of the US, the euro area, the UK and Japan.	Data have been transformed from local currency to US dollars. Then we calculate the ratio of aggregate liquidity provision to the aggregate GDP of the four countries/areas.
Private-to-GDP	**Definition:** total holdings of MBSs by the Fed and corporate bonds by the ECB, the BoE and BoJ; **Sources:** FRED; **Period:** 2009:1 to 2017:1; **Frequency:** monthly; **Description:** purchases of MBSs by the Federal Reserve and other private paper, such as corporate bonds, by the ECB, the BoE and BoJ; GDP of the US, the euro area, the UK and Japan.	Data have been transformed from local currency to US dollars. Then we calculate the ratio of aggregate liquidity provision to the aggregate GDP of the four countries/areas.
Fed funds rate	**Definition:** Effective Federal Funds rate; **Source:** FRED; **Period:** 2009:1 to 2017:1; **Frequency:** monthly.	
US term spread	**Definition:** Difference of the yield of the 10-year US Treasury benchmark bond vis-vi-à-vis the yield of the 2-year US Treasury bond; **Source:** Thomson Reuters Datastream; **Period:** 2009:1 to 2017:1; **Frequency:** monthly;	
Volatility risk premium	**Definition:** Difference between implied volatility (VIX) and the realized volatility of the S&P 500, measured as the standard deviation of daily returns for a rolling window of 30 calendar days; **Sources:** Thomson Reuters Datastream; **Period:** 2009:1 to 2017:1; **Frequency:** monthly.	

Table A.III.2 Descriptive statistics: sovereign yields					
	Mean	**Std. Dev.**	**Min.**	**Max.**	**Obs.**
Albania	8.440	0.392	7.350	9.500	97
Austria	2.141	1.231	0.063	4.342	97
Australia	3.877	1.128	1.856	5.776	97
Belgium	2.475	1.352	0.148	4.803	97
Brazil	4.358	1.025	2.264	7.148	97
Bulgaria	4.493	1.763	1.949	8.236	97
Canada	2.274	0.748	1.005	3.633	97
China	3.566	0.449	2.743	4.636	97
Colombia	7.446	1.069	4.755	10.631	97
Croatia	5.297	1.296	3.052	7.472	97
Czech Rep.	2.476	1.588	0.237	5.754	97
Denmark	1.852	1.151	0.035	3.932	97
Finland	1.972	1.161	0.029	4.086	97
France	2.197	1.127	0.128	4.011	97
Germany	1.699	1.094	-0.168	3.609	97
Greece	11.652	7.482	4.535	40.629	97
Hong Kong, China	1.858	0.645	0.639	3.020	97
Hungary	6.193	2.278	2.726	11.603	97
Iceland	6.737	0.910	5.019	9.729	97
India	8.015	0.701	5.328	9.145	97
Indonesia	7.973	1.702	5.167	14.191	97
Ireland	4.244	2.847	0.376	11.169	97
Italy	3.652	1.484	1.180	6.892	97
Japan	0.751	0.447	-0.253	1.482	97
Korea	3.498	1.142	1.363	5.420	97
Lithuania	4.816	3.658	0.400	14.230	97
Malaysia	3.878	0.283	3.093	4.375	97
Mexico	6.254	0.617	4.593	7.769	97
New Zealand	4.241	1.041	2.165	6.105	97
Netherlands	1.983	1.161	-0.002	4.075	97
Norway	2.569	0.925	0.987	4.262	97
Philippines	5.426	1.601	3.222	8.135	97
Poland	4.509	1.339	2.042	6.283	97
Portugal	5.686	3.163	1.530	15.377	97
Russia	8.956	1.793	6.530	14.090	97
Singapore	2.161	0.427	1.300	2.850	97
Slovakia	2.992	1.571	0.319	5.233	97
Spain	3.719	1.598	1.017	6.893	97
South Africa	8.345	1.571	6.362	10.004	97
Sweden	1.890	0.999	0.062	3.810	97
Switzerland	0.825	0.817	-0.584	2.388	97
Taiwan, China	1.358	0.251	0.673	1.722	97
Thailand	3.363	0.630	1.670	4.442	97
United Kingdom	2.505	0.894	0.673	4.111	97
United States	2.453	0.653	1.455	3.873	97

Note: Yields are reported in percentage points. The sample period is January 2009 to January 2017.

Table A.III.3 Descriptive statistics: sovereign credit ratings					
	Mean	**Std. Dev.**	**Min.**	**Max.**	**Obs.**
Albania	14.216	0.414	14	15	97
Austria	1.237	0.427	1	2	97
Australia	1	0	1	1	97
Belgium	2.701	0.562	2	4	97
Brazil	10.278	0.657	10	12	97
Bulgaria	9.329	0.473	9	10	97
Canada	1	0	1	1	97
China	4.247	0.434	4	5	97
Colombia	9.835	0.862	9	11	97
Croatia	10.495	0.503	10	11	97
Czech Rep.	5	0	5	5	97
Denmark	1	0	1	1	97
Finland	1.052	0.222	1	2	97
France	1.773	0.835	1	3	97
Germany	1	0	1	1	97
Greece	14.186	4.839	5	20	97
Hong Kong, China	2	0	2	2	97
Hungary	10.454	1.658	7	12	97
Iceland	9.474	0.891	7	10	97
India	10	0	10	10	97
Indonesia	11.144	1.465	10	13	97
Ireland	7.732	3.121	1	11	97
Italy	6.526	2.728	3	9	97
Japan	3.948	0.769	3	5	97
Korea	4.639	0.819	3	6	97
Lithuania	7.588	0.495	7	8	97
Malaysia	7	0	7	7	97
Mexico	8	0	8	8	97
New Zealand	2.948	0.222	2	3	97
Netherlands	1	0	1	1	97
Norway	1	0	1	1	97
Philippines	10.784	0.949	9	12	97
Poland	7	0	7	7	97
Portugal	9.392	3.525	3	12	97
Russia	8.577	0.977	8	11	97
Singapore	1	0	1	1	97
Slovakia	5	0	5	5	97
Spain	6.216	3.465	1	10	97
South Africa	8.525	0.596	8	10	97
Sweden	1	0	1	1	97
Switzerland	1	0	1	1	97
Taiwan, China	4	0	4	4	97
Thailand	8	0	8	8	97
United Kingdom	1.082	0.277	1	2	97
United States	1	0	1	1	97

Note: Foreign currency long-term issuer ratings have been transformed from alphanumeric to arithmetic values as follows: AAA/Aaa=1, AA+/Aa1=2, AA/Aa2=3. AA-/Aa3=4, A+/A1=5, A/A2=6, A-/A3=7, BBB+/Baa1=8, BBB/Baa2=9, BBB-/Baa3=10, BB+/Ba1=11, BB/Ba2=12, BB-/Ba3=13, B+/B1=14, B/B2=15, B-/B3=16, CCC+/Caa1=17, CCC/Caa2=18, CCC-/Caa3=19, CC/Ca and lower=20. As a result a higher value indicates lower credit rating. The sample period is January 2009 to January 2017.

Table A.III.4 Descriptive statistics: global variables					
	Mean	**Std. Dev.**	**Min.**	**Max.**	**Obs.**
Fed's discount window, Term Auction Facility, Primary Dealer Lending Facility and Securities Lending Facility	85	783.5	0.02	703.6	97
ECB's MROs & LTROs	888.6	288.4	539.9	1585.7	97
BoE's sterling repos	32.9	54.1	0.188	245.4	97
BoJ's funds-supplying operations against pooled collateral	96.1	86.5	0	329.2	97
Fed's LSAP (US Treasuries)	1,744.9	683.9	474.9	2,463.9	97
Fed's LSAP (MBSs)	1,216.2	454.6	7.377	1,760.9	97
ECB's PSPP	425.6	396.4	0.093	1,664.2	97
BoE's APF (UK Gilts)	463.9	149.7	18.1	642.6	97
BoJ's QQE (JGBs)	1,360.5	831.5	437.3	3,428.7	97
US GDP	15,702.8	901.8	14,418.8	17,096.2	9
EA GDP	12,108.8	1,033.4	10,160.6	13,229	9
JP GDP	5,227.1	634.6	4,354	6,370.8	9
UK GDP	2,651.4	218.1	2,295.7	2,999.8	9
Volatility risk premium	12.929	3.179	0.727	19.295	97
Fed funds rate	0.163	0.097	0.067	0.541	97
US term spread (UST 10y -2y)	1.904	0.567	0.821	2.836	97

Note: The table presents figures in billion US dollars for all variables except for the volatility risk premium, the fed funds rate and the US term spread. The two last variables are reported in percentage points, while the volatility risk premium is the difference of the implied volatility index VIX vis-à-vis realized volatility of the S&P-500. The sample period is January 2009 to January 2017.

Table 1 Tests for a common or individual unit root in yields

	Individual root IPS W-stat	Common root LLC t-stat	Hadri z-stat (null: stationarity)
Series with constant	1.701	1.469	15.100
	[0.955]	[0.929]	[0.000]
Series with intercept and trend	-2.300*	0.668	8.608
	[0.011]	[0.748]	[0.000]

Note: The IPS W-stat stands for the W statistic of Im, Pesaran and Shin (2003) for testing for individual unit roots in panel data sets, while the LLC t-stat stands for the t-stat test of Levin, Li and Chu (2002) for a common unit root in panel data sets. Hadri z-stat stands for the Hadri (2000) test under the null of stationarity. Figures in brackets [.] are p-values.

Table 2 Country-specific unit root tests								
	Series with intercept				**Series with intercept and trend**			
Country	**ADF**	**PP**	**ADF-GLS**	**PP-GLS**	**ADF**	**PP**	**ADF-GLS**	**PP-GLS**
Albania	-2.707	-2.310	-2.616*	-2.383*	-3.174	-2.752	-2.786	-3.107*
Austria	-0.730	-0.659	0.265	0.395	-3.553*	-3.663	-3.034	-2.925*
Australia	-0.948	-1.025	-0.697	-0.863	-3.017	-2.536	-2.944	-1.972
Belgium	-0.606	-0.561	0.189	0.177	-2.478	-2.494	-2.142	-1.962
Brazil	-3.057	-3.054*	-1.018	-1.904	-3.091	-3.077	-1.465	-1.967
Bulgaria	-0.929	-0.777	0.409	0.713	-3.179	-3.136	-3.177*	-2.579
Canada	-1.491	-1.505	-0.824	-1.081	-2.462	-2.462	-2.474	-2.089
China	-2.257	-2.404	-1.127	-1.407	-2.529	-2.593	-1.355	-1.506
Colombia	-4.482**	-4.313**	-0.318	-0.589	-3.930*	-3.899**	-1.219	-1.477
Croatia	-0.473	-0.583	-0.210	-0.193	-2.538	-2.709	-1.828	-1.729
Czech	-0.724	-0.727	0.115	0.112	-3.386	-3.542*	-2.660	-2.349
Germany	-0.770	-0.742	0.275	0.251	-3.112	-3.287	-2.883	-2.490
Denmark	-1.241	-1.242	0.217	0.097	-2.709	-3.022	-2.727	-2.445
Spain	-0.461	-0.384	-0.478	-0.481	-1.726	-1.667	-1.217	-1.145
Finland	-0.853	-0.785	0.188	0.241	-3.320	-3.447	-3.075*	-2.779
France	-0.858	-0.749	-0.003	-0.012	-3.319	-3.321	-2.907	-2.555
Greece	-1.861	-1.910	-1.520	-1.493	-1.889	-1.923	-1.649	-1.589
Hong Kong	-1.929	-2.084	-1.916	-1.631	-2.179	-2.370	-2.132	-1.791
Hungary	-1.048	-1.048	-0.084	-0.157	-2.822	-2.899	-2.783	-2.451
Iceland	-4.811**	-4.706**	-1.862	-0.206	-5.208**	-5.168**	-3.859**	-2.013
Ireland	-0.377	-0.377	-0.442	-0.417	-2.041	-2.041	-1.107	-1.031
India	-1.817	-2.031	-1.369	-0.712	-1.538	-1.592	-2.001	-0.847
Indonesia	-4.094*	-4.391**	-1.605	-0.499	-3.241	-3.794*	-2.316	-1.023
Italy	-0.695	-0.591	0.461	-0.458	-1.683	-1.608	-1.439	-1.379
Japan	-0.726	-0.697	0.547	0.365	-3.364	-3.467*	-3.239*	-2.289
Korea	-1.523	-1.457	0.089	-0.449	-3.596*	-3.602*	-3.445*	-2.230
Lithuania	-2.024	-1.134	-1.861	-0.424	-3.593*	-2.519	-3.086*	-3.077*
Malaysia	-3.386*	-3.386*	-3.075**	-1.494	-3.364	-3.364	-3.286*	-2.401
Mexico	-1.998	-2.211	-1.603	-1.538	-1.646	-1.842	-1.714	-1.608
New Zealand	-1.518	-1.321	-0.803	-1.419	-3.181	-2.445	-3.275*	-2.479
Netherlands	-0.889	-0.815	0.227	0.267	-3.326	-3.437	-3.174*	-2.821
Norway	-1.275	-1.303	-0.257	-0.229	-2.388	-2.693	-2.432	-2.269
Philippines	-2.405	-2.414	-0.339	-0.748	-2.700	-2.567	-1.893	-2.249
Poland	-1.162	-1.162	-0.489	-0.647	-1.877	-1.983	-1.885	-1.637
Portugal	-1.011	-1.133	-0.967	-0.946	-1.476	-1.553	-1.057	-1.002
Russia	-1.951	-2.126	-1.908	-1.509	-1.923	-2.102	-1.937	-1.762
Singapore	-2.393	-2.519	-2.395*	-2.212*	-2.368	-2.496	-2.409	-2.255
Slovakia	-0.438	-0.509	0.393	0.483	-2.096	-2.275	-1.671	-1.627
South Africa	-2.509	-2.363	-2.511*	-1.748	-2.482	-2.332	-2.527	-2.218
Sweden	-0.934	-0.936	-0.468	-0.622	-2.835	-2.916	-2.388	-2.007
Switzerland	-1.143	-1.104	0.167	0.217	-2.539	-2.614	-2.584	-2.397
Taiwan	-1.743	-1.925	-1.507	-1.637	-1.893	-2.097	-1.913	-1.789
Thailand	-2.143	-1.891	-1.813	-1.716	-3.104	-2.939	-3.053*	-1.978
United Kingdom	-1.268	-1.268	-0.445	-0.593	-2.466	-2.501	-2.473	-2.227
United States	-1.964	-2.033	-1.888	-1.833	-2.429	-2.555	-2.353	-2.011

Note: The table reports statistics of Augmented Dickey Fuller (ADF) and Philips-Perron (PP) tests for series with intercept (left hand columns) and linear trend (right hand columns). Both the simple and the GLS-modified versions of the tests have been used. Asterisks (**,*) denote rejection of the null of a unit root (or near unit-root in the case of the GLS-modified tests) at the 1% and 5% significance level, respectively.

Table 3 Panel cointegration tests

Panel A: Pairwise cointegration of yields with ratings				
	Panel PP-statistic		Panel ADF-statistic	
	within	between	within	between
Specification 1:	0.531	2.153	1.366	2.726
No intercept or trend	[0.702]	[0.984]	[0.914]	[0.997]
Specification 2: individual	-40.795**	-25.727**	-40.219**	-24.121**
intercept	[0.000]	[0.000]	[0.000]	[0.000]
Specification 3: individual	-54.744**	-26.274**	-54.545**	-25.061*
intercept and individual trend	[0.000]	[0.000]	[0.000]	[0.000]
Panel B: Pairwise cointegration of yields with total assets-to-GDP				
	Panel PP-statistic		Panel ADF-statistic	
	within	between	within	between
Specification 1:	0.916	2.587	0.458	2.488
No intercept or trend	[0.820]	[0.995]	[0.676]	[0.994]
Specification 2: individual	-39.518**	-26.282**	-38.819**	-23.766**
intercept	[0.000]	[0.000]	[0.000]	[0.000]
Specification 3: individual	-44.765**	-25.395**	-44.348**	-23.788**
intercept and individual trend	[0.000]	[0.000]	[0.000]	[0.000]
Panel C: Pairwise cointegration of yields with total assets-to-GDP*ratings				
	Panel PP-statistic		Panel ADF-statistic	
	within	between	within	between
Specification 1:	0.926	2.989	0.232	2.431
No intercept or trend	[0.823]	[0.995]	[0.592]	[0.991]
Specification 2: individual	-10.489**	-24.893**	-8.824**	-20.291**
intercept	[0.000]	[0.000]	[0.000]	[0.000]
Specification 3: individual	-21.389**	-25.326**	-16.167**	-15.017**
intercept and individual trend	[0.000]	[0.000]	[0.000]	[0.000]

Note: The statistics reported correspond to the Pedroni test for the null of no cointegration in heterogenous panel data sets. Optimal specification of lags, bandwidth selection (Newey-West) and Bartlett kernel for spectral estimation has been used. Alternative specifications (e.g. pre-specified number of lags) have also been tested. Figures in brackets [.] are p-values. Asterisks (* & **) denote rejection of the null of no cointegration (at the 5% and 1% level, respectively).

Table 4 Estimates of long-run relationship, equation (3)

	$\boldsymbol{\beta_1}$	$\boldsymbol{\beta_2}$	$\boldsymbol{\beta_3}$
	0.004**	-1.10×10^{-3}**	-2.24×10^{-5}**
	(3.07×10^{-4})	(5.31×10^{-5})	(7.74×10^{-6})
Adj. R-squared	Jarque-Berra	ADF z-stat	LLC t-stat
79.15%	189,591.6	-10.554**	-10.904**
	[0.000]	[0.000]	[0.000]

Note: The table reports Dynamic Ordinary Least Squares (DOLS) estimates of the long-run relationship between yields, ratings and total assets of the four central banks, i.e. the Fed, BoE, BoJ and ECB; an individual constant accounting for country fixed effects is included in the relationship and lags are selected based on the Bayesian Information Criterion. The null of the ADF test is the existence of individual unit roots in the residuals (see, Choi 2001), while that of the LLC test is the existence of a common unit-root in the panel data of residuals (see, Levin, Lin and Chu 2002); in both tests, the underlying assumption is that the series do not contain constants or trends. Figures in parentheses (.) are standard errors, while figures in brackets [.] are p-values; asterisks (* & **) denote significance (at the 5% & 1% level, respectively).

Table 5 Estimates of the short-run dynamics, equation (4)

	(1)	(2)	(3)
Constant	$-9.46x10^{-4}$**	-0.001**	$-6.49x10^{-4}$**
	$(1.2x10^{-4})$	$(1.2x10^{-4})$	$(1.2x10^{-4})$
Error correction term $_{it-1}$	-0.113**	-0.111**	-0.109**
	(0.009)	(0.009)	(0.009)
Δ(Total assets/GDP)$_{t-1}$	$-6.31x10^{-5}$	$-3.64x10^{-4}$**	
	$(4.49x10^{-5})$	$(6.80x10^{-5})$	
Δ(Total assets/GDP)$_{t-1}$*rating$_{it-1}$		$6.93x10^{-5}$**	
		$(1.22x10^{-5})$	
Δ(Liquidity/GDP)$_{t-1}$			$-4.54x10^{-4}$**
			$(1.50x10^{-4})$
Δ(Liquidity/GDP)$_{it-1}$*rating$_{it-1}$			$1.21x10^{-4}$**
			$(1.50x10^{-5})$
Δ(GvtBonds/GDP)$_{t-1}$			-0.001**
			$(1.53x10^{-4})$
Δ(GvtBonds/GDP)$_{t-1}$*rating$_{it-1}$			$8.36x10^{-4}$*
			$(3.08x10^{-4})$
Δ(Private/GDP)$_{t-1}$			-0.001**
			$(3.5x10^{-4})$
Δ(Private/GDP)$_{t-1}$*rating$_{it-1}$			$7.92x10^{-5}$
			$(5.87x10^{-5})$
Δ(rating)$_{it}$	0.001**	$8.13x10^{-4}$*	0.001**
	$(3.1x10^{-4})$	$(3.94\ x10^{-4})$	$(4.1x10^{-4})$
Δ(Fed funds rate)$_t$	0.007**	0.008**	0.008**
	(0.001)	(0.002)	(0.002)
Δ(Fed funds rate)$_t$*rating$_{it}$		$-2.62x10^{-4}$	$-5.2x10^{-4}$*
		$(2.91x10^{-4})$	$(3.5x10^{-4})$
Δ(US term spread)$_t$	0.005**	0.007**	0.007**
	$(2.4x10^{-4})$	$(3.61x10^{-4})$	$(5.5x10^{-4})$
Δ(US term spread)$_t$*rating$_{it}$		$-5.62x10^{-4}$**	$-5.7x10^{-4}$**
		$(6.44x10^{-5})$	$(7.7x10^{-5})$
Volatility risk premium$_t$	0.006**	0.008**	0.007**
	(0.001)	(0.001)	(0.001)
Volatility risk premium$_t$*rating$_{it}$		$-5.44x10^{-4}$**	$-4.1x10^{-4}$*
		$(2.07x10^{-4})$	$(1.9x10^{-4})$
FE	Yes	Yes	Yes
Obs.	4301	4301	4301
No. sections	45	45	45
Adj. R-squared	13.15%	15.89%	16.38%
DW	2.086	2.129	2.118
Jarque-Berra	658.44	823.98	820.03
	[0.000]	[0.000]	[0.000]

Note: FGLS estimates with fixed effects and cross-section weights for heterogeneity. All models are estimated with country fixed effects; asterisks (*,**) denote significance (at the 5%, 1% level, respectively). DW: Durbin-Watson statistic. Δ(Total assets/GDP): monthly change in aggregate assets of the four central banks as a percentage of combined GDP. Δ(Liquidity/GDP): monthly change in the aggregate liquidity provision of the four central banks as percentage of combined GDP. Δ(GvtBonds/GDP): monthly change of government bond holdings of the four central banks as a percentage of combined GDP. Δ(Private/GDP): monthly change of central bank holdings of bonds issued by the private sector as a percentage of combined GDP. Volatility risk premium: difference between S&P 500 implied volatility for the next 30 days and realized volatility of S&P 500. The error-correction term is the residual of Equation (3) in Table 4.

Table 6 Estimates of long-run relationship, equation (3): direct + spillover effects of QE

	$\boldsymbol{\beta_1}$	$\boldsymbol{\beta_2}$	$\boldsymbol{\beta_3}$
	0.012**	-8.79x10^{-4}**	-2.69x10^{-4}**
	(0.001)	(1.25x10^{-4})	(3.31x10^{-5})
Adj. R-squared	Jarque-Berra	ADF z-stat	LLC t-stat
76.34%	1,589.75	-8.364**	-8.548**
	[0.000]	[0.000]	[0.000]

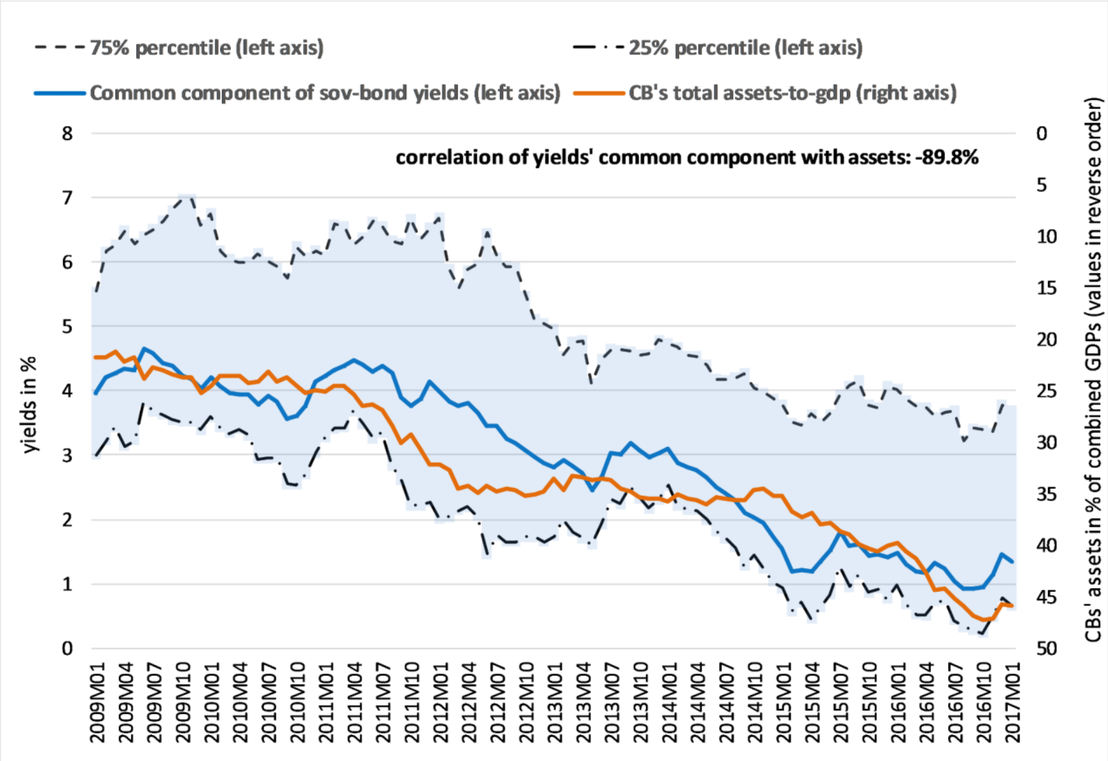
Note: Only countries whose sovereign bonds were in the list of assets purchased by any of the four CBs have been included in the system. The table reports Dynamic Ordinary Least Squares (DOLS) estimates of the long-run relationship between yields, ratings and total assets of the four central banks, i.e. the Fed, BoE, BoJ and ECB; an individual constant accounting for country fixed effects is included in the relationship and lags are selected based on the Bayesian Information Criterion. The null of the ADF test is the existence of individual unit roots in the residuals (see, Choi 2001), while that of the LLC test is the existence of a common unit-root in the panel data of residuals (see, Levin, Lin and Chu 2002); in both tests, the underlying assumption is that the series do not contain constants or trends. Figures in parentheses (.) are standard errors, while figures in brackets [.] are p-values; asterisks (* & **) denote significance (at the 5% & 1% level, respectively).

Table 7 Estimates of long-run relationship, equation (3): spillover effects of QE

	$\boldsymbol{\beta_1}$	$\boldsymbol{\beta_2}$	$\boldsymbol{\beta_3}$
	0.006**	-9.03x10^{-4}**	-2.70x10^{-5}
	(7.91x10^{-4})	(7.74x10^{-5})	(1.75x10^{-5})
Adj. R-squared	Jarque-Berra	ADF z-stat	LLC t-stat
79.36%	145,868.6	-10.398**	-10.158**
	[0.000]	[0.000]	[0.000]

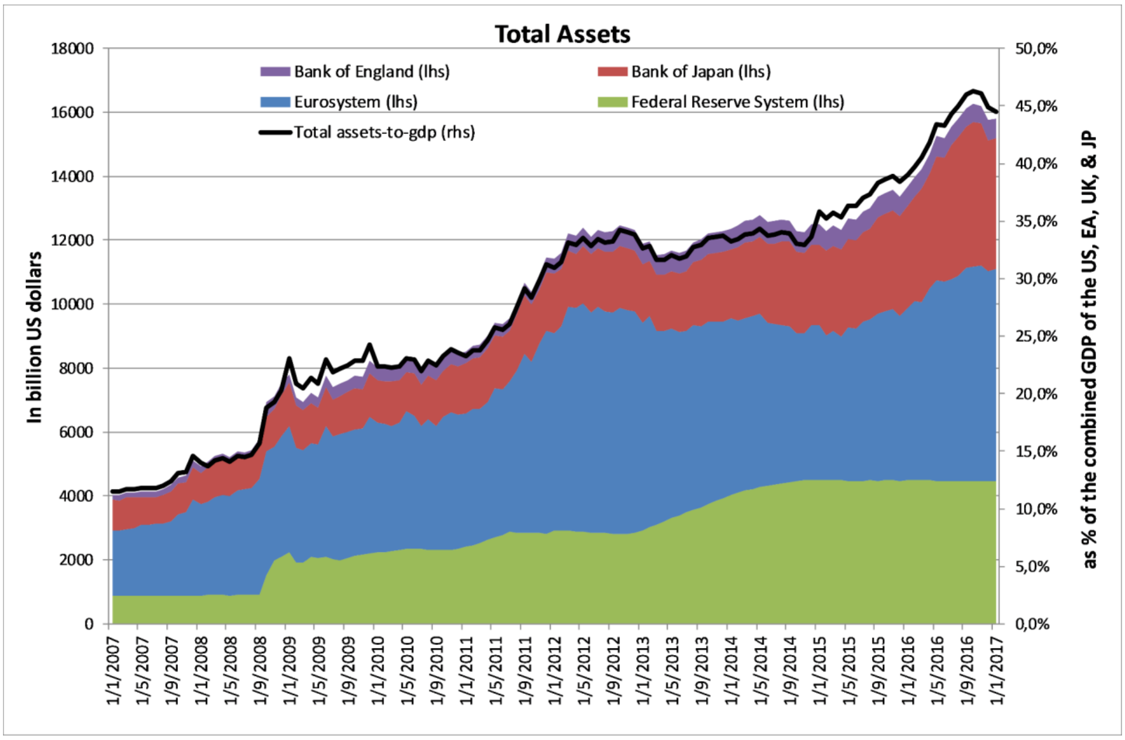
Note: Only countries whose sovereign bonds were not in the list of assets purchased by any of the four CBs have been included in the system. The table reports Dynamic Ordinary Least Squares (DOLS) estimates of the long-run relationship between yields, ratings and total assets of the four central banks, i.e. the Fed, BoE, BoJ and ECB; an individual constant accounting for country fixed effects is included in the relationship and lags are selected based on the Bayesian Information Criterion. The null of the ADF test is the existence of individual unit roots in the residuals (see, Choi 2001), while that of the LLC test is the existence of a common unit-root in the panel data of residuals (see, Levin, Lin and Chu 2002); in both tests, the underlying assumption is that the series do not contain constants or trends. Figures in parentheses (.) are standard errors, while figures in brackets [.] are p-values; asterisks (* & **) denote significance (at the 5% & 1% level, respectively).

Figure 1: Combined total assets and the common component of sovereign yields



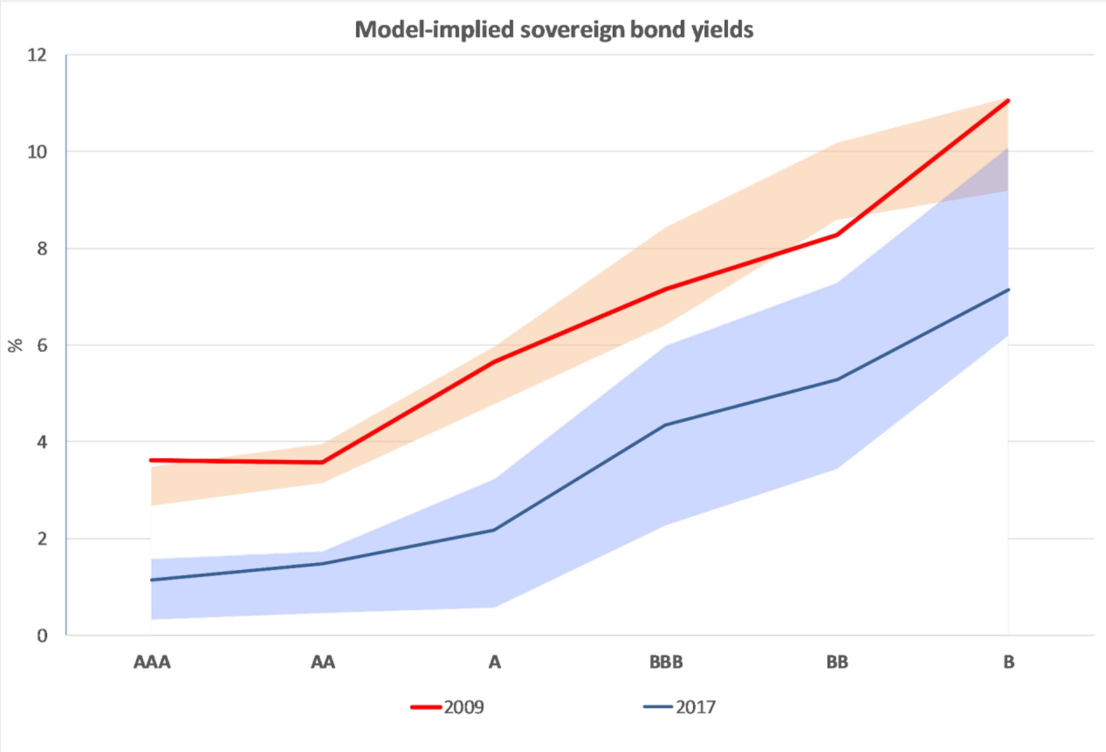
Note: CBs' total assets-to-gdp is the size of the combined balance sheet of the four major central banks (US Federal Reserve System, the European Central Bank, the Bank of Japan and the Bank of England) as a fraction of the combined GDP of the four countries/economic areas in US dollars. The common component of sovereign bond yields is the first principal component of the 10-year yields of the 45 sovereigns in our sample. The shaded area indicates the inter-quantile range of the yield distribution over time. Pearson's correlation coefficient is shown in the upper-right part of the figure.

Figure 2: Total assets of major central banks



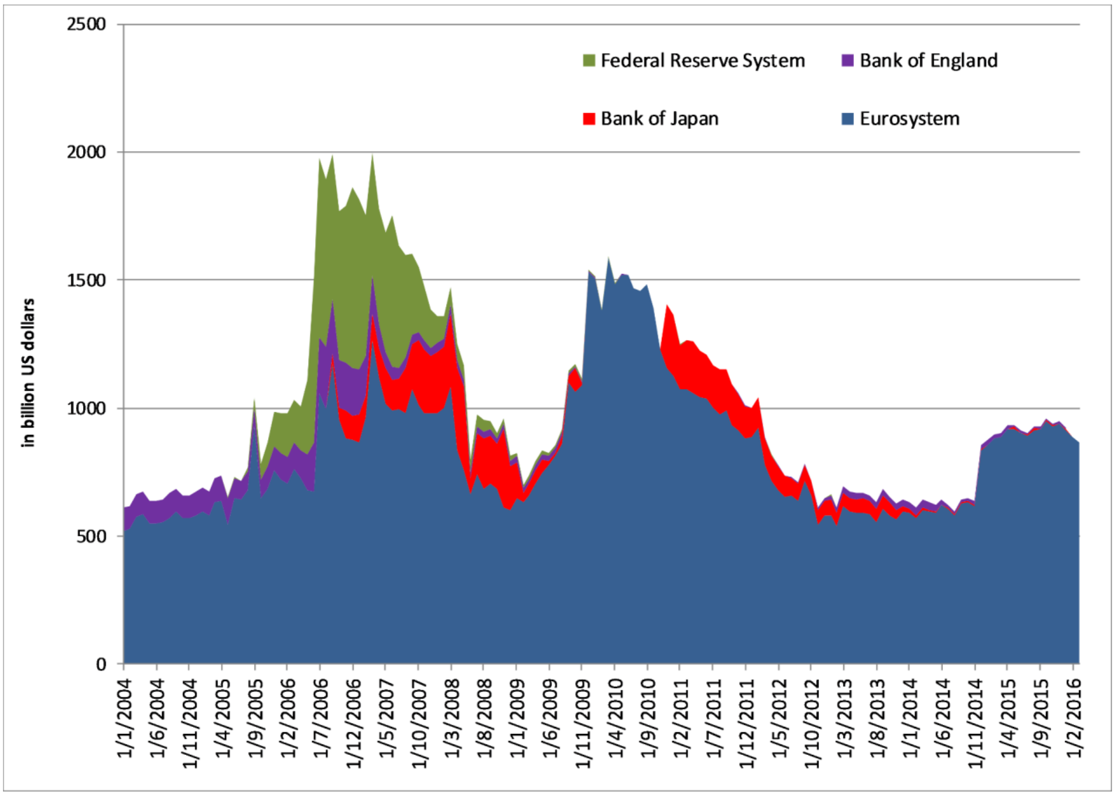
Note: The figure plots the size of the balance sheet of the four major central banks (Fed, ECB, BoE and BoJ). Values are in billion US dollars. "Total assets-to-gdp" measures the combined balance sheet of the four central banks as a fraction of the combined GDP of the four countries/economic areas.

Figure 3: Counterfactual: Estimated effect of QE on global bond yields



Note: The figure plots estimates of sovereign bond yields per rating category based on the long-run relationship, equation (3) in the text. The red line is the fitted value in January 2009. The blue line is the fitted value for January 2017, keeping credit ratings at their January 2009 level. The shaded areas depict the inter-quantile range (25%-percentile - 75%-percentile) of the yield distribution in the respective periods (orange area: January 2009, blue area: January 2017).

Figure 4: Liquidity provision



Note: The figure shows the provision of liquidity by (a) the Fed through the Term Auction Facility, Primary Dealer Credit Facility, Securities Lending Facility and the discount window, (b) ECB's MROs, LTROs and TLTROs, (c) Bank of England's sterling repos and (d) Bank of Japan's fund-supplying operations against pooled collateral. Figures are in billions of US dollars.

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