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Quantitative Easing, Bond Risk Premia and the Exchange Rate in a Small Open Economy

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Abstract

We assess the impact of large-scale asset purchases, commonly known as quantitative easing (QE), conducted by Sveriges Riksbank and the European Central Bank (ECB) on bond risk premia in the Swedish government bond market. Using a novel arbitrage-free dynamic term structure model of nominal and real bond prices that accounts for bond-specific safety premia, we find that Sveriges Riksbank's bond purchases raised inflation and short-rate expectations, lowered nominal and real term premia and inflation risk premia, and increased nominal bond safety premia, suggestive of signaling, portfolio rebalance, and safe asset scarcity effects. Furthermore, we document spillover effects of ECB's QE programs on Swedish bond markets that are similar to the Swedish QE effects only after controlling for exchange rate fluctuations, highlighting the importance of exchange rate dynamics in the transmission of QE spillover effects.

JEL Classification: C32, E43, E52, E58, F41, F42, G12

Keywords: term structure modeling, financial market frictions, safety premium, unconventional monetary policy

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1 Introduction

What happens to bond market functioning and bond risk premia when a central bank introduces a large-scale bond purchase program, also known as quantitative easing (QE)? The answer to that question regained importance after the spread of the coronavirus pandemic, as many central banks around the world had to turn to some form of QE to respond to the economic downturn caused by the pandemic. Furthermore, from an academic perspective, the question remains unsettled in the literature exactly how QE programs affect financial markets and the wider economy. Finally, it may have important policy implications for how best to design, implement, and communicate future asset purchase programs and how to navigate the exit from existing ones. With the current heightened inflation around the world, it is of great importance for policymakers to understand the effects of quantitative easing and tightening, that is, how central bank bond purchases and sales affect bond yields through different risk premia and over the term structure.

In this paper, we aim to provide a comprehensive evaluation of the most important transmission channels discussed in the literature. However, to offer a new perspective and minimize any bias and informed priors from previous studies, we focus on Sweden because it represents an understudied neutral[1] small open advanced economy with a well-established inflation target for monetary policy in which large-scale asset purchases have been implemented in addition to both forward guidance and negative interest rates. Specifically, we examine the monetary policies implemented between 2015 and 2019 by the Swedish central bank, the Riksbank, when it acquired large volumes of nominal and real Swedish government bonds through various QE programs.[2] Furthermore, as the Swedish government bond market is not as liquid as those in other larger countries, we explicitly model the liquidity conditions in the nominal and real bond markets separately.

We consider Sweden an interesting case for studying the transmission channels of QE for several notable reasons. Unlike the QE programs in many other countries, the asset purchase programs operated by the Riksbank were introduced to ease monetary policy in a low interest rate environment, rather than to improve the functioning of financial markets in times of distress. There are also a few institutional features that make the Swedish QE experience unique. For instance, the Riksbank started its bond purchases in the nominal government bond market, and later expanded them to include real bond purchases. At the same time, the Riksbank had lowered its main policy rate to negative levels.[3] Moreover, Sweden is unique in that it represents a small open economy that was affected by simultaneous domestic and foreign QE programs during the 2015–2019 period. When the Riksbank started its QE

[1] Sweden's application for NATO membership did not receive final approval by all NATO member states until February 26, 2024.

[2] We leave an evaluation of the measures taken during the COVID-19 pandemic for future research.

[3] See Christensen (2019) for an analysis of the Swedish bond market reaction to the introduction of negative interest rates.

program, the European Central Bank (ECB) was actively expanding its balance sheet through its public sector purchase program (PSPP) in the euro area. Sweden therefore offers a unique opportunity to compare and contrast the transmission channels of both domestic and foreign QE programs in the context of a small open economy.[4]

Equally importantly, the Swedish government bond market offers a near-ideal setting to perform a comprehensive analysis of domestic and foreign QE transmission channels. First, the Swedish government is not heavily indebted as it targeted a government surplus of 1 percent of nominal GDP on average over the business cycle for many years, following a conservative fiscal rule introduced in 2000. This surplus rule was replaced in 2019 with a balanced-budget target that caps the government net lending target over the business cycle to one-third of 1 percent of GDP. As a consequence of these strict budgetary rules, the Swedish government holds a triple-A credit rating. This implies that the credit risk of Swedish government bonds is entirely negligible. Second, the Riksbank has had an explicit inflation target of 2 percent since 1995, and the public views the inflation target as highly credible. In an attempt to ease monetary policy further and put upward pressure on inflation in the low inflation environment of the 2010s to meet this target, the Riksbank's QE program was designed with a clear single policy goal. Moreover, financial markets in Sweden at the time were stable and well-functioning. Hence, the transmission of conventional and unconventional monetary policy was not impaired, unlike what is the case for many of the programs studied in the early literature on QE; see Krishnamurthy and Vissing-Jorgensen (2011), among many others. As a consequence, we are able to cleanly identify and contrast different transmission channels.

Finally and crucially to our analysis, Sweden has followed a flexible floating exchange rate policy since the mid-1990s. As a result, the central bank rarely intervenes in the exchange rate markets. Although the Riksbank announced in January 2016 that it was prepared to use foreign exchange (FX) intervention to weaken the currency, it never actually implemented the policy. Bacchetta and Chikhani (2021) argue that the Riksbank's QE program may have induced a portfolio shift towards holding more foreign currency assets, which is in effect similar to direct FX interventions. Hence, this view poses an interesting question of whether the exchange rate can amplify or dampen the effects of domestic and foreign QE programs on domestic bond risk premia, an issue we aim to examine further and compare with key QE transmission channels from that perspective.

In the literature, the success of the U.S. Federal Reserve's large-scale asset purchases in reducing Treasury yields and mortgage rates is well established; see Gagnon et al. (2011), Krishnamurthy and Vissing-Jorgensen (2011), and Christensen and Rudebusch (2012), among many others.[5] These studies show that yields on longer-maturity Treasuries and other secu-

[4]See Christensen et al. (2023) for an analysis of the effects of U.S. and U.K. QE programs on Canadian government bond yields. However, the Bank of Canada did not operate any QE programs at the time.

[5]Similar evidence for U.K. interest rates can be found in Joyce et al. (2011).

rities declined on days when the Fed announced it would increase its holdings of longer-term securities. Such announcement effects are thought to be related to the effects on market expectations about future monetary policy and declines in risk premia on longer-term debt securities, known as signaling and portfolio rebalance effects, respectively; see Christensen and Krogstrup (2019, 2022) for detailed discussions. Christensen and Gillan (2022) argue that it is also possible for QE programs to reduce priced frictions to trading as reflected in liquidity premia through a liquidity channel.[6] This effect comes about because the operation of a QE program is tantamount to introducing a large committed buyer into the financial markets of the securities targeted by the program. The persistent presence of the central bank in these markets increases the bargaining power of sellers relative to buyers, which, as shown by Duffie et al. (2007), can lower the liquidity premia of these securities. D'Amico and King (2013) emphasize local supply effects as an important mechanism for QE to affect long-term interest rates. Under this local supply channel, declines in the stock of government debt available for trading induced by QE purchases should push up bond prices (temporarily) due to preferred habitat behavior on the part of investors. Finally, Hattori et al. (2016) stress that central bank asset purchases have the potential to provide insurance against macroeconomic tail risks by limiting the downside risk to asset prices. Unlike the liquidity channel discussed above, these effects are economy-wide in nature and would impact all asset classes instantaneously upon announcement, thanks to the forward-looking behavior of investors.[7]

To analyze these various transmission channels in a unified framework, we use a state-of-the-art term structure model of nominal and real bond prices developed by Christensen and Zhang (2023). The model allows us to identify bond investors' underlying inflation expectations as in Christensen et al. (2010) and hence account for inflation risk premia. Furthermore, it offers a way to generate market-based measures of the natural real rate r_t^*, which we define as in Christensen and Rudebusch (2019).[8] Finally, the model accounts for bond-specific safety premia in the prices of both nominal and inflation-indexed bonds as in Christensen and Mirkov (2022). The underlying mechanism assumes that, over time, an increasing proportion of the outstanding notional amount is locked up in buy-and-hold investors' portfolios. Given the forward-looking behavior of investors, this lockup effect means that a particular bond's sensitivity to the market-wide bond-specific risk factor will vary depending on how seasoned the bond is and how close to maturity it is. In a careful study of nominal U.S. Treasuries, Fontaine and Garcia (2012) also find a pervasive bond-specific risk factor that affects all bond prices, with loadings that vary with the maturity and age of each

[6]Gagnon et al. (2011) mention a liquidity, or market functioning, channel for the transmission of QE and stipulate a mechanism that shares similarities with the liquidity channel, but they do not provide any empirical assessment of the importance of such a channel. See also Hancock and Passmore (2011) and Krishnamurthy and Vissing-Jorgensen (2011) for discussions.

[7]There are other potential channels for QE to work. For example, it may affect the perception and pricing of risk, leading to a so-called "risk-taking" channel, as discussed in Borio and Zhu (2012).

[8]Their definition focuses on the real short rates expected to prevail five to ten years in the future, once all current transitory shocks to the economy have faded.

bond. By observing a cross section of security prices over time, the bond-specific risk factor in each market can be separately identified.

With this relevant model output in hand, we proceed to use it to shed light on the impact of the Riksbank's various unconventional monetary polices in the 2015–2019 period. First, to detect effects of the signaling channel emphasized by Christensen and Rudebusch (2012) and Bauer and Rudebusch (2014), we study the responses of estimates of standard nominal short-rate expectations, inflation expectations, and the natural real rate r_t^*. If the signaling channel is active, by committing to buy and hold a large portfolio of government bonds for an extended period, the central bank sends a credible signal to keep the policy rate low for longer than previously anticipated. Thus, the expectations for future short-term interest rates, inflation, and the natural real rate may react to the central bank bond purchase program.

Second, to assess the importance of portfolio rebalance effects as discussed in Gagnon et al. (2011), Joyce et al. (2011), and Christensen and Krogstrup (2019), we follow that literature and examine the changes in estimates of nominal and real term premia, in addition to effects on estimates of inflation risk premia. These premia represent the compensation investors demand to hold long-term bonds. With less available bond supply, investors will have to settle for a lower compensation for assuming the interest rate risk of long-term bonds, and this in turn should encourage businesses and households to borrow more and increase the overall credit supply in the economy.

Third, to evaluate the relevance of the liquidity or market functioning channel highlighted by Christensen and Gillan (2022) and Grimaldi et al. (2021), we use regressions to establish a connection between our estimated bond safety premia and the Riksbank's government bond purchases. If the liquidity conditions of the government bond markets improve or deteriorate following the central bank bond purchases, we expect the bond-specific risk premia to respond to variation in the purchase volumes under the QE program.

Lastly, to explore whether these policies had any impact on investors' perceptions about severe tail risks in the economy as stressed by Hattori et al. (2016), we study their impact on estimates of the deflation risk premium in the Swedish government bond market, calculated using formulas taken from Christensen et al. (2012). If the QE program affects the economy through investors' expectations of tail events, we can uncover the effects by examining the deflation risk premium as a measure of such perceived tail risks.

Overall, we find that the Riksbank's QE programs affected the bond market through the signaling, portfolio rebalance, and liquidity-scarcity channels. These effects are statistically significant and economically meaningful. For inflation expectations the results entail an increase of 2.74 basis points and 1.50 basis points at the five- and ten-year maturity, respectively, per 1 percentage point of Swedish nominal GDP in bond purchases. For the expected short rates, the corresponding increases are 9.98 basis points and 4.74 basis points, respectively. In addition, that same amount of bond purchases leads to a reduction in the nominal term, real term, and inflation risk premia of 12.20 basis points, 9.79 basis points, and 2.42 basis points, respectively, at the five-year maturity, while the corresponding declines at the ten-year maturity are 7.87 basis points, 6.48 basis points, and 1.40 basis points, respectively, although the latter estimate is not statistically significant. Moreover, that same amount of bond purchases raises the nominal safety premium by 4.48 basis points, while the real safety premium experiences a small, but statistically insignificant increase. These results confirm that signaling, portfolio rebalance, and scarcity transmission channels were active during the operation of the Riksbank's QE program. For perspective, the Riksbank purchased Swedish government bonds worth a total of SEK 383 billion between February 2015 and the end of 2021, or 6 percent of nominal GDP in 2021.[9] Combining this cumulative total with our regression results, we conclude that the Swedish QE bond purchases had a large impact on both bond investors' expectations for future monetary policy and Swedish bond risk premia, in particular those of nominal bonds, which were the primary target of the purchases. Furthermore, our results suggest that they did not significantly affect tail risks as measured by our deflation risk premia.

Interestingly, our initial results taken at face value would seem to suggest that the QE programs operated by the ECB tended to affect Swedish bond risk premia in the opposite direction of the effects associated with the Riksbank's QE program. However, these results are reversed once we include an interaction term between our measure of the ECB QE program and the spot SEK-EUR exchange rate in our regressions.[10] Hence, after accounting for the exchange rate effects, the ECB's QE program influenced the Swedish bond risk premia in broadly the same way as the Riksbank's domestic QE bond purchases, although mostly statistically insignificantly so. This surprising result is explained by the fact that the exchange rate fluctuations play a significant role—statistically and economically—and tend to mitigate or offset the spillover effects from the ECB's QE program. We add that these results do not hold up when we replace the spot exchange rate with the forward exchange rate. The key takeaway is that we need to take the simultaneous changes in the exchange rate into account to more fully understand the impact of the ECB's QE bond purchases on Swedish bond risk premia. A coincidental appreciation or depreciation of the exchange rate significantly affects the resulting net effects. We interpret these findings as evidence of an international spillover channel of unconventional monetary policy from the euro area to Sweden, a small open economy. In particular, the results highlight the importance of accounting for exchange rate fluctuations in understanding the cross-border effects flowing from unconventional monetary policies.

Besides the large literature on the effects of unconventional monetary policies, our paper contributes to several important strands of literature. Our analysis is relevant for the literature

[9] By April 2020, the Riksbank owned more than half of the outstanding nominal bonds and about a quarter of the inflation-linked bonds.

[10] We stress that this difference in results is not due to scaling effects, as the size of both QE purchases is measured as a fraction of the respective regional nominal GDP.

on small open economies with financial frictions. Huybens and Smith (1998) show that financial frictions can lead to the existence of two steady states where monetary policy changes can have opposite effects on economic activity. Schmitt-Grohé and Uribe (2003) compare five specifications of a standard small open economy model. Their results suggest that a complete asset market model can induce smoother consumption dynamics. Another related literature highlights the role played by the exchange rate in considering monetary policy and its transmission in small open economies (e.g. Cushman and Zha 1997, Gali and Monacelli 2005). More broadly, Itskhoki and Mukhin (2021) propose a dynamic general equilibrium model that can account for all major exchange rate puzzles, including an extended analysis on small open economies.

Our paper also has ties to the finance literature on bond risk premia broadly and on the connection between exchange rates and bond risk premia. A number of papers have investigated the joint dynamics of exchange rates, yield curves, bond risk premia, and macroeconomic fundamentals, including Backus et al. (2001), Bansal (1997), Chabi-Yo and Yang (2007), and Rogers et al. (2018). Hofmann et al. (2021) present evidence of endogeneous co-movements between bond risk premia and exchange rates that materialize through global investors' portfolio choices. In addition, our paper contributes to the literature on safety premia of safe assets specifically; see Caballero et al. (2017), Christensen and Mirkov (2022), and the review by Golec and Perotti (2017). Lastly, given that we provide a finance-based estimate of the natural real rate for Sweden, it also relates to the important literature on estimation of the level of the natural real rate; see Laubach and Williams (2003), Holston et al. (2017), and Christensen and Rudebusch (2019), among many others.

The remainder of the paper is structured as follows. Section 2 details the Swedish bond data, while Section 3 provides a description of the no-arbitrage term structure model we use. Section 4 presents the empirical results, including an examination of the estimated bond-specific safety premia, nominal and real term premia, long-term inflation expectations and risk premia, the natural real rate r_t^*, and the deflation risk premia. Section 5 analyzes the effects of the Riksbank and ECB's QE purchases on these expectations and risk premium components. Finally, Section 6 concludes the paper and offers some avenues for future research.

2 Swedish Government Bond Data

This section briefly describes the Swedish government bond data we use in the model estimation. We start with a description of the market for Swedish nominal fixed-coupon government bonds. We then proceed to describe the market for Swedish inflation-indexed bonds that reference the Swedish consumer price index (CPI), which are known as SGB ILs. To give a sense of the size of the Swedish government bond market, we note up front that, as of the end of December 2019, the total outstanding notional amount of marketable bonds issued by the Swedish government was SEK 1,113 billion, or 22 percent of GDP.

The relatively modest size of the Swedish government bond market is a key factor why the Swedish government holds a triple-A rating with either a stable or a positive outlook from all major rating agencies. Thus, there is essentially no credit risk to account for in the bond price data. More importantly, standard and inflation-indexed bonds have the same priority in the government debt structure, as argued by Fleckenstein et al. (2014). Hence, there is no relative credit risk to take into account in performing a joint modeling of the Swedish nominal and real bond prices.

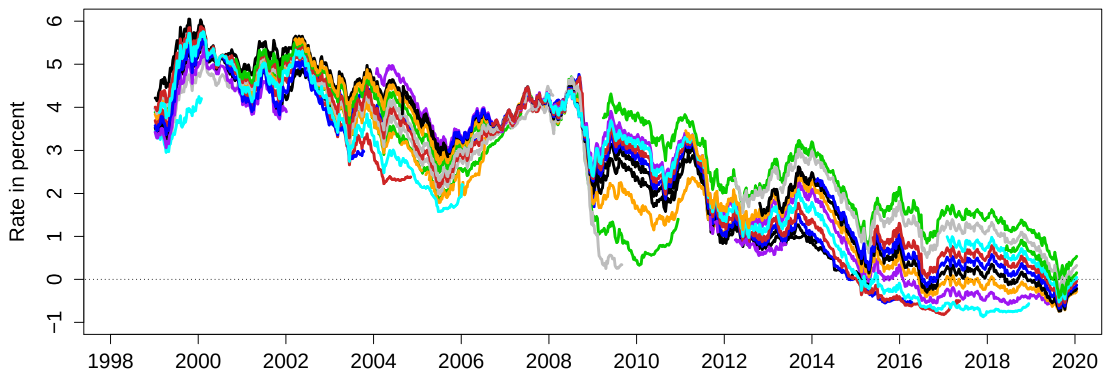
To estimate the nominal factors in our model, we follow Christensen et al. (2024) and use the prices of standard Swedish government fixed-coupon bonds starting in January 1999 when the euro was launched. These are all marketable, non-callable bonds denominated in Swedish kronor that pay a fixed rate of interest annually. We note that the Swedish government has systematically been issuing ten-year bonds mixed with occasional issuance of five- and fifteen-year bonds and a single thirty-year bond during this period. The dispersion in the cross-sectional distribution of the bonds provides the identification of the nominal level, slope, and curvature factor within our model in addition to the nominal common bond-specific risk factor.

Figure 1(a) shows the yields to maturity for all Swedish nominal government bonds in our sample at a weekly frequency from January 8, 1999, to December 27, 2019. The significant persistent decline in nominal yields over this 21-year period is clearly visible. Swedish long-term nominal government bond yields were close to 5 percent in the late 1990s and had dropped close to zero by December 2019.

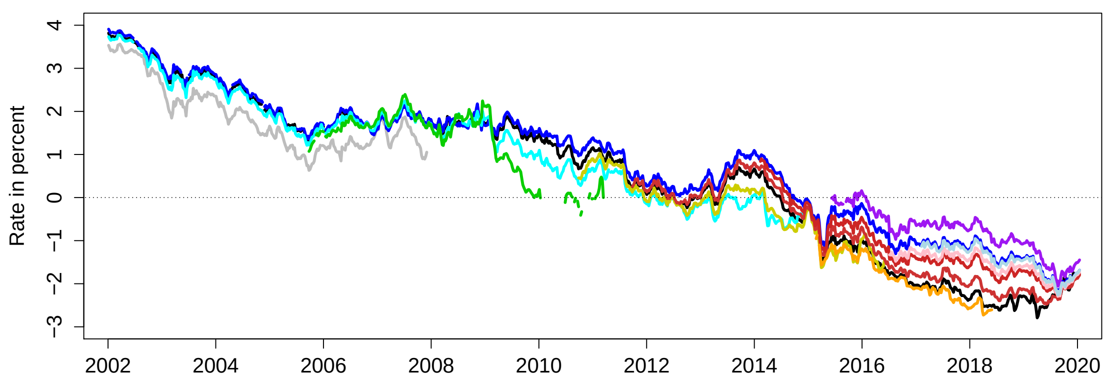
Regarding the important question of a lower bound, Sveriges Riksbank had already lowered its conventional policy rate well below zero during the last six years of our sample. As a consequence, short- and medium-term Swedish bond yields were significantly below zero during that period, with no visible lower constraint. Thus, it is not clear that one would need to impose a lower bound to model these data. Empirically, it is generally challenging to determine whether an unconstrained Gaussian model like ours is more appropriate than a model approach enforcing a lower bound in such cases; see Andreasen and Meldrum (2019) for a detailed discussion.

The Swedish government issued its first inflation-indexed bond on April 1, 1994. At the end of December 2019, the outstanding amount of Swedish inflation-indexed bonds was SEK 70 billion. Thus, this is a relatively small market in a European context. Furthermore, as noted by Gürkaynak et al. (2010), prices of inflation-indexed bonds near their maturity tend to be somewhat erratic because of the indexation lag in their payouts. Therefore, to facilitate model estimation, we censor the prices of the inflation-indexed bonds from our sample when they have less than one year to maturity.

We note that a repeated, although somewhat infrequent, issuance of long-term inflation-indexed bonds implies that there is a fairly wide range of available maturities in the data



(a) Nominal bonds



(b) Inflation-indexed bonds

Figure 1: **Yield to Maturity of Swedish Nominal and Real Government Bonds**

going back to the start of our sample in 2002. This cross-sectional dispersion provides the econometric identification of the real yield factors in our model, including the inflation-indexed bond-specific risk factor.

Figure 1(b) shows the yields to maturity for all 12 inflation-indexed bonds in our sample at a weekly frequency from January 4, 2002, to December 27, 2019. The significant persistent decline in real yields over this 18-year period is clearly visible. Swedish long-term real yields were around 3.5 percent in the early 2000s and had fallen well below -1 percent by December 2019.

3 Model and Estimation

In this section, we first detail the model that serves as the benchmark in our analysis before we describe its estimation and the restrictions imposed to achieve econometric identification.

3.1 An Arbitrage-Free Model of Nominal and Real Yields with Bond-Specific Risk Premia

To begin, let $X_t = (L_t^N, S_t, C_t, X_t^N, L_t^R, X_t^R)$ denote the state vector of our six-factor model. Here, L_t^N and L_t^R denote the level factor unique to the nominal and real yield curve, respectively, while S_t and C_t represent slope and curvature factors common to both yield curves. Finally, X_t^N and X_t^R represent the risk factors added to capture nominal and real bond-specific risk premia, respectively. We follow Christensen and Zhang (2023) and refer to this six-factor Gaussian model as the $G^{X^N,X^R}(6)$ model.

The instantaneous nominal and real risk-free rates are defined as

$$r_t^N = L_t^N + S_t, \tag{1}$$
$$r_t^R = L_t^R + \alpha^R S_t. \tag{2}$$

Note that the differential scaling of the real rates to the common slope factor is captured by the parameter α^R as in Christensen et al. (2010).

The risk-neutral $\mathbb{Q}$-dynamics of the state variables used for pricing are given by

$$\begin{pmatrix} dL_t^N \\ dS_t \\ dC_t \\ dX_t^N \\ dL_t^R \\ dX_t^R \end{pmatrix} = \begin{pmatrix} 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & \lambda & -\lambda & 0 & 0 & 0 \\ 0 & 0 & \lambda & 0 & 0 & 0 \\ 0 & 0 & 0 & \kappa_N^{\mathbb{Q}} & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & \kappa_R^{\mathbb{Q}} \end{pmatrix} \left[\begin{pmatrix} 0 \\ 0 \\ 0 \\ \theta_N^{\mathbb{Q}} \\ 0 \\ \theta_R^{\mathbb{Q}} \end{pmatrix} - \begin{pmatrix} L_t^N \\ S_t \\ C_t \\ X_t^N \\ L_t^R \\ X_t^R \end{pmatrix} \right] dt + \Sigma \begin{pmatrix} dW_t^{L^N,\mathbb{Q}} \\ dW_t^{S,\mathbb{Q}} \\ dW_t^{C,\mathbb{Q}} \\ dW_t^{X^N,\mathbb{Q}} \\ dW_t^{L^R,\mathbb{Q}} \\ dW_t^{X^R,\mathbb{Q}} \end{pmatrix},$$

where Σ is assumed to be a diagonal matrix as per Christensen et al. (2011).

Based on the $\mathbb{Q}$-dynamics above, nominal and real frictionless zero-coupon bond yields preserve a Nelson and Siegel (1987) factor loading structure

$$y_t^N(\tau) = L_t^N + \left(\frac{1-e^{-\lambda\tau}}{\lambda\tau}\right) S_t + \left(\frac{1-e^{-\lambda\tau}}{\lambda\tau} - e^{-\lambda\tau}\right) C_t - \frac{A^N(\tau)}{\tau}, \tag{3}$$
$$y_t^R(\tau) = L_t^R + \alpha^R \left(\frac{1-e^{-\lambda\tau}}{\lambda\tau}\right) S_t + \alpha^R \left(\frac{1-e^{-\lambda\tau}}{\lambda\tau} - e^{-\lambda\tau}\right) C_t - \frac{A^R(\tau)}{\tau}, \tag{4}$$

where $A^N(\tau)$ and $A^R(\tau)$ are convexity terms that adjust the functional form in Nelson and Siegel (1987) to ensure absence of arbitrage; see Christensen et al. (2011).

On the other hand, due to the bond-specific risk premia in the markets for nominal and real bonds, their pricing is not performed with the standard frictionless discount functions shown above, but rather with a discount function that accounts for the bond-specific risk:

$$\begin{aligned}\overline{r}_t^{N,i} &= r_t^N + \beta^{N,i}(1-e^{-\delta^{N,i}(t-t_0^i)})X_t^N = L_t^N + S_t + \beta^{N,i}(1-e^{-\delta^{N,i}(t-t_0^i)})X_t^N, \quad (5)\\ \overline{r}_t^{R,j} &= r_t^R + \beta^{R,j}(1-e^{-\delta^{R,j}(t-t_0^j)})X_t^R = L_t^R + \alpha^R S_t + \beta^{R,j}(1-e^{-\delta^{R,j}(t-t_0^j)})X_t^R, \quad (6)\end{aligned}$$

where t_0^i and t_0^j denote the dates of issuance of the specific nominal and real bonds, respectively, and $\beta^{N,i}$ and $\beta^{R,j}$ are their sensitivities to the variation in their respective bond-specific risk factors. Furthermore, the decay parameters $\delta^{N,i}$ and $\delta^{R,j}$ are assumed to vary across securities as well.

Christensen and Rudebusch (2019) show that the net present value of one unit of currency paid by nominal bond i at time $t+\tau^i$ has the following exponential-affine form

$$\begin{aligned}P_t^N(t_0^i,\tau^i) &= E^{\mathbb{Q}}\Big[e^{-\int_t^{t+\tau^i}\overline{r}^{N,i}(s,t_0^i)ds}\Big]\\ &= \exp\Big(B_1^N(\tau^i)L_t^N + B_2^N(\tau^i)S_t + B_3^N(\tau^i)C_t + B_4^N(t,t_0^i,\tau^i)X_t^N + A^N(t,t_0^i,\tau^i)\Big).\end{aligned}$$

Andreasen et al. (2021) show that the net present value of one consumption unit paid by real bond j at time $t+\tau$ has the following exponential-affine form

$$\begin{aligned}P_t^R(t_0^j,\tau^j) &= E_t^{\mathbb{Q}}\Big[e^{-\int_t^{t+\tau^j}\overline{r}^{R,j}(s,t_0^j)ds}\Big]\\ &= \exp\Big(B_1^R(\tau^j)S_t + B_2^R(\tau^j)C_t + B_3^R(\tau^j)L_t^R + B_4^R(t,t_0^j,\tau^j)X_t^R + A^R(t,t_0^j,\tau^j)\Big).\end{aligned}$$

These formulas imply that the model belongs to the class of Gaussian affine term structure models. Note also that, by fixing $\beta^{N,i}=0$ for all i and $\beta^{R,j}=0$ for all j, we recover the original model analyzed in Christensen et al. (2010) and denoted the $G(4)$ model.

Now, consider the whole value of the nominal bond i issued at time t_0^i with maturity at $t+\tau^i$ that pays an annual coupon C^i. Its price is given by[11]

$$\begin{aligned}\overline{P}_t^{N,i}(t_0^i,\tau^i,C^i) &= C^i(t_1-t)E^{\mathbb{Q}}\Big[e^{-\int_t^{t_1}\overline{r}^{N,i}(s,t_0^i)ds}\Big] + \sum_{k=2}^{n} C^i E^{\mathbb{Q}}\Big[e^{-\int_t^{t_k}\overline{r}^{N,i}(s,t_0^i)ds}\Big]\\ &\quad + E^{\mathbb{Q}}\Big[e^{-\int_t^{t+\tau^i}\overline{r}^{N,i}(s,t_0^i)ds}\Big].\end{aligned}$$

Similarly, the price of the real bond j issued at time t_0^j with maturity at $t+\tau^j$ that pays an annual coupon C^j is given by

$$\begin{aligned}\overline{P}_t^{R,j}(t_0^j,\tau^j,C^j) &= C^j(t_1-t)E^{\mathbb{Q}}\Big[e^{-\int_t^{t_1}\overline{r}^{R,j}(s,t_0^j)ds}\Big] + \sum_{k=2}^{n} C^j E^{\mathbb{Q}}\Big[e^{-\int_t^{t_k}\overline{r}^{R,j}(s,t_0^j)ds}\Big]\\ &\quad + E^{\mathbb{Q}}\Big[e^{-\int_t^{t+\tau^j}\overline{r}^{R,j}(s,t_0^j)ds}\Big].\end{aligned}$$

[11] This is the clean nominal bond price that does not account for any accrued interest and maps to our observed nominal bond prices. The same applies to the real bond price formula.

There are two minor omissions in the real bond price formula above. First, we do not account for the value of deflation protection offered by the inflation-indexed bonds, given that Christensen and Zhang (2023) find that this very time-consuming adjustment has little impact on the estimation results thanks to generally positive inflation in Sweden during our sample period. Second, we do not account for the lag in the inflation indexation of the real bond payoff, but the potential error should be modest in most cases; see Grishchenko and Huang (2013) and D'Amico et al. (2018) for evidence in the case of the U.S. Treasury Inflation-Protected Securities (TIPS) market.

So far, the description of the $G^{X^N,X^R}(6)$ model has relied solely on the dynamics of the state variables under the $\mathbb{Q}$-measure used for pricing. However, to complete the description of the model and to implement it empirically, we will need to specify the risk premia that connect the factor dynamics under the $\mathbb{Q}$-measure to the dynamics under the real-world (or historical) $\mathbb{P}$-measure. It is important to note that there are no restrictions on the dynamic drift components under the empirical $\mathbb{P}$-measure beyond the requirement of constant volatility. To facilitate empirical implementation, we use the essentially affine risk premium specification introduced in Duffee (2002). In the Gaussian framework, this specification implies that the risk premia Γ_t depend on the state variables; that is,

$$\Gamma_t = \gamma^0 + \gamma^1 X_t,$$

where $\gamma^0 \in \mathbf{R}^6$ and $\gamma^1 \in \mathbf{R}^{6\times 6}$ contain unrestricted parameters.

Thus, the resulting unrestricted six-factor $G^{X^N,X^R}(6)$ model has $\mathbb{P}$-dynamics given by

$$dX_t = K^{\mathbb{P}}(\theta^{\mathbb{P}} - X_t) + \Sigma dW_t^{\mathbb{P}},$$

where $K^{\mathbb{P}}$ is an unrestricted 6×6 mean-reversion matrix, $\theta^{\mathbb{P}}$ is a 6×1 vector of mean levels, and Σ is a 6×6 lower triangular volatility matrix. This is the transition equation in the extended Kalman filter estimation of this model.

3.2 Model Estimation and Econometric Identification

Due to the nonlinearity of the bond pricing formulas, the model cannot be estimated with the standard Kalman filter. Instead, we use the extended Kalman filter, as in Kim and Singleton (2012); see Christensen and Rudebusch (2019) for details. To make the fitted errors comparable across bonds of various maturities, we scale each bond price by its duration. Thus, the measurement equation for the nominal bond prices takes the following form:

$$\frac{\overline{P}_t^N(t_0^i,\tau^i)}{D_t^N(\tau^i)} = \frac{\widehat{P}_t^N(t_0^i,\tau^i)}{D_t^N(\tau^i)} + \varepsilon_t^{N,i},$$

where $\widehat{P}_t^N(t_0^i, \tau^i)$ is the model-implied price of nominal bond i and $D_t^N(\tau^i)$ is its duration, which is fixed and calculated before estimation. Similarly, the measurement equation for the real bond prices takes the following form:

$$\frac{\overline{P}_t^R(t_0^j, \tau^j)}{D_t^R(\tau^j)} = \frac{\widehat{P}_t^R(t_0^j, \tau^j)}{D_t^R(\tau^j)} + \varepsilon_t^{R,j},$$

where $\widehat{P}_t^R(t_0^j, \tau^j)$ is the model-implied price of real bond j and $D_t^R(\tau^j)$ is its duration, which is again fixed and calculated before estimation. See Andreasen et al. (2019) for evidence supporting this formulation of the measurement equations.

Since the bond-specific risk factors are latent factors that we do not observe, their level is not identified without additional restrictions. As a consequence, we let the second standard fixed-coupon bond in our sample have a unit loading on the nominal bond-specific factor X_t^N, that is, the fixed-coupon bond issued on July 22, 1991, with maturity on May 5, 2003, and a coupon rate of 10.25 percent has $\beta^i = 1$. Similarly, we let the first inflation-indexed bond in our sample have a unit loading on the real bond-specific factor X_t^N, that is, the inflation-indexed bond issued on June 6, 1996, with maturity on December 1, 2020, and a coupon rate of 4 percent has $\beta^j = 1$.

Furthermore, we note that the $\delta^{N,i}$ and $\delta^{R,j}$ parameters can be hard to identify if their values are too large or too small. As a consequence, we impose the restriction that they fall within the range from 0.01 to 10, which is without practical consequences for our results, as also noted by Andreasen et al. (2021). Also, for numerical stability during the model optimization, we impose the restriction that the $\beta^{N,i}$ and $\beta^{R,j}$ parameters fall within the range from 0 to 100, which turns out not to be a binding constraint at the optimum.

Finally, we assume that all nominal bond price measurement equations have *i.i.d.* fitted errors with zero mean and standard deviation σ_ε^N. Similarly, all real bond price measurement equations have fitted errors that are assumed to be *i.i.d.* with zero mean and standard deviation σ_ε^R.

4 Results

In this section, we briefly summarize our estimation results and detail the formulas underlying the yield decompositions we use.

Throughout we consider the preferred specification of the $G^{X^N,X^R}(6)$ model identified in Christensen and Zhang (2023) and estimated using our weekly data. It has a diagonal volatility matrix Σ as per Christensen et al. (2011), while its mean-reversion matrix takes the

$K^{\mathbb{P}}$	$K^{\mathbb{P}}_{\cdot,1}$	$K^{\mathbb{P}}_{\cdot,2}$	$K^{\mathbb{P}}_{\cdot,3}$	$K^{\mathbb{P}}_{\cdot,4}$	$K^{\mathbb{P}}_{\cdot,5}$	$K^{\mathbb{P}}_{\cdot,6}$	$\theta^{\mathbb{P}}$		Σ
$K^{\mathbb{P}}_{1,\cdot}$	1.8963	0	0	0	-1.9749	0	0.0612	σ_{11}	0.0053
	(0.3134)				(0.3418)		(0.0012)		(0.0001)
$K^{\mathbb{P}}_{2,\cdot}$	0	0.6564	0	0	0	1.6135	-0.0225	σ_{22}	0.0101
		(0.1925)				(0.2994)	(0.0095)		(0.0003)
$K^{\mathbb{P}}_{3,\cdot}$	-6.0403	0	0.2243	0	6.4303	0	-0.0413	σ_{33}	0.0177
	(0.5037)		(0.1862)		(0.5423)		(0.0278)		(0.0005)
$K^{\mathbb{P}}_{4,\cdot}$	0	0	0	0.5709	0	0	-0.0018	σ_{44}	0.0046
				(0.2869)			(0.0025)		(0.0002)
$K^{\mathbb{P}}_{5,\cdot}$	-3.4450	0	0	0	3.6205	0	0.0387	σ_{55}	0.0051
	(0.4101)				(0.4384)		(0.0012)		(0.0001)
$K^{\mathbb{P}}_{6,\cdot}$	2.6693	0	0	0	-2.9110	0.7669	0.0024	σ_{66}	0.0081
	(0.5097)				(0.5430)	(0.2645)	(0.0044)		(0.0005)

Table 1: **Estimated Dynamic Parameters of the Preferred $G^{X^N,X^R}(6)$ Model**
The table shows the estimated parameters of the $K^{\mathbb{P}}$ matrix, $\theta^{\mathbb{P}}$ vector, and diagonal Σ matrix for the $G^{X^N,X^R}(6)$ model preferred by Christensen and Zhang (2023). The estimated value of λ is 0.5600 (0.0033), while α^R = 0.7803 (0.0086), $\kappa^{\mathbb{Q}}_N$ = 1.9192 (0.0396), $\theta^{\mathbb{Q}}_N$ = -0.0012 (0.0001), $\kappa^{\mathbb{Q}}_R$ = 0.6369 (0.0176), and $\theta^{\mathbb{Q}}_R$ = -0.0026 (0.0002). The maximum log likelihood value is 100,661.2. The numbers in parentheses are the estimated parameter standard deviations.

form

$$K^{\mathbb{P}} = \begin{pmatrix} \kappa^{\mathbb{P}}_{11} & 0 & 0 & 0 & \kappa^{\mathbb{P}}_{15} & 0 \\ 0 & \kappa^{\mathbb{P}}_{22} & 0 & 0 & 0 & \kappa^{\mathbb{P}}_{26} \\ \kappa^{\mathbb{P}}_{31} & 0 & \kappa^{\mathbb{P}}_{33} & 0 & \kappa^{\mathbb{P}}_{35} & 0 \\ 0 & 0 & 0 & \kappa^{\mathbb{P}}_{44} & 0 & 0 \\ \kappa^{\mathbb{P}}_{51} & 0 & 0 & 0 & \kappa^{\mathbb{P}}_{55} & 0 \\ \kappa^{\mathbb{P}}_{61} & 0 & 0 & 0 & \kappa^{\mathbb{P}}_{65} & \kappa^{\mathbb{P}}_{66} \end{pmatrix}.$$

The estimated parameters of the preferred specification are reported in Table 1. The estimated $\mathbb{Q}$-dynamics used for pricing and determined by (Σ, λ, α^R, $\kappa^{\mathbb{Q}}_N$, $\theta^{\mathbb{Q}}_N$, $\kappa^{\mathbb{Q}}_R$, $\theta^{\mathbb{Q}}_R$) are close to those reported in Christensen and Zhang (2023). This implies that the model fit and the estimated bond-specific parameters are very similar to theirs and therefore not shown. Furthermore, the estimated objective $\mathbb{P}$-dynamics in terms of $\theta^{\mathbb{P}}$ and Σ are also qualitatively similar to those reported in their paper. Finally, we note that the bond-specific factor for the inflation-indexed bonds matters for the expected excess return of nominal bonds through $\kappa^{\mathbb{P}}_{26}$ in addition to its effect on the inflation-indexed bond pricing, while the real level factor is important for the expected return of both nominal and real bonds.

4.1 The Estimated Bond-Specific Safety Premia

We now use the estimated $G^{X^N,X^R}(6)$ model to extract the bond-specific risk premia in the Swedish government bond market. To compute these premia, we first use the estimated parameters and the filtered states $\left\{X_{t|t}\right\}_{t=1}^{T}$ to calculate the fitted bond prices $\left\{\hat{P}^i_t\right\}_{t=1}^{T}$ for

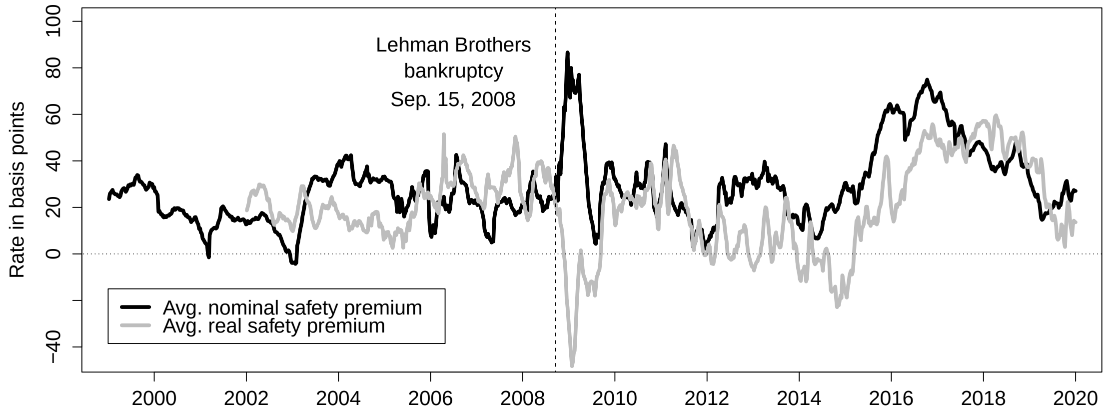


Figure 2: **Average Estimated Safety Premia**
Illustration of the average estimated bond-specific risk premia of Swedish nominal and inflation-indexed bonds for each observation date implied by our preferred $G^{X^N,X^R}(6)$ model. The nominal bond price data cover the period from January 4, 1999, to December 31, 2019, while the real bond price data cover the period from January 2, 2002, to December 31, 2019.

all outstanding securities in our sample. These bond prices are then converted into yields to maturity $\left\{\hat{y}_t^{c,i}\right\}_{t=1}^{T}$ by solving the fixed-point problem

$$\begin{aligned} \hat{P}_t^i &= C(t_1 - t)\exp\left\{-(t_1 - t)\hat{y}_t^{c,i}\right\} + \sum_{k=2}^{n} C\exp\left\{-(t_k - t)\hat{y}_t^{c,i}\right\} \\ &\quad + \exp\left\{-(T - t)\hat{y}_t^{c,i}\right\}, \end{aligned} \tag{7}$$

for $i = 1, 2, ..., n$, meaning that $\left\{\hat{y}_t^{c,i}\right\}_{t=1}^{T}$ is approximately the rate of return on the ith bond if held until maturity (see Sack and Elsasser 2004). To obtain the corresponding yields corrected for the bond-specific risk premia, we compute a new set of model-implied bond prices from the estimated $G^{X^N,X^R}(6)$ model using only its frictionless part, i.e., using the constraints that $X_{t|t}^N = 0$ for all t as well as $\sigma_{44} = 0$ and $\theta_N^Q = 0$, and $X_{t|t}^R = 0$ for all t as well as $\sigma_{66} = 0$ and $\theta_R^Q = 0$. These prices are denoted $\left\{\tilde{P}_t^i\right\}_{t=1}^{T}$ and converted into yields to maturity $\tilde{y}_t^{c,i}$ using equation (7). They represent estimates of the prices that would prevail in a world without any financial frictions or convenience premia. The bond-specific premium for the ith bond is then defined as

$$\Psi_t^i \equiv \tilde{y}_t^{c,i} - \hat{y}_t^{c,i}. \tag{8}$$

Figure 2 shows the average bond-specific risk premia in the nominal and inflation-indexed bond market across the outstanding set of bonds in each market at each point in time. The fact that the shown bond-specific premia are positive means that the frictionless yields are above the fitted yields from the bond price data. As a consequence, the bond-specific premia can be interpreted as convenience premia that cause the observed bond prices to be above the level we would expect to see in a world without any frictions to bond trading. We follow Christensen and Mirkov (2022), who report estimates of such convenience premia in the prices of Danish and Swiss government bonds, and refer to them as safety premia due to the high credit quality and relatively low liquidity of the considered bonds. Furthermore, these safety premia tend to be slightly larger for nominal bonds compared to those estimated for the inflation-indexed bonds. This could suggest that the size of the convenience premia of the inflation-indexed bonds are tempered or somewhat offset by illiquidity premia, thanks to their lower liquidity compared to the nominal bonds.

4.2 The Deflation Risk Premium

To have a consistent measure of deflation protection values across time that is not affected by variation in inflation index ratios, coupon differences, and maturity mismatches, we construct synthetic T-year real par-coupon yield spreads.

We calculate the deflation option values by comparing the price of a newly issued SGB IL that has deflation protection but no accrued inflation compensation and that of a similar SGB IL that does not offer this protection. First, consider the latter hypothetical SGB IL with T years remaining to maturity that pays an annual coupon C. As this bond does not offer any deflation protection, its par coupon is determined by the equation

$$\sum_{i=1}^{T} C E_t^Q[e^{-\int_t^{t_i} r_s^R ds}] + E_t^Q[e^{-\int_t^{T} r_s^R ds}] = 1.$$

The first term is the sum of the present value of the T coupon payments using the model's frictionless real yield curve at day t. The second term is the discounted value of the principal payment. We denote the coupon rate that solves this equation as C_{NO}.

Next, consider the corresponding SGB IL with deflation protection but no accrued inflation compensation. Since its coupon payments are not protected against deflation, the difference is in accounting for the deflation protection on the principal payment, as explained in Christensen and Spiegel (2022). Therefore, the par coupon for this bond is given by the solution to the following equation

$$\sum_{i=1}^{T} C E_t^Q[e^{-\int_t^{t_i} r_s^R ds}] + E_t^Q\left[e^{-\int_t^{T} r_s^R ds}\right] + \left[E_t^Q\left[e^{-\int_t^{T} r_s^N ds}\mathbf{1}_{\{\frac{\Pi_T}{\Pi_t}\leq 1\}}\right] - E_t^Q\left[e^{-\int_t^{T} r_s^R ds}\mathbf{1}_{\{\frac{\Pi_T}{\Pi_t}\leq 1\}}\right]\right] = 1,$$

where the last term on the left-hand side represents the net present value of the deflation protection of the principal in the SGB IL contract, which is calculated using formulas provided in Christensen et al. (2012). We denote as C_O the par-coupon yield of the new hypothetical SGB IL that solves this equation.

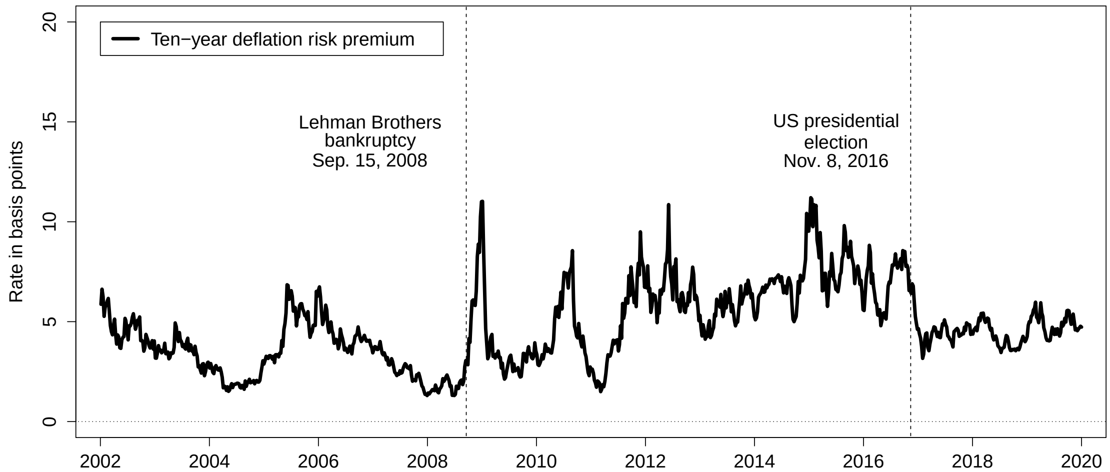


Figure 3: **Value of Ten-Year Deflation Protection Options**
Shown is the "deflation risk premium" defined as the spread between the par yield of a synthetic newly issued ten-year inflation-indexed bond lacking deflation protection and that of a deflation-protected bond with the same maturity.

The difference between C_{NO} and C_O is a measure of the advantage of holding a newly issued SGB IL at the inflation adjustment floor, and we refer to it as the deflation risk premium. Figure 3 shows the difference between the C_{NO} and C_O values that solve the pricing equations at the ten-year maturity using our preferred $G^{X^N,X^R}(6)$ model. Prior to the financial crisis, the differences between the two synthetic SGB IL yields were averaging less than 5 basis points. However, the yield differences then spiked with the onset of the crisis. After the crisis ended, the yield difference remained elevated until late 2016, when it fell notably following the U.S. presidential election on November 8, 2016. It remained at that lower level for the remainder of our sample.

4.3 Yield Decompositions

In this section, we describe the yield decompositions we use to generate the key dependent variables for our subsequent empirical analysis.

First, we define the nominal and real term premia in the usual way as

$$TP_t^j(\tau) = \tilde{y}_t^j(\tau) - \frac{1}{\tau}\int_t^{t+\tau} E_t^{\mathbb{P}}[r_s^j]ds, \quad j = N, R.$$

That is, the nominal term premium is the difference in expected nominal returns between a buy-and-hold strategy for a τ-year nominal bond and an instantaneous rollover strategy at the risk-free nominal rate r_t^N. The interpretation for the real term premium is similar.

The model thus allows us to decompose nominal and real yields into their respective term premia and short-rate expectations components. Importantly, we are using the frictionless yields $\tilde{y}_t(\tau)$ in these calculations, i.e., after accounting for the embedded safety premia.

Next, as explained in Christensen and Spiegel (2022), the price of a nominal zero-coupon bond with maturity in τ years can be written as

$$P_t^N(\tau) = P_t^R(\tau) \times E_t^{\mathbb{P}}\left[\frac{\Pi_t}{\Pi_{t+\tau}}\right] \times \left(1 + \frac{cov_t^{\mathbb{P}}\left[\frac{M_{t+\tau}^R}{M_t^R}, \frac{\Pi_t}{\Pi_{t+\tau}}\right]}{E_t^{\mathbb{P}}\left[\frac{M_{t+\tau}^R}{M_t^R}\right] \times E_t^{\mathbb{P}}\left[\frac{\Pi_t}{\Pi_{t+\tau}}\right]}\right),$$

where $P_t^R(\tau)$ is the price of a real zero-coupon bond that pays one consumption unit in τ years, M_t^R is the real stochastic discount factor, and Π_t is the price level.

By taking logarithms, this can be converted into

$$\tilde{y}_t^N(\tau) = \tilde{y}_t^R(\tau) + \pi_t^e(\tau) + \phi_t(\tau),$$

where $\tilde{y}_t^N(\tau)$ and $\tilde{y}_t^R(\tau)$ are nominal and real zero-coupon frictionless yields as described in the previous section, while the market-implied average rate of inflation expected at time t for the period from t to $t+\tau$ is

$$\pi_t^e(\tau) = -\frac{1}{\tau}\ln E_t^{\mathbb{P}}\left[\frac{\Pi_t}{\Pi_{t+\tau}}\right] = -\frac{1}{\tau}\ln E_t^{\mathbb{P}}\left[e^{-\int_t^{t+\tau}(r_s^N - r_s^R)ds}\right]$$

and the associated inflation risk premium for the same time period is

$$\phi_t(\tau) = -\frac{1}{\tau}\ln\left(1 + \frac{cov_t^{\mathbb{P}}\left[\frac{M_{t+\tau}^R}{M_t^R}, \frac{\Pi_t}{\Pi_{t+\tau}}\right]}{E_t^{\mathbb{P}}\left[\frac{M_{t+\tau}^R}{M_t^R}\right] \times E_t^{\mathbb{P}}\left[\frac{\Pi_t}{\Pi_{t+\tau}}\right]}\right).$$

This last equation demonstrates that the inflation risk premium can be positive or negative. It is positive if and only if

$$cov_t^{\mathbb{P}}\left[\frac{M_{t+\tau}^R}{M_t^R}, \frac{\Pi_t}{\Pi_{t+\tau}}\right] < 0.$$

That is, the riskiness of nominal bonds relative to real bonds depends on the covariance between the real stochastic discount factor and inflation, and is ultimately determined by investor preferences, as in, for example, Rudebusch and Swanson (2012).

Now, the breakeven inflation (BEI) rate is defined as the difference between nominal and real frictionless yields of the same maturity

$$BEI_t(\tau) \equiv \tilde{y}_t^N(\tau) - \tilde{y}_t^R(\tau) = \pi_t^e(\tau) + \phi_t(\tau).$$

Note that it can be decomposed into the sum of expected inflation and the inflation risk premium.

Finally, following Christensen and Rudebusch (2019), our definition of the equilibrium real rate of interest r_t^* is

$$r_t^* = \frac{1}{5}\int_{t+5}^{t+10} E_t^{\mathbb{P}}[r_{t+s}^R]ds, \tag{9}$$

that is, the average expected real short rate over a five-year period starting five years ahead, where the expectation is with respect to the objective $\mathbb{P}$-probability measure. We note that this 5yr5yr forward average expected real short rate should be little affected by short-term transitory shocks. Alternatively, r_t^* could be defined as the expected real short rate at an infinite horizon, as discussed in Christensen and Rudebusch (2019). However, this quantity will depend crucially on whether the factor dynamics exhibit a unit root. The typical spans of the available time series data do not distinguish strongly between highly persistent stationary processes and nonstationary ones. Our model follows the finance literature and adopts the former structure, so strictly speaking, our infinite-horizon steady-state expected real rate is constant. However, our data sample likely has insufficient information in the ten-year to infinite horizon to definitively pin down that steady state.

4.3.1 Estimated Nominal and Real Term Premia

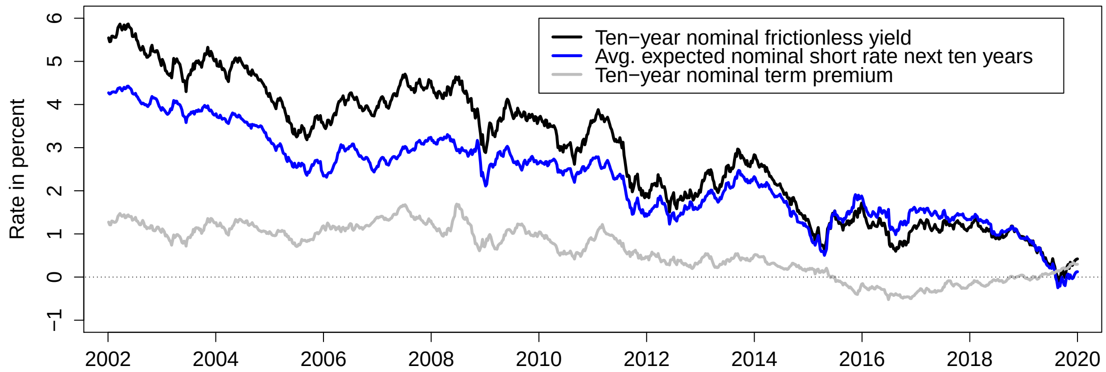
Figure 4 shows these decompositions at the ten-year maturity for both nominal and real yields since 2002. Note that the ten-year frictionless nominal and real yields have trended persistently lower during this period. Furthermore, the average expected nominal and real short rates trend down in tandem during our sample period. This leads to very similar patterns in the estimated nominal and real term premia.

4.3.2 Empirical BEI Decomposition

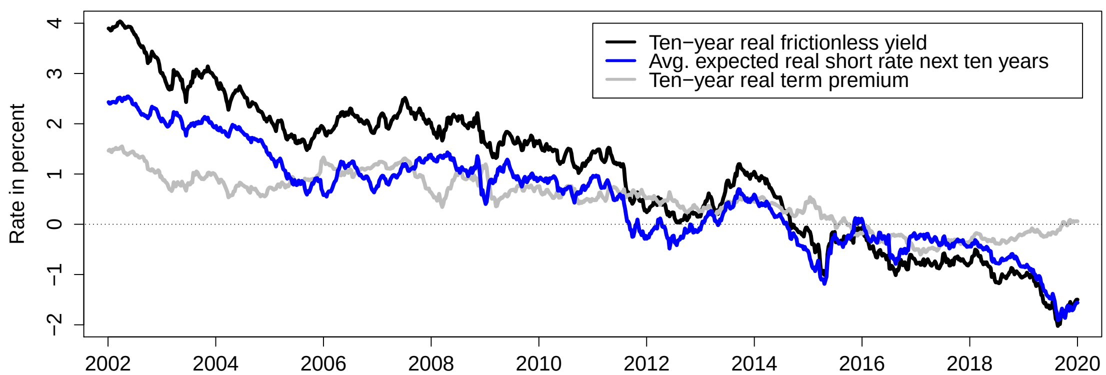
In this section, we describe the decomposition of the ten-year BEI implied by our estimation results.

The starting point for the decomposition is the fitted ten-year BEI rate from the $G(4)$ model, which offers the cleanest and most straightforward fit of the raw bond data without any adjustments. This measure of ten-year BEI is shown with a solid black line in Figure 5. The estimated ten-year frictionless BEI from the $G^{X^N,X^R}(6)$ model, which does not contain any bond-specific safety premia, is shown with a solid gray line. It fluctuates mostly above the ten-year fitted BEI, which implies that the safety premia of nominal bonds are generally larger than those of inflation-indexed bonds, as also evident from Figure 2.

As explained in Section 4.3, the $G^{X^N,X^R}(6)$ model also provides a decomposition of the estimated ten-year frictionless BEI into an expected CPI inflation component (solid red line) and the associated inflation risk premium (solid green line). The ten-year inflation risk pre-



(a) Nominal yields



(b) Real yields

Figure 4: **Ten-Year Nominal and Real Yield Decompositions**
Illustration of the ten-year nominal and real yield decompositions implied by the preferred $G^{X^N,X^R}(6)$ model. The shown data cover the period from January 2, 2002, to December 31, 2019.

mium is variable and mostly positive, but it did turn negative briefly in late 2015 and early 2016 when global energy and commodity prices fell sharply.[12] In addition, it experienced a temporary softening around the peak of the financial crisis in late 2008, when CPI inflation in Sweden and elsewhere started to fall; see Christensen et al. (2012) for a U.S. analysis of this episode. Many studies have found inflation risk premia to be positive on average and relatively stable; see Ang et al. (2008), Buraschi and Jiltsov (2005), and Hördahl and Tristani (2014), among many others. Thus, we consider the estimated inflation risk premium from the $G^{X^N,X^R}(6)$ model to be reasonable in terms of both its level and time-series variation.

In comparison, the estimated ten-year inflation expectations are less variable and char-

[12]Note that, due to the model's Gaussian dynamics, the conditional variance of expected inflation is constant. As a result, changes in the inflation risk premium reflect changes in the risk premia within the model.

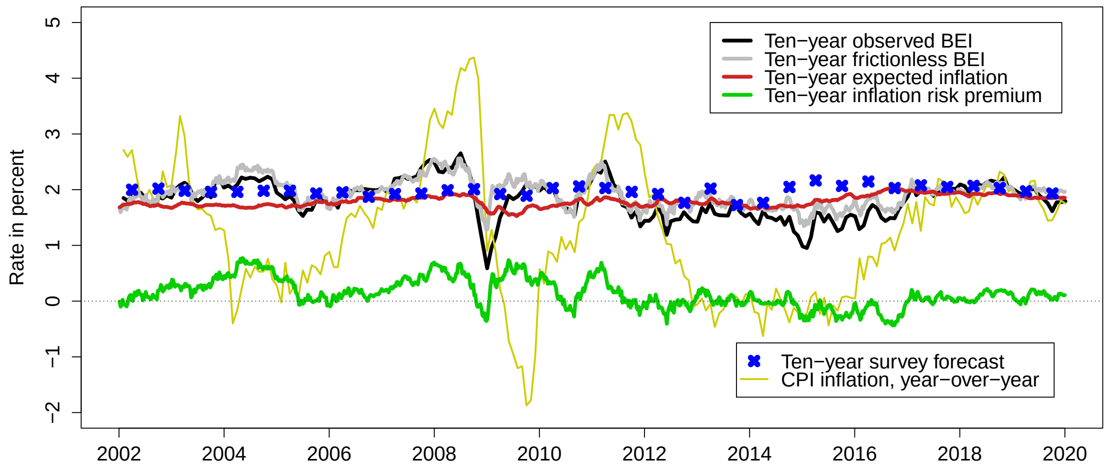


Figure 5: **Ten-Year BEI Decomposition**
Illustration of the ten-year fitted BEI implied by the $G(4)$ model, i.e. the model without adjustment for bond-specific premia in the prices of nominal and real bonds, and its decomposition into (1) the fitted frictionless BEI, (2) the ten-year expected inflation, and (3) the residual ten-year inflation risk premium based on the preferred $G^{X^N,X^R}(6)$ model. Also shown are the ten-year inflation forecasts from the Consensus Forecasts and the year-over-year change in the Swedish CPI.

acterized by a very stable pattern remaining close to 2 percent for the entire period. This suggests that investors' long-term inflation expectations in Sweden are very well anchored near the Riksbank's 2 percent inflation target. This is also consistent with the responses to the Consensus Forecasts survey of professional forecasters, who twice a year are asked about their expectations for inflation over the following ten years. The mean responses in each survey since 2002 are shown with blue crosses in Figure 5 and have remained very close to 2 percent throughout this period. As a consequence, both investors and the forecasters appear to agree that the variation in Swedish long-term BEI rates mainly reflects fluctuations in inflation risk premia rather than changes in the expected inflation. Importantly, we stress that this result is not a consequence of lack of persistence of the state variables within our model or their assumed stationarity as evidenced by the pronounced declines in the expectations component of nominal and real ten-year yields in Figure 4; see Bauer et al. (2012) for a discussion.

4.3.3 Estimates of the Natural Real Rate

Our market-based measure of the natural rate is the average expected real short rate over a five-year period starting five years ahead. This 5yr5yr forward average expected real short rate should capture the persistent trends in the natural real rate.

Figure 6 shows the preferred $G^{X^N,X^R}(6)$ model decomposition of the 5yr5yr forward fric-

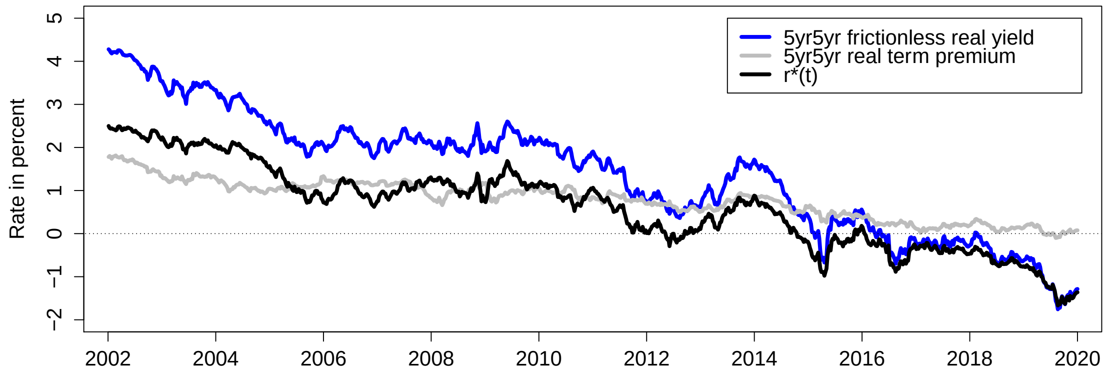


Figure 6: **5yr5yr Real Yield Decomposition**

tionless real yield based on the standard definition of the real term premium

$$TP_t^R(\tau) = \tilde{y}_t^R(\tau) - \frac{1}{\tau}\int_t^{t+\tau} E_t^{\mathbb{P}}[r_s^R]ds,$$

where $y_t^R(\tau)$ is the fitted frictionless real zero-coupon yield with maturity in τ years. The solid gray line is the 5yr5yr forward real term premium, which has exhibited a mild lower trend since 2002 that leaves it close to zero at the end of 2019. In comparison, the estimate of the natural real rate of interest implied by the $G^{X^N,X^R}(6)$ model—the black line—shows a steeper and more pronounced decline from above 2 percent in the early 2000s to below -1 percent by the end of the sample. Thus, much of the downward trend in the 5yr5yr forward real yield is driven by declines in this measure of r_t^*, while the corresponding real term premium has declined much less on net during this period.

5 The Transmission of QE to Bond Yields

In this section, we first provide a brief description of the key events and motivations behind the Riksbank's unconventional monetary policies during the 2015-2019 period before we turn to our empirical analysis of their impact on Swedish government bond yields.

5.1 The Riksbank's Unconventional Monetary Policies

In response to the low inflation in the years after the Global Financial Crisis of 2008-2009 and the European Sovereign Debt Crisis of 2011-2012, Sveriges Riksbank lowered its policy rate (repo rate) to zero and later moved it into negative territory starting in February 2015. At the same time, the Riksbank introduced a QE program involving large-scale asset purchases to provide further monetary stimulus. Initially, the Riksbank only purchased standard nominal

Date	ΔRate	Rate	Riksbank's QE announcements
Feb 12, 2015	-10	-10	Purchase government bonds for SEK 10 billion and is prepared to act on short notice.
Mar 18, 2015	-15	-25	Purchase government bonds for SEK 30 billion.
Apr 29, 2015	0	-25	Riksbank buys government bonds for SEK 40-50 billion.
Jul 2, 2015	-10	-35	Purchases of government bonds extended by SEK 45 billion.
Oct 28, 2015	0	-35	Purchases bonds of SEK 65 billion more.
Dec 15, 2015	0	-35	The Riksbank is still highly prepared to act.
Feb 11, 2016	-15	-50	
Apr 21, 2016	0	-50	Purchase government bonds of a further SEK 45 billion.
Oct 27, 2016	0	-50	Riksbank Executive Board ready to extend government bond purchases in Dec. 2016.
Dec 21, 2016	0	-50	Further purchases of government bonds SEK 30 billion.
Apr 27, 2017	0	-50	Government bond purchases extended by SEK 15 billion.
Jul 4, 2017	0	-50	Continue bond purchases according to plan.
Sep 7, 2017	0	-50	Continue bond purchases according to plan.
Dec 20, 2017	0	-50	Bond reinvestments starting in January 2018.
Dec 20, 2018	25	-25	
Dec 19, 2019	25	0	

Table 2: **Key Riksbank Monetary Policy Decisions and QE Announcements 2015–2019**

Swedish government bonds with long maturities. In April 2016, the Riksbank added purchases of inflation-indexed government bonds to its existing nominal bond purchase program. By April 2020, it owned more than half of the outstanding nominal bond market and about a quarter of the market for inflation-indexed bonds. Table 2 summarizes the key monetary policy decisions and QE announcements made by the Riksbank in the 2015–2019 period.[13] Note that the table only includes monetary policy decision dates with interest rate changes or QE announcements.

5.2 ECB Unconventional Monetary Policy

The European Central Bank (ECB) also implemented unconventional monetary policy in the form of QE aimed at stimulating the economy and combatting deflationary pressures. The QE program of the ECB started operating in March 2015.[14] At its peak in 2022, the Eurosystem held assets in an amount equal to around 56 percent of euro-area nominal GDP.

The primary goal of the ECB's QE program was to bring the inflation rate up to the ECB's 2 percent target and boost economic growth in the Eurozone. Under the program, the ECB purchased a substantial amount of government bonds and other eligible assets issued by countries in the Eurozone. The ECB had certain selection criteria for the eligible assets. For instance, bonds had to be above a minimum credit rating and meet certain maturity requirements. This helped maintain the quality and safety of the assets held by the ECB

[13] During the coronavirus pandemic, the Riksbank announced a number of measures that led to a further increase in its balance sheet to alleviate the negative economic impact of the government policies imposed to fight the pandemic. The Riksbank decided to expand its balance sheet up to a maximum of SEK 700 billion by the end of 2021, which included purchases of government bonds, treasury bills, covered bonds (mortgage bonds), municipal bonds, and corporate debt securities. These measures aimed at stimulating the economic recovery and supporting market liquidity and functioning. Given that these measures fall outside of our sample period, we leave it for future research to evaluate their effects.

[14] On 22 January 2015, the ECB announced the Public Sector Purchase Programme (PSPP), which would supplement its existing Asset-Backed Securities and Covered Bonds Purchase Programmes, known as ABSPP and CBPP3, respectively.

Date	ECB's QE announcements
Jan 2, 2015	Draghi hints that ECB is in preparations to adjust its stimulus program
Jan 22, 2015	Expanded Asset Purchase Program (EAPP) is announced. ECB will buy 60 billion per month until September 2016
Sep 3, 2015	Draghi hints about further purchases
Oct 22, 2015	Draghi hints that further measures will be announced in December 2015
Dec 3, 2015	ECB lowers its deposit facility rate and extends the asset purchase program to March 2017
Jan 21, 2016	ECB signals more easing to come in March 2016
Mar 10, 2016	ECP lowers policy rates and expands EAPP to 80 billion per month, expected to last until March 2017
Sep 8, 2016	ECB surprises with not announcing EAPP extension
Oct 20, 2016	ECB hints that EAPP extension will be announced in December 2016
Dec 8, 2016	EAPP extended to December 2017, with purchases reduced to 60 billion per month
Jun 27, 2017	Draghi's speech in Sintra suggests that ECB is considering to scale back the asset purchase
Sep 7, 2017	ECB leaves rates on hold and paves the way for tapering its stimulus program
Oct 26, 2017	Purchases under EAPP extended to September 2018, but reduced to 30 billion per month from January 2018
Jun 14, 2018	Purchases under EAPP to end in December 2018, but reduced to 15 billion per month from October 2018
Sep 13, 2018	ECB confirms that EAPP asset purchases will decline to 15 billion per month until December 2018
Oct 25, 2018	Purchases under EAPP to end in December 2018 provided that data confirm the expected medium-term outlook
Dec 13, 2018	ECB to keep key interest rates at least through the summer of 2019. Purchases under EAPP will end in December 2018
Mar 7, 2019	ECB announces its TLTRO-III program to start in September 2019 and end in March 2021
Jun 18, 2019	Draghi's speech in Sintra reveals that additional stimulus is needed if outlook does not improve
Jul 25, 2019	ECB keeps policy on hold, but signals additional stimulus
Sep 12, 2019	ECB announces -10 bps rate cut, 20 billion per month in EAPP

Table 3: **Key ECB Speeches and QE Announcements 2015–2019**

under the QE program. These purchases have been shown to have direct impacts on financial markets; see, for example, De Santis (2020), Koijen et al. (2021), Arrata et al. (2020), among many others. They have also been found to have substantial effects on the macroeconomy; see Gambetti and Musso (2017) and Hohberger et al. (2019), among others. Table 3 contains a number of key speeches and announcements about the ECB's monetary policy and QE programs in the 2015-2019 period.

Finally, we obtain weekly balance sheet and transactions data from the Riksbank with details of the execution of its QE programs, including information on the price, amount, and maturity of the bonds acquired in each purchase auction. We will use this data in our empirical analysis.

5.3 Empirical Results

In this section, we use time series regressions to examine the channels through which the Riksbank's bond purchases affected Swedish government bond yields of various maturities. As discussed in the introduction, we look into four channels: signaling, portfolio rebalancing, liquidity-scarcity, and tail risk.

In general, our baseline regressions take the form

$$\Phi_t = \alpha + \beta Q_t + \beta^* Q_t^* + \gamma X_t + \epsilon_t, \tag{10}$$

where the dependent variable, Φ_t, is a component from the weekly yield decompositions produced by our preferred $G^{X^N,X^R}(6)$ dynamic term structure model described earlier, while Q_t quantifies the Riksbank's QE program in terms of total purchases, measured as a percentage of Swedish nominal GDP.[15] We examine spillover effects from the ECB's bond purchases by including the ECB's QE program measured as a fraction of nominal GDP in the euro area

[15] The reported results are robust to instead using the Riksbank's bond holdings, which takes into account that certain bonds matured in the Riksbank portfolio. It does not change the results if we use the nominal value of the bond holdings instead of the ratio to Swedish GDP.

and denoted Q_t^*.

To control for yield changes unrelated to the Riksbank's bond purchases, we add several monetary policy shock measures in the regressions, including the monetary policy rate changes (Int. rate), the monetary policy surprises (MPS) calculated using the measure of De Rezende and Ristiniemi (2020), and the QE surprises (QES) normalized by Swedish GDP.[16] We also include a dummy variable for announcement dates regarding the Riksbank's QE program. Moreover, we control for broader bond market conditions using a noise measure to account for limits to arbitrage capital (Hu et al. 2013), the average bond age, and realized volatility of the ten-year yield to proxy for liquidity (Houweling et al. 2005). Note that these three variables can be computed for the nominal and real bond market separately, so we include all six series throughout the analysis.

Finally, we note that the sample used throughout for the regression analysis contains weekly data covering the period from March 13, 2015, to December 27, 2019, a total of 251 observations. This allows us to focus squarely on the part of our sample during which both the Riksbank and the ECB operated QE programs.

5.3.1 Signaling Channel

There is a large literature arguing that the operation of large-scale asset purchase programs sends a strong signal about future monetary policy. Specifically, by committing to buy and hold a large portfolio of government bonds for an extended period, the central bank sends a credible signal that it plans to keep the policy rate low for longer than previously anticipated.

In this section, we investigate whether the Riksbank's bond purchases had signaling effects on the inflation and short-rate expectations as well as the natural real rate r_t^* extracted from our yield curve model. That is, we run the regression in equation (10) with the estimated expectations components from our yield decompositions as the dependent variable. The results are reported in Table 4. Columns 1 and 2 show the results for the effects on the extracted five- and ten-year inflation expectations. We note that there are significant effects of the Riksbank's bond purchases on inflation expectations, with positive coefficients at both maturities. Importantly, in these initial baseline regressions, the ECB's asset purchases put significant downward pressure on Swedish inflation expectations, and more so in the near term. We examine the robustness of this finding later on.

Columns 3 and 4 report the effects on the short-rate expectations implied from the yield curve model. These results show that the bond purchases are associated with rising short-rate expectations at both horizons. The effect from conventional monetary policy surprises is in the same direction as indicated by the positive estimated coefficients for the MPS variable, although these estimated coefficients are small in magnitude and statistically insignificant.

[16] These are computed as the difference between market survey expectations of the QE amounts and the actual announced amounts.

	Inflation Expectations (bps)		Short-Rate Expectations (bps)		r^*
	5yr	10yr	5yr	10yr	
Riksbank's QE	2.736***	1.502***	9.978***	4.735**	-0.775
	(0.597)	(0.338)	(3.191)	(2.308)	(1.819)
ECB's QE	-0.770***	-0.409***	-3.007**	-1.420*	0.214
	(0.238)	(0.135)	(1.202)	(0.859)	(0.687)
Int. rate (bps)	-0.300	-0.157	-2.533	-1.882*	-1.218**
	(0.291)	(0.158)	(1.577)	(1.013)	(0.471)
MPS (bps)	0.226	0.123	1.196	0.760	0.304
	(0.368)	(0.204)	(2.262)	(1.625)	(1.138)
QES	-2.264	-1.171	-15.612*	-10.797*	-5.906
	(1.610)	(0.893)	(8.354)	(5.591)	(3.669)
D(News)	2.835	1.579	9.334	4.606	-0.444
	(2.876)	(1.599)	(15.189)	(10.525)	(7.693)
Noise^N	2.606*	1.398*	14.684	9.413	3.953
	(1.488)	(0.821)	(9.169)	(6.630)	(4.712)
Age^N	3.492	2.610	-34.909	-38.013**	-42.847***
	(4.128)	(2.243)	(26.019)	(18.410)	(11.879)
RVol^N	-0.306	-0.170	-2.461	-1.937	-1.379
	(0.435)	(0.244)	(2.562)	(1.879)	(1.445)
Noise^R	-1.611**	-0.894**	-8.491	-5.441	-2.215
	(0.808)	(0.436)	(6.221)	(4.826)	(3.790)
Age^R	-7.511***	-3.846***	-56.618***	-40.238***	-23.682***
	(1.253)	(0.676)	(8.025)	(5.677)	(3.640)
RVol^R	-3.917	-1.708	-38.842	-27.251	-16.163
	(4.291)	(2.326)	(29.422)	(21.861)	(15.822)
No. of obs.	251	251	251	251	251
R^2	0.666	0.645	0.779	0.786	0.760
Adj. R^2	0.649	0.628	0.767	0.775	0.748

Table 4: **QE Program Impact on Inflation Expectations, Short-Rate Expectations and the Natural Real Rate**
The dependent variables represent weekly estimates of expected inflation, short-rate expectations, and the natural real rate from the preferred $G^{X^N,X^R}(6)$ model, all measured in basis points. The QE bond holdings are normalized by Swedish nominal GDP. The ECB QE amounts are normalized by the nominal GDP in the euro area. Additional control variables include the repo interest rate changes (bps), the monetary policy surprises (bps), the QE surprises normalized by Swedish nominal GDP, the QE announcement dummy, the nominal and real bond market noise measure, the average nominal and real bond age, and the nominal and real bond realized volatility. We report the statistical significance using Newey West standard errors with four lags. Asterisks *, ** and *** indicate significance at the 10 percent, 5 percent and 1 percent levels, respectively.

Overall, we take these results to imply that medium- to long-term short-rate expectations were significantly positively affected by the Riksbank's asset purchases.

Moreover, we find that the impact of the Riksbank's bond purchases on our estimate of r^* is negative, but insignificant. Thus, the QE bond purchases do not seem to affect the level of the natural rate much.

Furthermore, as already noted, the ECB's QE program had a tendency to depress both inflation and short-rate expectations in Sweden. Hence, Swedish bond investors seem to take a strong negative signal about the general economic and inflation outlook from the ECB's operation of its QE program. This contrasts with the generally positive market response to the domestic QE program operated by the Riksbank. We will return to this point later to explore the underlying mechanisms driving these results.

Finally, we see a tendency for our liquidity control variables—that is, the average age of our nominal and real bonds and the realized one-month volatility of the ten-year nominal and real yields—to negatively affect our expectations measures. Thus, when financial market conditions deteriorate and liquidity risk goes up, inflation and short-rate expectations and the level of the natural rate all decline. This suggests that financial market liquidity and economic uncertainty significantly affect Swedish investors' perceptions about the outlook for both inflation and monetary policy in addition to the steady-state level of real interest rates.

5.3.2 Portfolio Rebalancing Channel

The portfolio rebalancing channel works by affecting the compensation investors demand for assuming the risk of holding long-term bonds. In our analysis, this compensation is quantified by the nominal and real term premium series in addition to the inflation risk premium. We therefore explore the effects of the Riksbank's and ECB's QE programs on these risk premium series.

Table 5 presents the regression results for our term premium and inflation risk premium estimates at the five- and ten-year maturities. The results suggest that the bond purchases affected nominal and real term premia negatively at both maturities. The effects are statistically significant, with a 1 percentage point of Swedish GDP increase in the Riksbank's bond holdings reducing the five-year nominal term premium by 12.20 basis point, while the effect at the ten-year maturity is a smaller 7.87 basis points. The corresponding results for the real term premia and the inflation risk premia are somewhat smaller, but still statistically significant, with the exception of the ten-year inflation risk premium. In general, the effects at the long end of the yield curve are smaller, which seems reasonable given that the five-year horizon is likely the more relevant horizon for monetary policy effects. Moreover, the Riksbank's bond purchases were concentrated around the five-year maturity point.

The economically and statistically significant reduction of nominal and real term premia along the yield curve in response to the QE program shows that the portfolio rebalancing channel may be a strong and active transmission mechanism in Sweden during the operation of the domestic QE program.

The analysis shows that the premium demanded to hold both nominal and real bonds dropped, and even the premium for assuming the involved inflation risk declined. This is the case even as inflation and monetary policy expectations were firming, as noted in Table 4. Hence, it is truly the prices of these risks that were being squeezed by the Riksbank's QE program.

In contrast and interestingly, the ECB's QE program had the exact opposite effect as it

	Nominal Term Premium		Real Term Premium		Inflation Risk Premium	
	5yr	10yr	5yr	10yr	5yr	10yr
Riksbank's QE	-12.199***	-7.867***	-9.789***	-6.476***	-2.421**	-1.398
	(2.531)	(1.466)	(2.157)	(1.265)	(1.035)	(1.012)
ECB's QE	3.785***	2.551***	2.440***	1.484***	1.348***	1.069***
	(0.987)	(0.586)	(0.846)	(0.505)	(0.413)	(0.408)
Int. rate (bps)	2.509*	1.245*	1.982*	1.004	0.526**	0.241
	(1.309)	(0.710)	(1.092)	(0.633)	(0.251)	(0.150)
MPS (bps)	-1.262	-0.683	-1.169	-0.726	-0.093	0.043
	(1.964)	(1.056)	(1.520)	(0.818)	(0.526)	(0.374)
QES	12.347*	6.124	10.426*	5.620*	1.926	0.508
	(7.217)	(4.185)	(5.394)	(2.925)	(2.348)	(1.931)
D(News)	-11.671	-6.350	-16.589	-12.650**	4.896	6.289
	(13.748)	(8.190)	(10.156)	(5.503)	(5.003)	(4.350)
Noise^N	-10.118	-5.229	-8.405	-4.635	-1.718	-0.598
	(8.034)	(4.600)	(6.325)	(3.701)	(2.621)	(2.211)
Age^N	12.599	-4.020	18.120	5.179	-5.538	-9.207**
	(23.634)	(12.612)	(19.294)	(10.729)	(6.005)	(4.627)
RVol^N	1.155	0.148	2.128	1.369	-0.973	-1.220*
	(2.137)	(1.195)	(1.669)	(0.914)	(0.747)	(0.653)
Noise^R	9.309**	5.044**	8.393**	5.126**	0.917	-0.080
	(4.678)	(2.406)	(4.025)	(2.164)	(1.415)	(1.329)
Age^R	41.328***	19.635***	33.615***	16.811***	7.721***	2.831*
	(6.561)	(3.480)	(5.397)	(3.110)	(1.982)	(1.652)
RVol^R	34.796	20.937*	8.628	-2.494	26.160***	23.428***
	(23.661)	(12.259)	(20.723)	(12.046)	(6.123)	(5.411)
No. of obs.	251	251	251	251	251	251
R^2	0.746	0.685	0.740	0.724	0.705	0.653
Adj. R^2	0.733	0.669	0.727	0.710	0.690	0.636

Table 5: **QE Program Impact on Standard Bond Risk Premia**
The dependent variables represent weekly estimates of the nominal and real term premium and the inflation risk premium from the preferred $G^{X^N,X^R}(6)$ model, all measured in basis points. The QE bond holdings are normalized by Swedish nominal GDP. The ECB QE amounts are normalized by the nominal GDP in the euro area. Additional control variables include the repo interest rate changes (bps), the monetary policy surprises (bps), the QE surprises normalized by Swedish nominal GDP, the QE announcement dummy, the nominal and real bond market noise measure, the average nominal and real bond age, and the nominal and real bond realized volatility. We report the statistical significance using Newey West standard errors with four lags. Asterisks *, ** and *** indicate significance at the 10 percent, 5 percent and 1 percent levels, respectively.

tended to put upward pressure on all three risk premia in this initial set of regressions. Lastly, as for the remaining control variables, we note that increased financial market frictions and liquidity risk tends to raise the price of risk demanded by investors, which explains the mostly positive coeffecients on our proxy variables (noise, age, realized volatility) for these market risks.

5.3.3 Liquidity-Scarcity Channel

Next, we examine the effect of the Riksbank's QE program on the bond-specific safety premia using the regression framework with the results reported in Table 6. The first column shows

	Nominal Safety Premium	Real Safety Premium
Riksbank's QE	4.484***	0.716
	(0.726)	(0.732)
ECB's QE	-1.679***	0.139
	(0.282)	(0.276)
Int. rate (bps)	-0.452	-0.746**
	(0.381)	(0.349)
MPS (bps)	0.486	0.278
	(0.484)	(0.544)
QES	-3.428	-3.131*
	(2.387)	(1.832)
D(News)	2.262	1.107
	(4.861)	(2.946)
Noise^N	4.367*	2.666
	(2.468)	(2.213)
Age^N	8.272	-3.880
	(5.566)	(6.287)
RVol^N	0.557	-1.192*
	(0.540)	(0.619)
Noise^R	-1.218	-2.313**
	(1.299)	(1.113)
Age^R	-11.269***	-11.846***
	(1.760)	(1.949)
RVol^R	-15.468***	-2.325
	(5.518)	(6.446)
No. of obs.	251	251
R^2	0.771	0.701
Adj. R^2	0.760	0.686

Table 6: **QE Program Impact on the Average Nominal and Real Safety Premium** The dependent variables represent weekly estimates of the average nominal and real safety premium from the preferred $G^{X^N,X^R}(6)$ model, both measured in basis points. The QE bond holdings are normalized by the Swedish GDP. The ECB QE amounts are normalized by the nominal GDP in the euro area. Additional control variables include the repo interest rate changes (bps), the monetary policy surprises (bps), the QE surprises normalized by the Swedish GDP, the QE announcement dummy, the nominal and real bond market noise measure, the average nominal and real bond age, and the nominal and real bond realized volatility. We report the statistical significance using Newey West standard errors with four lags. Asterisks *, ** and *** indicate significance at the 10 percent, 5 percent and 1 percent levels, respectively.

that the average nominal safety premium goes up as the Riksbank increases its bond holdings. The estimated coefficient indicates that an increase in the Riksbank's cumulated bond purchases equal to 1 percentage point of Swedish nominal GDP raises the average nominal safety premium by 4.48 basis points. We take this statistically significant result to imply that the Riksbank's bond purchases made the nominal bonds more scarce and exclusive. As reported in the second column, the real bond safety premium was only marginally affected by the QE program, with an estimated coefficient of 0.72 basis point that is not statistically significant. This weaker result for the real bond market may reflect the fact that the Riksbank's purchases of inflation-indexed bonds started later and were much smaller relative to the nominal bond purchases.

Finally, similar to the previous results, the ECB asset purchases have an offsetting effect in that they tend to lower the safety premium of Swedish nominal government bonds. Christensen and Mirkov (2022) report similar results for the impact of the ECB's QE program on Danish and Swiss government bond safety premia, while Christensen et al. (2024) extend that analysis to include German and Swedish government bond safety premia and confirm these findings for all four bond markets.

5.3.4 Tail Risk Channel

Hattori et al. (2016) present evidence that the QE programs in the United States helped lower both the option-implied volatility in the stock market and the level of interest rate risk. While their analysis employed event study regressions to analyze the impact from unconventional monetary policy announcements, we focus on the effect of QE on an extreme downside tail risk to the inflation outlook that we measure through our estimated deflation risk premia, as in Christensen and Spiegel (2022). Moreover, instead of relying on an event-study approach, we run regressions using our continuous tail risk measure as the dependent variable.[17]

Table 7 reports the regression results for the effect of the QE bond purchases on our estimates of the deflation risk premium. Consistent with the findings for the expected inflation in Table 4, the QE purchases push down the deflation risk premium 3.91 basis points and 2.25 basis points at the five- and ten-year maturity, respectively, but these effects are not statistically significant. Thus, the Riksbank's QE program does not appear to have affected investors' perceptions about downside tail risks to the Swedish economy. For context, though, it should be kept in mind that the deflation risk premium in Sweden had been relatively low all along, as shown in Figure 3. Furthermore, if the most serious downside risks to the Swedish economy are foreign shocks, as suggested by the Global Financial Crisis and the European Sovereign Debt Crisis, the Riksbank's actions, including its QE program, may only play a secondary role for Swedish deflation risk premia.

5.3.5 A Comment on the Spillover Effects of the ECB's QE Program

In our initial set of regressions, the spillover effects from the ECB's QE program onto the Swedish government bond markets appear to be negative, essentially counteracting or offsetting the stimulus provided by the Riksbank's domestic QE program. Thus, the joint effect appears to have a "beggar-thy-neighbor" or zero-sum feature to it that seems counterintuitive, given that both central banks were actively pursuing policies to ease financial conditions and promote economic growth. This raises the question of whether there is a role to be played by the fluctuations in the SEK-EUR exchange rate for our assessment of the effects on Swedish bond markets from the ECB's QE programs.

[17] As there are only a very small number of announcements regarding the Riksbank's QE programs, an event-study approach will have very limited statistical power.

	Deflation Risk Premium	
	5yr	10yr
Riksbank's QE	-3.911	-2.249
	(3.515)	(8.100)
ECB's QE	-1.438	-5.020
	(1.379)	(3.255)
Int. rate (bps)	-0.825	-0.708
	(0.827)	(1.431)
MPS (bps)	-1.248	-2.551
	(1.409)	(2.566)
QES	0.578	4.544
	(5.184)	(12.479)
D(News)	-38.970***	-72.459**
	(11.590)	(28.397)
Noise^N	-1.048	-4.535
	(7.946)	(16.187)
Age^N	1.167	57.109*
	(14.831)	(33.293)
RVol^N	7.870***	14.064***
	(2.308)	(4.925)
Noise^R	2.700	7.618
	(4.205)	(10.553)
Age^R	2.579	13.193
	(5.453)	(12.045)
RVol^R	-122.758***	-208.442***
	(28.012)	(51.351)
No. of obs.	251	251
R^2	0.781	0.715
Adj. R^2	0.770	0.701

Table 7: **QE Program Impact on Deflation Risk Premia**
The dependent variables represent weekly estimates of deflation risk premium at the five- and ten-year maturities from the preferred $G^{X^N,X^R}(6)$ model, both measured in basis points. The QE bond holdings are normalized by the Swedish GDP. The ECB QE amounts are normalized by the nominal GDP in the euro area. Additional control variables include the repo interest rate changes (bps), the monetary policy surprises (bps), the QE surprises normalized by the Swedish GDP, the QE announcement dummy, the nominal and real bond market noise measure, the average nominal and real bond age, and the nominal and real bond realized volatility. We report the statistical significance using Newey West standard errors with four lags. Asterisks *, ** and *** indicate significance at the 10 percent, 5 percent and 1 percent levels, respectively.

Furthermore, these results are also puzzling because of the close relationship between Sweden and the euro area through both economic and financial linkages. In a small open economy with a floating exchange rate regime like Sweden, the domestic financial markets are well connected with other European markets due to the free mobility of capital. Still, financial frictions in exchange rate markets could play an important role in determining the spillover effects from the ECB's unconventional monetary policies. As a consequence, we expand our empirical analysis to study the impact of accounting for the SEK-EUR exchange rate fluctuations on our assessment of the transmission channels through which both the Riksbank's and the ECB's QE programs operated.

5.4 Role of the Exchange Rate for Spillover Effects of Foreign QE

In the previous section, we investigated the effects of both the domestic QE program implemented by the Riksbank and the simultaneous foreign QE program operated by the ECB. The regressions seem to suggest that the bond market effects of domestic and foreign asset purchases on bond risk premia move in opposite directions with a tendency to offset each other. However, the SEK-EUR exchange rate, which moves in response to both QE programs and could play an important role for the demand of government bonds, has not been considered directly in the analysis so far. There exist both an empirical and a theoretical literature that provide support for a link between the exchange rate and the market for, and properties of, safe assets such as the Swedish government bonds examined here. Avdjiev et al. (2019) and Engel and Wu (2021) both relate the U.S. dollar exchange rate to the safety and convenience services provided by U.S. Treasuries. Jiang et al. (2021) show within a theoretical model that the demand for U.S. dollar-denominated safe assets affects the U.S. dollar exchange rate. Essentially, this literature establishes that the convenience or safety premia can be linked to the exchange rate through the safe asset demand of foreign investors. Recently, Jiang et al. (2022) further demonstrate that the demand for safe assets is an important but understudied channel through which the Federal Reserve affects the U.S. dollar exchange rate via its QE programs.

While U.S. dollar-denominated safe securities are the primary safe assets demanded by global investors, it is reasonable to believe that other relevant classes of safe assets exist, including government bonds denominated in domestic currencies. Due to market incompleteness and market segmentation, investors from other countries will need safe assets denominated in their local currencies to hold or pledge as collateral in their domestic financial markets. At the same time, home-biased investors would have an appetite for holding local currency-denominated safe assets, rather than combining U.S. safe assets with a foreign exchange rate hedging strategy. Typically, such strategies are too costly for most investors to profitably pursue. In our initial set of baseline regressions, the ECB's bond purchases are normalized using the nominal GDP in the euro area, so the SEK-EUR exchange rate should not affect our measure of the ECB QE program as it is without a monetary unit. However, using a standard small open economy model with Ricardian equivalence and perfect asset substitutability, Bacchetta and Chikhani (2021) argue that a QE program can be viewed as equivalent to direct foreign exchange interventions. In turn, this points to a potentially important role for the exchange rate in the resulting effects of domestic and foreign QE programs. Against this background of unsettled theoretical questions, it is ultimately an empirical question whether accounting for exchange rate fluctuations can help us better understand the effects of foreign QE programs on domestic bond risk premia.

We add that our basic hypothesis in the following is that the ECB asset purchases may have some effect on the SEK-EUR exchange rate—as suggested by the analysis in Jiang et al.

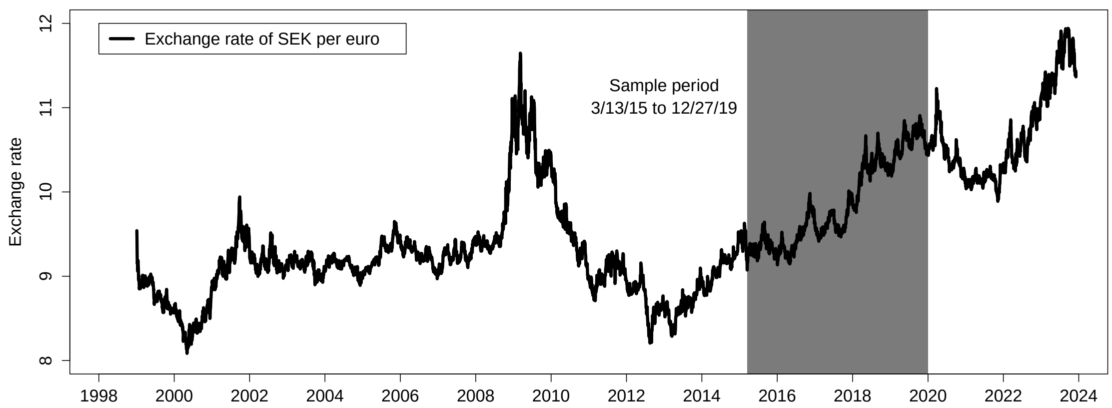


Figure 7: **Exchange Rate of the Swedish Kronor to the Euro**

(2022)—but many other factors influence the exchange rate, including Swedish QE purchases. Hence, our modified regression model below is an attempt to condition the effects of the ECB's QE purchases on the level of the SEK-EUR exchange rate.

To account for such exchange rate effects in our analysis, we refine our regression analysis to allow for an explicit role of the exchange rate. Specifically, the regression model is modified to include the exchange rate via its interaction with the ECB's QE program variable:

$$\Phi_t = \alpha + \beta_1 Q_t + \beta_2 Q_t^* + \beta_3 Q_t^* \times E_t + \gamma X_t + \epsilon_t, \tag{11}$$

where E_t stands for the SEK-EUR exchange rate, i.e. the number of Swedish kronor per euro. Note that the interaction term shows how the exchange rate mitigates or amplifies the effects from the ECB's QE program (Q_t^*), depending on the sign of its coefficient β_3.

In the following, we will discuss the new results for the signaling, portfolio rebalancing, liquidity-scarcity, and tail risk channels, with a special emphasis on the role of the exchange rate in explaining the spillover effects of ECB's QE program on Swedish bond markets. However, to set the stage, Figure 7 shows the exchange rate of the Swedish kronor to the euro since 1999. Note that it fluctuated in the range between 9.07 and 10.91 during our sample period, which runs from mid-March 2015 through the end of December 2019. This matters for interpreting our refined regression results.

5.4.1 Signaling Channel

In assessing the role of the signaling channel, we focus on the expected inflation and expected future short rates, both averaged over the next five years and ten years, respectively, and the natural real rate as the dependent variables in our regressions with the results presented in

	Inflation Expectations (bps)		Short-Rate Expectations (bps)		r^*
	5yr	10yr	5yr	10yr	
Riksbank's QE	2.351***	1.301***	7.384***	2.917	-1.800
	(0.574)	(0.331)	(2.774)	(2.026)	(1.762)
ECB's QE	0.926	0.479	8.427	6.593*	4.730*
	(0.811)	(0.436)	(5.471)	(3.985)	(2.743)
ECB's QE× E_t	-0.154**	-0.081**	-1.040**	-0.729*	-0.411
	(0.072)	(0.038)	(0.520)	(0.380)	(0.255)
Int. rate (bps)	-0.240	-0.126	-2.133*	-1.602*	-1.060**
	(0.241)	(0.132)	(1.280)	(0.828)	(0.428)
MPS (bps)	0.213	0.116	1.104	0.696	0.268
	(0.356)	(0.196)	(2.343)	(1.717)	(1.228)
QES	-1.792	-0.924	-12.433*	-8.569*	-4.650
	(1.490)	(0.832)	(7.427)	(4.934)	(3.353)
D(News)	2.145	1.218	4.680	1.344	-2.283
	(2.698)	(1.522)	(12.452)	(8.313)	(6.443)
Noise^N	2.698*	1.446*	15.304*	9.847	4.198
	(1.395)	(0.766)	(9.118)	(6.728)	(4.923)
Age^N	5.019	3.409*	-24.616	-30.799**	-38.782***
	(3.515)	(1.927)	(21.733)	(15.605)	(10.823)
RVol^N	-0.118	-0.071	-1.190	-1.046	-0.877
	(0.401)	(0.225)	(2.496)	(1.887)	(1.515)
Noise^R	-1.830**	-1.009**	-9.966	-6.475	-2.798
	(0.779)	(0.421)	(6.169)	(4.827)	(3.838)
Age^R	-4.736**	-2.394**	-37.920***	-27.133***	-16.298**
	(1.910)	(1.025)	(13.152)	(9.517)	(6.328)
RVol^R	-3.991	-1.746	-39.340	-27.600	-16.359
	(3.935)	(2.126)	(28.254)	(21.297)	(15.843)
No. of obs.	251	251	251	251	251
R^2	0.684	0.663	0.796	0.801	0.769
Adj. R^2	0.667	0.644	0.785	0.791	0.756

Table 8: **QE Program Impact on Inflation Expectations, Short-Rate Expectations and the Natural Real Rate: Exchange Rate Effects**
The dependent variables represent weekly estimates of expected inflation, short-rate expectations, and the natural real rate from the preferred $G^{X^N,X^R}(6)$ model, all measured in basis points. The regression takes the form $\Phi_t = \alpha + \beta_1 Q_t + \beta_2 Q_t^* + \beta_3 Q_t^* \times E_t + \gamma X_t + \epsilon_t$. The QE bond holdings are normalized by Swedish nominal GDP. The ECB QE amounts are normalized by the nominal GDP in the euro area. Additional control variables include the repo interest rate changes (bps), the monetary policy surprises (bps), the QE surprises normalized by Swedish nominal GDP, the QE announcement dummy, the nominal and real bond market noise measure, the average nominal and real bond age, and the nominal and real bond realized volatility. We report the statistical significance using Newey West standard errors with four lags. Asterisks *, ** and *** indicate significance at the 10 percent, 5 percent and 1 percent levels, respectively.

Table 8. First and importantly, we note that the estimated coefficients on the Riksbank's bond purchases are qualitatively similar to, although somewhat smaller than, those reported in Table 4. Thus, our main findings about the effects of the Riksbank's domestic QE program on Swedish bond investors' expectations about future inflation and monetary policy carry through after including the interaction between the ECB's QE program and the SEK-EUR exchange rate.

Second and equally importantly, the estimated effects of the ECB's bond purchases are now all positive, although none is statistically significant at the 5 percent level. This shows that the ECB QE program complements the Riksbank's QE program in terms of the transmission of QE to investors' expectations about future inflation and monetary policy.

Third, as for the effects of the added interaction between the measure of the ECB's QE program and the SEK-EUR exchange rate, the estimated coefficients are all negative and mostly statistically significant except for the regression with the natural real rate as the dependent variable. Thus, the fluctuations in the exchange rate indeed do play a role for how foreign QE programs affect domestic investors' economic outlook.

As for the impact of adding the exchange rate to our analysis, we note for starters that the ECB QE program should push down euro-area interest rates and put downward pressure on the value of the euro against other currencies, including the Swedish kronor. Hence, if the SEK depreciates against the euro (an increase in E_t) during the ECB QE program as documented in Figure 7, it means that some economic forces specific to Sweden are able to offset the baseline push towards an appreciation of the Swedish kronor—the leading candidate would be the Riksbank's own QE purchases. The negative regression coefficients on the interaction term with the ECB QE measure then suggest that these economic forces primarily affect and lower investors' inflation and short-rate expectations, while they appear to matter little for our estimate of the natural real rate. Overall, this would be consistent with an easing of financial conditions in Sweden.

Given that the SEK-EUR exchange rate fluctuated between 9 and 11 during our sample period, the estimated coefficients on the interacted terms with the exchange rate imply that the net effect of the ECB's QE program on Swedish inflation and short rate expectations is negative, but to varying degrees depending on the level of the exchange rate. Again, the natural real short rate is the exception, where the net effect is positive for all assumed values of E_t during our sample period.

On the other hand, if the SEK appreciates against the euro—meaning E_t declines—while the ECB is operating its QE program, investors' inflation and short-rate expectations will tend to increase more than indicated by the insignificant regression coefficients of the ECB QE measure on their own. That is, an appreciation in the midst of foreign QE tends to be correlated with a firming of domestic inflation and monetary policy expectations. This could be interpreted as investors being bullish about the prospects for the domestic Swedish economy under those circumstances.

Finally, as for the remaining control variables, their estimated coefficients are very similar to the previous results reported in Table 4 and hence little affected by the addition of the exchange rate interaction term.

	Nominal Term Premium		Real Term Premium		Inflation Risk Premium	
	5yr	10yr	5yr	10yr	5yr	10yr
Riksbank's QE	-10.522***	-7.160***	-7.958***	-5.386***	-2.575**	-1.780*
	(2.152)	(1.358)	(1.725)	(1.050)	(1.026)	(0.996)
ECB's QE	-3.607	-0.567	-5.635	-3.320	2.026*	2.752**
	(4.267)	(2.207)	(3.624)	(2.044)	(1.225)	(1.070)
ECB's QE× E_t	0.672	0.283	0.734**	0.437**	-0.062	-0.153*
	(0.411)	(0.206)	(0.350)	(0.194)	(0.109)	(0.093)
Int. rate (bps)	2.250**	1.136*	1.700*	0.836	0.549**	0.300*
	(1.103)	(0.614)	(0.884)	(0.507)	(0.261)	(0.179)
MPS (bps)	-1.202	-0.658	-1.104	-0.688	-0.099	0.029
	(1.991)	(1.053)	(1.554)	(0.817)	(0.527)	(0.380)
QES	10.292	5.257	8.181*	4.284*	2.114	0.976
	(6.622)	(3.948)	(4.756)	(2.565)	(2.337)	(1.945)
D(News)	-8.662	-5.081	-13.302	-10.695**	4.620	5.603
	(12.231)	(7.737)	(8.317)	(4.594)	(4.979)	(4.326)
Noise^N	-10.519	-5.398	-8.843	-4.895	-1.681	-0.507
	(7.617)	(4.369)	(5.883)	(3.363)	(2.635)	(2.254)
Age^N	5.944	-6.826	10.851	0.854	-4.928	-7.691*
	(20.284)	(11.088)	(16.336)	(9.218)	(5.693)	(4.569)
RVol^N	0.333	-0.198	1.231	0.835	-0.898	-1.033
	(2.066)	(1.152)	(1.582)	(0.840)	(0.740)	(0.644)
Noise^R	10.263**	5.447**	9.436**	5.746***	0.830	-0.297
	(4.658)	(2.386)	(3.957)	(2.097)	(1.409)	(1.299)
Age^R	29.241***	14.537**	20.410**	8.954*	8.830***	5.584**
	(11.193)	(5.809)	(8.780)	(4.641)	(3.169)	(2.393)
RVol^R	35.119	21.073*	8.980	-2.285	26.130***	23.354***
	(22.591)	(11.788)	(19.046)	(10.791)	(6.035)	(5.033)
No. of obs.	251	251	251	251	251	251
R^2	0.758	0.694	0.763	0.748	0.705	0.661
Adj. R^2	0.745	0.677	0.750	0.734	0.689	0.642

Table 9: **QE Program Impact on Standard Bond Risk Premia: Exchange Rate Effects**

The dependent variables represent weekly estimates of the nominal and real term premium and the inflation risk premium from the preferred $G^{X^N,X^R}(6)$ model, all measured in basis points. The regression takes the form $\Phi_t = \alpha + \beta_1 Q_t + \beta_2 Q_t^* + \beta_3 Q_t^* \times E_t + \gamma X_t + \epsilon_t$. The QE bond holdings are normalized by Swedish nominal GDP. The ECB QE amounts are normalized by the nominal GDP in the euro area. Additional control variables include the repo interest rate changes (bps), the monetary policy surprises (bps), the QE surprises normalized by Swedish nominal GDP, the QE announcement dummy, the nominal and real bond market noise measure, the average nominal and real bond age, and the nominal and real bond realized volatility. We report the statistical significance using Newey West standard errors with four lags. Asterisks *, ** and *** indicate significance at the 10 percent, 5 percent and 1 percent levels, respectively.

5.4.2 Portfolio Rebalancing Channel

To re-examine the effects of the portfolio rebalancing channel with the exchange rate interaction term for the ECB QE variable included, Table 9 presents the regression results for the nominal and real term premium and the inflation risk premium, all measured at both the five- and ten-year maturities.

First, we note that the Riksbank's domestic QE program still significantly lowered standard bond risk premia in the Swedish government bond market, even after including the exchange rate interaction term. These results are consistent with transmission through the conventional portfolio rebalancing channel emphasized in the existing literature on QE and underscores the strength of this particular conclusion from our analysis.

Second, now ECB's QE bond purchases give rise to negative but insignificant effects on Swedish nominal and real term premia, while they tend to have significantly positive effects on Swedish inflation risk premia. Mechanically, this latter finding comes about because the ECB QE purchases tend to lower Swedish real term premia more than the nominal term premia.

Against that background it seems reasonable that the coefficient on the interaction term between the ECB QE variable and the exchange rate is only significantly positive in the regressions with the real term premium series as the dependent variable. This implies that an exchange rate appreciation (E_t decline) in the midst of ongoing ECB QE purchases will tend to reinforce the downward pressure on Swedish real term premia that is already in place from the ECB QE purchases themselves. Such reinforcing effects from an exchange rate appreciation also exist but are statistically insignificant at the 5 percent level for the Swedish nominal term and inflation risk premia.

Importantly, given that SEK-EUR exchange rate fluctuated in the 9 to 11 range during this period, it is once more the case that the interaction term dominates and determines the sign of the net effect from the ECB QE purchases. Thus, the counterintuitive effects reported in our baseline regressions seem to materialize as the squeeze of Swedish standard bond risk premia we should have observed from the ECB's QE purchases get counteracted by the depreciation of the Swedish kronor. In general, a depreciation should coincide with an increase in domestic bond yields through higher term premia (assuming no change in monetary policy or monetary policy expectations) to keep the expected bond return measured in the foreign currency unchanged. Our results would be consistent with this exact mechanism.

Finally, the estimated coefficients for the other control variables remain little affected by the inclusion of the exchange rate interaction term. In particular, the regression coefficients on the control variables for the bond market conditions, including the noise measure, the average bond age, and the realized yield volatility are mostly consistent with the results in Table 5.

5.4.3 Liquidity-Scarcity Channel

We next investigate the spillover effects of the ECB asset purchases on the Swedish bond-specific safety premia with the regression results that include the exchange rate interaction term for the ECB QE variable included, reported in Table 10. The first column shows the result for the average nominal safety premium, while the second column contains the results for the average real safety premium. First, as in our baseline regression, we note the

	Nominal Safety Premium	Real Safety Premium
Riksbank's QE	4.009***	0.206
	(0.732)	(0.658)
ECB's QE	0.412	2.384*
	(1.247)	(1.236)
ECB's QE$\times$ E_t	-0.190*	-0.204*
	(0.111)	(0.117)
Int. rate (bps)	-0.379	-0.667**
	(0.320)	(0.293)
MPS (bps)	0.469	0.260
	(0.492)	(0.545)
QES	-2.846	-2.507
	(2.244)	(1.669)
D(News)	1.411	0.194
	(4.580)	(2.487)
Noise^N	4.481*	2.788
	(2.520)	(2.165)
Age^N	10.155**	-1.859
	(4.943)	(5.207)
RVol^N	0.790	-0.943
	(0.510)	(0.613)
Noise^R	-1.488	-2.603**
	(1.261)	(1.112)
Age^R	-7.849***	-8.175**
	(2.660)	(3.273)
RVol^R	-15.560***	-2.422
	(5.491)	(6.011)
No. of obs.	251	251
R^2	0.781	0.717
Adj. R^2	0.769	0.702

Table 10: **QE Program Impact on the Average Nominal and Real Safety Premium: Exchange Rate Effects**
The dependent variables represent weekly estimates of the average nominal and real safety premium from the preferred $G^{X^N,X^R}(6)$ model, both measured in basis points. The regression takes the form $\Phi_t = \alpha + \beta_1 Q_t + \beta_2 Q_t^* + \beta_3 Q_t^* \times E_t + \gamma X_t + \epsilon_t$. The QE bond holdings are normalized by the Swedish GDP. The ECB QE amounts are normalized by the nominal GDP in the euro area. Additional control variables include the repo interest rate changes (bps), the monetary policy surprises (bps), the QE surprises normalized by the Swedish GDP, the QE announcement dummy, the nominal and real bond market noise measure, the average nominal and real bond age, and the nominal and real bond realized volatility. We report the statistical significance using Newey West standard errors with four lags. Asterisks *, ** and *** indicate significance at the 10 percent, 5 percent and 1 percent levels, respectively.

highly significant positive effects of the Riksbank's domestic bond purchases on the nominal safety premia, which is consistent with increased scarcity of the very safe Swedish nominal government bonds. Although there remains a positive effect on the average safety premium of real bonds as well, it is smaller than before and entirely without statistical significance. Again, these results seem reasonable, given that the Riksbank's bond purchases were concentrated in the nominal bond market.

Second, the results show that, after including the interaction term with the exchange rate, the ECB's bond purchases also tend to put upward pressure on Swedish safety premia, presumably through a relative scarcity channel, although these effects are not significant at the 5 percent level. Importantly, the exchange rate interaction terms have negative estimated coefficients that are borderline significant. For the relevant values of E_t between 9 and 11, the net effect becomes negative, consistent with our original baseline results as well as the findings of Christensen et al. (2024). That paper relates its findings from an international panel of safety premia that includes the Swedish nominal safety premia examined here to increased supply of truly safe assets in the euro area; our results in this study suggest that part of this negative effect materializes through a depreciation of the exchange rate, which may make Swedish safe assets less attractive as a store of value—from the perspective of foreign investors.

Third, the estimated negative coefficient on the interaction term with the exchange rate implies that an exchange rate appreciation (E_t decline) in the midst of ongoing ECB QE purchases will tend to reinforce the upward pressure on Swedish safety premia, in tandem with the reduction in nominal and real term premia described in the previous section. This pattern is similar to the one found for Danish bond risk premia by Christensen and Hetland (2023) in their analysis of the temporary Danish halt to debt issuance announced in January 2015.

5.4.4 Tail risk channel

In the final exercise, we focus on the impact of an extreme downside tail risk that is likely to be relevant to investors and policymakers alike in Sweden. Specifically, we examine the effect on the deflation risk premium, calculated at the five- and ten-year maturity. The regression results with the deflation risk premium as the dependent variable and with the exchange rate interaction term for the ECB QE variable included are reported in Table 11. First, we note that the effects of the Riksbank's domestic QE purchases remain negative and insignificant at the five-year maturity, although smaller relative to our baseline results. Meanwhile, the estimated coefficient has turned positive at the ten-year maturity, but remains insignificant. Overall, these results imply that there is now even less evidence to suggest that the Riksbank can significantly lower extreme downside tail risks such as the risk of deflation through QE.

In contrast, the ECB's QE purchases now have estimated coefficients that are negative and highly statistically significant. This suggests that ECB's QE program indeed was able to mitigate macroeconomic downside tail risks for the euro area and beyond, including neighboring satellite economies like Sweden, in much the same way as reported by Hattori et al. (2016) for the Fed's QE program and its impact on U.S. macroeconomic downside tail risks.

Moreover, the interaction term of the ECB QE variable with the SEK-EUR exchange rate has significant positive estimated coefficients. This suggests that, if the Swedish kronor depreciates against the euro (an increase in E_t) while ECB's QE program is ongoing, the

	Deflation Risk Premium	
	5yr	10yr
Riksbank's QE	-1.127	3.171
	(3.179)	(7.544)
ECB's QE	-13.713***	-28.914***
	(3.682)	(8.387)
ECB's QE$\times$ E$_t$	1.116***	2.173***
	(0.331)	(0.740)
Int. rate (bps)	-1.255*	-1.545
	(0.703)	(1.298)
MPS (bps)	-1.149	-2.358
	(1.326)	(2.690)
QES	-2.835	-2.101
	(5.182)	(12.392)
D(News)	-33.973***	-62.732**
	(11.707)	(27.416)
Noise^N	-1.713	-5.830
	(7.717)	(16.282)
Age^N	-9.883	35.599
	(14.169)	(31.832)
RVol^N	6.507***	11.410**
	(2.008)	(4.600)
Noise^R	4.284	10.702
	(4.011)	(10.100)
Age^R	-17.493**	-25.882
	(7.740)	(16.341)
RVol^R	-122.223***	-207.401***
	(23.374)	(43.392)
No. of obs.	251	251
R^2	0.801	0.735
Adj. R^2	0.790	0.721

Table 11: **QE Purchases Impact on Deflation Risk Premia: Exchange Rate Effects** The dependent variables represent weekly estimates of deflation risk premium at the five- and ten-year maturities from the preferred $G^{X^N,X^R}(6)$ model, both measured in basis points. The regression takes the form $\Phi_t = \alpha + \beta_1 Q_t + \beta_2 Q_t^* + \beta_3 Q_t^* \times E_t + \gamma X_t + \epsilon_t$. The QE bond holdings are normalized by the Swedish GDP. The ECB QE amounts are normalized by the nominal GDP in the euro area. Additional control variables include the repo interest rate changes (bps), the monetary policy surprises (bps), the QE surprises normalized by the Swedish GDP, the QE announcement dummy, the nominal and real bond market noise measure, the average nominal and real bond age, and the nominal and real bond realized volatility. We report the statistical significance using Newey West standard errors with four lags. Asterisks *, ** and *** indicate significance at the 10 percent, 5 percent and 1 percent levels, respectively.

reductions in the perceived level of deflationary tail risk for the Swedish economy would be partially offset, but the net effect would remain negative for any value of E_t in the relevant interval from 9 to 11. These results seem reasonable given that we found that this combination of outcomes would also tend to lower investors' inflation expectations, which in turn should raise the risk of low-inflation outcomes (all else being equal). However, we stress that the marginal effects flowing from the exchange rate fluctuations will never dwarf the significantly positive *direct* effects of the ECB's QE program that help to reduce the perceived likelihood of extremely unfavorable macroeconomic outcomes, which is an important function of monetary policy, in particular during times of economic and financial stress.

Finally, as in the previous sections, the remaining control variables that were significant before continue to be so.

Taken together, our findings demonstrate that the link between different components of the Swedish bond yield curve and domestic and foreign QE programs can be significantly affected by movements in the exchange rate. Once we allow the foreign QE program to interact with the exchange rate fluctuations, we find that active bond purchases by both domestic and foreign monetary authorities will tend to push up domestic investors' inflation and monetary policy expectations and put downward pressure on the domestic nominal and real term premia. Importantly, though, the estimated coefficients on the interaction terms with the exchange rate are such that they more than offset these positive effects for the relevant values of the exchange rate, which explains the surprising counterintuitive results from our baseline set of regressions that failed to account for the exchange rate effects. Thus, the bond market effects materializing through the additional variation in the exchange rate are able to fully offset the direct stimulating foreign QE effects. Based on these results we feel that we can rule out the existence of some kind of negative "beggar-thy-neighbor" implications of foreign QE programs, at least in the context of advanced European economies. Furthermore, even if the exchange rate moves in such a way as to give rise to negative spillover effects from foreign QE programs, our results clearly indicate that they can be successfully countered through a domestic QE program.

Overall, our results suggest that the literature on the role of the exchange rate in relating safe asset demand and convenience and safety premia can be expanded further, to understand the interaction and complementarity among the documented QE transmission channels and the exchange rate channel.

6 Conclusion

In this paper, we aim to provide novel evidence on how domestic and foreign central bank large-scale asset purchases work and affect interest rates in a small open economy with an established inflation target for monetary policy and a flexible exchange rate regime. To do so, we focus on Sweden, a neutral advanced small open economy with the added advantage that its central bank, Sveriges Riksbank, has implemented both negative interest rates and forward guidance in addition to engaging in quantitative easing through government bond purchases. At the same time, the ECB operated its own asset purchase program, which spilled over to the Swedish economy through trade and financial market linkages. Our study highlights the importance of evaluating the effects arising from both domestic and foreign unconventional monetary policy in a joint framework, while allowing for a role for the exchange rate.

By relying on a novel state-of-the-art term structure model of nominal and inflation-indexed bond prices, we report accurate estimates of bond-specific safety premia for all bonds in our sample, in addition to producing convincing decompositions of nominal and real yields and breakeven inflation into their respective expectations and risk premium components. This allows us to empirically examine within a unified framework the relative importance of four transmission channels highlighted in the existing literature on QE and unconventional monetary policy: signaling, portfolio rebalancing, liquidity-scarcity, and tail risk.

Using regression analysis with the various components from our yield decompositions as dependent variables, we find that the Riksbank's bond purchases raised inflation and short-rate expectations along with the level of the natural real rate r_t^*, lowered nominal term premia, and increased nominal bond safety premia by statistically significant and economically meaningful amounts. These results suggest that the signaling, portfolio rebalancing, and scarcity channels were operating during the Swedish QE programs. In contrast, we find no significant effects on the tail risk as measured by the deflation risk premia produced by our yield curve model. However, interestingly, we find significant effects on Swedish investors' perceptions of these tail risks from the ECB's QE program in that those purchases have tended to put downward pressure on Swedish deflation risk premia. This points to an important international spillover channel from unconventional monetary policies pursued by one of the world's major central banks.

Another important takeaway from the empirical analysis using the exchange rate dynamics is that it is crucial to control for the effect of fluctuations in the exchange rate when it comes to evaluating the spillover effects from foreign QE programs, even if the asset purchases are measured as a fraction of GDP. Without properly accounting for the spot exchange rate, the foreign QE program will appear as crowding out or reversing the domestic QE program in terms of its effects on the domestic bond market—akin to a classic "beggar-thy-neighbor" outcome. However, factoring in the exchange rate changes is the key to uncovering the complementarity of domestic and foreign QE programs. This reveals that the foreign QE program has the same economic impact on domestic bond risk premia as domestic central bank's bond purchases, but exchange rate movements can partially—and sometimes fully—offset the effects based on our estimates. We leave it for future research to explore whether these results carry over to other advanced or emerging small open economies with inflation targets and flexible exchange rates. A two-country asset pricing model could potentially rationalize our findings and provide insights into the intriguing interaction between exchange rate dynamics and the prices of safe assets. However, we also leave that endeavor for future research.

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