EVALUATING CENTRAL BANK ASSET PURCHASES IN A TERM STRUCTURE MODEL WITH A FORWARD-LOOKING SUPPLY FACTOR

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Abstract

The theoretical literature on term structure models emphasises the importance of the expected absorption of duration risk during the residual life of term bonds in order to understand the yield curve effect of central banks' government bond purchases. Motivated by this, we develop a forward-looking, long-horizon measure of euro area government bond supply net of Eurosystem holdings, and use it to estimate the impact of the ECB's asset purchase programmes in the context of a no-arbitrage affine term structure model. We find that an asset purchase shock equivalent to 10% of euro area GDP lowers the 10-year average yield of the euro area big four by 59 basis points (bp) and the associated term premium by 50 bp. Applying the model to the risk-free (OIS) yield curve, the same shock lowers the 10-year rate and term premium by 35 and 26 bp, respectively.

Keywords: monetary policy, ECB, asset purchase programme, yield curve, term premium, risk-neutral rate.

JEL classification: E43, E44, E47.

Resumen

La literatura teórica de modelos de curva de tipos enfatiza la importancia de la absorción de riesgo de duración esperada durante la vida residual de los bonos para entender el efecto de las compras de activos de los bancos centrales sobre las curvas de tipos. Motivados por esto, construimos una medida de oferta esperada, a horizontes de largo plazo, de bonos soberanos del área del euro neta de tenencias del Eurosistema, y la empleamos para estimar el impacto de los programas de compra de activos del BCE en un modelo afín de curva de tipos sin arbitraje. Encontramos que un *shock* de compra de activos equivalente al 10 % del PIB del área del euro reduce el tipo medio a diez años de los cuatro grandes países del área del euro en 59 puntos básicos (pb) y la prima de plazo asociada en 50 pb. Aplicando el modelo a la curva de tipos libre de riesgo (OIS), el mismo *shock* reduce el tipo a diez años y la prima de plazo en 35 pb y 26 pb, respectivamente.

Palabras clave: política monetaria, BCE, programas de compra de activos, curva de tipos, prima de plazo, tipo neutral al riesgo.

Códigos JEL: E43; E44; E47.

1 Introduction

The sovereign yield curve is a key element in the transmission of monetary policy to overall financial conditions. The importance of the yield curve became especially prominent in the period since the Great Financial Crisis when, due to the proximity of (short-term) policy interest rates to their effective lower bounds (ELB), central banks resorted to (then) unconventional monetary policy instruments –such as large-scale asset purchases or forward guidance on future policy– in order to provide further stimulus by lowering medium and long-term rates.

Focusing on large-scale asset purchase (LSAP) programs, soon after their implementation in the United States and other advanced economies in the wake of the 2008-9 crisis, the empirical literature found sizable effects of those programs on sovereign yield curves, and explored some of their transmission channels (see, e.g., Gagnon, Raskin, Remache, and Sack (2011), Li and Wei (2013) and Neely (2015), among others). In a seminal paper, Vayanos and Vila (2021) provided a solid theoretical foundation for these effects. They proposed a microfounded model of the government bond market, where risk-averse arbitrageurs with limited wealth trade bonds across the entire maturity spectrum.[1] In this model, central bank asset purchases reduce bond yields by removing long-term bonds from the market and thus reducing the amount of duration risk to be absorbed by arbitrageurs. This makes them more willing to bear that risk, leading to a lower market price of duration risk and hence lower term premia. Thus, in the literature, this transmission channel of asset purchases is often referred to as 'duration risk absorption'.[2] Under this light, what matters for bond prices is not the total supply of bonds outstanding, but their supply *net* of central bank holdings.

Inspired by these theoretical insights, a subsequent literature incorporated net supply factors into otherwise standard no-arbitrage affine term structure models (ATSM) in order to investigate the impact of asset purchase policies.[3] ATSM combine the theoretical rigour associated to the absence of arbitrage with the tractability afforded by their

[1]The work by Vayanos and Vila first appeared in working paper format in 2009; see Vayanos and Vila (2009). Following the latter publication, researchers have extended the Vayanos-Vila framework to analyze a wide range of issues, including how the presence of the ELB constraint affects the duration absorption channel (King (2019)), the transmission of monetary policy in an international environment with exchange rate adjustment (Gourinchas, Ray, and Vayanos (2022)) or in a New-Keynesian macroeconomic framework (Ray (2019)), or the relevance of 'credit risk absorption' –as opposed to duration absorption– in a heterogeneous monetary union such as the euro area (Costain, Nuño, and Thomas (2022)).

[2]To be precise, and as explained by Vayanos and Vila (2021, pp. 79-80), duration risk absorption describes how asset purchases affect the yield curve in their model in the special case in which the short-term interest rate is the only risk factor, but not in the more general case with shocks to the net supply of bonds. Despite this, 'duration risk extraction' has become the standard way of referring to the transmission channel of asset purchases in models in the Vayanos-Vila tradition.

[3]See e.g. Hamilton and Wu (2012), Li and Wei (2013), and Eser, Lemke, Nyholm, Radde, and Vladu (2019). We discuss these works and our contribution to this literature in Section 2. For a general overview of ATSM, see e.g. Gürkaynak and Wright (2012).

affine (linear plus a constant) solution for equilibrium bond yields. Moreover, the fact that they impose less behavioral cross-equation restrictions than models with stronger microfoundations allows them to fit yield curve data remarkably well, both over time and across maturities.

A key implication that emerges from the Vayanos and Vila (2021) framework is that the term premium earned by a bond depends not just on the contemporaneous net supply of bonds of different maturities, but on the *expected future* amount of net bond supply during the residual life of the bond. This explains, for instance, the large yield impact associated to central banks' (unexpected) announcements about future asset purchases, as shown by the empirical literature based on event studies.[4] Motivated by this result, we contribute to the literature by building a monthly-frequency ATSM with a *forward-looking* net supply factor, which we then use to investigate the impact of the European Central Bank's (ECB) asset purchases on euro area yield curves.

A difficulty in constructing such a forward-looking factor is that, for each month in the sample period, one needs to project, over a long-term horizon, the future path of both the supply of government bonds issued by euro area national governments and the absorption of that supply by the ECB's asset purchase programs. We overcome this difficulty by using, on the one hand, ECB/Eurosystem staff projections of outstanding government bonds of euro area countries and, on the other, regular survey information on monetary analysts' expectations of future Eurosystem asset purchases –together with actual ECB official announcements–. By subtracting the latter set of projections from the former, and discounting the resulting paths, we construct a monthly series of projected net bond supply that is then included in the set of risk factors, alongside a level and a slope factor.

Another contribution relates to how we jointly treat the slope and net supply factors. In the ATSM literature, it is customary to use two factors related to the term structure: the level and the slope (the latter measured e.g. as the difference between a long-term and a short-term rate). The advantage of using these two factors is that they are able to capture most of the yield curve shapes, ensuring a good fit of observed yields. In those models, the slope factor accounts for both expected future evolution of short-term rates and the compensation for the duration risk assumed by investors. However, using together the slope and the supply factor leads to underestimating the contribution of net bond supply, and hence asset purchases, to yield curve variations. The reason is that asset purchases affect the yield curve precisely by flattening it, through a reduction in the amount of duration risk to be absorbed by the market. Therefore, part of the genuine effect of net bond supply on yields may be actually captured by the slope factor.[5] In

[4]See, for instance, Gagnon, Raskin, Remache, and Sack (2011), Krisnamurthy and Vissing-Jorgensen (2011), D'Amico, English, López-Salido, and Nelson (2012), D'Amico and King (2013) or, more recently, Altavilla, Carboni, and Motto (2021) and D'Amico and Seida (2022).

[5]In fact, the use of both level and slope factors forces the supply factor to play the minor role typically associated with the curvature factor, affecting the medium-term and not the long-term section of the term structure.

order to avoid this, we orthogonalize the slope factor with respect to the net supply one, and then use the orthogonalized slope factor in the estimation. This approach is plausible under the assumption that changes in the slope due to asset purchases -and net bond supply more generally- and those due to other drivers -such as forward guidance on interest rates- are orthogonal to each other. We provide some evidence in this direction.

We estimate the model to the average yield curve of the four largest euro area countries (Germany, France, Italy and Spain; henceforth the 'big-four') for the sample period 2008-2021, and investigate the yield curve impact of shocks to future expected net bond supply.[6] Qualitatively, our results are consistent with previous literature: asset purchase shocks flatten the yield curve mostly by compressing term premia, with this effect being stronger for longer maturities. Quantitatively, we find larger impacts of asset purchase shocks compared to other studies applied to the euro area. For instance, a purchase shock equivalent to 10% of euro area GDP reduces the ten-year average sovereign yield of the big-four by 59 bp. This elasticity lies in the upper range of estimates in the literature.[7]

We attribute our larger effects to the two key features of our analysis: the forward-looking nature of our net supply factor, which magnifies the impact of central bank QE announcements when the latter have implications for their bond portfolio that extend over many years; and the orthogonalization of the slope factor, which rebalances the role of the slope vs the net supply factor in explaining yield curve fluctuations in favor of the latter.

Our estimated effects of asset purchases are also larger than those found in US studies.[8] However, to some extent this also reflects the presence of sizable *credit* risk premia in the yields of sovereign issuers such as Italy and Spain –and therefore in the yield curve of the big-four– and their sensitivity to ECB asset purchases. The latter channel is absent in analyses of US studies, since US Treasury debt is considered to be default-free. Our model does not explicitly account for credit risk, so part of the impact of asset purchases on term premia in fact captures the response of peripheral credit risk premia. For this reason, we also estimate the model for the euro area risk-free yield curve, using as a proxy for the latter the overnight interest rate swap (OIS) curve, finding effects of net supply shocks that are smaller –35 bp in the case of the ten year yield– and hence closer to those found in US studies. In any case, we view the development of ATSMs that explicitly incorporate sovereign default risk as an important task for future work.[9]

[6] The start of the sample period is determined by the availability of ECB/Eurosystem debt projections.

[7] Breckenfelder, De Fiore, Andrade, Karadi, and Tristani (2016) show that the effects of asset purchase shocks of the same size estimated across studies for the euro area range between 27 and 64 bp. In a closely related study, Eser, Lemke, Nyholm, Radde, and Vladu (2019) estimate an overall impact of the APP of 95 basis points on the average big-4 10-year yield. Since the APP had reached around 25% of euro area GDP at the end of their sample, their estimates suggest an impact of almost 40bp on the 10-year yield as a result of purchases amounting to 10% of euro area GDP.

[8] See, for instance, Gagnon, Raskin, Remache, and Sack (2011), Hamilton and Wu (2012) and Li and Wei (2013), among others.

[9] Costain, Nuño, and Thomas (2022) extend the Vayanos-Vila model to a two-country monetary union setup where one of the countries issues defaultable bonds. Their analysis shows that, in the euro area context, asset purchase announcements affect peripheral yield curves mostly by reducing credit risk premia, through a channel which they refer to as "credit risk absorption".

The reminder of the paper is structured as follows. We first place our contribution in the context of the related literature. In Section 3 we lay out the affine term structure model and specify our forward-looking measure of net bond supply. Section 4 explains the data and estimation method employed. Section 5 presents the empirical results. The final section concludes.

2 Related literature

Our paper belongs to the literature on no-arbitrage affine term-structure models, which have a long tradition in the finance and macro-finance literature (see Dai and Singleton (2000), Ang and Piazzesi (2003) and Bekaert, Cho, and Moreno (2010) among others).

Our analysis is most closely related to the empirical literature on ATSMs that incorporates net supply factors and evaluates the effect of LSAP programs, following the theoretical work of Vayanos and Vila (2021), itself a microfounded ATSM. Hamilton and Wu (2012) estimated (a discrete-time version of) the Vayanos-Vila model and used the model's structural relationship between the price of risk factors and the maturity composition of arbitrageurs' bond portfolio in order to construct a vector of net supply factors. They show that these supply factors have predictive content both for excess holding returns and for the standard yield factors (level, slope and curvature). They then estimate the (reduced-form) relationship between the yield factors, their own lags, and the supply factors, and use it to quantify the impact of a hypothetical US Federal Reserve purchase of long-term bonds financed with the sale of its entire short-term bond portfolio. Greenwood and Vayanos (2014) use a version of the Vayanos-Vila model to construct an empirical measure of duration risk and derive testable implications, finding that the maturity-weighted supply of outstanding bonds is positively related to bond yields and future returns, the effects being stronger for longer-maturity bonds.

Li and Wei (2013) estimate a standard no-arbitrage ATSM that includes both yield factors (level and slope) and net supply factors, the latter both for Treasury debt and agency MBS. They then use it to evaluate the term premium effects of the US Federal Reserve's LSAP programs. Eser, Lemke, Nyholm, Radde, and Vladu (2019) build on Li and Wei (2013) by constructing a no-arbitrage ATSM with a net supply factor and estimating it with euro area data. They exploit security-level information on sectoral asset holdings and ECB asset purchases in order to construct a novel measure of the "free float" of duration risk borne by price-sensitive investors, which most closely correspond to the arbitrageurs in the Vayanos-Vila framework. They then use their estimated model to evaluate the impact of the ECB's Asset Purchase Programme (APP) on the average sovereign yield curve of the euro area big-four.

Importantly, none of the above papers constructs a *forward-looking* net supply factor that is then used in the time-series estimation of the model, as we do. In the models estimated by Hamilton and Wu (2012) and Li and Wei (2013), yields depend on *contemporaneous* measures of net bond supply. Li and Wei (2013) use their estimated model to compute the yield curve impact of Fed announcements of future asset purchases. Since such announcements entail predetermined paths of the net supply factors that deviate from the projected dynamics implied by their estimated laws of motion, the authors modeled such announcements as a sequence of future pre-announced supply shocks. Eser, Lemke, Nyholm, Radde, and Vladu (2019) estimate their model by minimising the weighted sum of two fitting criteria. The first criterion measures the time series fit of euro area sovereign bond yields over the period before markets started pricing large-scale asset purchases by the ECB, under the assumption that yields depended on their *contemporaneous* free float measure. The second criterion is based on the fit of the cumulative yield decline over ECB communication events in the run-up to and around the announcement of the APP, using Li and Wei's (2013) sequence-of-supply-shocks approach. By contrast, we construct a forward-looking net supply measure covering our entire sample period (2008-2021) and use it directly in the time-series estimation. Thus, our analysis incorporates the notion that investors priced bonds according to their expectations of future net supply also *before* the ECB started the APP in 2015. In other words, our analysis is consistent with the view that the theoretical predictions of structural models such as Vayanos and Vila (2021) apply to the pricing of sovereign bonds over different periods, including the period before the generalization of LSAP programs.

Outside the ATSM literature, Kim, Laubach, and Wei (2020) use primary dealer expectations of the Federal Reserve's asset holdings in order to construct a forward-looking LASP measure, which is then included in the estimation of a proxy structural VAR applied to the analysis of the macroeconomic effect of LSAP programs and forward guidance. However, the horizon for their expectations of Fed asset holdings is one year ahead only. By contrast, our projections have a horizon of ten years and are both for bond supply by governments and bond absorption by the central bank, consistently with the Vayanos-Vila prediction that investors need to forecast the *net* bond supply that they will have to absorb over the *same horizon* as the bonds they are pricing.

3 A Term Structure Model

This section presents the term structure model proposed in this paper. We first present the term structure model and the yield curve (level and slope) risk factors. We then introduce the forward-looking net supply factor which will be key to evaluate the effectiveness of the asset purchase programs.

3.1 Affine Model

We model the term structure of interest rates through a standard no-arbitrage affine model, where yields linearly depend on a set of macro-finance risk factors. In addition to a net supply factor –which we explain in detail in the next subsection–, our model includes two additional factors to capture the level and the slope of the yield curve. Similarly to Li and Wei (2013), we use the short-term interest rate as the observed level factor –in particular, the 1-month sovereign rate. We measure the slope of the yield curve with the difference between the 10-year and 1-month yields. However, we refine this second factor by including only the part of the slope which is orthogonal to the net supply factor. In this way, we separate the influence of central bank asset purchases from other forces that can also affect the slope of the yield curve.

The risk factors, which are collected in the 3×1 vector Z_t, follow a standard VAR(1) process:

$$Z_t = c + \Phi Z_{t-1} + \Sigma u_t. \tag{1}$$

We assume that the one-period risk-free rate is an affine function of the factors:

$$y_{t,1} = a_1 + b_1' Z_t. \tag{2}$$

Bond prices satisfy the no-arbitrage condition following Duffie and Kan (1996):

$$P_{t,n} = E_t[M_{t+1} P_{t+1,n-1}]. \tag{3}$$

As is common in affine asset pricing models, the pricing kernel or stochastic discount factor of all financial assets has the following log-affine form:

$$M_{t+1} = \exp(-y_{1,t} - 0.5\lambda_t' \lambda_t + \lambda_t' u_{t+1}). \tag{4}$$

The prices of risk are also assumed to be affine functions of the risk factors:

$$\lambda_t = \lambda + \Lambda Z_t. \tag{5}$$

Bond prices are conjectured to be log-affine functions of the risk factors as follows:

$$P_{t,n} = \exp(\bar{a}_n + \bar{b}_n' Z_t), \tag{6}$$

Combining equations (1) to (6), it is possible to obtain the following recursive solution for the affine bond pricing coefficients:

$$\bar{b}_n' = \bar{b}_{n-1}'(\Phi - \Sigma\Lambda) - b_1' \tag{7}$$

$$\bar{a}_n = \bar{a}_{n-1}' + \bar{b}_{n-1}'(c - \Sigma\lambda) + \frac{1}{2}\bar{b}_{n-1}' \Sigma\Sigma' \bar{b}_{n-1} - a_1 \tag{8}$$

where $\Phi^Q = \Phi - \Sigma\Lambda$ and $c^Q = c - \Sigma\lambda$ are the risk-neutral projection parameters. Under the risk-neutral probability measure, the conditional expectations of the risk factors are

$$E_t^Q Z_{t+1} = c^Q + \Phi^Q Z_t. \tag{9}$$

Taking logs in equation (6), and using the definition of yields, we obtain the following affine solution for yields,

$$y_{t,n} = -\frac{1}{n}\log P_{t,t+n} = -\frac{1}{n}(\bar{a}_n + \bar{b}_n Z_t) = a_n + b_n Z_t \tag{10}$$

where $a_n = -\frac{\bar{a}_n}{n}$ and $b_n = -\frac{\bar{b}_n}{n}$.

Given the risk-averse and risk-neutral expressions for the law of motion of the risk factors, one can obtain the overall risk premium:

$$E_t Z_{t+1} - E_t^Q Z_{t+1} = (c - c^Q) + (\Phi - \Phi^Q) Z_t = \Sigma\lambda + \Sigma\Lambda Z_t = \Sigma\lambda_t. \tag{11}$$

An important object of analysis by academics and policy makers is the term premium associated with longer term yields, because asset purchase programs affect the latter largely by compressing term premia. The n-period time-varying term premium is the difference between the n-period bond yield and the "risk-neutral rate", i.e. the average expected short-term rate during the bond's life:

$$tp_{t,n} = y_{t,n} - \frac{1}{n} E_t \sum_{i=0}^{n-1} y_{1,t+i}. \tag{12}$$

In section 4, we will explain the data sources and the econometric technique employed to estimate the model. Before that, we specify our model's net supply factor, explaining its connection to recent theoretical literature on term structure modelling.

3.2 A forward-looking net bond supply factor

A key insight of the Vayanos and Vila (2021) model is that the market price of interest-rate risk –or 'duration risk'–[10] depends on arbitrageurs' entire bond portfolio, where holdings of bonds of different maturities are weighted by the sensitivity of their price to the short-term rate.[11] Since that sensitivity increases with maturity for standard model calibrations, the market price of duration risk in that model can be reasonably

[10] In the discussion that follows, the concept of 'market price of duration risk' refers to the theoretical model of Vayanos and Vila (2021) and is not to be confused with the market prices of risk in our affine term structure model, which are given by the term λ_t in equation (5). In our model, it is the latter prices that determine the term premia in bond yields.

[11] More specifically, in the Vayanos-Vila model the market price of interest-rate risk is proportional to $\int_0^\infty X_t^{(\tau)} A_r(\tau) d\tau$, where $X_t^{(\tau)}$ is the arbitrageurs' position in maturity-τ bonds and $A_r(\tau)$ is the loading of (minus the log of) their price on the short-term rate in the model's (log) affine solution.

well approximated by the aggregate amount of duration risk in the hands of arbitrageurs. Costain, Nuño, and Thomas (2022) show that, in the version of the Vayanos and Vila (2021) model where the short-term rate is the only risk factor, the term premium on a bond depends on the future path of the market price of interest-rate risk during the bond's remaining life. That path is discounted by a factor that, for standard model calibrations, decreases with the forecast horizon.[12]

Inspired by these insights, our strategy is to include in the set of state variables of our model (Z_t) a factor that depends on the future expected present-discounted amount of duration risk that must be absorbed by "arbitrageur"-type investos. We start by constructing a variable capturing bond supply net of central bank holdings[13] expressed in ten-year equivalents, so as to account for the overall amount of duration risk. Following Eser, Lemke, Nyholm, Radde, and Vladu (2019), we calculate the ten-year equivalent of a bond portfolio by multiplying its value by its weighted average maturity (WAM) divided by 10. The contemporaneous amount of net duration supply, denoted by Θ_t, is measured therefore as

$$\Theta_t = (S_t - Ab_t)\,\frac{WAM_t}{10}, \tag{13}$$

where S_t is the supply of government bonds, Ab_t is the absorption of that supply by the central bank, and WAM_t is the weighted average maturity of outstanding bond supply at time t.[14] We then compute the expected discounted path of Θ_t in equation (13) as follows:

$$NS_t = E_t \sum_{s=1}^{s_{\max}} \frac{A^s}{\sum_{s=1}^{s_{\max}} A^s}\Theta_{t+s}, \tag{14}$$

where $A \in (0,1)$ is a discount factor, which we normalized by $\sum_{s=1}^{s_{\max}} A^s$ so that the net supply factor has the same scale as Θ_t.[15] Finally, following Li and Wei (2013) and Greenwood and Vayanos (2014) we rescale our net supply variable by (euro area) nominal GDP (Y_t): $NS_t^y = NS_t/Y_t$, where NS_t^y will be our net supply factor.

[12]In particular, Costain, Nuño, and Thomas (2022) show that, in the one-factor version of the Vayanos and Vila (2021) model, the term premium on a bond with residual maturity $\tau \geq 0$ is given by

$$TP_t(\tau) = \frac{1}{\tau}E_t \int_0^\tau A(\tau - s)\lambda_{t+s}ds,$$

where λ_t is the market price of interest-rate risk. Therefore, the term premium depends on the expected discounted path of future market prices of risk during the bond's residual life (τ). Since the loadings $A(\tau)$ increase with τ for standard model calibrations, the discount factor $A(\tau - s)$ in the above expression *decreases* with the forecast horizon $s \in [0, \tau]$.

[13]Note that our measure of net supply implicitly treats all sectors other than the central bank as "arbitrageurs" in the sense of Vayanos and Vila (2021). In reality, other sectors, including private-sector institutions such as insurance companies and pension funds, typically follow hold-to-maturity investment strategies, which makes them relatively price-insensitive and therefore resemble more Vayanos and Vila's preferred-habitat investors rather than arbitrageurs. Motivated by this observation, Eser, Lemke, Nyholm, Radde, and Vladu (2019) use security-level data on sectoral bond holdings in order to construct a measure of 'free float' of duration risk in the hands of price-insensitive investors, which is then used as a factor in the estimation of their ATSM. Here, we do not attempt to account for bond holdings by price-insensitive sectors other than the central bank. Instead, for simplicity we only consider central bank holdings for the purpose of constructing our net supply factor.

4 Data and Estimation

4.1 Data and yield curve factors

Figure 1 shows the evolution of sovereign yields of different maturities between January 2008 until June 2021 at monthly frequency –we use end of month data–. The maturities included in the figure are the 1-, 3- and 6-months yields; 1-, 2- up to 15-years yields. Thus, our sample includes a total of 18 different maturities. The series are the average sovereign yields of the big four euro area countries weighted by their share in GDP.

Our sample begins at the start of 2008 –due to the availability of the government debt projections used in the construction of our net supply factor– and extends until mid 2021. Before 2015 –the first year of the APP– we generally observe larger dispersion between yields of different maturities and, overall, a negative trend. After 2015, yields of different maturities become more stable and compressed, in a context in which policy rates were close to their perceived ELB and were expected to remain at low levels for some time.

We next explain how we measure our net supply factor laid out in the previous section. As shown by equations (13) and (14), we need to calculate projections of duration supply, $S_t \cdot \frac{WAM_t}{10}$, and of duration absorption, $Ab_t \cdot \frac{WAM_t}{10}$, over a sufficiently long projection horizon. We first set the latter to 10 years ($s_{\max} = 120$ months), which corresponds well with the horizon over which the Eurosystem has been expected to absorb a meaningful amount of duration risk at any time in our sample period.

To measure duration supply, we use ECB/Eurosystem quarterly projections of general government debt of each of the four largest euro area countries (Germany, France, Italy and Spain), or 'big-4', which are available since 2008:Q1.[16] Because not all government debt is in the form of bonds –as it also includes bank loans and other forms of financing–, we use Eurostat quarterly data on the outstanding value of each country's general government debt securities and assume that, from each projection date onwards, the latter value is expected to grow at the same rate as total government debt over the entire projection horizon. Therefore, we assume that investors expect the share of

[14] We assume that WAM of central bank's government bond holdings is the same as the WAM of government bond supply. This is broadly consistent with the principle of 'market neutrality' followed by the ECB in its asset purchase program (APP), which also applies to the maturity distribution of bond purchases. In reality, the WAM of the Eurosystem government bond portfolio is roughly similar to that of the outstanding bond supply.

[15] Notice that our forward-looking net supply factor has a fixed forecast horizon $s_{\max}$. An alternative –closer to the theory– would be to construct a different supply factor for each maturity τ, with a forecast horizon equal to that maturity. However, for simplicity we restrict ourselves to a single net supply factor.

[16] Each quarterly vintage contains projections of the year-end stock of government debt (in euros) in the current and the following ten years. We interpolate linearly year-end projections in order to obtain a monthly projected path. In doing so, we abstract from the fact that monthly debt stocks may exhibit some seasonality within each year. However, this is unimportant for the purpose of calculating present-discounted sums of bond supply projections over a 10-year horizon, as we do.

debt securities in overall government debt to remain constant at the last observed value over the projection horizon. To transform euro amounts into 10-year equivalents, we use ECB/Eurosystem data on the weighted average maturity (WAM) of each country's outstanding debt. Then, at each projection date, we multiply each country's path of bond supply by the respective contemporaneous WAM divided by 10.[17] In order to match the monthly frequency of our model, we transform the quarterly projections of duration supply into monthly projection vintages.[18] Finally, we aggregate across countries to obtain aggregate (big-4) expected duration supply at each future date $s = 0, 1, 2, ..., s_{\max}$ for each projection date t:

$$\sum\nolimits_{i=DE,FR,IT,ES} E_t(S_{t+s,i}\frac{WAM_{t+s,i}}{10}) = E_t(S_{t+s}\frac{WAM_{t+s}}{10}),$$

where $S_t = \sum_i S_{t,i}$ is aggregate bond supply and $WAM_t = \sum_i \frac{S_{t,i}}{\sum_i S_{t,i}} WAM_{t,i}$ is the (supply-weighted) average WAM of the big-4.

In order to measure duration absorption, we use official ECB announcements on its asset purchase programs –the APP since January 2015, the PEPP since March 2020– and Bloomberg surveys[19] in order to construct analogous monthly-frequency, 10-year ahead projections of duration absorption. These announcements and surveys contain information on the horizon and monthly pace of net asset purchases,[20] and the horizon for reinvestments of maturing principals,[21] as announced (or expected) at each projection date since October 2014 –the date of the first Bloomberg survey containing expectations on ECB large-scale asset purchases; prior to that, expected absorption is simply zero. This allows us to construct monthly projections of the path of future Eurosystem asset holdings up until the end of the expected reinvestment horizon. In order to project the evolution of asset holdings after the end of reinvestments, we assume that investors expected the Eurosystem to run off its APP and PEPP bond portfolio through redemptions, consistently with ECB communication that sales of APP securities are not expected to occur regularly. We next translate overall asset purchases into holdings of government bonds of each big-4 country by taking into account the share of such purchases directed to public-sector bonds (which in the case of the APP averaged 82% over our sample period),[22] the fraction of public-sector purchases directed to national jurisdictions (ini-

[17]Therefore, we assume that bond investors expect the WAM of each country's outstanding government bond portfolio to remain constant over the projection horizon.

[18]For those months in which the quarterly projections are produced (typically, February, May, August and November each year), the projection coincides with the actual one (interpolated monthly over the projection horizon, as explained before). For the next two months, we simply use the latest projected path, shifted one and two months forward, respectively. The assumption therefore is that projections are not updated in-between quarterly projection rounds.

[19]Bloomberg surveys of analysts' expectations of future ECB monetary policy are typically conducted the week before each ECB Governing Council monetary policy meeting.

[20]Following Eser, Lemke, Nyholm, Radde, and Vladu (2019), we assume a linear 'tapering' of net asset purchases from the baseline monthly pace down to zero. In particular, we assume net purchases to fall by 10 bn EUR each month during the tapering phase.

[21]After the ECB first introduced a reinvestment commitment in December 2015.

[22]The remaining public-sector purchases were directed to private-sector assets, such as non-financial

tially 88%, later increased to 90% in April 2016),[23] and the fraction of the latter directed to each big-4 country, which under the APP –and, somewhat more loosely, under the PEPP– was determined by that country's 'capital key'.[24] Analogously to duration supply, we transform euro holdings into 10-year equivalents by multiplying holdings of each country's bonds by the respective WAM as of each projection date.[25], i.e. the share of the corresponding Eurosystem national central bank (NCB) in the ECB's capital. We finally sum across countries to obtain aggregate (big-4) expected duration absorption at each future date for each projection date: $E_t(Ab_{t+s}\frac{WAM_{t+s}}{10})$, where $Ab_t = \sum_i Ab_{t,i}$ is aggregate bond absorption.

For illustration, Figure 2 shows a few projection vintages of duration supply (left panel) and absorption (right panel), corresponding to October 2014, January and October 2015, and January 2016, and expressed in 10-year equivalents. The supply projections increase monotonically over the projection horizon, reflecting a rising expected trajectory of government bond supply and (once converted into 10-year equivalent) of duration supply. As regards absorption projections, the October 2014 vintage reflects analysts' expectations at that time of an imminent ECB large-scale asset purchase program. The official announcement of the APP in January 2015 led to a material revision to analysts' expectations of the size and length of duration absorption by the Eurosystem. The October 2015 vintage reflects how markets expected a substantial enhancement of the APP already ahead of its first recalibration in December that year. Finally, the January 2016 vintage reflects how the ECB's commitment –introduced the previous month– to temporarily reinvest APP redemptions implied expectations of a slower decline of duration extraction after the end of net purchases.[26]

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corporate bonds, covered bank bonds, and asset backed securities (ABS).

[23]The remaining public-sector purchases were directed to bonds issued by supranational European institutions, the so-called 'supras'.

[24]The 'capital key' represents the share of the corresponding Eurosystem national central bank (NCB) in the ECB's capital. These are 26.4% for Germany, 20.4% for France, 17,0% for Italy, and 12.0% for Spain (reduced to 11.9% after January 2020), collectively amounting to about 76%.

[25]Regarding the projected path of the WAM of the Eurosystem bond portfolio, we assume that during the positive net purchase phase it remains constant at the level observed as of the projection date, consistently with the principle of market neutrality in the maturity distribution of purchases applied under the ECB's programs. For the reinvestment period, we allow the WAM to (slightly) decrease in order to capture the so-called 'portfolio ageing effect', i.e. the fact that replicating the maturity distribution of asset holdings in reinvestment purchases is not enough to preserve the portfolio's average maturity. Lacking precise information on the overall maturity distribution of APP and PEPP holdings, in order to project the evolution of the WAM during the reinvestment phase, as well as in the post-reinvestment phase –in which the WAM falls more strongly reflecting the mechanical effect of time and redemptions on residual maturities–, we assume for simplicity that Eurosystem bond holdings are uniformly distributed across maturities. This allows us to obtain closed-form formulas for the evolution of the WAM in both phases.

[26]Notice that reinvestments slow down but do not avoid the decline in duration extraction after the expected end date of net purchases. This reflects both the well-known 'portfolio ageing effect' (i.e. the fact that a bond portfolio's residual weighted average maturity (WAM) declines mechanically as time goes by) and the fact that the maturity distribution of reinvestment purchase flows was intended to replicate that of the portfolio itself, which by itself is not enough to fully offset the portfolio's ageing.

Given the duration supply and absorption projections, we subtract the latter from the former to obtain monthly vintages of expected net duration supply paths. At each projection time t, we calculate the present-discounted value of the projected path as described in equation (14). Calibrating the discount factor A is difficult, as it does not exactly map into the structural parameters of the Vayanos and Vila (2021) model. We set A to 0.925, which allows our model to have plausible properties along several dimensions (such as model fit and the shape of factor loadings across maturities; see Section 5).[27]. In this way, we produce a monthly time series for NS_t. We finally obtain our net supply factor by re-scaling NS_t by the contemporaneous nominal euro area GDP (Y_t).

Figure 3 shows our forward-looking measure of net duration supply. From 2008 until 2010, our measure rises abruptly, reflecting the effect of the financial crisis on euro area governments debt projections and GDP. The European sovereign debt crisis produced a period of stabilized debt projections as some countries worked to reduce their public deficit in a context of high indebtedness. In the latter part of 2014, the expected discounted path of net duration supply dropped notably, reflecting expectations of an imminent ECB large-scale asset purchase program, the announcement of which in early 2015 let to further reductions in projected net duration supply. In early 2020, our net supply factor spikes up as large expansionary fiscal policies were expected to be implemented in response to the pandemic. However, the PEPP announcement in March 2020 and subsequent implementation mitigated this spike and eventually –together with the economic recovery– reverted it.

We next turn to the measurement of the level and the slope factors. Similarly to Li and Wei (2013), we use the short-term interest rate as the observed level factor: in particular, the average 1-month sovereign yield. We measure the slope of the yield curve with the difference between the 10-year and 1-month yields. However, as explained in Section 3.1, we refine this second factor by including only the part of the slope which is orthogonal to the net supply factor. Figure 4 compares the original and the orthogonalized slope factors.[28] Broadly speaking, the two series show a similar behavior over time. However, the gap between the actual and the orthogonalized slope tends to widen at the onset of crises, such as the 2008-9 Great Recession or the pandemic crisis initiated in March 2020. The reason is that such crises gave rise to expectations of higher future government indebtedness (for the euro area big-4 as a whole) and hence in projected net duration supply, which is precisely the driver of slope changes that is stripped out through our orthogonalization approach.

Our approach is plausible under the assumption that changes in the slope due to projected net bond supply and those due to other drivers are orthogonal to each other.

[27] Sensitivity analyses show that our results are fairly similar for alternative values of A in the range 0.9-1. We chose 0.925 because it is representative of the average effects of shocks to net supply on 10-year yields and term premia obtained for values in that range.

[28] The R^2 of regressing the slope factor on the net supply is 0.42.

One prominent such driver is forward guidance, through which central banks signal the likely future path of their short-term policy rate, and which influences the yield curve slope through the expectations component. Thus, to investigate the validity of the above assumption, we performed the following exercise. We constructed a forward guidance dummy variable that takes a value of one in months with official announcements of forward guidance and zero otherwise.[29] We then regressed the net supply factor on a constant and the forward guidance dummy. The coefficient on the latter (equal to -0.16) is not statistically significant (with a t-stat of -1.11). The R^2 of this regression is 0.008. In addition to forward guidance, the ECB's negative interest rate policy might have also affected expectations of future short-term rates over and above formal forward-guidance announcements. Thus, we also constructed a negative interest rate policy dummy and regressed the net supply factor on the latter and a constant. The coefficient on the negative interest rate policy dummy (equal to 0.01) is again not statistically significant (t-stat: 0.07), with an R^2 as low as 0.0001. Similar results are obtained if both forward guidance and negative interest rate policies are included as regressors. These exercises therefore suggest that our net supply measure is uncorrelated with other potential drivers of the yield curve slope.

Figure 5 shows the evolution of the level and (orthogonalized) slope factors. The level factor (blue line) plummeted after the finantial crisis hit the world economy and the ECB cut down its policy rates, and remained at slightly negative values since 2014 following the implementation of the negative interest rate policy. The orthogonalized slope factor takes mostly positive values until 2014, after which it takes predominantly negative values, possibly reflecting the combination of negative rate and forward guidance policies.

4.2 Estimation

Our model is estimated according to the procedure in Joslin, Le, and Singleton (2013). Their one-step estimation approach relies on several simplifying assumptions that allow mapping a latent factor model into one with observables. We write the risk neutral parameters as functions of the latent factor model parameters which can be estimated directly by rotating those factors into yield portfolios. A second rotation from yield portfolios to our three model factors allows us to estimate their effect on term premia and yields. This second rotation is based on a change of variable where we implicitly assume that all information contained in our factors that is useful to predict yields is spanned by our yield portfolios. This assumption is not controversial in the case of our first two factors and was explicitly tested for our net supply factor.

[29]We take the dates of forward-guidance and other policy announcements from Table 1 of Rostagno, Altavilla, Carboni, Lemke, Motto, and Guilhem (2021), which collects a comprehensive list of the ECB's Governing Council decisions on these policies.

5 Results

In this section we present our empirical results. We first show that the model provides a very good fit of yield data and decompose the 10-year yield into the risk-neutral rate and the term premium component. The next subsection shows the effects of asset purchase shocks –i.e. negative shocks to net duration supply– on the yield curve and its components. Finally, we analyze the effect of alternative reinvestment commitments, and re-estimate the model with alternative term structure data.

5.1 Estimated Yield Curve

In our benchmark analysis, we estimate the model with the sovereign yield curve of the big 4 countries in Europe (Germany, France, Italy and Spain) weighted by their GDP.[30] The left panel of figure 6 shows the estimates of the factor loadings in equation (10) for the different bond maturities. Loadings on the level factor are essentially flat, and those on the slope factor increase monotonically with maturity, as expected. The loading on the forward-looking net-supply factor also exhibits a monotonic increase with maturity. Thus, the expected absorption of future duration risk by asset purchase programs tends to lower the slope of the yield curve.

We now assess how the factor loadings implied by our semi-structural affine model compare with the unconstrained factor loadings implied by OLS regressions. The right panel of figure 6 shows that the factor loadings for net supply are very similar,[31] implying that the cross-equation restrictions implied by the affine model do not worsen the in-sample fit of the yields. To further assess the goodness of fit, Figure 7 compares the model-predicted yields with the observed time series of the 1, 5, 10 and 15 year maturities. The fit is remarkably good. The root mean square fitting error of yields is 9.24 basis points (v/s 9.00 basis points for the unconstrained OLS model).

Given the estimated law of motion for the short-rate and the risk factors, we then perform the decomposition of the 10-year yield into the risk-neutral rate (the expectations hypothesis component of the long-rate) and the term premium. As shown in Figure 8, the term premium exhibits a downward pattern along the sample period, but remains positive at all times. Figure 8 also shows that most of the dynamics of the 10-year yield are explained by the term premium. This is due to the fact that the short-rate has hovered around zero during most of the sample, which is reflected in its estimated law of motion and the corresponding expected path. The risk neutral rate started to become

[30] Alternative weighting schemes for yields resulted in very similar estimates of the APP effects on yields.

[31] The same is true for the level and slope factor. Results are available upon request.

clearly negative around 2014, reflecting the negative rate policy implemented by the ECB since then.[32]

5.2 Effects of the ECB's asset purchase programs

In this section we discuss the effects of ECB asset purchases on euro area sovereign yields, as well as on their two components: the risk-neutral rate and the term premium. To this end, we project the impulse response functions generated by the estimates of the state factor VAR model together with the estimates of the term structure model. The shocks associated with the macro-finance model are identified with a triangular identification system, where the ordering is level, slope and net supply, with the net supply factor reacting to level and slope shocks contemporaneously, but shocks to the former not affecting the level and (orthogonalized) slope.

Figure 9 plots the contemporaneous responses of the yields, and the associated risk-neutral rates and term premiums, to a one-standard-deviation negative shock to our forward-looking net supply factor (i.e. a positive shock to projected duration absorption). It shows a decline across the yield curve and of the associated term premia for all maturities. The figure shows that the effects become larger with maturity. The contemporaneous effects on the associated risk-neutral rates are considerably smaller and non-monotonic, with a maximum impact at a 3-year horizon, suggesting a certain signalling effect of asset purchases on the future short-term rate path over a medium-term horizon.

Figure 10 shows the dynamic responses of the 10-year yield, the term premium and the risk-neutral rate to the same expected net-supply shock. The impact is very persistent, with a half life of about 4 years. Most of the 10-year yield response is explained by the term premium. In turn, Figure 11 shows that the spread between the 10-year yield and 1-month rate decreases persistently following a negative net-supply shock. In sum, Figures 10 to 11 show that, according to our model, and consistently with earlier literature, asset purchases flatten the yield curve in a persistent manner, and that this effect is achieved mostly through a compression of term premia, the more so the longer the maturity.

Finally, in order to uncover the economic effects of asset purchases on yields and to make our estimates comparable to other studies, we normalize the size of the shock to net duration supply such that it amounts to 10% of euro area GDP. In performing this normalization, we also make the necessary adjustments to take into account how much of that amount was actually devoted to purchases of general government securities of

[32] Our model however is likely to underestimate the expectations component in long-term yields, especially in the second half of our sample, for two reasons. First, the estimated process for the short-term rate implies that the latter is roughly expected to return to its sample mean, which is negative in our sample period. Second, since the short-term rate is also estimated to depend on the net supply factor, the start of the APP in 2015 entails further downward pressure on the future projected path of the short rate.

each big-4 jurisdiction (see Section 4.1 for further details) and to transform the resulting country-specific allocations into 10-year equivalents.

We find that an asset purchase shock of 10% of euro area GDP lowers the sovereign 10-year yield by 59 basis points, while the term premium yield falls by 50 basis points. Our estimated yield effect lies close to the upper bound of the range of estimates across euro area studies reported by Breckenfelder, De Fiore, Andrade, Karadi, and Tristani (2016), of 27-64 bp, with a median of 43 pb. It is also somewhat higher than the corresponding elasticity, of approximately 40 bp, implied by the results of Eser, Lemke, Nyholm, Radde, and Vladu (2019). We attribute our relatively high elasticity both to our treatment of the net supply and (orthogonalized) slope factors –which rebalances their respective role in explaining yield curve fluctuations in favor of the former–, and to the forward-looking nature of our net supply factor –which amplifies the impact of asset purchase announcements when the latter have implications for central bank bond holdings that extend over many years.

5.3 The Effects of Reinvestment Commitments

As a further policy exercise, we now study the effects on yields of changes in the horizon of the reinvestment commitments by the central bank. Indeed, changes in reinvestment horizons are immediately reflected by our forward-looking measure of net bond supply and thus have an impact on yields. Table 1 shows the effect on impact of three different reinvestment policies on 2-, 5- and 10-year sovereign yields. The first two policies consist of extending the reinvestment period for 1 and 2 years, respectively. In both cases expected duration absorption becomes longer-lasting and our forward looking net duration supply measure falls, thus depressing yields, the more so the longer their maturity. The effect of a 2-year extension is less than twice the effect of a 1-year extension because of discounting. The third scenario consists of eliminating reinvestments altogether. This lowers the expected horizon of duration absorption and increases net bond supply, resulting in an increase of yields, which in the case of the 10-year maturity is as high as 15 basis points.

5.4 Application to the risk-free (OIS) curve

We also estimated the model with the euro area risk-free curve, as proxied by the OIS curve.[33] In this way, we account for the possibility that part of the effects of Eurosystem asset purchases on the big-four average sovereign yields actually reflects a reduction in the credit risk premia of some of these jurisdictions (notably Italy and Spain), as opposed

[33] For an earlier study applying an ATSM to the analysis of the impact of Eurosystem asset purchases on the euro OIS curve, see Bundesbank (2020).

to term premia, an effect that we have not modelled here.[34] Given that results are qualitatively analogous to those obtained for sovereign yields, we do not show them here. The only relevant difference is in the quantitative effects of asset purchases, which are lower in the case of the OIS curve. For instance, an asset purchase shock of size 10% of euro area GDP decreases the 10-year OIS rate by 35 basis points (instead of 59 in the case of sovereign yields) and the associated term premium by 26 basis points (instead of 50). This difference can be related to the impact of asset purchases on the credit risk premia of countries such as Italy or Spain, an effect that is absent in the case of the OIS curve.

6 Concluding Remarks

We have analyzed the effect of the ECB asset purchase programs on euro area sovereign bond yields, in the context of a standard no-arbitrage term structure model with level, slope and net supply factors. Our net supply factor consists of the discounted future expected path –over a long-term horizon– of duration supply net of duration absorption by the Eurosystem asset purchase programs. This is inspired by recent theoretical advances on yield curve modelling, according to which term premia on long-dated bonds depend on the expected future discounted path of duration risk to be absorbed by the market over the bonds' life.

Our findings suggest relatively large effects of asset purchase commitments, of more than 60 basis points in the case of 10-year average euro area sovereign yields following a net supply shock equivalent to 10% of euro area GDP, reflecting mostly a compression of term premia. Analogous estimation of the model with the credit-risk-free OIS curve implies a drop of 40 basis points of the 10-year rate. These results thus suggest that ECB large-scale asset purchases made a significant contribution to easing financing conditions in the euro area.

A contribution of our paper is methodological: we construct a forward-looking net duration supply measure –over a long-term projection horizon– capturing the difference between the future path of duration supply by euro area governments and duration absorption by the Eurosystem. Based on this, we evaluated the impact of ECB asset purchases and conducted different policy exercises, such as the impact of reinvestment commitments on bond yields and term premia. We leave for future work other interesting policy exercises, such as targeting specific maturities in purchase programs aiming at changing the weighted average maturity of the bond portfolio held by the central bank.

[34]Costain, Nuño, and Thomas (2022) explicitly model the impact of asset purchases on the credit risk premia of peripheral countries in the euro area, in the context of a microfounded model of yield curves in an asymmetric monetary union.

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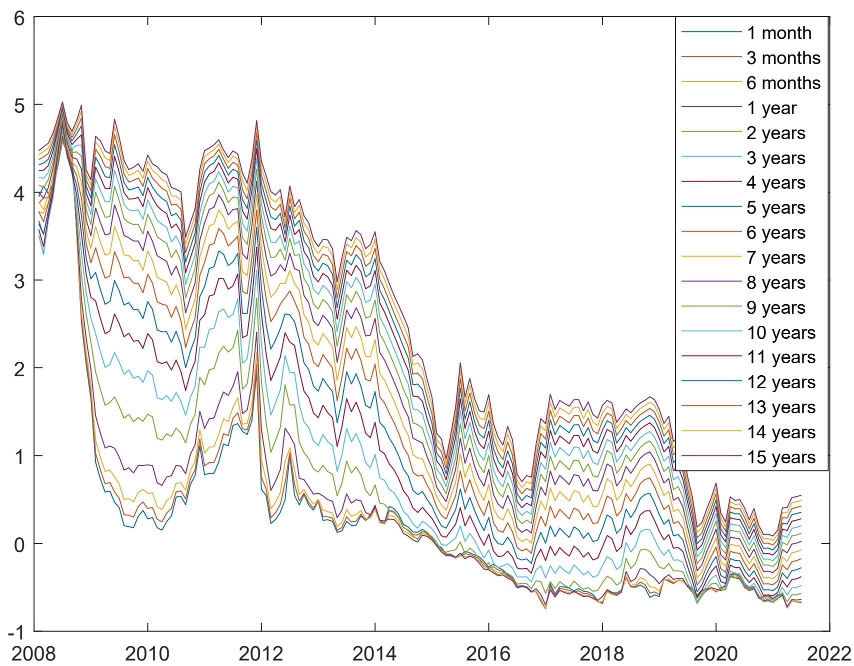
Table 1: **On-impact effect of changing the reinvestment period**

Yield maturity	Extension for 1 year	Extension for 2 years	NO reinvestments
2 years	-1,3	-2,0	5,3
5 years	-2,5	-4,0	10,5
10 years	-3,5	-5,6	14,6

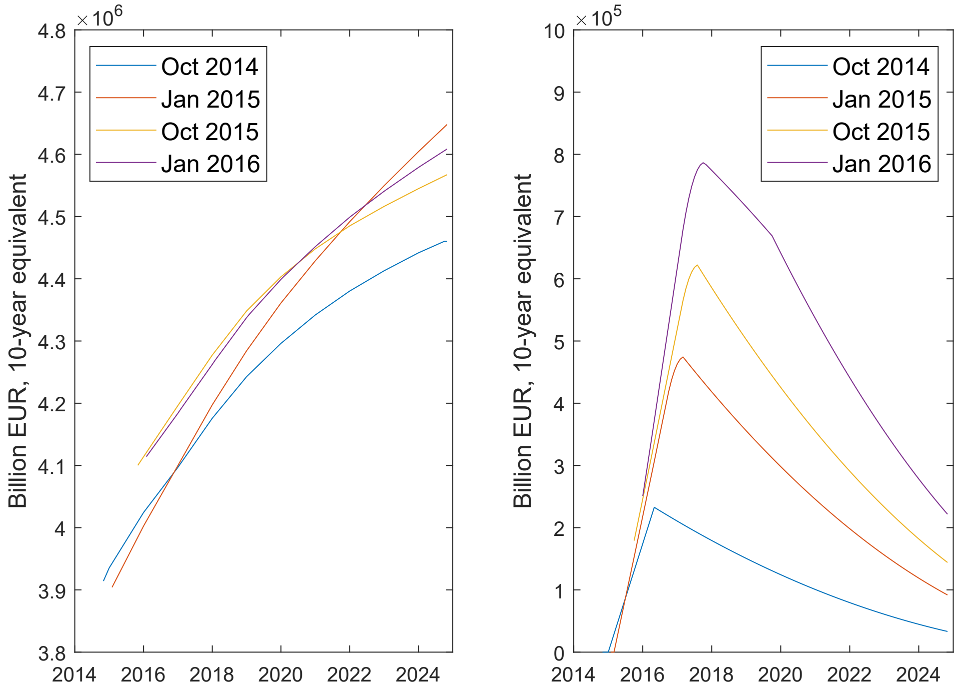
Effects are measured in basis points

Figure 1: Sovereign Yield Data



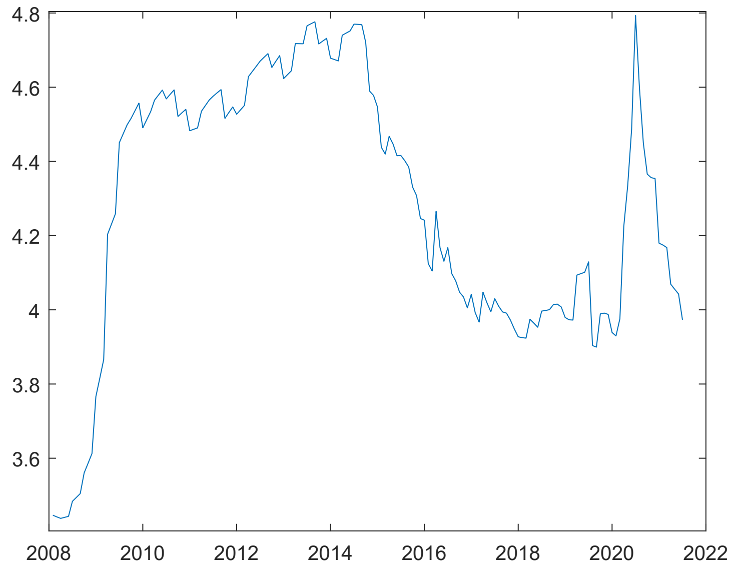
This figure plots the Euro areas sovereign yields of different maturities.

Figure 2: Vintages of expected duration supply and absorption



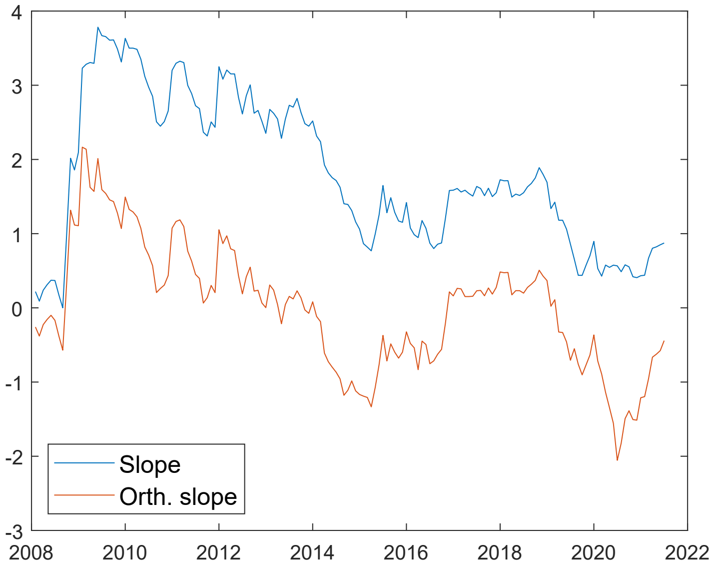
This figure plots expectations over the next months of debt supply (left-hand side) and absorption (right-hand side) in billion of euros for several vintages dated in October 2014, January and October 2015, and January 2016.

Figure 3: Forward-looking Net Bond Supply Factor



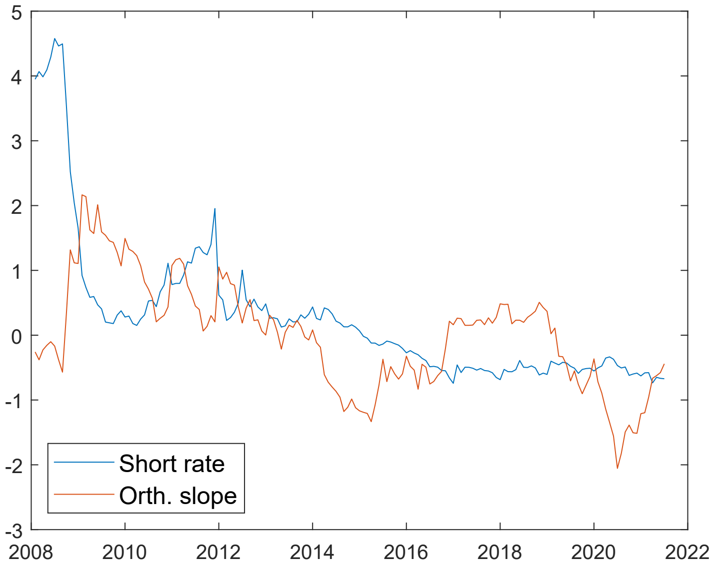
This figure plots our forward-looking measure of the net bond supply.

Figure 4: Original and orthogonalized yield slope factor



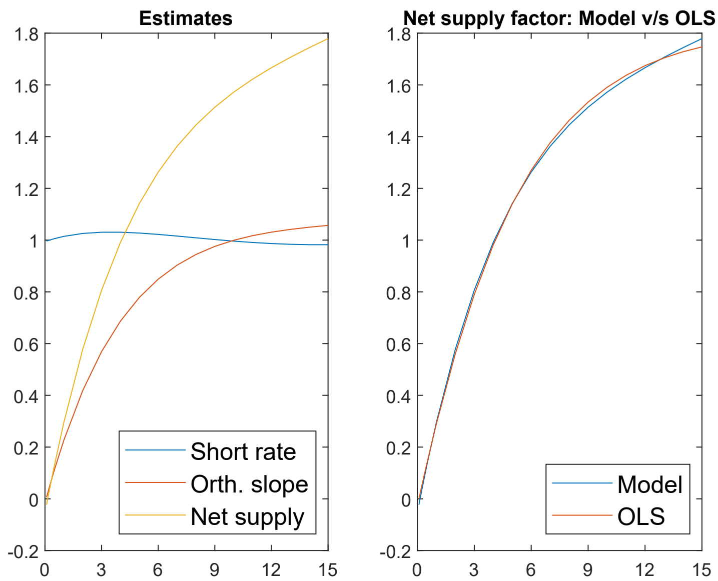
This figure plots the slope of the yield curve and the slope orthogonalized to our net bond supply measure.

Figure 5: Yield Model Factors: Level and Slope



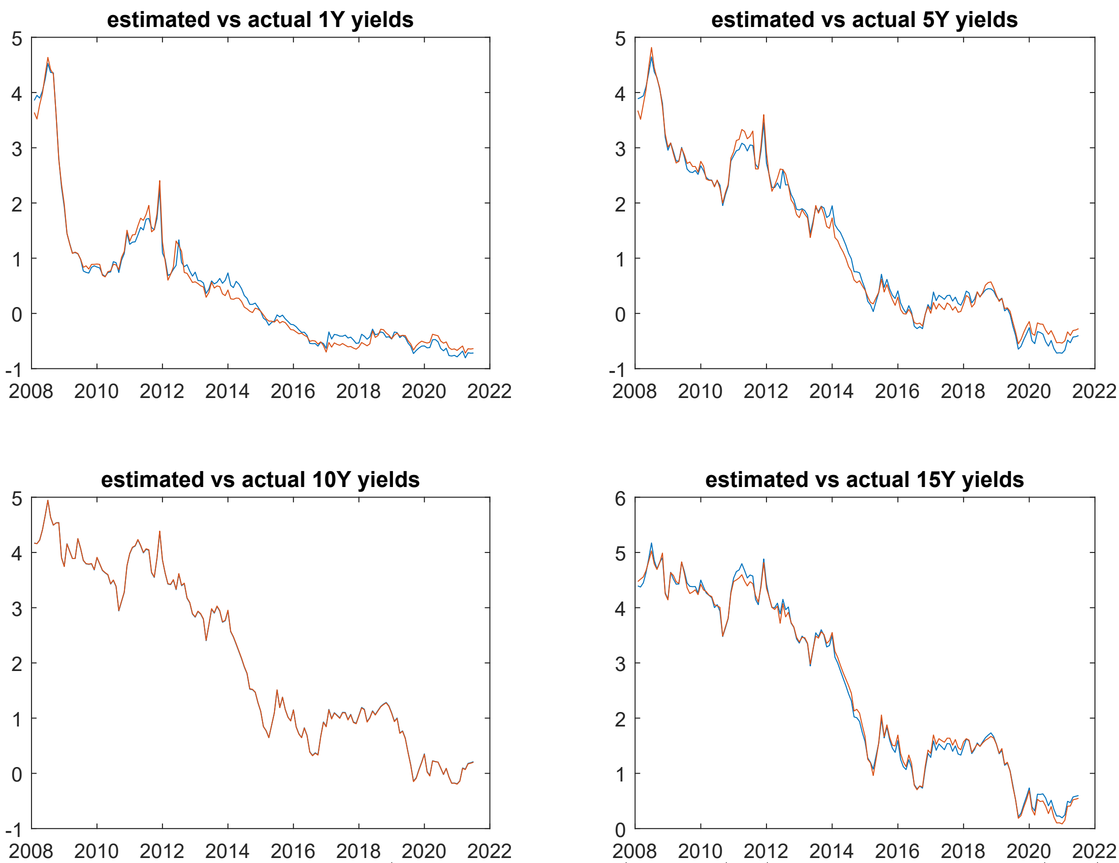
This figure plots the level and (orthogonalized) slope factors of the affine term structure model.

Figure 6: Factor Loadings



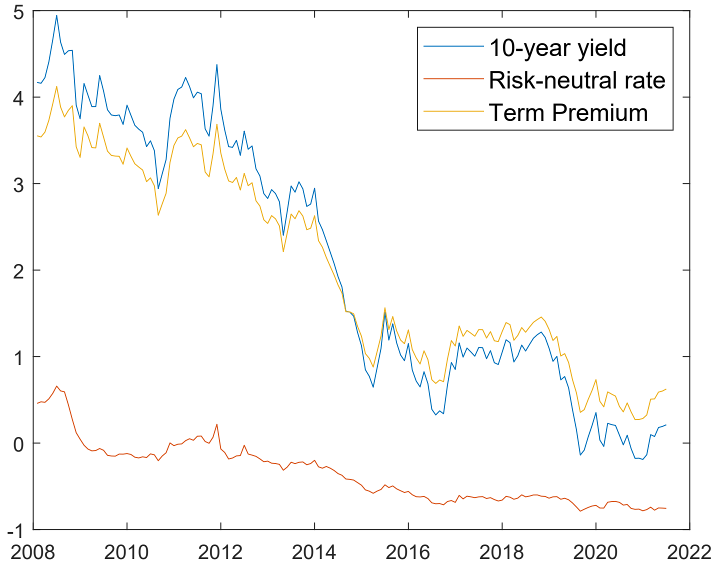
The figure on the left plots the factor loadings associated with the 3 model factors. The figure on the right plots the factor loadings associated with the net-supply factor for both unconditional OLS regressions and our model.

Figure 7



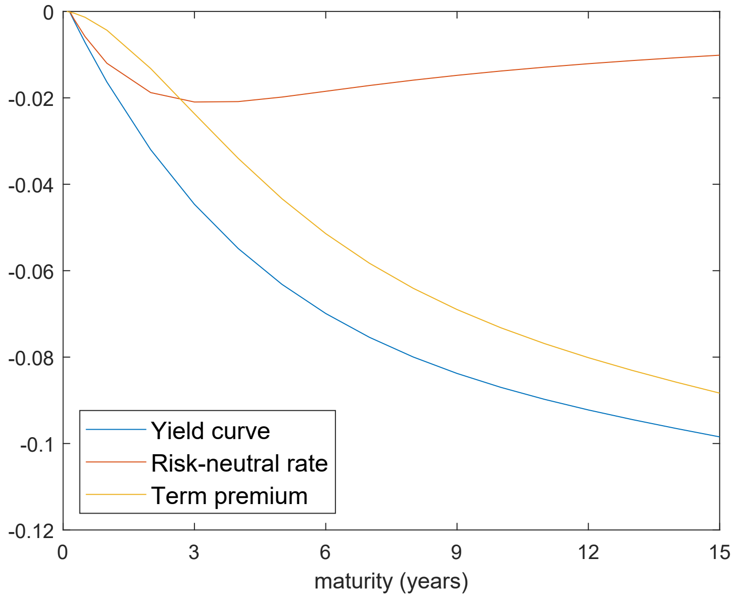
This figure plots the model implied (1, 5, 10 and 15-year) yields (red) and the actual yields (blue).

Figure 8: 10-year yield, Term Premium and Risk-Neutral Rate



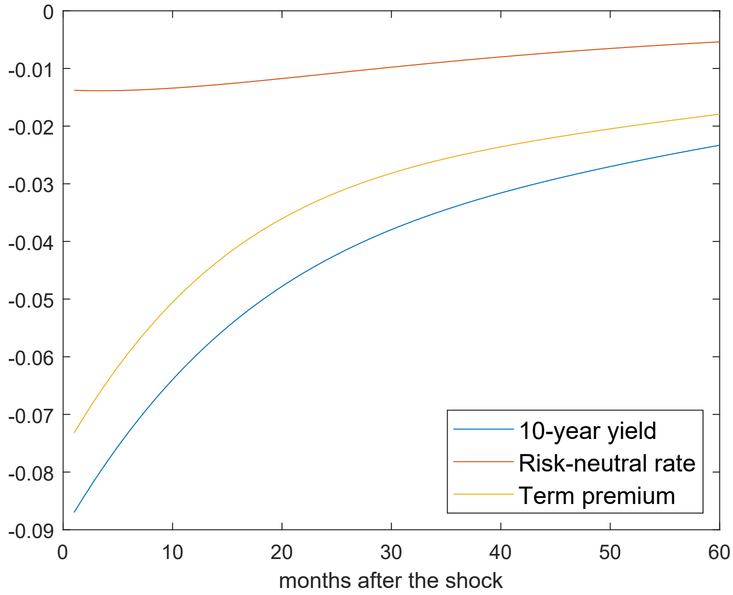
This figure plots the 10-year yield and the model implied 10-year term premium and risk-neutral rate.

Figure 9: Contemporaneous Responses of Yield, Term Premium and Risk-Neutral Rate to a Net-Supply Shock



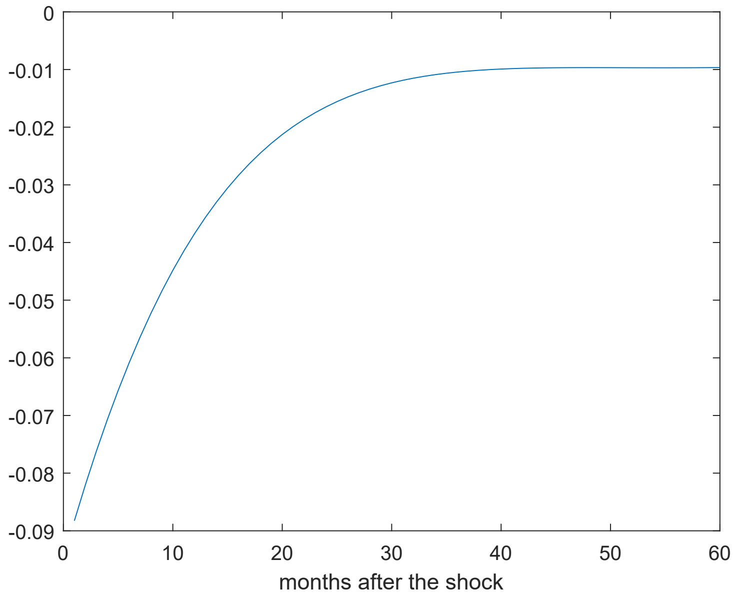
This figure plots the contemporaneous responses of yields across maturities, the associated term premiums and risk-neutral rates to a negative net-supply shock (an increase in absorption analogous to an APP).

Figure 10: Dynamic Responses of 10-Year Yield, Term Premium and Risk-Neutral Rate to a Net-Supply Shock



This figure plots the dynamic responses of the 10-year yield and the associated term premium and risk-neutral rate to a negative net-supply shock (an increase in absorption analogous to an APP).

Figure 11: Dynamic Responses of 10-Year Spread to a Net-Supply Shock



This figure plots the dynamic response of the 10-year spread to a negative net-supply shock (an increase in absorption analogous to an APP).

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