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Tracing the impact of the ECB's asset purchase programme on the yield curve

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Abstract

We trace the impact of the ECB's asset purchase programme (APP) on the sovereign yield curve. Exploiting granular information on sectoral asset holdings and ECB asset purchases, we construct a novel measure of the "free-float of duration risk" borne by price-sensitive investors. We include this supply variable in an arbitrage-free term structure model in which central bank purchases reduce the free-float of duration risk and hence compress term premia of yields. We estimate the stock of current and expected future APP holdings to reduce the 10y term premium by 95 bps. This reduction is persistent, with a half-life of five years. The expected length of the reinvestment period after APP net purchases is found to have a significant impact on term premia.

JEL classification: C5, E43, E52, E58, G12

Keywords: Term structure of interest rates, term premia, central bank asset purchases, non-standard monetary policy measures, European Central Bank

Non-technical summary

The ECB launched its asset purchase programme (APP) in January 2015 pledging the purchase of €60 bn of public and private sector securities a month from March 2015 until at least September 2016. Successive rounds of recalibrations of the APP took the eventual size of the portfolio to around €2.6 trn by the end of net purchases in December 2018, which amounts to around 25% of euro area GDP.

With the APP the ECB joined other major central banks in employing large-scale purchases – also known as "quantitative easing (QE)" – to provide monetary policy accommodation in the proximity of the effective lower bound on interest rates. Asset purchases are intended to decrease long-term yields, ease financing conditions for households and firms, and thereby stimulate the economy and contribute bringing inflation rates back in line with the central bank's price stability objective.

We trace the impact of the APP on the sovereign yield curve at announcement and over time. Our paper is the first to provide a comprehensive assessment of both the contemporaneous and dynamic effects of the APP across the term structure. By contrast, previous studies have largely focused only on the impact of the initial announcement impact of the APP on yields.

Long-term bond yields can be seen as having two components: average expectations of short-term interest rates over the life of the bond ("expectations component") and a compensation for the risk of future unpredictable yield changes ("term premium component"). In order to study the APP impact on the term premium, we deploy a so-called affine term structure model, building on an earlier study by Li and Wei (2013) for the US.

Our empirical model embodies the idea put forward in the theoretical framework of Vayanos and Vila (2009): lower aggregate duration risk increases the risk-bearing capacity of price-sensitive bond market participants. This, in turn, decreases their desired risk compensation per unit of risk exposure (i.e. the "price of risk") and, hence, the term premium. In line with that reasoning, in our empirical model the APP decreases the overall duration risk to be borne by arbitrageurs and hence compresses the term premium and bond yields. Finally, we assume that the APP does not affect the expectations component, thereby excluding a "rate signalling" channel of central bank asset purchases.

We construct a granular measure of duration risk borne by price-sensitive investors in the market, which are akin to the arbitrageurs. To this end, we exploit security-level information on sectoral bond holdings from the ECB's Securities Holding Statistics. From overall bond supply we subtract holdings by investor groups that are considered to be relatively price-insensitive: domestic central banks, governments, private hold-to-maturity investors and the foreign official sector. We weight the remaining holdings of price-sensitive investors according to their duration (closely related to their maturity) and scale them by the total duration supply of outstanding government bonds.

We report four main findings:

First, we find that the APP has indeed compressed term premia across maturities and flattened the yield curve. A 10y term premium compression of around 50 bps was associated with the initial APP announcement in January 2015. With the expansion of the programme the yield curve impact has become more marked and is estimated to be around 95 bps in June 2018.

Second, we find that the term premium compression due to the APP is persistent. Based on the path of APP net purchases envisaged in June 2018, we estimate a half-life of around 5 years for the 10y term premium impact. The fading of the impact over time reflects two factors: first, the ageing of the portfolio, i.e. the gradual loss of duration as the securities held in the portfolio mature; second, and more importantly, the run-down of the portfolio that market participants anticipate to follow the reinvestment phase.

Third, the expected length of the reinvestment period after net purchases has a significant impact on term premia. The longer the reinvestment horizon the larger is the term premium impact.

Finally, we find that the model accounts well in a real time exercise for the observed yield curve changes around APP announcements that implied major surprises regarding the future free-float.

1 Introduction

We trace the impact of the European Central Bank's (ECB) asset purchase programme (APP) on the euro area sovereign yield curve at announcement and over time. The ECB launched the APP in January 2015 by pledging the purchase of €60 bn of public and private sector securities a month from March 2015 until at least September 2016, amounting to €1.1 trn. Successive rounds of recalibrations of the APP in December 2015, March 2016, December 2016, October 2017 and June 2018 took the eventual size of the portfolio to around €2.6 trn by the end of net purchases in December 2018, corresponding to around 25% of euro area GDP. The ECB thus joined other major central banks, such as the Federal Reserve, in employing large-scale purchases - also known as "quantitative easing (QE)" - to provide monetary policy accommodation in the proximity of the effective lower bound by seeking to lower longer-term yields.[1]

For our analysis we deploy an affine term structure model in which central bank asset holdings compress term premia by reducing the amount of duration risk borne by price-sensitive investors, building on Li and Wei (2013). In affine term structure models that are commonly used to study bond yield dynamics[2] supply effects of securities do not play an explicit role. By contrast, the micro-founded model by Vayanos and Vila (2009), featuring price-insensitive preferred-habitat investors and price-sensitive arbitrageurs, links the term premium to the amount of duration risk to be absorbed by the arbitrageurs: lower aggregate duration risk increases the risk-bearing capacity of the arbitrageurs, thereby decreasing risk compensation per unit of risk exposure (i.e. the "price of risk") and hence the term premium. It is the overall amount of duration risk that matters for the term premium. Therefore, a change in bond supply at a specific maturity does not only affect that maturity bracket but term premia along the entire curve. Moreover, the model by Vayanos and Vila (2009) predicts that it is the whole sequence of current and discounted future aggregate duration in the market that determines current bond prices.

This link between bond supply and the term premium is captured in our term structure model by including a quantitative measure of duration risk in addition to standard level and slope yield curve factors. This allows us to study the term premium effect of the ECB's APP, which decreases the overall duration risk to be borne by arbitrageurs. Finally, as Li and Wei

[1]While the ECB previously embarked on outright asset purchases in the form of the Securities Markets Programme (SMP), these purchases were categorically different from QE-type large scale asset purchases and instead consisted of sterilised temporary interventions to provide liquidity to selected debt markets, see Eser and Schwaab (2016), Ghysels, Idier, Manganelli, and Vergote (2016) and De Pooter, Martin, and Pruitt (2018).

[2]Cf. Joslin, Singleton, and Zhu (2011), Adrian, Crump, and Mönch (2013) and Kim and Wright (2005).

(2013), we restrict the supply factor to not affect current and expected future short-term interest rates, thereby excluding a "rate signalling" channel of central bank asset purchases.[3]

Our empirical measure of duration risk in the market corresponds to the theory developed by Vayanos and Vila (2009). Rather than considering the exposure of all private investors, as in Li and Wei (2013) and Ihrig, Klee, Li, Wei, and Kachovec (2018), we exploit security-level information on sectoral bond holdings from the ECB's Securities Holding Statistics (SHS) to develop a more granular measure. From total bond holdings we not only exclude bond holdings by domestic central banks and governments, but also the portfolios of domestic hold-to-maturity investors as well as the foreign official sector, since these investor groups are unlikely to respond to changes in the supply and maturity structure of outstanding bonds. As a residual, we obtain the bond holdings of price-sensitive investors, akin to the arbitrageurs in Vayanos and Vila (2009). We weight these holdings according to their duration and normalise them by total duration supply of outstanding government bonds. We refer to the share of duration risk exposure borne by price-sensitive investors relative to total duration risk supply as the "free-float of duration risk".

We estimate the model by minimising the weighted sum of two fitting criteria. The first criterion measures the time series fit of euro area sovereign bond yields (zero-coupon, averaged across the largest four countries) over the period before markets started pricing large-scale asset purchases by the ECB. The second criterion is based on the fit of the cumulative yield decline over events (ECB press conferences and speeches) in the run-up to and around the announcement of the APP, which were perceived by markets to contain information on the forthcoming purchase programme. We rely on this novel approach as our sample is relatively short, as we can only construct our free-float measure from December 2009 based on the SHS data. Moreover, Eurosystem[4] bond holdings only became a significant source of variation in the

[3]Signalling effects of the ECB's non-standard monetary policy measures have been analysed by e.g. Altavilla, Carboni, and Motto (2015), Andrade, Breckenfelder, De Fiore, Karadi, and Tristani (2016), Arrata and Nguyen (2017) and Lemke and Werner (2017). Such effects have been found to be small in magnitude compared to the effects of the duration extraction channel. By contrast, based on a shadow-rate term structure model estimated for the OIS yield curve Geiger and Schupp (2018) find that unconventional monetary policy shocks have stronger impact on expected short rates than on the forward term premium up to seven years. We do not separately identify the role of reserves creation for term premium compression as Christensen and Krogstrup (2018) do based on Swiss data, as reserve- and supply-induced effects cannot be independently identified for QE programmes involving purchases of long-term securities. We also abstract from flow effects of purchases, which are of a more temporary nature, see D'Amico and King (2013) and Kandrac and Schlusche (2013) for the US, Joyce and Tong (2012) for the UK, as well as De Santis and Holm-Hadulla (2019) and Schlepper, Hofer, Riordan, and Schrimpf (2017) for the euro area.

[4]The Eurosystem comprises the ECB and the 19 national central banks of the euro area Member States.

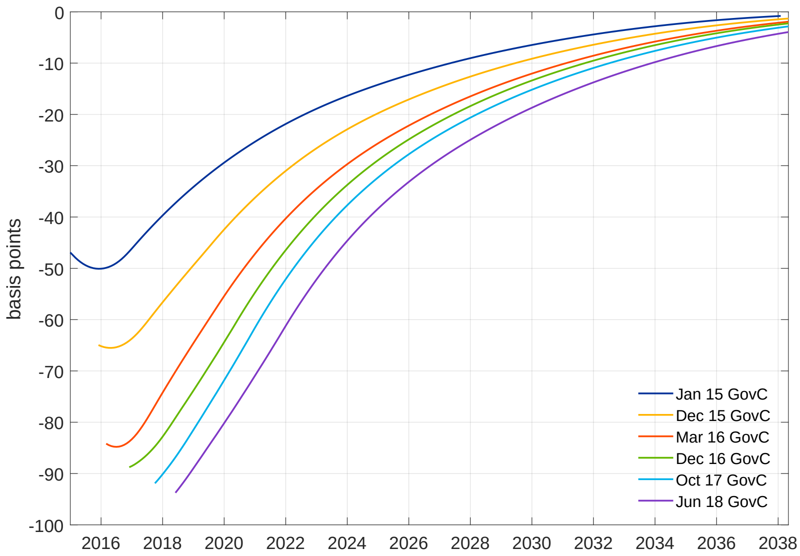

Figure 1: **The impact of the APP on the 10y term premium over time.** For selected dates, the figure shows the impact of the APP on the term premium component of the 10y sovereign bond yield (averaged across the four largest euro area countries) over time.

free-float with the start of APP. This contrasts the US experience, where the Federal Reserve's monetary policy portfolio exhibited significant variations already before the inception of its large-scale asset purchases (LSAPs).

We report four main results. First, we estimate that overall the APP has compressed 10y sovereign term premia through the duration channel by around 95 bps (see Figure 1).[5] The 5-95% confidence interval, which accounts for parameter uncertainty, ranges from 65-130 bps. The impact on shorter maturities is smaller, so the APP flattened the yield curve. We find that a term premium compression of around 50 bps was associated with the initial APP announcement of January 2015.[6] Our estimates appear broadly in line with those for the Federal Reserve, taking into account the uncertainty bands around impact estimates as well as the different market environment and purchase modalities on the two sides of the Atlantic.[7]

[5]This figure is consistent with Hartmann and Smets (2018) who report that in December 2016 the cumulated and joint impact of the APP together with credit easing measures and interest rate cuts amounts to around 150 bps for the euro area 10y sovereign yield.

[6]This is in line with several other papers that have mainly focused on the announcement effects of the APP: Altavilla et al. (2015), Andrade et al. (2016), De Santis (2016) and Blattner and Joyce (2016).

[7]Applying the model by Li and Wei (2013) to the US, Ihrig et al. (2018) estimate a peak cumulative impact of the Federal Reserve's LSAPs and its Maturity Extension Program of around 125 bps for a purchase volume of $ 4.5 trn. A direct comparison of our impact estimates with the US figures is challenging due to factors such

Second, we find that the term premia compression due to the APP is persistent. Based on the path of APP net purchases envisaged by the Governing Council in June 2018, and assuming a horizon for full reinvestments of 3 years, we estimate a half-life of around 5 years for the 10y term premium impact (Figure 1). The fading of the impact over time reflects, to some extent, the ageing of the portfolio, i.e. the gradual loss of duration as the securities held in the portfolio mature, as well as, in particular, the run-down of the portfolio that market participants anticipate to follow the reinvestment phase.

Third, the expected length of the reinvestment period after net purchases has a significant impact on term premia. The longer the reinvestment horizon the larger the term premium impact. For example, under the counterfactual of no reinvestment, relative to an assumed reinvestment horizon of 3 years, the long-term interest rate would have been around 15 bps higher in June 2018.

Fourth, we use our model to make real-time predictions of the yield curve effect of the various APP recalibrations and compare these predictions to the observed yield curve reactions upon announcement, controlling for the expectations of APP parameters prevailing ahead of the announcement. We find that the model accounts well out of sample for the observed yield curve changes around APP announcements that implied major surprises regarding the future free-float.

The remainder of the paper is structured as follows. Section 2 explains the construction of our free-float measure and the yield data. Section 3 describes the model and inspects the mechanism of how central bank purchases affect the term premium. Section 4 outlines the estimation approach and documents the model fit. Section 5 reports the main results, i.e. the impact on the yield curve at different points in time, the persistence of those effects, the role of reinvestment and the impact of selected APP recalibrations. It also sheds some light on the robustness of results. The last section concludes.

as a different sovereign bond market structure, a different global financial environment at the time of purchases, and a different allocation of purchases over time. Moreover, ideally a comparison would be based on a granular free-float measure of the type we construct, but its US counterpart is not available to us. Using instead the size of the economy as a very rough yardstick of comparison, overall purchase volumes amount to around one quarter of GDP in both cases. Hence, under such scaling, the US impact would range in the upper part of the confidence band obtained for the APP.

2 APP duration extraction and euro area yields

We construct a theory-consistent measure of the free-float of duration risk, which enters our term structure model as supply variable (Section 2.1); we explain how to project it into the future using official ECB communication and survey information (Section 2.2); and we introduce the yield curve data (Section 2.3).

2.1 A theory-consistent measure of the free-float of duration risk

As in Vayanos and Vila (2009) the term premium is affected by the amount of duration-risk to be absorbed by arbitrageurs (price-sensitive investors). Consistent with this, we construct a measure of the free-float of duration risk as follows:

$$\text{free-float of duration risk} = \frac{\text{duration-weighted bond holdings of price-sensitive investors}}{\text{duration-weighted total bond supply}}. \tag{1}$$

For our measure of the free-float of duration risk we focus on the general government bonds of the four largest euro area countries (Germany, France, Italy and Spain; henceforth "big-four"). These countries accounted for around 80% of euro area sovereign debt and around 76% of euro area GDP at the end of 2016.

The APP initially consisted of three components, a public sector purchase programme (PSPP), an asset-backed securities purchase programme (ABSPP), and a covered bond purchase programme (CBPP3). A fourth component was added with the corporate sector purchase programme (CSPP) in March 2016. The PSPP is by far the largest component, making up 84% of total net purchases, against 8% in the CBPP3, 7% in the CSPP, and 1% in the ABSPP. Within the PSPP, 90% of purchases (88% until March 2016) are made in national sovereign bonds, while 10% (12%) are allocated to euro area supranational issuers. The allocation of purchases across national bond markets is guided by the subscription of the 19 euro area national central banks (NCBs) in the ECB's capital key.[8] General government bonds comprise central government bonds, regional and local government bonds, as well as some social security funds. We hence abstract from the remaining 15 euro area countries which account for the remaining 20% of euro area debt, the purchase of other agencies and supranational bonds, as well as private sector purchases within the ABSPP, the CSPP and the CBPP3.

[8] The so-called ECB capital key refers to the subscription shares by the euro area NCBs in the capital of the ECB. The capital key subscription reflects the share of the respective Member States in the total population and gross domestic product of the euro area, in equal measure.

An advantage of our focus on the general government bonds of the big-four euro area countries is that it allows us to construct a granular and accurate measure of the free-float of duration risk. By contrast, using also the data for the remaining 15 countries, as well as private sector assets, would come at considerable computational cost and could introduce measurement errors, as the sectoral holdings data, which we exploit to identify the holdings by price-sensitive investors, require significant data cleaning. Importantly, our measure of the free-float of duration risk is a ratio, which captures the free-float of duration borne by price-sensitive investors relative to total duration supply. Considering the private sector purchases and supply as well as the remaining 15 jurisdictions should leave the evolution of this ratio essentially unchanged, as both the numerator and the denominator of this ratio would adjust.

To construct our measure of the free-float of duration risk, see equation (1), we use security-level information from the quarterly Securities Holdings Statistics (SHS) for non-Eurosystem holdings of general government debt securities. These data are available from 2009Q4. In addition, we use information on Eurosystem holdings derived from the ECB-internal security-level data on sovereign bond purchases. For each security our data set comprises information on the nominal value, the residual maturity and the holding sector. For euro area holdings granular information on the holding sector is available: monetary and financial institutions (MFI), money market funds (MMF), non-MMF investment funds, insurance corporations and pension funds (ICPF), other financial institutions, non-financial corporations, and households. By contrast, for foreign, i.e. non-euro area, holdings only a distinction between official and non-official portfolios is available.

The information on foreign holdings in the SHS is subject to two reporting biases. We address these as follows. First, nominal holdings by foreign private investors are inflated due to a custodial over-reporting bias of foreign non-official holdings. To address this bias, we benchmark the nominal value of total outstanding government bonds for each country as per the SHS with the corresponding information from the ECB's Government Finance Statistics (GFS). We then adjust the foreign sector holdings obtained from the SHS downwards so that the sum of outstanding amounts across all sectors from the SHS data matches the totals from the GFS. Second, during the preliminary SHS data collection period from 2009Q4 to 2013Q3 foreign official sector holdings are largely unreported. To address this issue, we backcast the nominal foreign official sector holdings for all countries from their 2013Q4 levels based on the dynamics of euro area external financial liabilities as reported in the IMF's Coordinated Portfolio

Investment Survey (CPIS) and the Currency Composition of Official Foreign Exchange Reserves (COFER). In addition, we assume that the weighted average maturity (WAM) of foreign official sector holdings is constant over the preliminary SHS data collection period at the level of the average WAM of the pre-APP official reporting period.

To account for the role of different types of investors in the transmission of central bank asset purchases (the numerator in equation (1)), we divide holding sectors into two groups, in line with Vayanos and Vila (2009). In the group of arbitrageurs (price-sensitive investors) we include - for the euro area - MFIs (excluding the Eurosystem), non-financial corporations (NFCs), households, MMFs, and non-MMF investment funds. In terms of magnitude, MFIs are the dominant private domestic holding sector of euro area sovereign bonds. In addition, we include in the group of arbitrageurs all foreign non-official sector holdings.[9]

By contrast, our group of preferred-habitat or price-insensitive investors comprises insurance companies and pension funds (ICPFs) and the official sector, both euro area and foreign. ICPFs tend to follow hold-to-maturity strategies, as they match long-dated liabilities with long-dated assets, and are subject to regulatory requirements. ICPFs are, thus, unlikely to rebalance away from their preferred habitats. Similarly, we assume official sector demand for government bonds to be price-insensitive. Official holdings comprise foreign exchange reserves by non-euro area central banks, holdings of the intra-euro area general government sector, as well as Eurosystem portfolios. The latter include both monetary policy related sovereign bond holdings, such as those accumulated under the Securities Markets Programme (SMP) and the PSPP, as well as holdings which are unrelated to monetary policy and subject to the Agreement on Net Financial Assets (ANFA).

Before the start of the APP, euro area MFIs held the largest portion of big-four sovereign bonds, followed by the official sector other than the Eurosystem, which mainly reflects foreign reserve holdings (see Table 1). On balance, close to 55% of all outstanding big-four government bonds were in the hands of arbitrageurs pre-APP. Differences in the pre-APP average maturity of sectoral portfolios point to different investment strategies. For instance, MFI and foreign non-official holdings tended to be concentrated in shorter maturity segments compared to the maturity distribution of all outstanding government bonds, while ICPFs held substantially longer-dated paper.

[9] Our classification of investor types as price-sensitive vs. price-insensitive is in line with the evidence on sectoral portfolio rebalancing in response to the PSPP in Koijen, Koulischer, Nguyen, and Yogo (2017), Koijen, Koulischer, Nguyen, and Yogo (2018) and Bergant, Fidora, and Schmitz (2018).

	Holdings (€bn)		WAM (years)	
	pre-APP	2018Q2	pre-APP	2018Q2
arbitrageurs	*3281*	*2632*	*6.1*	*6.7*
– MFI	1334	1141	5.0	5.4
– other domestic	1126	976	6.5	7.8
– foreign non-official	815	514	7.3	7.7
preferred-habitat investors	*2716*	*3860*	*6.6*	*7.4*
– ICPF	1009	1241	10.8	10.6
– other official	1305	1096	4.1	4.3
– Eurosystem	402	1523	4.5	7.0

Table 1: **Sovereign bond holdings by investor type and sector.** The table reports the nominal value and WAM of sector-specific holdings of bonds issued by the general governments of France, Germany, Italy and Spain. The pre-APP period refers to average sector holdings in the period 2013Q4 to 2014Q4. The sector "other official" includes domestic euro area governments and the foreign official sector; "other domestic" includes NFCs, households and financial institutions other than banks.

Since the start of the APP, a notable portfolio rebalancing has taken place across sectors. The share of Eurosystem holdings in total outstanding big-four government bonds has risen from less than 7% to around 23% by mid-2018, see Table 1. ICPFs were the only investors who increased their holdings alongside the Eurosystem. These increases in portfolio holdings have been accommodated by net issuance of big-four general government bonds and a reduction in sovereign debt holdings by other sectors. All sectors classified as arbitrageurs, and among these most prominently banks and foreign non-official investors, have been net sellers of government bonds. As a result, the share of holdings by arbitrageurs as a fraction of total outstanding big-four government bonds has fallen from 55% to around 41%.

To account for the duration of the bonds held by arbitrageurs, we consider the sectoral holdings in terms of their 10y equivalents. The 10y equivalent portfolio is a hypothetical portfolio that consists only of 10y zero-coupon bonds and that has the same duration risk as the actual portfolio. The nominal amount (par value) of an individual bond j is converted into the 10y equivalent using the formula: $10y \quad equivalent_j = nominal_j \cdot \frac{duration_j}{10}$. We use the maturity as a duration proxy. This measure has the advantage of abstracting from endogenous feedback effects from yield levels on other portfolio duration measures, such as modified duration. For a portfolio with weighted average maturity $WAM = \sum_{j=1}^{bonds}(nominal_j \cdot maturity_j) / \sum_{j=1}^{bonds} nominal_j$, the 10y equivalent of the portfolio is obtained by weighting the portfolio's nominal value by $\frac{WAM}{10}$.

Finally, we arrive at our measure of the free-float of duration risk by normalising duration absorption by arbitrageurs with the total supply of duration risk, i.e. the 10y equivalent value of the nominal amount of outstanding government bonds of the big-four euro area jurisdictions, see

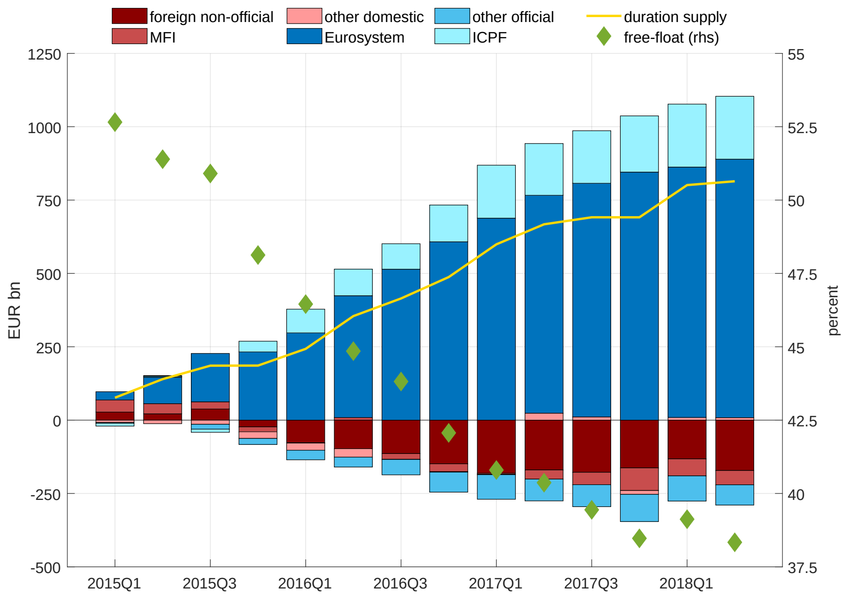

Figure 2: **Evolution of duration supply and its absorption by investor type.** On the left axis, the chart shows cumulative changes in 10y equivalent holdings of big-four general government bonds in €bn compared to pre-APP holdings as of 2014Q4. On the right axis, the evolution of the free-float as a percentage of total duration supply is shown.

the denominator in equation (1). We refer to this share of duration risk exposure of arbitrageurs in the total duration risk supply as the free-float of duration risk, see green diamonds in Figure 2. For the estimation of the model the quarterly free-float series is interpolated linearly to obtain observations at monthly frequency.

Our free-float definition departs in two dimensions from that used by Li and Wei (2013). First, Li and Wei (2013) consider US Treasury securities in the hands of all private investors as the relevant metric to explain variation in term premia. By contrast, we control for preferred-habitat investors such as ICPF and official sector holdings other than the Eurosystem. This gives us a more precise measure of the free-float of duration risk in the hands of arbitrageurs, which is also more closely aligned with Vayanos and Vila (2009).[10] Second, we normalise the risk exposure of price-sensitive investors with total duration supply, rather than nominal GDP as in Li and Wei (2013).

Figure 2 illustrates that since the start of the APP the Eurosystem has broadly offset the increase in the 10y equivalent bond supply to the market through the issuance of big-four general

[10]See also Hamilton and Wu (2012). The annex provides a more detailed discussion of the mapping between Vayanos and Vila (2009) and our model.

government debt securities. ICPFs have increased their exposure to duration risk over the same period, which is consistent with their classification as preferred-habitat investors. By contrast, arbitrageurs, such as foreign private investors and, to a lesser extent, euro area banks, have reduced their relative exposure to duration risk since the start of the APP, as is evident from the material decline of the free-float.

2.2 Projecting APP duration extraction over time

Central bank asset purchases exert their impact on the term structure by reducing the free-float of duration risk to be borne by price-sensitive arbitrageurs. Importantly, the theoretical model by Vayanos and Vila (2009) implies that the yield impact of central bank asset purchases in a specific maturity spectrum depends on the evolution of the discounted duration of the stock of bonds held by the central bank over the entire life of bonds in this spectrum. Therefore, beyond measuring the contemporaneous free-float of duration risk, we also need to project, at any given point in time, the free-float of duration risk, and its reduction through central bank asset purchases, into the future.

Projecting the evolution of the duration-weighted central bank portfolio requires information on future purchase volumes. We use the fact that the ECB's forward guidance on the path of net asset purchases was communicated in terms of an intended monthly purchase pace and horizon. For example, at the initial announcement of the APP in January 2015, the ECB Governing Council communicated its intention to make net purchases of €60 bn a month from March 2015 to at least September 2016. After this initial announcement, the Governing Council made changes to the purchase horizon and/or the size of monthly flows in December 2015, March 2016, December 2016, October 2017 and June 2018. Each of these dates provides an "APP vintage", which is associated with a specific announced path for net purchases.[11]

In addition, we assume that announced net purchases are wound down along a linear tapering path, which reflects the ECB's early guidance that net purchases would not end abruptly. The linear tapering is assumed to reduce the monthly net purchase volume from the announced end-date in steps of €10 bn. Moreover, in December 2015 it was announced that maturing principals would be reinvested "for as long as necessary". From then on we asume a reinvestment phase to

[11] The "time leg" of the forward guidance on asset purchases was complemented by a state-contingent forward guidance element, according to which purchases would "in any case be conducted until the Governing Council would see a sustained adjustment in the path of inflation which is consistent with its aim of achieving inflation rates below, but close to, 2% over the medium term".

follow net asset purchases. From December 2015 to October 2017 we assume the reinvestment horizon to be 2 years. This is in line with median survey-based reinvestment expectation in the December 2017 Bloomberg survey, which first recorded reinvestment expectations. For June 2018, we use a median reinvestment horizon of 3 years as recorded in the respective Bloomberg survey. Table 2 summarises, under the label "GovC", the key parameters for the various APP vintages.

Projecting the duration-weighted central bank portfolio also requires information on the maturity distribution of purchases. As announced in January 2015, securities with maturity of two to 30 years were eligible for purchase. Within this spectrum, the Governing Council communicated that purchases would be made in a "market neutral manner". "Market neutrality" is understood to mean that the maturity distribution of the monthly flow of purchases is proportional to the eligible bond universe. Furthermore, initially, no purchases of securities with a yield below the deposit facility rate were undertaken. This constraint was relaxed in December 2016 from when purchases of securities with a yield below deposit facility rate were allowed "to the extent necessary". At the same point, the eligible maturity spectrum was extended from an interval spanning two to 30 years to a wider range of one to 30 years.

In addition, the projections account for further eligibility and operational criteria, which guided the implementation of historical purchases and affect their composition along several dimensions. First, the distribution of purchases across countries is determined by the ECB's capital key. Second, purchases respect an issue and issuer limit of 33%. Finally, future issuance of purchaseable securities is taken into account and based on the debt projections that enter the ECB's quarterly staff macroeconomic projection exercises and that were available at the given point in time.[12] Figure 3 shows the resulting projections of the APP portfolio in terms of 10y equivalents for the different APP vintages summarised in Table 2.

[12] For details on the aggregate debt projections, see Bouabdallah, Checherita-Westphal, Warmedinger, de Stefani, Drudi, Setzer, and Westphal (2017).

Date	Type	Monthly pace (€bn) and horizon		Total net purchases (€bn)	WAM (years)
22 Jan. ‘15	GovC	60	Mar. ‘15 - Sep. ‘16	1290	8.29
		linear taper	Oct. ‘16 - Feb. ‘17		
12 Mar. ‘15	survey	60	Mar. ‘15 - Sep. ‘16	1290	8.43
		linear taper	Oct. ‘16 - Feb. ‘17		
25 Nov. ‘15	survey	60	Mar. ‘15 - Dec. ‘15	1988	8.30
		75	Jan. ‘16 - Mar. ‘17		
		linear taper	Apr. ‘17 - Oct. ‘17		
03 Dec. ‘15	GovC	60	Mar. ‘15 - Mar. ‘17	1650	8.23
		linear taper	Apr. ‘17 - Aug. ‘17		
		reinvestment	Sept. ‘17 - Aug. ‘19		
03 Mar. ‘16	survey	60	Mar. ‘15 - Mar. ‘16	2020	8.69
		80	Apr. ‘16 - Mar. ‘17		
		linear taper	Apr. ‘17 - Oct. ‘17		
		reinvestment	Nov. ‘17 - Oct. ‘19		
10 Mar. ‘16	GovC	60	Mar. ‘15 - Mar. ‘16	2020	8.70
		80	Apr. ‘16 - Mar. ‘17		
		linear taper	Apr. ‘17 - Oct. ‘17		
		reinvestment	Nov. ‘17 - Oct. ‘19		
02 Dec. ‘16	survey	60	Mar. ‘15 - Mar. ‘16	2388	8.49
		80	Apr. ‘16 - Mar. ‘17		
		72	Apr. ‘17 - Aug. ‘17		
		linear taper	Sep. ‘17 - Apr. ‘18		
		reinvestment	May ‘18 - Apr. ‘20		
08 Dec. ‘16	GovC	60	Mar. ‘15 - Mar. ‘16	2430	7.27
		80	Apr. ‘16 - Mar. ‘17		
		60	Apr. ‘17 - Dec. ‘17		
		linear taper	Jan. ‘18 - May ‘18		
		reinvestment	Jun. ‘18 - May ‘20		
18 Oct. ‘17	survey	60	Mar. ‘15 - Mar. ‘16	2550	7.52
		80	Apr. ‘16 - Mar. ‘17		
		60	Apr. ‘17 - Dec. ‘17		
		linear taper	Jan. ‘18 - Sep. ‘18		
		reinvestment	Oct. ‘18 - Sep. ‘20		
26 Oct. ‘17	GovC	60	Mar. ‘15 - Mar. ‘16	2580	7.21
		80	Apr. ‘16 - Mar. ‘17		
		60	Apr. ‘17 - Dec. ‘17		
		30	Jan. ‘18 - Sep. ‘18		
		linear taper	Oct. ‘18 - Nov. ‘18		
		reinvestment	Dec. ‘18 - Nov. ‘20		
07 Jun. ‘18	survey	60	Mar. ‘15 - Mar. ‘16	2593	7.24
		80	Apr. ‘16 - Mar. ‘17		
		60	Apr. ‘17 - Dec. ‘17		
		30	Jan. ‘18 - Sep. ‘18		
		linear taper	Oct. ‘18 - Dec. ‘18		
		reinvestment	Jan. ‘19 - Dec. ‘21		
14 Jun. ‘18	GovC	60	Mar. ‘15 - Mar. ‘16	2595	7.24
		80	Apr. ‘16 - Mar. ‘17		
		60	Apr. ‘17 - Dec. ‘17		
		30	Jan. ‘18 - Sep. ‘18		
		15	Oct. ‘18 - Dec. ‘18		
		reinvestment	Jan. ‘19 - Dec. ‘21		

Table 2: **APP parameters based on Governing Council announcements and survey expectations.** The table reports the main APP purchase parameters for the different Governing Council announcements (“GovC”), as well as based on market expectations as reflected in Bloomberg surveys (“survey”). The WAM reported is the WAM at the end of the net purchases associated. For each GovC series a linear tapering is added to the announced pace and horizon, in line with the GovC communication that net purchases would not end abruptly. The survey parameters reported reflect the median responses. For the Mar. ‘15, Nov. ‘15 and Mar. ‘16 only the expected end date of net purchases is reported in the survey, and the linear tapering is added by assumption. Following the announcement at the Dec. ‘15 GovC that maturing principals would be reinvested “for as long as necessary”, a reinvestment phase is assumed. From Dec. ‘15 to Oct. ‘17 the assumed reinvestment phase is 2 years, in line with median survey-based reinvestment expectation in the Dec. ‘17 survey, which first recorded such expectations. In Jun. ‘18 the median reinvestment expectation was 3 years.

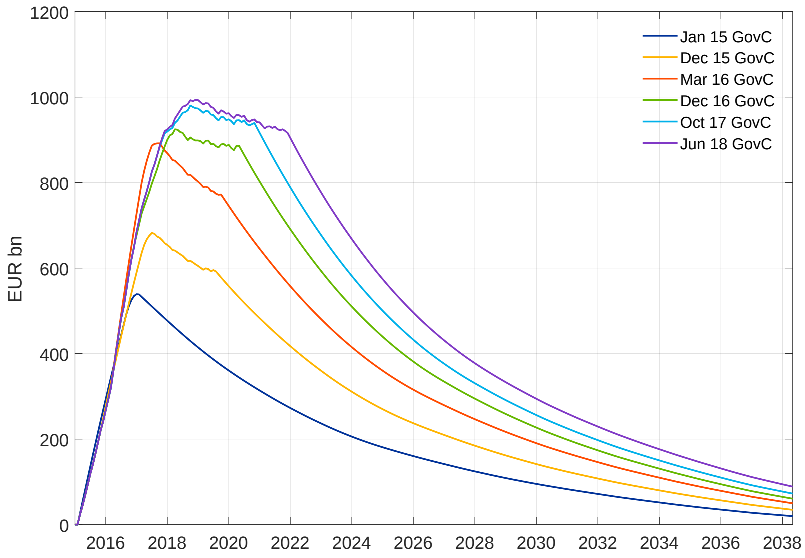

Figure 3: **Evolution of ECB's duration-weighted government bond holdings.** The figure shows the projected evolution of the government bond holdings for the big-four euro area countries in terms of 10y equivalents. The different paths correspond to the APP vintages summarised in Table 2.

Finally, we construct the trajectory of the free-float of duration risk over time by complementing the projections of the Eurosystem duration absorption with projections for duration supply. The projected duration supply is again based on the debt projections that enter the Eurosystem staff projections at a given point and are hence revised over time. In addition, we make the assumption that the WAM of the market portfolio remains unchanged over the projection horizon at the last observed WAM in each bond market. Figure 4 illustrates the compression of the free-float measure induced over time by the different vintages of the APP. Each line shows the reduction of the free-float relative to the counterfactual of no APP.

Below we also study the effect of announcements on asset purchases on the yield curve. These should have an impact on sovereign bond yields only to the extent that they are unanticipated by financial markets. To quantify the yield impact of the initial APP announcement, as well as subsequent recalibration vintages we, therefore, isolate the surprise in terms of additional future duration absorption associated with each announcement relative to what is already priced-in based on pre-announcement market expectations, similar to Ihrig et al. (2018). We exploit the regular surveys by Bloomberg to obtain market expectations on the future purchase path of the

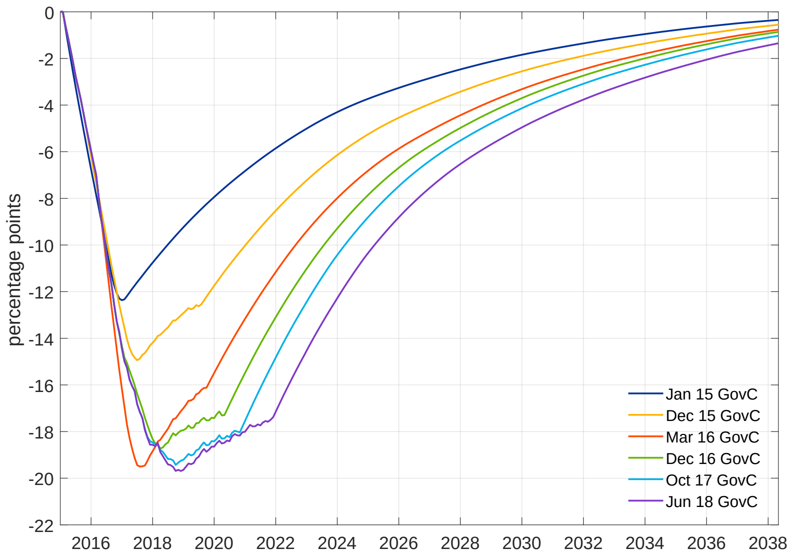

Figure 4: **Reduction in the free-float for different APP vintages.** The figure shows the compression of the free-float measure induced over time by the successive vintages of the APP. Each line shows the reduction of the free-float relative to the counterfactual of no APP. The different vintages are summarised in Table 2.

APP. The resulting parameters are summarised in Table 2 under the label "survey". We show for every APP recalibration the corresponding market expectations ahead of the recalibration announcement. In addition, we report the March 2015 survey path, as we use this in the estimation of our model (see Section 4.1).

The Bloomberg surveys were conducted systematically every six weeks from March 2015, and are typically published in the days ahead of the ECB Governing Council meetings.[13] The March 2015, November 2015 and December 2016 surveys did not contain information on expected "tapering" volumes. In those cases, we assume a linear tapering. The December 2016 survey contained information on expected tapering volumes, which we take into account. The October 2017 and June 2018 surveys provided a fully specified path for net asset purchases. Starting from the Governing Council's December 2015 reinvestment announcement until October 2017 we use a 2y reinvestment phase for the survey-based APP projections, in line with the Bloomberg survey of December 2017. For June 2018, we use a 3y reinvestment horizon in line with the corresponding survey. The maturity distribution of purchases for the survey vintages is assumed

[13]The March 2015 Governing Council meeting and survey provide an exception: the 12 March 2015 survey was conducted and published after the 5 March 2015 Governing Council meeting.

to follow the market-neutrality principle, in line with the approach taken for the Governing Council vintages. Using the survey-based information on the expected path of the APP, as well as assuming a market neutral maturity distribution of purchases, we create projections of the evolution of the market-expected duration-weighted APP portfolio, and the implied reduction of the free-float of duration risk.

2.3 Yields

In contrast to the US Treasury market, there is no single sovereign fixed income market at the level of the euro area as a whole. Each individual sovereign issues its own bonds. In order to provide a good representation of the overall sovereign debt market of euro area countries, we focus on the dynamics of the synthetic big-four euro area sovereign yield curve, which we construct as the GDP-weighted average of zero-coupon yields of Germany, France, Italy, and Spain.[14] The country-specific zero-coupon yields are constructed from prices of nominal bonds reported for transactions on the MTS platform. Bond prices are converted to zero-coupon yields using the Nelson-Siegel-Svensson methodology.[15] Our econometric analysis starts in December 2009 (in line with the availability of our SHS data) and ends in June 2018, when the Governing Council first expressed its anticipation to cease asset purchases by the end of December 2018, which was then subsequently confirmed. Figure 5 shows daily time series of the synthetic big-four zero-coupon yields for selected maturities over this period.

[14]The vector of weights for Germany, France, Italy, Spain, is $0.38, 0.27, 0.21, 0.14$.

[15]Information about the ECB's methodology for deriving zero-coupon yields is available at https://www.ecb.europa.eu/stats/financial_markets_and_interest_rates/euro_area_yield_curves/html/index.en.html.

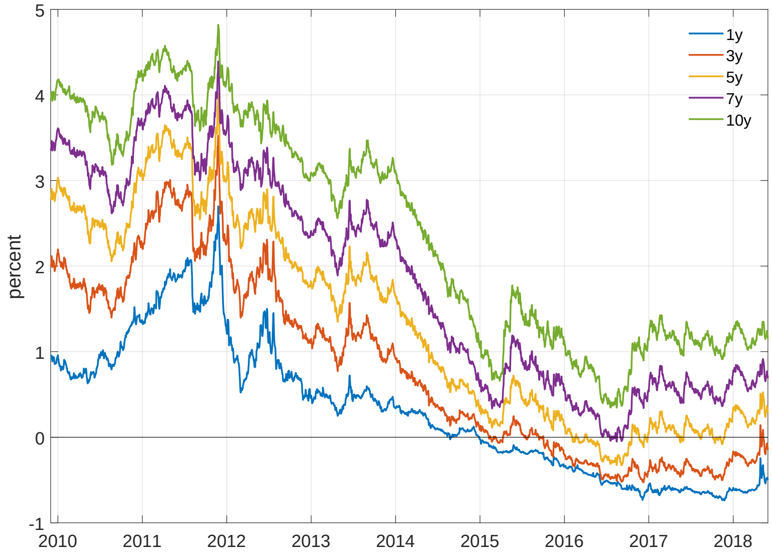

Figure 5: **Euro area zero-coupon yields.** The figure displays daily time series of the GDP-weighted synthetic zero-coupon yields for selected maturities of the big-four euro area countries for selected maturities from December 2009 to June 2018.

3 The model

3.1 A term structure model with quantities

For tracing the impact of the APP on the yield curve we rely on the model introduced by Li and Wei (2013). Yield curve dynamics are parsimoniously captured by three observable factors. The first two factors are given by the first two principal components (PCs) extracted from a cross-section of observed yields, see details in Section 4.1. We denote the first PC as the level factor L_t and the second PC as the slope factor S_t. The third factor, Q_t, is our free-float measure, see equation (1). We collect the three factors in the vector $X_t = (L_t, S_t, Q_t)'$.

The short-term interest rate i_t is a linear combination of the factors

$$i_t = \delta_0 + \delta_1' X_t, \tag{2}$$

where we impose the constraint that $\delta_1 = (\delta_{1L}, \delta_{1S}, 0)'$, i.e., as in Li and Wei (2013), Q_t does not impact the short rate contemporaneously.

The factors X_t follow a VAR(1),

$$X_t = c + \mathcal{K}X_{t-1} + \Omega\epsilon_t, \quad \epsilon_t \sim N(0, I). \tag{3}$$

Following Li and Wei (2013), we constrain the autoregressive matrix $\mathcal{K}$ to be block-diagonal with the two blocks (L_t, S_t) and Q_t. In addition, the contemporaneous shock impact matrix Ω is assumed to be lower triangular:

$$\mathcal{K} = \begin{pmatrix} \mathcal{K}_{LL} & \mathcal{K}_{LS} & 0 \\ \mathcal{K}_{SL} & \mathcal{K}_{SS} & 0 \\ 0 & 0 & \mathcal{K}_{QQ} \end{pmatrix}, \quad \Omega = \begin{pmatrix} \Omega_{LL} & 0 & 0 \\ \Omega_{SL} & \Omega_{SS} & 0 \\ \Omega_{QL} & \Omega_{QS} & \Omega_{QQ} \end{pmatrix}. \tag{4}$$

Together with the assumption that the last element of δ_1 is zero, equation (4) implies that the free-float measure Q_t does not forecast the short rate. In other words, the model excludes a potential signalling channel of central bank asset purchases. In addition, the quantity measure is assumed not to be predictable by the yield curve factors.

The pricing kernel M_t is exponentially affine in the factors

$$M_{t+1} = \exp\left(-i_t - 0.5\lambda_t'\lambda_t - \lambda_t'\epsilon_{t+1}\right), \tag{5}$$

where the market prices of risk λ_t are also affine in the factors

$$\lambda_t = \lambda_0 + \Lambda_1 X_t. \tag{6}$$

As in Li and Wei (2013) we impose the following zero constraints on the risk-compensation parameters λ_0 and Λ_1:

$$\lambda_0 = \begin{pmatrix} \lambda_{0,L} \\ \lambda_{0,S} \\ 0 \end{pmatrix}, \quad \Lambda_1 = \begin{pmatrix} \Lambda_{1,LL} & \Lambda_{1,LS} & \Lambda_{1,LQ} \\ \Lambda_{1,SL} & \Lambda_{1,SS} & \Lambda_{1,SQ} \\ 0 & 0 & 0 \end{pmatrix}. \tag{7}$$

This means that we assume that only level and slope risk is priced, but that the corresponding risk prices are driven by all three factors, including the quantity variable. Innovations to the quantity variable themselves are not priced, i.e. their market price of risk is zero.

The market price of risk vector λ_t is where the effects of central bank asset purchases are determined in the model: changes in the quantity variable affect risk prices of level and slope risk and thereby term premia. The economic interpretation of this link between bond supply and term premia is discussed in more detail in Section 3.3 below.

Zero-coupon bond prices P_t^n of bonds with maturity n satisfy the no-arbitrage pricing equation

$$P_t^n = E\left(M_{t+1}P_{t+1}^{n-1}|X_t\right), \quad P_t^0 = 1. \tag{8}$$

Bond prices are converted into yields via $y_t^n = -\frac{1}{n}\log P_t^n$. Given the affine structure of the model, yields turn out to be affine functions of X_t

$$y_t^n = -\frac{1}{n}\left(A_n + B_n' X_t\right), \tag{9}$$

where A_n and B_n satisfy the usual difference equations

$$A_{n+1} = A_n + B_n'(c - \Omega\lambda_0) + \frac{1}{2}B_n'\Omega\Omega' B_n - \delta_0, \tag{10}$$

$$B_{n+1}' = B_n'(\mathcal{K} - \Omega\Lambda_1) - \delta_1', \tag{11}$$

with $A_0 = 0$ and $B_0 = 0$. If $\Lambda_{1,LQ} \neq 0$ and $\Lambda_{1,SQ} \neq 0$, then $B_{n,Q}$, the third element of B_n, is different from zero. Hence, the quantity variable affects bond yields through the impact on the risk-compensation parameters, but does not have a contemporaneous effect on the short rate.[16]

3.2 Bond supply and the yield curve: modelling anticipated shocks

How does the model translate a change in central bank asset purchases into changes in term premia and bond yields?

Under the standard approach in affine term structure models, time-t bond yields can only change if the time-t factors change. Iterating the no-arbitrage bond pricing equation (8) forward, one obtains

$$P_t^n = E\left(M_{t+1} \cdot M_{t+2} \cdot \ldots \cdot M_{t+n}|X_t\right). \tag{12}$$

[16] The quantity variable does forecast level and slope factors – and hence future short-term rates via (2) – under the so-called risk-neutral dynamics. In a nutshell, under the risk-neutral probability measure, denoted by $\mathbb{Q}$, the pricing equation (8) boils down to discounting with the short-term rate (as opposed to the pricing kernel (5) involving risk corrections), i.e. $P_t^n = E^{\mathbb{Q}}(e^{-i_t}P_{t+1}^{n-1}|X_t)$, and incorporating the risk correction implicitly by using an amended factor process, which under the $\mathbb{Q}$ measure follows $X_t = \tilde{c} + \tilde{\mathcal{K}}X_{t-1} + \Omega\epsilon_t^Q$, where $\tilde{c} = c - \Omega\lambda_0$ and $\tilde{\mathcal{K}} = \mathcal{K} - \Omega\Lambda_1$.

Bond prices (and thus yields) depend on the expected sequence of future pricing kernels (short rates and risk compensation), which are, in turn, a function of future state variables and their innovations. Thus, current yields depend on the full path of our free-float measure over the lifetime of the bond. At the same time, the information set in equation (12) is just the current state variables X_t which are driven by a VAR. As a result, expectations of future state variables (including Q) and pricing kernels can only change if the current state variables X_t change. Accordingly, as indicated by the closed-form solution of the model (9), bond yields change if and only if current factors change. In particular, changes to central bank asset purchases could only be captured by a change to current Q_t. This change would trigger a change of future expected Q_{t+h} and future risk pricing – via equation (6)) – but this change in expectations of future quantities is fully determined by the change in the current (time-t) quantity.

However, the rigid link between future expectations and current state variables – implied by the standard approach described before – does not square well with the empirical evidence. For in practice, the pure announcement of central bank asset purchases (i.e. statements about future Q_{t+h}) can have a significant impact on the yield curve today without contemporaneously moving Q_t at all. Moreover, while asset purchases are on-going, too, further announced and credible changes to future purchase parameters, for example, a prolongation of the reinvestment horizon, can affect current bond yields even if they do not contemporaneously affect Q_t. Finally, even if an innovation to the path of central bank asset purchases does affect the current free-float Q_t, the announced future changes to Q may differ from those implied by the conditional expectations $E_t(Q_{t+h})$ as prescribed by the VAR in equation (3).

To capture the possibility that anticipated future free-float changes have an impact on the current yield curve over and beyond what is implied by the current states, Li and Wei (2013) allow anticipated innovations to the quantity variable to enter the bond pricing equation. Specifically, their approach amounts to conditioning bond pricing not only on current state variables, as in equation (8), but also on a sequence of future anticipated free-float ratios $\bar{\mathcal{Q}}_t = \{\bar{Q}_t, \bar{Q}_{t+1}, \bar{Q}_{t+2}, ...\}$

$$P_t^n = E\left(M_{t+1}P_{t+1}^{n-1}|X_t, \bar{\mathcal{Q}}_t\right), \quad P_t^0 = 1. \tag{13}$$

This is the same pricing expression as in equation (8), except that it uses an enhanced set of conditioning information. Denote by $\mathcal{Q}_t^0 = \{Q_t^0, Q_{t+1}^0, Q_{t+2}^0, ...\}$ the sequence of expected free-float ratios based on the state vector X_t and the VAR dynamics in equation (3). Let $u_{t+h} = \bar{Q}_{t+h} - Q^0_{t+h}$ denote the anticipated innovation of the free-float to the "baseline" and $\mathcal{U}_t = \{u_t, u_{t+1}, u_{t+2}, ...\}$ the corresponding sequence of anticipated innovations. Li and Wei (2013) show that bonds priced under the enhanced information set in equation (13) satisfy the yield equation:

$$y^n_t = -\frac{1}{n}A_n + dy_n(\mathcal{U}_t) - \frac{1}{n}B'_n X_t, \tag{14}$$

where A_n and B_n are the same expressions as in equation (9) in the standard set-up and

$$dy_n(\mathcal{U}_t) = -\frac{1}{n}\left[B_{n,Q}u_t + \sum_{h=1}^{n} B_{n-h,Q}(u_{t+h} - \mathcal{K}_{QQ}u_{t+h-1})\right]. \tag{15}$$

The expression $dy_n(\mathcal{U}_t)$ is the impact of a sequence of anticipated innovations to the quantity factor on the n-period term premium and corresponding yield over and beyond what is incorporated in current factors X_t.[17]

We can alternatively rearrange the terms in equation (15) to obtain

$$dy_n(\mathcal{U}_t) = \sum_{h=1}^{n} \gamma^n_h u_{t+h-1} = \gamma^{n\prime}\mathcal{U}_t, \tag{16}$$

where $\gamma^n = (\gamma^n_1, \ldots, \gamma^n_n)'$ with

$$\gamma^n_h = -\frac{1}{n}\left(B_{n-h+1,Q} - \mathcal{K}_{QQ}B_{n-h,Q}\right). \tag{17}$$

The model stipulates a linear relationship between changes in the trajectory of the expected future free-float over the tenor of a bond and the change in the yield of that bond. The sensitivity of yields to anticipated innovations in the future free-float are captured by maturity and horizon-specific "impact factors" γ^n_h, which are a function of the model parameters, such as the persistence of factors, innovation volatility and market prices of risk.

In Section 5 we deploy equation (16) to investigate how APP-recalibrations have affected the yield curve. A certain APP surprise at time t is summarised by a corresponding $\mathcal{U}_t$ sequence and the yield impact is obtained via (16).

[17] We consistently use $\mathcal{U}$ sequences that are longer than the lifetime of any bond. Therefore, we do not need to obey the distinction in Li and Wei (2013) regarding the upper summation limit that becomes relevant if $\mathcal{U}$ sequences are shorter than bond maturities. In terms of notation, in any scalar product involving $\mathcal{U}$, such as e.g. in (16), $\mathcal{U}$ is assumed to have the same length as the corresponding multiplying vector.

3.3 Bond supply and the yield curve: interpreting the transmission channel

In this section we provide further detail on the transmission channel of shocks to the free-float of duration risk implied by central bank asset purchases in our empirical model. First, we recall the standard decomposition of yields and show how expected future free-float measures $E(Q_{t+h}|X_t)$ – with expectations being fully determined by current states – affect expected future excess returns and hence term premia. Second, we show that that the same transmission channel holds for anticipated shocks, i.e. free-float innovations u_{t+h} that are *not* implied by contemporaneous state variables: we find that the effect of such an anticipated free-float shock u_{t+h} on future expected excess returns and hence term premia is the same as the effect stemming from a change in expected free-float induced by a change in current states, i.e. $E(Q_{t+h}|X_t)$.

The n-period bond yield can be represented as the sum of the expectations component (average expected future short rates over the life-time of the bond) and the term premium. The term premium component is, in turn, given by the average of expected future excess returns:

$$y_t^n = \underbrace{\frac{1}{n}E_t\sum_{h=0}^{n-1} i_{t+h}}_{\text{Expectations component}} + \underbrace{\frac{1}{n}E_t\sum_{h=1}^{n} rx_{t+h}^{n-h}}_{\text{Term premium}}, \tag{18}$$

where $rx_{t+h}^{n-h} = \ln P_{t+h}^{n-h} - \ln P_{t+h-1}^{n-h+1} - i_{t+h-1}$ is the one-period excess return for a bond with maturity $n-h+1$ purchased at time $t+h-1$. Unless specified otherwise, the conditional expectation $E_\tau(\cdot)$ is equivalent to $E(\cdot|X_\tau)$.

The identity in (18) is independent of a specific model. Different term structure models imply different parametric expressions for the expectations component and the term premium. For the affine model introduced in Section 3.1, each expected future excess return, conditional on information at the time of the purchase of the bond, can be expressed as[18]

$$E_{t+h-1}rx_{t+h}^{n-h} = B'_{n-h}\Omega\lambda_{t+h-1} + JI. \tag{19}$$

The term $B'_{n-h}\Omega$ captures factor sensitivity or "duration risk", i.e. the exposure of (log) bond prices to unexpected changes in risk factors, while λ_{t+h-1} is the time-varying 'price of risk', i.e. the amount of excess return compensation per unit of risk. This compensation varies over time

[18] The link between equations (18) and (19) can be seen by conditioning, in (19), the future expected one-period excess return on information (factors) at time t and applying the law of iterated expectations.

but is the same across bonds of all maturities, thus excluding arbitrage opportunities. The last item is a convexity adjustment (Jensen inequality) term, given by $JI = -0.5B'_{n-h}\Omega\Omega' B_{n-h}$, which does not depend on the factors.

The zero restrictions in (7) imply that level and slope risk is priced, while the risk at any future time of unexpected changes in the free-float measure is not priced, i.e. $\lambda_{t+h-1,Q} \equiv 0$. Grouping the level and slope factor as $Z_t = (L_t, S_t)'$ and writing the corresponding model matrices in a partitioned fashion (denoting the upper 2×2 part of Λ_1 in equation (7) by $\Lambda_{1,ZZ}$, etc.) the market price of level/slope risk, i.e. the 2×1 vector $\lambda_{t+h-1,Z}$, is given by

$$\lambda_{t+h-1,Z} = \lambda_{0,Z} + \Lambda_{1,ZZ} Z_{t+h-1} + \Lambda_{1,ZQ} Q_{t+h-1}. \tag{20}$$

The time variation in the market price of level/slope risk is driven by the level and slope itself ($\Lambda_{1,ZZ} Z_{t+h-1}$) as well as by the free-float measure ($\Lambda_{1,ZQ} Q_{t+h-1}$). Rewriting (19) we obtain

$$\begin{aligned} E_{t+h-1} rx^{n-h}_{t+h} &= \underbrace{\Theta_{n-h} + \theta'_{n-h} Z_{t+h-1}}_{\text{Terms independent of } Q} \\ &+ \underbrace{(B'_{n-h,Z}\Omega_{ZZ} + B_{n-h,Q}\Omega_{QZ})}_{\text{Exposure to level/slope risk}} \quad \underbrace{\Lambda_{1,ZQ} Q_{t+h-1}}_{\text{Price of risk components driven by } Q}, \end{aligned} \tag{21}$$

where Θ_{n-h} is a constant comprising the Jensen term JI in (19) and the time-invariant risk compensation (as function of $\lambda_{0,Z}$). The term $\theta'_{n-h} Z_{t+h-1}$ depends on the level and slope factors but not on the free-float measure. The last summand is the time-varying contribution of the quantity factor to the one-period expected excess return h-1 periods ahead. The first part in parentheses ("Exposure to level/slope risk") is the log bond price sensitivity to $\epsilon_Z = (\epsilon_L, \epsilon_S)'$ shocks in (3). This part affects the level and slope factors, and hence bond prices, either directly, via $B'_{n-h,Z}\Omega_{ZZ}$, or indirectly, by contemporaneously affecting the Q factor (via Ω_{QZ}) and affecting bond prices via the respective factor loading $B_{n-h,Q}$. The second part ("Price of risk components driven by Q") is the time-varying contribution of Q_{t+h-1} to the respective prices of level and slope risk. Conditioning equation (19) on information at time t, we note that if the current free-float Q_t changes, this affects $E_t(Q_{t+h-1})$ via the VAR, which in turn shifts expected future excess returns at time t through a change in the expected market price of risk and thus the time-t term premium.

Having shown how expected free-floats – with expectations spanned by current state variables – impact on term premia in the standard approach of affine term structure models, we now explain that the same transmission channel holds for anticipated shocks, i.e. free-float innovations u_{t+h} that are not implied by contemporaneous state variables.

Recall that the impact factors γ_h^n in equation (16) are expressed in terms of factor loadings on the free-float factor $B_{.,Q}$, see equation (17). We now convert them into an alternative expression that highlights their economic interpretation as risk premium contribution. Starting from the recursion in equation (11) and defining a selection vector $s = (0, 0, 1)'$, the impact of Q on the m-maturity log bond price is given by

$$B_{m,Q} = B'_{m-1}\mathcal{K}s - B'_{m-1}\Omega\Lambda_1 s - \delta'_1 s. \tag{22}$$

Grouping again $Z_t = (L_t, S_t)'$, partitioning system matrices accordingly, and noting the zero restrictions in $\mathcal{K}$, Ω and Λ_1, we obtain

$$\mathcal{K} \cdot s = \mathcal{K}_{QQ} \cdot s, \quad \Omega\Lambda_1 s = \begin{pmatrix} \Omega_{ZZ}\Lambda_{1,ZQ} \\ \Omega_{QZ}\Lambda_{1,ZQ} \end{pmatrix}, \quad \delta'_1 s = 0.$$

Therefore,

$$B_{m,Q} = B_{m-1,Q}\mathcal{K}_{QQ} - \left(B'_{m-1,Z}\Omega_{ZZ} + B_{m-1,Q}\Omega_{QZ}\right)\Lambda_{1,ZQ}.$$

Rewriting this expression for $m = n - h + 1$ we obtain from equation (16) the expression for the impact factors

$$\gamma_h^n = -\frac{1}{n}\left(B'_{n-h,Z}\Omega_{ZZ} + B_{n-h,Q}\Omega_{QZ}\right)\Lambda_{1,ZQ}. \tag{23}$$

This is the same expression as in the last line of equation (21). Therefore, an anticipated innovation u_{t+h-1} to the free-float has the same impact on the term premium as a change in the expected future free-float $E(Q_{t+h-1}|X_t)$ due to a change in current Q_t.

Overall, the model used in this paper can be viewed as a reduced-form multi-factor counterpart of the equilibrium model introduced by Vayanos and Vila (2009)and Greenwood and Vayanos (2014). A detailed comparison of the empirical model and the theoretical framework is provided in the annex.

4 Estimation

4.1 Estimation approach

While we rely on the same modelling framework as Li and Wei (2013), we modify their two-step estimation approach in order to address specific challenges posed by the euro area data. In the first step we estimate a VAR of the risk factors, including the free-float variable, and the relation between the short-term rate and these factors. In the second step, we quantify the market prices of risks by using a dual objective: we simultaneously match the time series evolution of bond yields between December 2009 and August 2014, as well as the portion of the yield curve decline between September 2014 and March 2015 that can be attributed to markets gradually pricing in expectations for large scale asset purchases by the Eurosystem.

Specifically, in the first step we fit a VAR(1) to an empirical level and slope factor (L_t and S_t, respectively) and to our observed free-float measure Q_t, see equation (1), over the pre-APP subperiod from December 2009 to August 2014. The level and the slope factors are extracted as the first two principal components from the cross-section of observed yields with maturities 1y, 2y, $\cdots$, 10y. Figure 6 shows monthly time series of the three factors over the full sample from December 2009 to June 2018. The shock impact matrix Ω is the Choleski decomposition of the variance-covariance matrix of the reduced-form shocks implied by the estimated VAR model. We estimate the parameters δ_0 and δ_1 in equation (2) with OLS. For the VAR and the OLS regression we impose the zero restrictions on $\mathcal{K}$ from equation (4) and δ_1 from equation (2), respectively.

In the second step, we estimate the market-price-of-risk parameters. In theory, we could follow Li and Wei (2013) and match the observed time series of bond yields and term premia estimates obtained from an auxiliary term structure model (Kim and Wright (2005)) that excludes bond supply information. However, in practice two aspects of the euro area data prevent us from relying on such a pure time series approach. First, our sample is relatively short due to the limited availability of the euro area free-float measure, which is available only from December 2009. Second, Eurosystem bond holdings only became a sizeable source of variation in the free-float with the start of APP. By contrast, the Federal Reserve's SOMA portfolio exhibited significant variations already before the inception of the Federal Reserve's LSAPs. Hence, based on the euro area data it is more challenging for the model to learn about the parameters from the covariation of Q and bond yield dynamics.

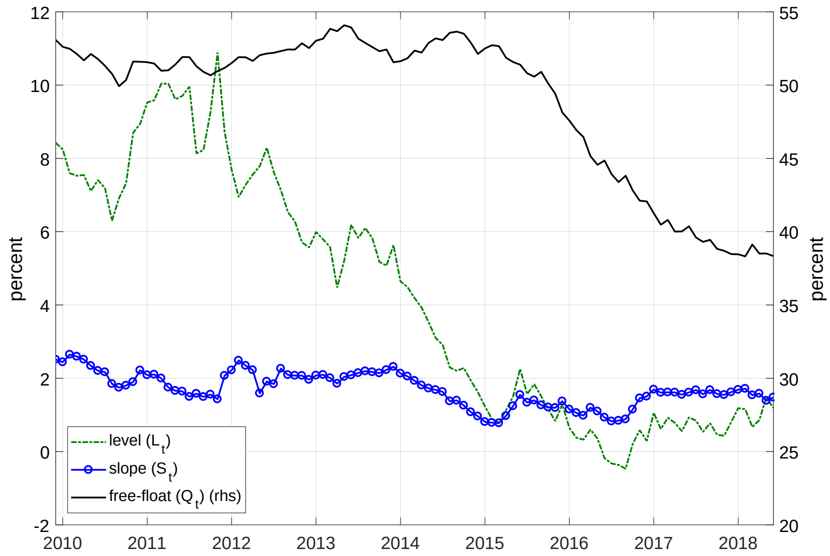

Figure 6: **Model factors**. The figure shows end-of-month time series of the level and the slope factors (left axis) and the free-float factor expressed as a percentage of total duration supply (right axis).

Therefore, for estimating the market-price-of-risk parameters our second step uses a dual objective function that not only takes into account the time series fit of bond yields but also the model's ability to capture the initial decline of the yield curve from September 2014 to March 2015. From September 2014, expectations about a possible ECB future large-scale asset purchase programme were building in financial markets ahead of the start of the APP in March 2015.

For the first part of the objective function, denote by y_t^o the cross-section of observed yields with maturities 1y, 2y, ..., 10y, and by $\hat{y}_t \equiv \hat{y}_t(\lambda_0, \Lambda_1 | X_t; , \hat{c}, \hat{\mathcal{K}}, \hat{\Omega}, \hat{\delta}_0, \hat{\delta}_1)$ the corresponding fitted yields, using equation (9) and taking the estimated VAR and short-rate parameters from the first step as given. Our distance measure is the average (across maturities and time) squared fitting error using end-of-month yields from December 2009 to August 2014:

$$F_1(\lambda_0, \Lambda_1) = \frac{1}{M_1 T} \sum_{t=1}^{T} [y_t^o - \hat{y}_t]'[y_t^o - \hat{y}_t], \tag{24}$$

where T=56 denotes the number of time series observations and $M_1 = 10$ the number of maturities used in the cross-section.

For the second part of the objective function, we assume that part of the euro area bond yield decline observed from September 2014 to March 2015 (when the APP was officially announced and launched) was due to the build-up of private sector expectations of large-scale sovereign bonds purchases. To infer the cumulative yield decline over this time window that can be attributed to the anticipation of the APP we conduct an event study. We then match the observed APP-induced cumulative change in bond yields with the model-implied change in term premia, conditional on a proxy for the prevailing APP expectations at the time.

For the selection of events with APP-related news, we follow Altavilla et al. (2015) and focus on 17 dates at which the ECB conveyed news about the APP in the form of ECB press conferences as well as speeches given by ECB President Draghi. The first date is 4 September 2014, the day of the ECB press conference at which the initial purchases under the ABSPP and the CBPP3, which preceded the announcement of the APP in January 2015, were communicated. Moreover, at the same point President Draghi indicated that a "[...] broad asset purchase programme was discussed, and some Governors made clear that they would like to do more."[19] The last date is 5 March 2015, when the ECB announced final technical details of programme, which complemented the information provided at the press conference following the 22 January 2015 Governing Council, and which confirmed 9 March 2015 as the starting date for the APP.

For our event-study we analyse the changes of zero-coupon yields over two-day windows.[20] We assume that the observed changes in yields around those event dates are primarily driven by market participants' changing expectations about the APP. Following Altavilla et al. (2015), we conduct two versions of the event study: one in which we control for news about key macroeconomic variables on those event dates, and another without such controls. We restrict our focus on the medium- and long-term segment of the yield curve and disregard changes of yields with less than 5y maturity. This is motivated by the fact that average short rate expectations over shorter horizons may also reflect monetary policy news unrelated to the APP. From 3 September 2014 to 6 March 2015 zero-coupon bond yields declined by 89 bps at the 10y maturity (and 46 bps the 5y maturity). Averaging the results of the two event-study analyses (controlled vs. uncontrolled), we attribute cumulative reductions of the 10y (and 5y) zero-coupon bond yield

[19]See `https://www.ecb.europa.eu/press/pressconf/2014/html/is140904.en.html`.

[20]Most of the relevant ECB announcements were made in the afternoon on a given day. We consider two-day rather than one-day yield changes as the construction of zero-coupon yields (see section 2.3) for a given day may incorporate prices prevailing before noon. Thus, if the announcement took place at date t some of the price changes underlying the construction of zero-coupon yields between $t-1$ and t may not reflect the event of day t's afternoon.

of 48 bps (and 33 bps) to to APP-announcements.

To operationalise the second component of the objective function, let dy^o denote the change in bond yields for maturities 5y, 6y, ..., 10y, which is attributable to news about the APP as estimated by the aforementioned event study approach. For example, $dy^o_{10y} = -48$ bps. Let $\hat{dy} \equiv \hat{dy}(\lambda_0, \Lambda_1 | \mathcal{U}_t; \hat{c}, \hat{\mathcal{K}}, \hat{\Omega}, \hat{\delta}_0, \hat{\delta}_1)$ denote the corresponding model-implied changes over the same period, computed by deploying equation (16) for the respective maturities. The $\mathcal{U}$ sequence used in (16) represents the expected trajectory for duration extraction determined by the APP as of 5 March 2015. This trajectory is constructed based on survey expectations prevailing at that date, which were closely aligned to the Governing Council's January 2015 announcements. We assume that this $\mathcal{U}$ sequence represents the APP expectations prevailing when the programme was launched, as they had built up "from zero" from September 2014. The second part of the objective function is then given by the distance measure:

$$F_2(\lambda_0, \Lambda_1) = \frac{1}{M_2}[dy^o - \hat{dy}]'[dy^o - \hat{dy}], \tag{25}$$

where $M_2 = 6$ denotes the number of maturities used in the second part of the objective function.

The optimisation problem for estimating the market-prices-of-risk parameters then is:

$$\{\hat{\lambda}_0, \hat{\Lambda}_1\} = \underset{\{\lambda_0, \Lambda_1\}}{\arg\min}\ \omega F_1(\lambda_0, \Lambda_1) + (1-\omega) F_2(\lambda_0, \Lambda_1), \tag{26}$$

where ω is a weighting parameter that balances the importance of the time series fit criterion F_1 and the "event window" fit criterion F_2 for the overall objective function. Choosing ω requires judgement. With a view of imposing a "flat prior" across the two criteria we set $\omega = 0.5$.

4.2 Parameter estimates

Table 3 reports estimates of the model parameters. Using estimates of the price-of-risk-parameters λ_0 and Λ_1, which are derived in the second estimation step, we compute estimates for the parameters $\tilde{c}$ and $\tilde{\mathcal{K}}$ that govern the risk-neutral dynamics of factors X_t. The higher eigenvalues of $\tilde{\mathcal{K}}$ than $\mathcal{K}$ indicate that all three factors are more persistent under the risk-neutral ($\mathbb{Q}$) than the real-world ($\mathbb{P}$) probability measure.

Given these parameter estimates and using the affine relation (9) between factors X_t and bond yields y^n_t, we report in Table 4 the reaction of the yield curve to a time-t increase in each

	δ_0			
	0.0046			
	δ_1			
L_t	0.1297			
S_t	-0.4489			
Q_t	0			
		$\mathcal{K}$		c
L_t	0.9704	-0.1373	0	0.0040
S_t	0.0116	0.7904	0	0.0034
Q_t	0	0	0.8903	0.0571
eig ($\mathcal{K}$)	0.7997	0.8903	0.9611	
		Ω		
L_t	0.0067	0	0	
S_t	-0.0002	0.0017	0	
Q_t	0.0001	0.0003	0.0040	
		Λ_1		λ_0
L_t	-7.0480	-26.8246	-0.5618	0.9455
S_t	32.8646	-79.9354	1.7518	-0.9813
Q_t	0	0	0	0
		$\tilde{\mathcal{K}}$		$\tilde{c}$
L_t	1.0178	0.0433	0.0038	-0.0024
S_t	-0.0466	0.9212	-0.0031	0.0054
Q_t	-0.0095	0.0266	0.8898	0.0574
eig($\tilde{\mathcal{K}}$)	0.8912	0.9512	0.9864	

Table 3: **Parameter estimates.** This table reports parameter estimates of the model obtained by using the two-step approach described in Section 4.1. In the first step we derive estimates for c, $\mathcal{K}$ and Ω - which govern the real-world dynamics of factors X_t - and of δ_0 and δ_1 - which map linearly factors X_t into the short rate - and, in the second step, for market-price-of-risk parameters λ_0 and Λ_1. Given these estimates, we compute $\tilde{c} = c - \Omega\lambda_0$ and $\tilde{\mathcal{K}} = \mathcal{K} - \Omega\Lambda_1$, which govern the risk-neutral dynamics of factors X_t.

factor, which amounts to a one standard deviation of the reduced-form shocks derived from the estimate of the shock variance-covariance matrix $\Omega\Omega'$. The first column of Table 4 indicates that the loadings of yields on the level factor L_t are positive and of similar size across maturities. Thus, a positive shock to this risk factor leads to an (almost) parallel upward shift of the entire yield curve. A positive shock to the slope risk factor S_t leads to a steepening of the yield curve, as indicated by the second column of Table 4.

A contemporaneous shock to the quantity factor Q_t shifts the entire yield curve in the same direction as the shock, as indicated by the third column of Table 4. Therefore, in line with economic intuition, yields decrease when the free-float measure is reduced by the Eurosystem's duration extraction. The yield impact of a shock to the free-float is hump-shaped across maturities. This is one of two possible shapes that can arise in the equilibrium model by Greenwood and Vayanos (2014). As argued by the authors, the hump-shaped pattern can occur when the shock to the free-float is mean-reverting relatively quickly. Indeed, according to the estimated $\mathcal{K}_{QQ}$ of 0.8903 from Table 3 - which represents also the persistency of the Q factor due to the imposed restrictions on the interactions with the other two factors - the impact of a shock to the free-float has a half life of only seven months. In addition, we find that a shock to the free-float moves the contemporaneous one-period expected returns $E_t rx_{t+1}^{n-1} = B'_{n-1}\Omega\lambda_t$ of all bonds in the same direction as the shock, and that the effect is increasing across maturities. Also this empirical finding of our euro area model is in line with the prediction of the theoretical model of Greenwood and Vayanos (2014), see Section 1.3 of their paper.

Finally, we inspect the estimated impact factors γ that map sequences of innovations of the free-float from the expected path implied by the VAR dynamics – equation (3) – into yield curve reactions. Figure 7 plots the estimated impact factors γ_h^n for maturities $n =$ 2-, 5- and 10y over the relevant horizons h. The impact factors decrease monotonically over the future horizons within the tenor of any bond. Therefore, changes in free-floating duration supply over the near term have a larger effect on the term premium component of a yield than changes occurring in the more distant future. This pattern holds for bonds of any maturity.

4.3 Model fit

For our time series fitting criterion F_1 in (26), the model delivers a good fit to the yield level data over time. Root mean squared errors over the estimation period range from 3 to 14 bps across maturities. This is comparable in size to the fit of US yields in Li and Wei (2013). In

Maturity of yield (years)	L_t	S_t	Q_t
1	15	-5	0.29
2	20	-2	0.41
3	22	-1	0.44
4	23	0	0.44
5	23	1	0.42
6	23	1	0.41
7	23	2	0.38
8	22	2	0.36
9	21	2	0.34
10	20	2	0.32

Table 4: **Reaction of the yield curve to changes in the factors.** The table reports changes in yields in response to a one standard deviation shock in time-t to each factor in $X_t = (L_t, S_t, Q_t)'$. The changes are derived using equation (9). The changes are reported in basis points.

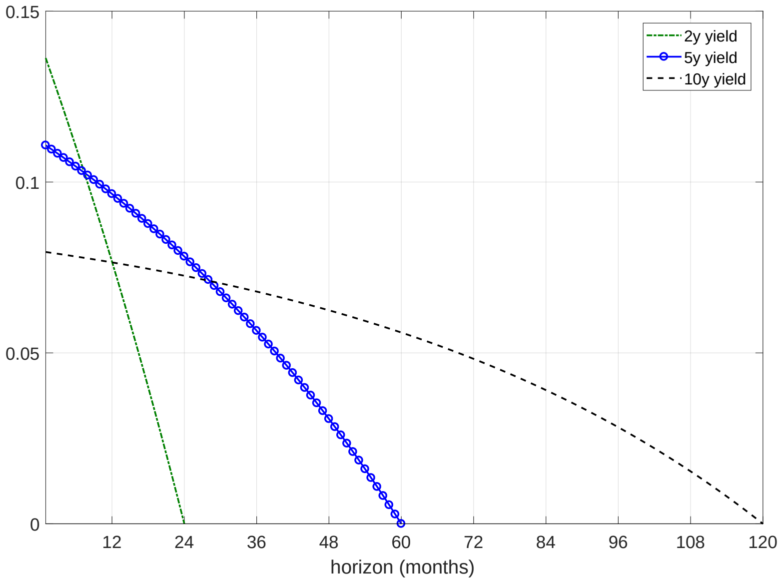

Figure 7: **Estimated impact factors.** The figure shows the estimated impact factors γ_h^n that map a sequence of revisions to the current and expected free-float into changes in yields of bonds with maturity n = 2-, 5-, and 10y, see equation (16). The vertical axis shows the yield change contribution per unit of free-float change at the respective horizon. For instance, an anticipated free-float reduction in 3 years by 1 percentage point contributes to lowering the 5y yield by 0.05 percentage points contemporaneously.

particular, medium and long-term yields are fitted well in sample.

Focusing on F_2, the second part of the objective function in (26), the left panel of Figure 8 presents the model fit of the APP-induced cumulative decrease in the sovereign yield curve over selected event dates from September 2014 to March 2015, as discussed in Section 4.1. The right panel of Figure 8 plots the series of anticipated future APP-induced free-float innovations $\mathcal{U}$ as of 5 March 2015 that underlies these fitted yield changes. Each model-implied yield decline shown is the result of multiplying the maturity-specific impact factors γ_h^n, see equation (16), with the part of this $\mathcal{U}$ sequence spanning the horizons of each yield tenor. For example, the 10y yield APP-induced compression (of about 49 bps) is the product of γ_h^{10y}, the dashed line in Figure 7, and the part of the $\mathcal{U}$ sequence from the right panel of Figure 8 starting in March 2015 and ending in February 2024.

The model fits almost perfectly the decreases in yields with maturities of 5y and more, which corresponds to the data used in the second part of the objective function. For shorter maturities, which do not enter the estimation criterion, the model predicts less pronounced yield decreases than observed for the selected events. As the model captures only the effect of the APP on term premia due to the duration extraction channel, the observed undershooting of the model prediction is attributable to factors outside our model, such as a signaling channel of APP-related communication, or changes in the ECB's key interest rate policy rates.

The reduction in the future free-float induced by the anticipation of the APP – see the right panel of Figure 8 – that underlie the fitted decreases in yields between September 2014 to March 2015 is large relative to the average variation of the supply factor from December 2009 to August 2014. The standard deviation of innovations to the free-float in this early period amounts to only 0.4 percentage points (see the estimate of the shock variance-covariance matrix $\Omega\Omega'$ from Table 3). By contrast, in March 2015 the anticipated reduction in the free-float induced by the APP was envisaged to peak at about twelve percentage points at the end of the net purchases phase and to still amount to about four percentage points in 2025, see again Figure 8. Furthermore, in contrast to the short-lived persistence of a shock to the free-float in the pre-APP period (with a half-life of only seven months, see Table 3), the APP represents a very persistent reduction in the supply of available bonds. To illustrate further the extraordinary dimension of the APP impulse, we can compute the unanticipated contemporaneous free-float shock that, when multiplied with the respective yield loading $B_{10y,Q}$, would give the same 49 bps impact on the 10y yield as the anticipated free-float shock sequence as of March 2015. It turns out that this hypothetical

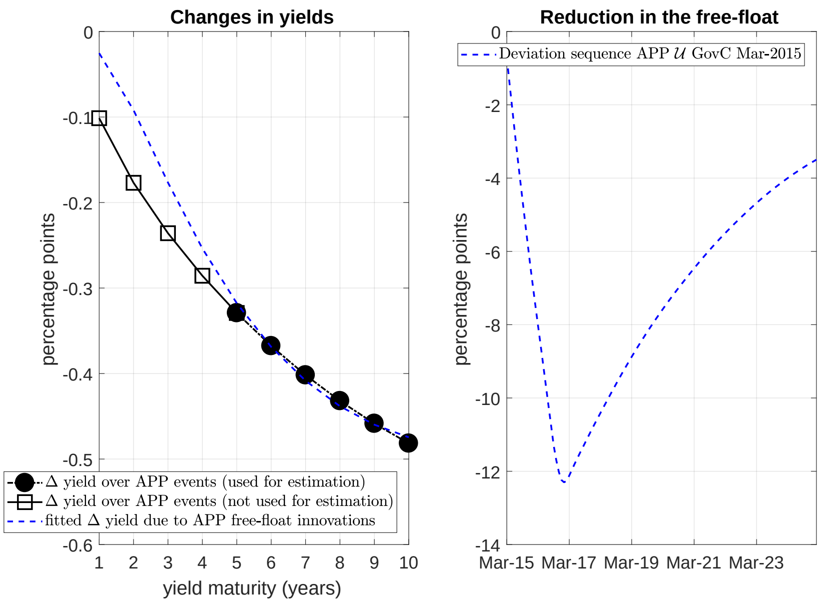

Figure 8: **Impact of the anticipation of the APP on the yield curve through expected future free-float compression.** The left panel plots observed and fitted changes in yields over an event window: the black line represents the cumulative decreases in yields over the APP-related events from early September 2014 to early March 2015; the blue dashed line plots the model-implied changes in yields due to future APP-induced free-float innovations $\mathcal{U}$ as of 5 March 2015 (shown in the right panel). Decreases in yields with maturities as of 5y up to 10y (circle markers) are used in the estimation of the model, while the decreases of yields with shorter maturities (square markers) are left out.

shock would amount to 61 percentage points. This represents more than the actual supply of bonds available to price sensitive investors at the time the programme was launched, see Figure 6. Overall, both the size and the persistence of APP-induced innovations to future free-float are several orders of magnitude higher than the free-float variation observed in the pre-APP sample.

5 The impact of the APP on the yield curve

We use our estimated model to infer the impact of the APP on the sovereign yield curve through the duration extraction channel. First, we estimate the compression of term premia along the yield curve for different vintages of the APP (Section 5.1). Second, we examine the persistence of the term premium compression over time and investigate the contribution made by reinvestments of maturing principals (Section 5.2). Third, we compare the yield changes observed around APP recalibration announcements to the real-time predictions of our model (Section 5.3). Finally, we assess the robustness of our results (Section 5.4).

5.1 Term premium compression across the yield curve

Figure 9 shows the estimated impact of the APP across the yield curve for the different APP vintages at the time of their announcement. Each curve shows the estimated term premium compression relative to the counterfactual of no duration-extraction through the APP. The date shown in the legend indicates both the respective APP vintage, i.e. the specific path of net purchases implied by the vintage, as well as the point in time at which the term premium compression is estimated. For example, the curve labelled “Jan 15 GovC” shows the estimated term premium compression due to the January 2015 APP vintage in January 2015.

We obtain these yield curve impact estimates by feeding the free-float reduction implied by the different APP vintages (see Figure 4) into our model. In detail, the estimated term premium compression is constructed using equation (16), which maps the sequence of anticipated free-float innovations ($\mathcal{U}$) into a yield impact using the impact factors (see illustrations of γ_h^n for selected maturities in Figure 7). For the example of January 2015, the sequence of free-float innovations relevant for the 10y term premium is the part of the dark-blue line corresponding to the January 2015 APP vintage in Figure 4 that ranges from January 2015 ten years to December 2024. To compute the 5y term premium the relevant sequence free-float innovations consists just of the

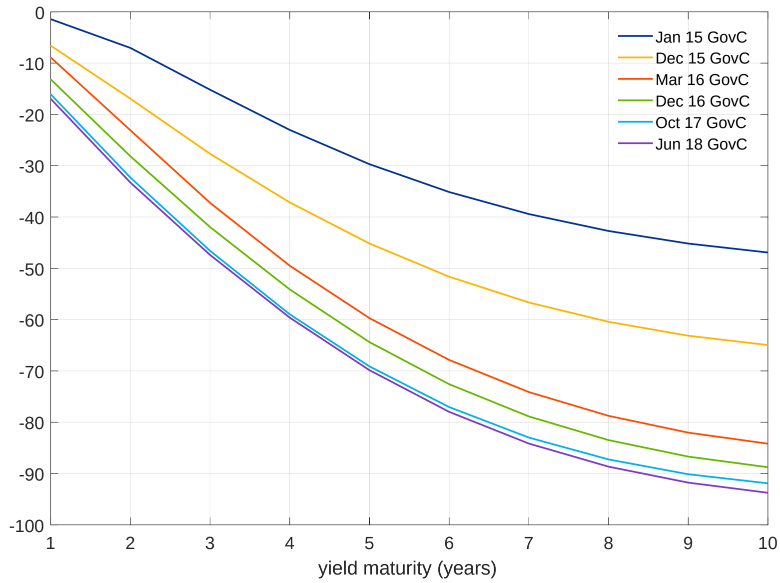

Figure 9: **Impact of different APP vintages on the yield curve.** The figure shows the contemporaneous impact of the APP on the term structure of interest rates. For the indicated dates t and maturity n, the respective point on the line provides an estimate of how much the sovereign n-period yield at the respective time t is compressed due to the impact on the term premium via the duration extraction channel.

five years from January 2015 until December 2019 in Figure 4.

For January 2015, the impact on the 5y and 10y term premium is found to be around 30 and 50 bps, respectively. Also for the subsequent vintages, the term premium impact is estimated to be higher for longer tenors, i.e. the APP has led to a flattening of the curve. The overall term structure impact has become stronger over time as the APP has been expanded in length and volume. For the June 2018 APP vintage we estimate that in the absence of the APP the 10y sovereign bond yield would have been around 95 bps higher at that point (Figure 9).

5.2 Term premium compression over time

Figure 1 plots the term premium impact at the 10y maturity for different APP vintages over time. At each point in time indicated on the horizontal axis, the figure shows the estimated 10y term premium compression for the different APP vintages.

Figure 1 is constructed as follows. For each of the trajectories shown there, the starting point is the initial impact, i.e. the 10y maturity point in Figure 9. For each of the trajectories shown the impact over time is then obtained by moving to the right along the corresponding free-float compression curve in Figure 4. To this end, we use the impact formula (16) – reproduced here for convenience: $dy_n(\mathcal{U}_{t+h}) = \gamma^{n\prime}\mathcal{U}_{t+h}$ – by applying the impact vector γ^{10y} to the sequences of anticipated innovations $\mathcal{U}$ that start in the future at time $t+h$. For example, for the June 2018 vintage we estimate the 10y term premium reduction in January 2025, by taking the segment of the violet free-float impact curve in Figure 4 that starts in January 2025 and ends in December 2034 as our sequence for the free-float reduction. The scalar product with the time-invariant impact factor vector (γ^{10y}) then delivers an estimated 10y yield impact of around 35 bps in January 2025.

The estimated term premium impact is fairly persistent but gradually fades over time. Across the APP trajectories shown, the half-life of the initial impact on the 10y yield is around five to six years. While the projected 10y term premium compression falls below 10 bps by around 2033, it only dissipates completely once the portfolio has been entirely wound down.

For shorter maturities, the impact of the programme also diminishes over time, albeit more slowly than at longer maturities, see Figure 10 for the June 2018 APP vintage. Looking at the 2y maturity, the initial term premium effect is smaller than for the 10y, which implies a flattening of the curve, as discussed above. As the 2y impact fades more slowly than the 10y impact, the yield curve becomes again steeper over time. The markedly greater persistence of the 2y term premium compression over the nearer term reflects the impact of reinvestments, which were anticipated to follow the end of net purchases in December 2018 and assumed to last for three years. Hence, even in early 2020 most of the term of a 2y bond is falling into the reinvestment phase, which is not true for longer term bonds.

The fading of the term premium compression reflects, to some extent, the "ageing" of the portfolio – i.e. its gradual loss of duration as the securities held in the portfolio mature – as well as, in particular, the run-down of the portfolio that market participants anticipate will eventually follow the end of the expected horizon of reinvestments.

The pure "ageing" effect is due to the fact that day by day the duration of the central bank portfolio falls even in the absence of any redemptions. The reinvestment of maturing principals conducted in line with "market neutrality" – i.e. with the maturity distribution of purchases guided by the maturity distribution of the eligible universe of securities – offsets this gradual loss of duration to some extent (see the continuous vs. the dotted line in Figure 11) over the reinvestment horizon (assumed to be two years). By contrast, under a counterfactual "no ageing" reinvestment policy (dashed-dotted line in Figure 11), the portfolio would remain constant in

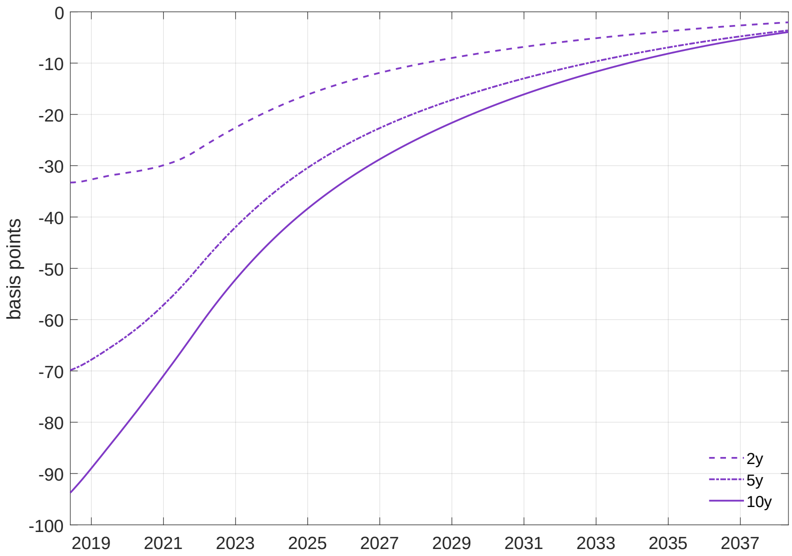

Figure 10: **The impact of the APP on the 2y, 5y and 10y term premium over time.** The figure shows for the June 2018 APP vintage the impact of the APP on the term premium component of the 2y, 5y and 10y sovereign bond yield (averaged across the four largest euro area countries) over time.

terms of 10y-equivalents during the reinvestment phase. Figure 12 illustrates the term premium compression that would result from such a counterfactual "no ageing" reinvestment policy.[21] It turns out that even if the portfolio was prevented from ageing during the reinvestment phase, the term premium impact of the central bank purchases would still fade gradually over time. This suggests that the bulk of the fading term premium impact in the future reflects market expectations of a gradual roll-down of the portfolio after the end of reinvestments.

Apart from the relevance of reinvestment in mitigating the ageing effect, the reinvestment horizon as such makes an important contribution to the reduction in term premia and its persistence over time. Figure 13 illustrates for the June 2018 APP vintage the 10y term premium reduction for reinvestment horizons ranging from 0 to 10 years. The longer is the reinvestment horizon, the higher is the contemporaneous yield impact. However, the marginal impact of an additional year of reinvestment is shrinking with the length of the reinvestment horizon. For instance, reinvesting for 3 years instead of 0 years generates an additional term premium impact of around 18 bps, while moving from 7 to 10 years of reinvestment induces an additional

[21] This type of reinvestment policy would be challenging to implement in practice as it would require reinvestments into very long-term securities, with an average maturity of around 13 years.

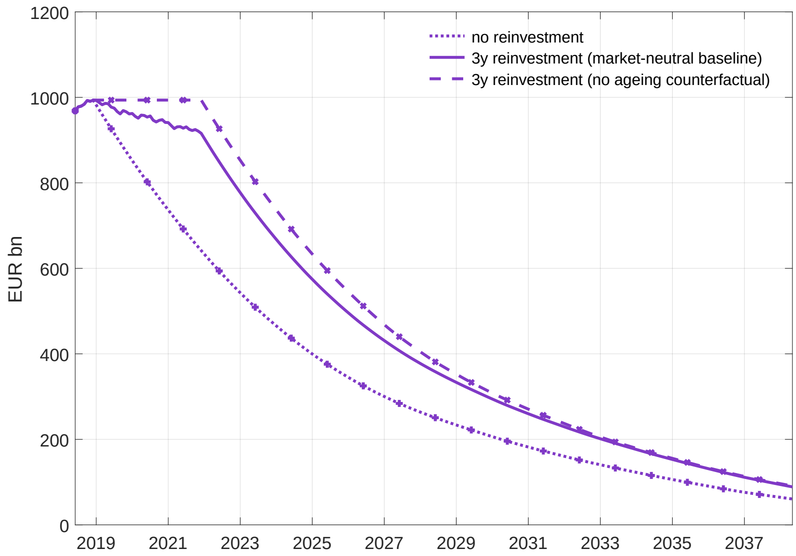

Figure 11: **Illustrating "portfolio ageing" - the evolution of duration-weighted government bond holdings under different reinvestment scenarios.** For the June 2018 APP vintage of net purchases the figure shows the projected evolution of the big-four government bond holdings in terms of 10y equivalents under three reinvestment scenarios. Under the "no reinvestment" scenario the portfolio starts running down after the end of net purchases in December 2018. In the "3y reinvestment scenario (market-neutral baseline)" scenario, reinvestments are made for three years starting in January 2019 in line with a "market neutral" maturity distribution of purchases. In the "3y reinvestment (no ageing counterfactual)" scenario reinvestments are again conducted over a period of three years starting in January 2019, but deviating from our baseline case it is assumed that reinvestments are made in sufficiently long maturities to offset the "ageing" of the portfolio during the reinvestment phase.

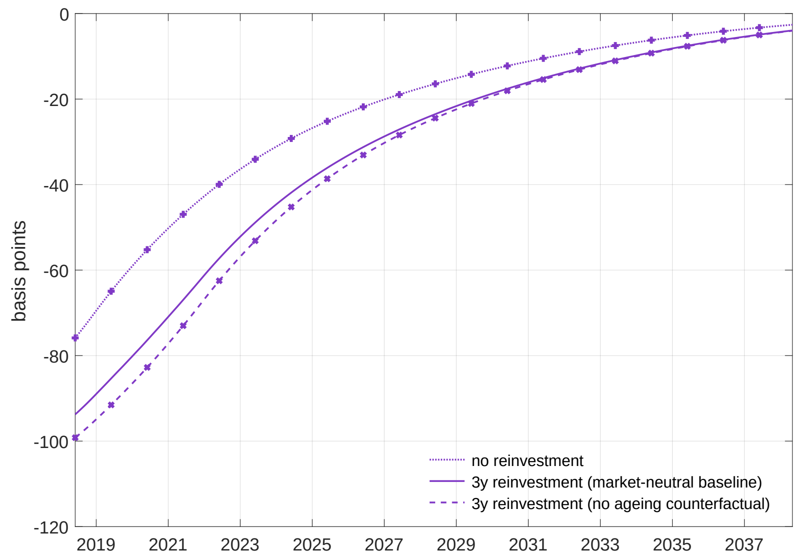

Figure 12: **Illustrating "portfolio ageing" - the APP's 10y term premium impact under different reinvestment scenarios.** The figure shows the 10y term premium impact over time that is implied by the trajectory of central bank holdings shown in Figure 11.

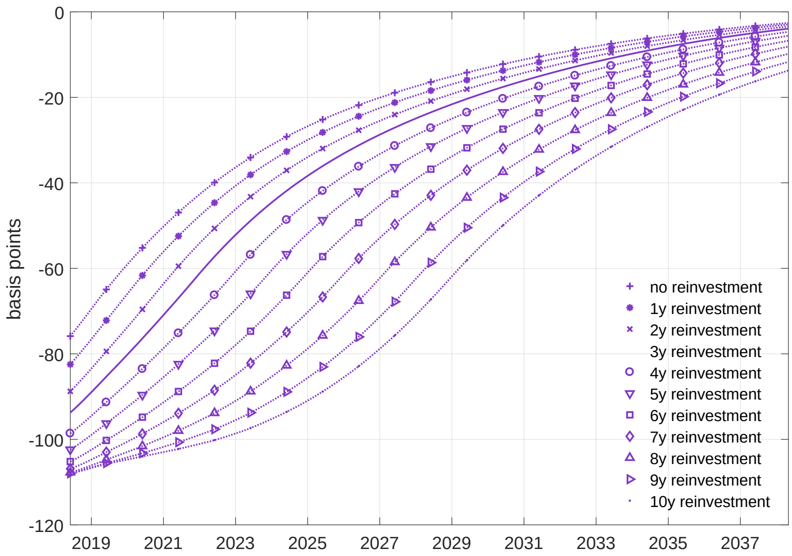

Figure 13: **Evolution of the 10y term premium compression through the APP for different reinvestment horizons** For the June 2018 APP vintage, the figure shows the 10y term premium compression over time for different reinvestment horizons following the end of net asset purchases in December 2018.

compression of a mere 2 bps. This declining marginal effect reflects discounting: the additional free-float reduction in the 7y vs 10y reinvestment scenario happens 7 years from now, which is priced into contemporaneous term premia via low levels of impact factors, see Figure 7 again. But the picture changes over time: standing in, say, 2026, the marginal impact of going from 7y to 10y reinvestment (following the end of net purchases in December 2018) is larger than in June 2018.

5.3 Benchmarking the announcement effects of APP recalibrations

In a real-time exercise, we benchmark the term premium impact of APP recalibration announcements predicted by our model against the observed yield curve changes observed in narrow windows around APP recalibrations. Since our model estimation is not informed by any post-March 2015 data, these exercises are conducted out of sample and, hence, constitute an ambitious cross-check of our model.

To calculate the surprise entailed by the APP recalibration announcements for the future free-float we control for pre-announcement market expectations. For each of the APP announcements we first simulate the free-float trajectory based on market expectations on the path of the APP before the announcement and then again based on the actually announced purchase parameters (see Table 2). The difference between these two free-float trajectories gives us the sequence of surprises to the free-float due to the APP recalibration announcement. We feed these surprises into our model (using them as the $\mathcal{U}$ sequence in equation (16)), and compare this model prediction to the one-day and two-day yield curve changes measured around the APP recalibration announcement.

For the observed yield curve changes we control for both changes in the bond yield's expectations component (average short-rate expectations over the bond's maturity) as well as macro surprises. This makes the observed yield changes more closely comparable to the yield changes predicted by our term structure model, which captures the change in yields purely based on the term premium compression via duration risk extraction. First, to control for the expectations component we subtract from the full observed yield change the change in the estimated expectation component of the euro area OIS yield curve, which we obtain from a benchmark affine term structure model based on Joslin et al. (2011). Second, we account for macroeconomic surprises on the days of the announcements of APP recalibrations by cleansing yield changes for macro effects relying on the sensitivity of yields to macroeconomic surprises obtained in Section 4.1. The yield changes shown on the right-hand side of Figure (14) are the average of the yield changes cleansed of macro effects and those not cleansed of such effects.

Figure 14 shows on the left-hand side the surprises in the free-float sequences for four APP recalibrations. The right-hand side shows the corresponding model-implied changes in the yield curve, as well as the observed yield curve changes. The December 2015 and, to a lesser extent, the December 2016 APP recalibration announcements implied some upward revisions to the free-float of duration risk, which is reflected in the observed yield curve reaction to the announcement. At the same time, the March 2016 and June 2018 APP recalibrations implied small, if any, revisions to the expectations on the free-float. In those two cases we nonetheless see some flatting of the yield curve, which can be rationalised by factors unrelated to duration extraction and hence outside our model.

In December 2015, the ECB announced the first recalibration of the APP since the initial announcement of the programme in January 2015. The recalibration involved the announcement of, first, a prolongation of net purchases by six months until March 2017 at an unchanged purchase pace of €60 bn per month, and, second, a reinvestment policy for maturing principals beyond the net purchase horizon "for as long as necessary". While market participants had

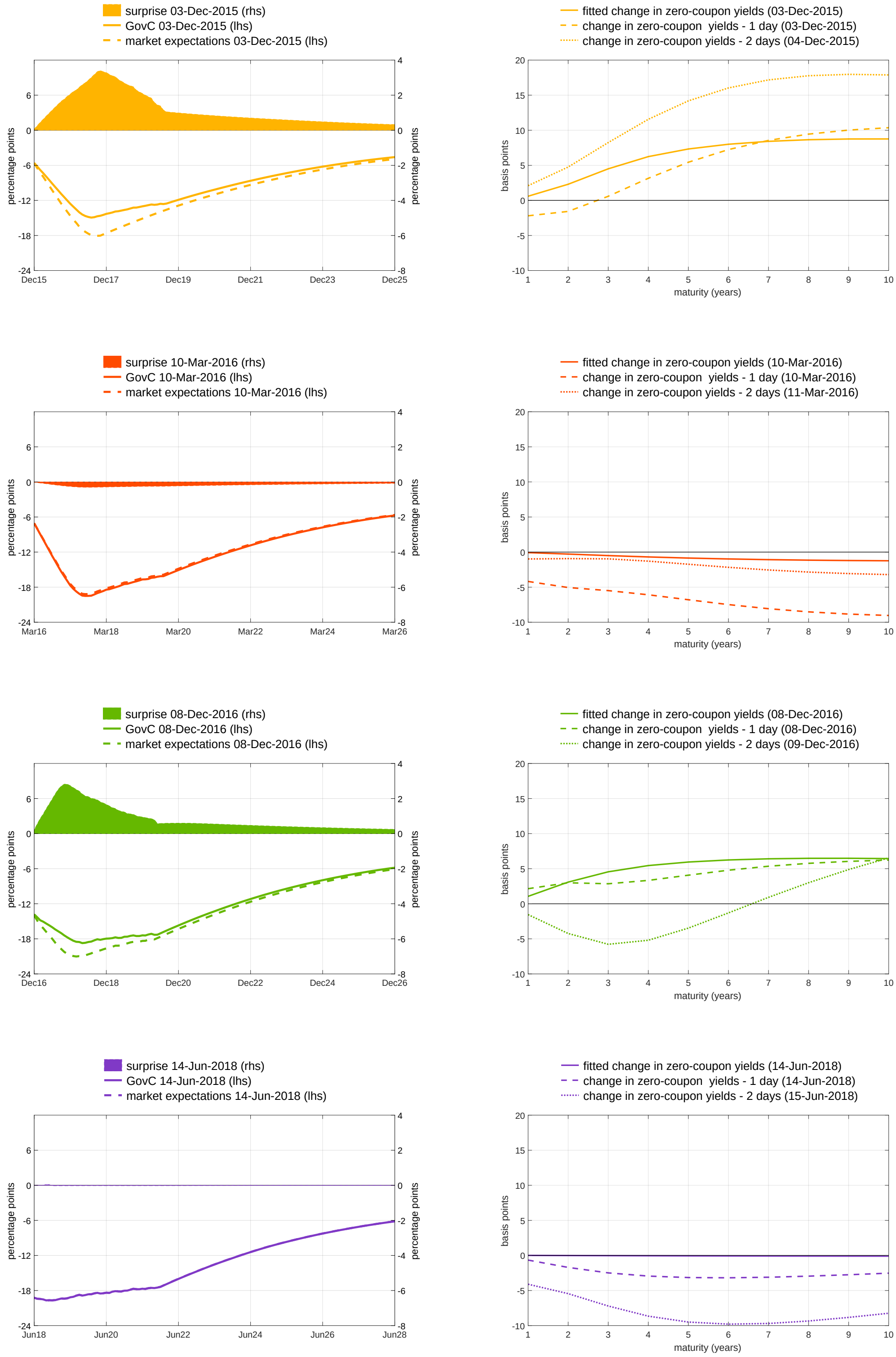

Figure 14: **Announcement effects of APP recalibrations.** Left-hand side: The dashed lines represent the expected free-float paths constructed from surveys before the APP recalibration was announced. The continuous lines represent the expected free-float paths after the APP recalibration announcement, constructed based on the announced APP parameters. The difference between these two pre- and post-APP recalibration free-float projections, is the free-float surprise, which is shown as an area. The right-hand side shows the model-implied term premium impact due to APP recalibrations vs. observed yield changes. The observed changes are shown for one-day and two-day changes in the zero-coupon sovereign yield curve (dashed and dotted lines, respectively), each time controlling for changes in the expectations component as well as macroeconomic surprises.

anticipated the prolongation of net asset purchases ahead of the December 2015 Governing Council, the predominant expectation had been for the ECB to also increase the monthly pace of purchases (see Table 2). As a result, and despite the announcement of the reinvestment policy, the APP recalibration implied a significantly lower duration absorption over the near-term than expected by market participants. This resulted in an upward revision of the expected future free-float with an increase of as much as almost four percentage points. This disappointment of market expectations and the resulting revision of the free-float sequence filtered through our model can explain the observed reaction of the yield curve. Yields increased for all but the shortest maturities on the day of the Governing Council announcement, thereby steepening the curve. The model prediction of a 10 bps increase of the 10y yield matches the one-day change of the zero-coupon rate and comes in somewhat below the two-day change.

The December 2016 recalibration featured an extension of net purchases at a reduced monthly pace of €60 bn for nine months until December 2017. Market expectations were for an extension over a somewhat shorter horizon at a slightly higher monthly pace, see Table 2. In addition, the ECB extended the eligible maturity bracket from two to one year at the lower end and also opened the door to purchases at yields below the deposit facility rate "to the extent necessary". The somewhat lower monthly purchase pace and increased scope for buying short-term papers implied some upward surprise on the expected path of the free-float. Filtered through our model, this implied a moderate steepening of the curve, which is broadly matched by the one-day change in the zero-coupon curve. The observed two-day change posts a comparable increase at the long end, but exhibits a fall in yields at the short end. These lower short-term yields could reflect that the prolongation of net purchases over a horizon longer than anticipated by market participants led to an adjustment of policy rate expectations, beyond what is controlled for by our cleansing of the observed yield data for changes in the expectations component.

In the March 2016 APP recalibration the monthly purchase pace was increased from €60 bn to €80 bn. This increase had been widely anticipated by markets. At the same time, due to compositional effects, on account of an increased share of purchases of sovereign bonds relative to supranational bonds, as well as the introduction of the CSPP, the resulting free-float reduction was only mildly above market expectations. The model-implied slight flattening of the yield curve is mirrored in the one-day change of the zero-coupon curves. At the same time, over the two-day window, the observed yield curve flattening was more pronounced than predicted by the model. This is likely to reflect additional factors outside our model, such as the 10 bps reduction of the deposit facility rate to -40 bps, which was announced at the same time.

Similarly, the decision at the June 2018 Governing Council to outline a gradual wind-down of net asset purchases, conditional on continued progress towards a sustained adjustment in the path of inflation, was largely in line with market expectations. The surprise to the future free-float path was, hence, close to nil. This notwithstanding, the yield curve at the long end fell by as much as 5 bps on the day of the announcement - and again by almost the same amount on the day after the policy meeting. The observed flattening of the curve is likely to reflect that the eventual net asset purchases remained state-contingent and a further continuation hence remained, in principle, a possibility. Moreover, at the June 2018 meeting the Governing Council also reinforced forward guidance on the path of policy rates, by signalling that they were expected to remain at their prevailing levels "at least through the summer of 2019". Such factors did not lead to a quantifiable revision in the free-float trajectory and therefore cannot be captured by our model that relies on duration extraction as the transmission channel of the APP.

5.4 Uncertainty and robustness of results

Finally, we conduct sensitivity analyses around the results presented above, conducting three exercises. First, we account for parameter uncertainty based on bootstrapping; second, we conduct a bias adjustment of the estimated factor dynamics; and third, we extend the estimation sample beyond March 2015.

To account for parameter uncertainty, we rely on a bootstrap procedure. We do so as our two-step estimation approach and the limited number of available observations prevent a straightforward application of asymptotic results. For the bootstrap we resample the data and obtain bootstrap estimates of the model parameters based on our two-step estimation approach outlined in Section 4.1.

In detail, in the ith bootstrap run, for the first step of our estimation approach, we take random draws from the centred residuals of our estimated factor VAR and use them as innovations in generating a new time series of factors, based on the point estimates of VAR parameters $\hat{c}$ and $\hat{\mathcal{K}}$. Using those bootstrap factor realisations, we reestimate the factor VAR parameters – under the same zero restrictions as in our baseline estimation – and obtain bootstrap estimates $\check{c}^{(i)}$, $\check{\mathcal{K}}^{(i)}$ and $\check{\Omega}^{(i)}$. Similarly, we reestimate the short-rate equation (2) and obtain bootstrap estimates $\check{\delta}_0^{(i)}$ and $\check{\delta}_1^{(i)}$ of δ_0 and δ_1. For the second step of our estimation, we bootstrap the realisations of the components featuring in our dual objective function (26). For the first part of that objective function, F_1, we construct a bootstrap realisation of the time series of yields by adding measurement errors to fitted yields, where these errors are drawn from the pool of centred fitting residuals of our estimated model. For the second component, F_2, we then generate a bootstrap realisation of the change in the yield curve over our event window by applying noise around the fitted yield changes.[22] Given the bootstrap draw of the yield changes over the event window and the bootstrap draw of the yields sequence we conduct the second step of our estimation approach, i.e. we minimise the dual objective criterion (26) for given $\check{c}^{(i)}$, $\check{\mathcal{K}}^{(i)}$, $\check{\Omega}^{(i)}$, $\check{\delta}_0^{(i)}$ and $\check{\delta}_1^{(i)}$ and obtain bootstrap estimates $\check{\lambda}_0^{(i)}$ and $\check{\Lambda}_1^{(i)}$ of λ_0 and Λ_1, respectively. We repeat this procedure for K =1000 bootstrap repetitions. Collecting our parameters in a vector θ, the distribution of our point estimate $\hat{\theta}$ is hence approximated by the sampling distribution $(\check{\theta}^{(1)}, \ldots, \check{\theta}^{(K)})$ of our bootstrap estimates. Similarly, the distribution of (nonlinear) functions of the parameters $g(\theta)$ – like, e.g., the impact factors $\gamma_h^n \equiv \gamma_h^n(\theta)$ – are approximated by the corresponding bootstrap sampling distribution $g(\check{\theta}^{(1)}), \ldots, g(\check{\theta}^{(K)})$. This enables us to generate distributions around all our impact estimates that reflect the uncertainty stemming from parameter estimation.

Figure 15 shows the APP's dynamic impact on the 10y term premium based on the June 2018 APP vintage with our estimated confidence bands. The mid point (solid violet line) is the same as in Figure 1. The uncertainty band is the bootstrap-based confidence band reflecting parameter uncertainty. For the contemporaneous term premium impact as of June 2018, the 5-95% confidence band ranges from 65 to 130 bps around the 95 bps estimate. The width of the confidence bands accounting for parameter uncertainty is of the same order of magnitude as that reported in Ihrig et al. (2018). Over time the uncertainty band gradually narrows, as the point estimate and the uncertainty around it converge to zero. Formally, this can be seen from the fact that at any future point in time $t + h$ the yield impact is given by the product of impact factors and a sequence of APP free-float innovations going forward, $dy_n(\mathcal{U}_{t+h}) = \sum_{k=1}^{n} \gamma_k^n(\theta) u_{t+h+k-1}$: as the innovations u_{t+h+k} eventually shrink to zero, so does the overall scalar product.

As second robustness check we conduct a bias adjustment of the estimated factor dynamics.

[22] Proceeding in the standard fashion as we did for the bootstrap generation of factors and yields, we could draw from the residuals corresponding to the fit of our six yield changes over the event window. However, as these residuals are very small (not exceeding 2 bps), we see a risk of underestimating the true uncertainty and take a more conservative approach by drawing the noise from six independent normal distributions with zero mean and a standard deviation of 10 bps.

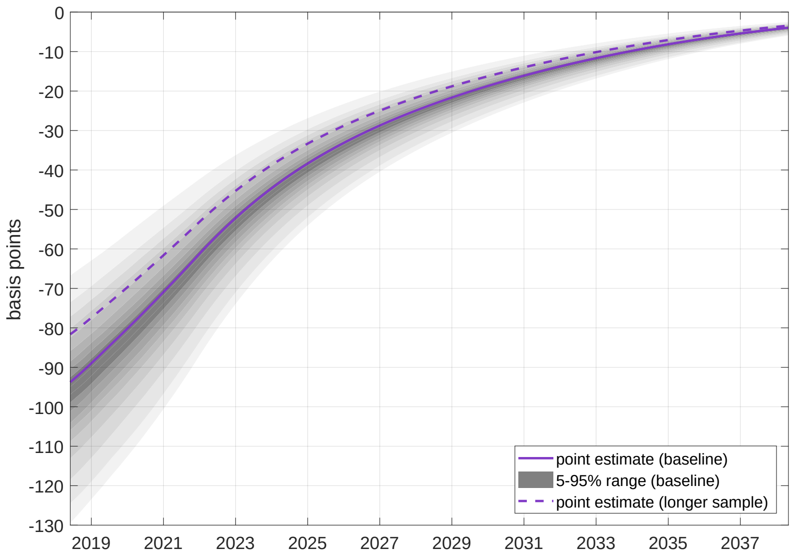

Figure 15: **The APP's 10y term premium impact: parameter uncertainty and sample robustness.** Conditional on June 2018 information, the figure shows the impact of the APP on the 10y term premium over time. The solid line is the point estimate, identical to the violet line in figure 1. The shaded area is the 5-95% confidence band stemming from parameter uncertainty computed using a bootstrap approach. The dashed line is an alternative point estimate that uses the full-sample yield information (until June 2018) for estimation, whereas the baseline estimate ignores data after March 2015.

As noted in the literature[23], term structure models tend to underestimate the high persistence exhibited by bond yields, in particular when the estimation sample is short. Bauer et al. (2012) and others have, therefore, suggested to conduct a bias correction when estimating the VAR dynamics of factors. For our model and data, in fact, the estimated degree of persistence of the factor VAR is already high, with a maximum eigenvalue of 0.961 (Table 3). Nevertheless, we apply the bias correction methods suggested by Bauer et al. (2012).[24] Overall, the bias correction leaves the main results regarding the APP's impact on the yield curve essentially unchanged. We attribute this to the fact that, despite different dynamics of factors under the $\mathbb{P}$ measure, the cross-section information in bond yields, especially their change over the event-window dates, ensures that key objects like the impact factors γ_h^n in (16), which depend on both $\mathbb{P}$ and market price of risk parameters, are hardly affected.

Finally, we vary the estimation sample. In our baseline specification we only use data up to March 2015 to estimate the model. This approach allows undertaking a clean out-of-sample benchmarking exercise, as discussed in Section 5.3. As a robustness check we here also include data from March 2015 to June 2018. Specifically, for the first step of our estimation approach, we estimate the factor VAR and the short-rate equation using this full data set. For the second step, we leave the second component of the dual objective function in equation (26) unchanged, but include the full time series of bond yields until June 2018 in the first component of the dual objective function. As shown in Figure 15, dashed line, using the full sample, the estimated impact of the APP is of a similar magnitude, if somewhat smaller (77 vs. 88 bps on impact in June 2018; and 37 vs. 43 bps after five years).

6 Conclusion

Central bank bond purchases extract duration risk which otherwise would be borne by price-sensitive investors. This decreases the market price of risk and compresses the term premium component of bond yields across the term structure. This paper quantifies the strength of the duration channel for the European Central Bank's APP. We deploy an arbitrage-free term structure model along the lines of Li and Wei (2013). In addition to the level and slope factors, aggregate duration impacts the market price of level and slope risk and hence the term premium

[23]See Kim and Orphanides (2012) and Bauer, Rudebusch, and Wu (2012).

[24]We deploy an analytical bias approximation, a bootstrap-based bias correction and an indirect inference estimator for bias correction, all based on the code for Bauer et al. (2012) provided on Cynthia Wu's website.

across maturities. This link between bond supply and yields is consistent with the micro-founded equilibrium model of Vayanos and Vila (2009).

We find that, first, the contemporaneous impact of the APP flattens the yield curve and amounts to around 95 bps for the 10y maturity. This impact is comparable to point estimates found for the Federal Reserve's large-scale asset purchase programmes. Second, the effect is persistent and expected to only slowly fade over time, with a half-life of around five years. Third, the expected length of the reinvestment period after net purchases has a significant impact on term premia. For example, as of June 2018, relative to a counterfactual of no reinvestment, an expected reinvestment horizon of 3 years compressed term premia by an additional 18 bps. Finally, recalibrations of APP purchase parameters imply surprises due to the central bank's expected path of duration extraction. Overall, our model accounts well – in real time – for the duration-implied yield curve impact of such recalibrations on the term structure of interest rates, while at the same time other factors – going beyond the duration channel – can move the yield curve around such announcements but are outside the scope of our model.

Our contribution to the literature is three-fold. First and foremost, our paper is the first to provide a comprehensive assessment of the contemporaneous and dynamic effects of the ECB's APP across the term structure and their evolution over time. By contrast, other available studies have largely focused on the impact of the initial announcement impact of the APP on asset prices. Second, based on security-level information of asset holdings, aggregate issuance data and ECB portfolio holdings, we construct a novel granular measure of the "free-float of duration risk", i.e. the duration-weighted share of public-sector debt in the hands of price-sensitive investors. Our measure is fully consistent with the theory set out in Vayanos and Vila (2009). Moreover, we construct projections of that free-float measure, which is a crucial input for the model-based translation of changes in APP purchase parameters into changes in the term premium. To this end, we not only rely on the purchase parameters announced by the ECB, but also account for market expectations by exploiting survey expectations on the path of ECB asset purchases and projecting the market-expected trajectory of reductions in the free-float due to the APP. Third, on the methodological side, we meet the constraints imposed by the relatively short time series of euro area data by deploying a new two-step estimation approach that relies on both fitting the time series of bond yields as well as on utilising event-based information in the run-up to the ECB's APP. Given this non-standard approach, we also provide a fully-fledged bootstrap procedure to gauge the impact of parameter uncertainty on our estimates.

While our approach utilises a reduced-form term structure model incorporating the no-arbitrage condition and a stylised version of the duration extraction channel formulated in Vayanos and Vila (2009), our analysis can inform a more structural modelling of the duration channel of central bank asset purchases. In particular, it could help support the specification and quantification of micro-founded equilibrium models.[25] On the empirical side, our approach could be taken further by also studying the impact of the APP across other asset classes, in particular corporate bonds, or by taking a more disaggregated view on the impact across individual euro area countries.

[25] For example, King (2018) examines features that are necessary – in particular with regard to the properties of the implied stochastic discount factor – for general equilibrium models to exhibit a duration channel of the kind we analyse in this paper.

Annex: Comparing the empirical model to Vayanos and Vila (2009) and Greenwood and Vayanos (2014)

The reduced-form model used in this paper can be viewed as an empirical multi-factor counterpart of the equilibrium model introduced by Vayanos and Vila (2009) and Greenwood and Vayanos (2014). They model explicitly a representative agent's ('arbitrageur') portfolio choice and require time-varying bond supply across the maturity spectrum to be absorbed by the investor. As in the model described here, expected excess returns arise from the product of an individual bond's factor sensitivities multiplied with respective market prices of risk. In Vayanos and Vila (2009), there are two sources of uncertainty: innovations to the supply factor β_t and innovations to the short-term interest rate i_t.[26] Both innovations are being priced, but the market prices of risk vary only with variation in supply and not with the short-term rate itself. In the specification used here, level and slope risk are being priced, while unexpected changes in supply are not being priced; however, the prices of level and slope risk are driven by the supply variable, and they also depend on variations in level and slope. In order to have a meaningful comparison between our model vs Vayanos and Vila (2009) and Greenwood and Vayanos (2014), we will inspect how the supply factor impacts on short-rate risk compensation in the structural model and how it influences level/slope risk compensation in our model.

In Greenwood and Vayanos (2014) the market price of short-rate risk is given by

$$\lambda_{i,t} = a\sigma_i^2 \int_0^T x_t^{(\tau)} C_i(\tau) d\tau, \tag{27}$$

where a is the risk aversion parameter, σ_i^2 is the innovation volatility to the short rate process, $x_t^{(\tau)}$is outstanding bond supply with maturity τ to be absorbed by the arbitrageur, and $C_i(\tau)$ is the loading of the log bond price on the short-rate factor.

In the empirical model used here, the market price of level/slope risk is shown in (20). The time-varying contribution of the supply factor is $\Lambda_{1,ZQ}Q_t$. This is of the same form as in (27), i.e. it is a product of a constant coefficient ($a\sigma_i^2$ vs $\Lambda_{1,ZQ}$) and a quantity variable ($\int_0^T x_t^{(\tau)} C_i(\tau) d\tau$ vs Q_t).

Regarding the time-constant multiplier, our reduced-form parameter $\Lambda_{1,ZQ}$ may hence be interpreted as reflecting risk aversion. At the same time, though, it has to be noted that such a

[26] We somewhat amend the notation used in Vayanos and Vila (2009) and Greenwood and Vayanos (2014) in order to align it with our notation.

mapping from a structural to a reduced-form model (with more factors) is necessarily incomplete.

Regarding the supply variable, the expression $\int_0^T x_t^{(\tau)} C_i(\tau) d\tau$ in Greenwood and Vayanos (2014) can be interpreted as aggregate duration risk in the market. $C_i(\tau)$ is the individual bond's (with maturity τ) exposure to short-rate risk. This is weighted by the outstanding bond supply $x_t^{(\tau)}$ for that maturity and summed up (integrated) across maturities. Greenwood and Vayanos (2014) compare that measure to 'simple dollar duration' defined as $\int_0^T x_t^{(\tau)} \tau d\tau$, i.e. the weighting is not the bond-specific sensitivity but simply the maturity of the respective bond. Note that the latter expression is analogous to that appearing in the enumerator of our free-float measure Q in (1), i.e. multiplying maturities with corresponding supply volumes prevailing in those maturity For Greenwood and Vayanos (2014), this measure of simple dollar duration turns out to be closely correlated to their model-implied (using their parameter calibration) counterparts of short-rate and supply-duration risk.

Summing up, the overall economic mechanism through which a change in bond supply affects the term premium is the same in both the equilibrium models of Vayanos and Vila (2009) and Greenwood and Vayanos (2014), and the non-structural empirical model used here: an increase in future expected central bank purchases would reduce (current and) expected aggegate duration risk to be absorbed by the market. This reduces the market price of risk, which leads to lower expected excess returns in the future and hence to a contemporaneous compression of term premia and bond yields across maturities.

References

Adrian, T., R. Crump, and E. Mönch (2013). Pricing the term structure with linear regressions. *Journal of Financial Economics 110*(1), 110–138.

Altavilla, C., G. Carboni, and R. Motto (2015). Asset purchase programmes and financial markets: lessons from the euro area. *ECB Working Paper 1864*.

Andrade, P., J. Breckenfelder, F. De Fiore, P. Karadi, and O. Tristani (2016). The ECB's asset purchase programme: an early assessment. *ECB Working Paper 1956*.

Arrata, W. and B. Nguyen (2017). Price impact of bond supply shocks: evidence from the Eurosystem's asset purchase program. *Banque de France Working Paper 623*.

Bauer, M. D., G. D. Rudebusch, and J. C. Wu (2012). Correcting estimation bias in dynamic term structure models. *Journal of Business and Economic Statistics 30*(3), 454–467.

Bergant, K., M. Fidora, and M. Schmitz (2018). International capital flows at the security level - evidence from the ECB's asset purchase programme. *ECMI Working Paper 7*.

Blattner, T. and M. Joyce (2016). Net debt supply shocks in the euro area and the implications for QE. *ECB Working Paper 1957*.

Bouabdallah, O., C. Checherita-Westphal, T. Warmedinger, R. de Stefani, F. Drudi, R. Setzer, and A. Westphal (2017). Debt sustainability analysis for euro area sovereigns: a methodological framework. *ECB Occasional Paper 185*.

Christensen, J. H. and S. Krogstrup (2018). Transmission of Quantitative Easing: the role of central bank reserves. *The Economic Journal forthcoming*.

D'Amico, S. and T. B. King (2013). Flow and stock effects of large-scale Treasury purchases: evidence on the importance of local supply. *Journal of Financial Economics 108*(2), 425–448.

De Pooter, M., R. F. Martin, and S. Pruitt (2018). The liquidity effects of official bond market intervention. *Journal of Financial and Quantitative Analysis 53*(1), 243–268.

De Santis, R. (2016). Impact of the asset purchase programme on euro area government bond yields using market news. *ECB Working Paper 1939*.

De Santis, R. A. and F. Holm-Hadulla (2019). Flow effects of central bank asset purchases on euro area sovereign bond yields: evidence from a natural experiment. *Journal of Money, Credit and Banking forthcoming.*

Eser, F. and B. Schwaab (2016). Evaluating the impact of unconventional monetary policy measures: empirical evidence from the ECB's Securities Markets Programme. *Journal of Financial Economics 119*(1), 147–167.

Geiger, F. and F. Schupp (2018). With a little help from my friends: survey-based derivation of euro area short rate expectations at the effective lower bound. *Deutsche Bundesbank Discussion Paper 27.*

Ghysels, E., J. Idier, S. Manganelli, and O. Vergote (2016). A high-frequency assessment of the ECB Securities Markets Programme. *Journal of the European Economic Association 15*(1), 218–243.

Greenwood, R. and D. Vayanos (2014). Bond supply and excess bond returns. *Review of Financial Studies 27*(3), 663–713.

Hamilton, J. D. and J. C. Wu (2012). Effectiveness of alternative monetary policy tools in a zero lower bound environment. *Journal of Money, Credit and Banking 44*(s1), 3–46.

Hartmann, P. and F. Smets (2018). The first twenty years of the European Central Bank: monetary policy. *ECB Working Paper 2219.*

Ihrig, J., E. Klee, C. Li, M. Wei, and J. Kachovec (2018). Expectations about the Federal Reserve's balance sheet and the term structure of interest rates. *International Journal of Central Banking 14*(2), 341–390.

Joslin, S., K. J. Singleton, and H. Zhu (2011). A new perspective on Gaussian dynamic term structure models. *Review of Financial Studies 24*(3), 926–970.

Joyce, M. and M. Tong (2012). QE and the gilt market: a disaggregated analysis. *The Economic Journal 122*(564), F348–F384.

Kandrac, J. and B. Schlusche (2013). Flow effects of large-scale asset purchases. *Economics Letters 121*(2), 330–335.

Kim, D. and J. Wright (2005). An arbitrage-free three-factor term structure model and the recent behavior of long-term yields and distant-horizon forward rates. *Federal Reserve Board Discussion Paper 33*.

Kim, D. H. and A. Orphanides (2012). Term structure estimation with survey data on interest rate forecasts. *Journal of Financial and Quantitative Analysis 47*(1), 241–272.

King, T. B. (2018). Duration effects in macro-finance models of the term structure. *mimeo*.

Koijen, R. S. J., F. Koulischer, B. Nguyen, and M. Yogo (2017). Euro-area quantitative easing and portfolio rebalancing. *American Economic Review 107*(5), 621–627.

Koijen, R. S. J., F. Koulischer, B. Nguyen, and M. Yogo (2018). Inspecting the mechanism of quantitative easing in the euro area. *Banque de France Working Paper 601*.

Lemke, W. and T. Werner (2017). Dissecting long-term Bund yields in the run-up to the ECB's public sector purchase programme. *ECB Working Paper 2106*.

Li, C. and M. Wei (2013). Term structure modeling with supply factors and the Federal Reserve's large-scale asset purchase programs. *International Journal of Central Banking 9*(1), 3–39.

Schlepper, K., H. Hofer, R. Riordan, and A. Schrimpf (2017). Scarcity effects of QE: a transaction-level analysis in the Bund market. *BIS Working Paper 625*.

Vayanos, D. and J. Vila (2009). A preferred-habitat model of the term structure of interest rates. *NBER Working Paper 15487*.

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