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* Views expressed are those of the authors and do not necessarily reflect official positions of De Nederlandsche Bank.

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Spillover effects of sovereign bond purchases in the euro area[1]

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Abstract

This paper investigates cross-border spillover effects from the Eurosystem's Public Sector Purchase Programme (PSPP) on euro area government bond yields. We distinguish between the direct effects of domestic bond purchases by national central banks and the indirect effects from bond purchases by national central banks in other euro area countries over the period March 2015 - December 2018. The results reveal substantial spillover effects across the euro area, providing evidence for strong arbitrage within the euro area. These spillover effects are particularly large for long-term bonds and for bonds issued by non-core countries. The larger impact of spillovers in these cases can be explained by investors rebalancing towards higher yielding government bonds. In addition, purchases under PSPP had their largest impact on bond yields in 2015.

Keywords: Public Sector Purchase Programme; euro area; spillovers; government bonds

JEL Codes: E52; E58; G12

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1. Introduction

Over the past decade, major central banks have conducted large-scale asset purchase programs.[3] One of these programs is the Eurosystem's Public Sector Purchase Programme (PSPP), which was launched in 2015 to ease financing conditions across the euro area by lowering government bond yields.[4] This paper investigates the impact of PSPP purchases on individual bond yields for the ten largest euro area countries. In addition, we distinguish between the effect of purchases of a specific bond by a country's national central bank and spillover effects from bond purchases by other national central banks in the Eurosystem. We further disentangle these purchases by a breakdown into different maturity segments and different country groups. This empirical approach accounts for the unique characteristics of the euro area bond markets and examines market arbitrage within the euro area. It provides fundamental knowledge on the transmission mechanism of large-scale asset purchases and offers information for calibration of future purchase programs.

The literature on the effectiveness of the PSPP in the euro area has expanded in recent years. Several studies focus on announcement effects, which capture the pricing-in of future central bank purchases, while others investigate the effects of actual purchases. Most studies find that bond purchases significantly reduced yields in the euro area (see Section 2). Our paper builds on De Santis and Holm-Hadulla (2020), who analyze the effects of actual purchase operations on sovereign bond prices using daily PSPP purchase data from March 2015 up to June 2016. These authors find that purchases of a specific bond as well as purchases of domestic bonds with comparable characteristics (i.e. close substitutes) significantly increase bond prices. De Santis and Holm-Hadulla (2020) do not examine spillovers from purchases by central banks in other euro area countries, however.

We add to the existing literature in several ways. First, we investigate how the price effects of actual purchases are transmitted across heterogeneous euro area bond markets. The euro area sovereign bond markets comprise bonds issued by nineteen national governments. These government bonds are not perfect substitutes since national bond markets vary in

[3] See Dell'Ariccia et al. (2018) for an overview of unconventional monetary policies in the euro area, Japan and the United Kingdom, and Kuttner (2018) for the United States.

[4] Note that the PSPP is different from the ECB's Pandemic Emergency Purchase Programme (PEPP) launched in March 2020. While the goal of the ongoing purchases under the PSPP remains to ease general monetary conditions in the euro area, the PEPP has been introduced as a temporary asset purchase program for private and public sector securities, with a purpose to "address illiquidity and heightened volatility in core segments of euro area financial markets that threatened to impair the smooth transmission of monetary policy" (Schnabel, 2020) and to counter serious risks to the economic outlook for the euro area posed by the COVID-19 crisis. Evaluating the effects of the PEPP is a promising avenue for future research.

creditworthiness, liquidity and size, as well as attract different types of investors. In addition, governments have different issuance needs and preferences, while macroeconomic conditions differ considerably between countries. As a result, sovereign bond yields contain credit and liquidity spreads which the European sovereign debt crisis clearly revealed (see e.g., Bekkour et al., 2015).

Second, we examine the effects of bond purchases using different categories of purchase volumes. We do so by regressing the yield of a specific bond on the relative volume purchased of i) the bond itself, ii) other bonds issued by the same government (close and distant substitutes), and iii) bond purchases by other euro area countries (foreign spillovers). Purchase volumes and bond yields are taken on a monthly frequency. Spillovers from other countries are distinguished based on an individual country's credit rating, risk group, and a bond's maturity segment. As an extension, we investigate whether the effects of purchases differ across country groups, maturity segments, and time periods.

Third, our study contributes in terms of the scope. In contrast to country-specific studies, e.g. on Germany (Schlepper et al., 2020) or France (Arrata and Nguyen, 2017), our analysis comprises bond purchases in 10 euro area countries. Moreover, we cover the entire first phase of net purchases from 2015 until the end of 2018, while the above mentioned studies are limited to a narrower time interval.

Our findings show that both domestic and foreign PSPP purchases significantly reduce bond yields in the euro area. In terms of magnitude, however, the average monthly effect of foreign spillovers on bond yields is much larger than the effect of domestic purchases. This suggests that spillovers from other countries in the euro area – i.e. the general purchase pace of the ECB - are a dominant component of the PSPP's effectiveness. It also provides evidence for the importance of arbitrage within the euro area government bond markets. The impact of spillovers is found to be particularly large for both long-term government bonds and for bonds issued by non-core countries (Ireland, Italy, Portugal, and Spain). The larger impact of spillovers in these cases can be explained by investors rebalancing towards higher yielding government bonds. Finally, PSPP purchases had their largest impact on bond yields in 2015.

The rest of the paper is structured as follows. Section 2 reviews the related theoretical literature and previous empirical evidence. Section 3 provides details on the structure and implementation of the PSPP. Sections 4 and 5 describe the data construction and methodology,

respectively. Section 6 presents the main empirical results and extensions. Section 7 concludes with a summary and policy implications.

2. Literature review

2.1. Channels and spillovers from asset purchases to bond yields

The literature describes several channels through which central bank asset purchases may reduce bond yields. The two prominent channels are the *signaling channel* and the *portfolio rebalancing channel*.[5]

Through the *signaling channel*, central bank communication on asset purchases shapes investors' expectations about future monetary policy and short-term interest rates, which are transmitted to long-term interest rates and asset prices (Joyce et al., 2011; Bauer and Rudebusch, 2014; Bhattarai et al., 2015). While the *signaling* channel emphasizes the importance of communication and market expectations, tracing primarily the impact of central bank announcements, actual transactions conducted under asset purchase programs can influence bond yields through the *portfolio rebalancing* channel.

The *portfolio rebalancing* channel implies that a purchase-induced price change in one asset spills over to prices of other assets that investors perceive as close substitutes (Vayanos and Vila, 2009; Greenwood and Vayanos, 2014). Thus, by purchasing government bonds, the central bank changes supply and demand conditions in various market segments beyond the targeted instrument of a specific asset purchase program.

The *portfolio rebalancing* channel can have direct as well as indirect effects. Through direct effects, price movements are caused by the flow of bonds from investors to the central bank. Through indirect effects, transactions in the bond market influence a broader spectrum of asset prices by changing relative yields. These indirect effects can be triggered by other domestic purchases (i.e. domestic purchases of bonds other than the specific bond that is bought under the PSPP) as well as by spillovers from purchases of bonds issued by other countries.

Ferdinandusse et al. (2017) show with a search theoretical model that the strength of the portfolio rebalancing channel depends on the share of bonds held by preferred habitat investors. These investors have a preference for holding assets of a specific market segment and are only

[5] Quantitative easing may also affect asset prices through other channels, involving liquidity and credit risk (see e.g., Krishnamurthy and Vissing-Jorgensen, 2011; Christensen and Gillian, 2015).

willing to move out of that segment when they receive a risk premium. In a similar vein, Vayanos and Vila (2009) and Greenwood and Vayanos (2014) develop a term structure model in which investors have preferences for specific maturities, while risk-averse arbitrageurs integrate markets by trading across different maturities. However, when the group of preferred habitat investors is large, they create a shortage that drives up bond prices and thereby reduces bond yields in specific markets. Meanwhile, arbitrageurs spread the shortage - created by the central bank asset purchases in a particular bond - across maturities and bonds with similar characteristics.

Apart from domestic purchases, spillovers from purchases by central banks in other countries play a role. Two theoretical studies are relevant in this regard. The first one by Alpanda and Kabaca (2020) evaluates the international spillovers of large-scale asset purchases (LSAPs) using a two-country (the U.S. and the rest of the world) dynamic stochastic general equilibrium (DSGE) model. In their model, portfolio balance effects arise from imperfect substitutability between short- and long-term, as well as between domestic and foreign bonds in bond portfolios of each country. Alpanda and Kabaca (2020) show that LSAPs in the U.S. reduce domestic and foreign long-term bond yields and stimulate economic activity both in the U.S. and in the rest of the world. The key for this result is the decline in the term premia abroad through the portfolio rebalancing channel, as relative demand for the rest of the world's long-term bonds increases following LSAPs in the U.S.

In a similar framework, Kabaca et al. (2020) examine an optimal allocation of government bond purchases within a monetary union, using a two-region (core and periphery) DSGE model where regions are asymmetric with respect to their economic size and portfolio characteristics. The authors show that a union-wide quantitative easing (QE) affects government asset prices in three ways: first, it directly lowers the term premium component of domestic long-term yields; second, lower term premia spill over through portfolio rebalancing of cross-border assets within the union; third, lower outstanding government debt held by private agents lowers the risk premia on these assets. Kabaca et al. (2020) find that a union-wide QE lowers yields more in the periphery than in the core. This is explained by a lower elasticity of substitution between long- and short-term bonds and a higher home bias in bond holdings in the periphery compared to the core.

Based on the two studies discussed above, the impact of spillovers may depend on a number of factors, such as the size of asset purchases relative to the pool of substitutable assets,

the degree of substitutability of domestic bonds with foreign ones, the risk premium on domestic and foreign bonds, as well as the maturity of different assets.

2.2. Effects of central bank purchases on government bond yields – empirical evidence

Previous studies show that unconventional monetary policy measures through government bond purchases have a significant and lasting impact on bond yields and other asset prices.[6] The magnitude of the estimated effect varies across purchase programs, countries, applied methodologies, and sample periods.

Several studies find that announcements of Quantitative and Qualitative Monetary Easing measures by the Bank of Japan significantly lowered yields by 10-14 basis points on average for the 10-year Japanese government bond (see e.g., Lam, 2011; Hausman and Wieland, 2014; Arai, 2017). Similarly, De Rezende (2016) and De los Rios and Shamloo (2017) conclude that the effects of QE were relatively small in the case of the Sveriges Riksbank's program. They find that 10-year government bond yields in Sweden dropped on average by around 13-17 basis points after five Riksbank's announcements involving bond purchases in 2015, with an estimated cumulative total decline of around -46 basis points.

A more sizable impact is reported for the QE policy in the U.K., with the estimated effect on medium to long-term government bond yields ranging between -45 and -100 basis points (e.g., Joyce et al., 2011; Christensen and Rudebusch, 2012; Joyce and Tong, 2012; McLaren et al., 2014). Several studies for the U.S. report that the effect of the Fed's QE programs on 10-year Treasury bond yield ranges between -30 and -123 basis points (see e.g., Gagnon et al., 2011; Krishnamurthy and Vissing-Jorgenson, 2011; Chen et al., 2012; D'Amico et al., 2012; D'Amico and King, 2013; Kandrac and Schlusche, 2013; Bauer and Neely, 2014), although the results vary across the studies (Kuttner, 2018).

Previous studies for the euro area come to mixed conclusions about the QE impact (see Table A1 in the Appendix for an overview). They estimate the PSPP announcement effects on bond yields to range between -30 and -95 basis points for an average 10-year government bond (see e.g., Altavilla et al., 2015; Andrade et al. 2016; Eser et al., 2019; De Santis, 2020). Meanwhile, the actual PSPP purchases are reported to have led to a significant further reduction in bond yields, ranging between -13 and -57 basis points per 10% of outstanding amount

[6] The effects of LSAPs on other market segments, e.g. corporate bonds or bank loans, is beyond the scope of our paper. See e.g. Albertazzi et al. (2018) for transmission effects of the PSPP to other market segments.

purchased (Arrata and Nguyen, 2017; Koijen et al., 2020). Using daily data for bond prices and purchase volumes, De Santis and Holm-Hadulla (2020) and Schlepper et al. (2020) find that a daily 100 mln EUR purchase volume increases the average bond price by 4-9 basis points. The evidence is inconclusive on how asset purchases transmit to bond yields and which channels contribute the most to the monetary policy transmission.

The empirical literature on spillovers of central bank asset purchases is scant. To the best of our knowledge, two studies - Bauer and Neely (2014) and Neely (2015) - find evidence for such spillovers from the U.S. to other countries: the Fed's QE announcements significantly reduced international bond yields.

Our paper contributes to the debate by considering spillovers of the PSPP in the euro area. Specifically, we examine how PSPP influences bond yields and to what extent the rebalancing of investors' portfolios spreads the impact to other bond market segments. Such spillover effects may reflect, for instance, search for yield by investors (Becker and Ivashina, 2013), externally imposed risk limits or the need to match durations (Domanski et al., 2015, Koijen et al. 2017). To account for various factors driving spillover effects, we examine purchases on the basis of countries' credit ratings, risk group, and a bond's maturity segment.

3. The Eurosystem's public sector purchase programme (PSPP)

In the period between March 2015 and December 2018 the Eurosystem expanded its balance sheet by €2545 bln through several QE programs. These purchases comprised more than a quarter of the entire outstanding sovereign debt in the euro area and were in the same order of magnitude as the QE programs implemented by the U.S. Fed and the Bank of Japan.

The Eurosystem's QE program – the extended asset purchase program (APP) – includes several subprograms, of which the public sector purchase program (PSPP) is by far the largest (82% of total purchased volume). Under the PSPP, bonds issued by euro area central and local governments, agencies, and European institutions are bought in the secondary market. The largest share of purchases involves national government and agencies bonds, accounting for around 90% of total PSPP purchases, compared to 10% for bonds issued by European (supranational) institutions.

During our sample period (March 2015 - December 2018), the ECB communicated a fixed calendar date on which the APP would end, with the additional qualification that the program could run until the ECB's Governing Council sees a sustained adjustment in the path of

inflation consistent with its inflation aim of 'below, but close to 2%'. Over time, there have been several extensions of the program and adjustments of the purchase pace. In addition, the ECB lowered its main policy rate – the rate on the deposit facility – twice. Table 1 provides an overview of the most relevant ECB decisions with respect to the APP during the sample period.

Table 1. An overview of the ECB's decisions with respect to the APP during 2014-2018

Announcement date	Announced decision	Time horizon	Announced volume
2 October 2014	Buy simple and transparent asset-backed securities (ABSs) and euro-denominated covered bonds	At least 2 years	N/A
22 January 2015	Start of PSPP with total monthly purchase of €60 bln	Until September 2016 + SAPI	€1080 bln
9 November 2015	Increase the issue share limit to 33%	Until September 2016 + SAPI	N/A
3 December 2015	Extension of APP Reinvestment of maturing bonds	Until March 2017 + SAPI	€1440 bln
10 March 2016	Increase total monthly purchases within PSPP to €80 bln Start of CSPP and TLTRO-II from April 2016 Increase the issue share limit of supranationals to 50%	Until March 2017 + SAPI	€1720 bln
8 December 2016	Reduction in PSPP monthly pace to €60 bln Broadening the criteria for eligible bonds (removal of DFR restriction and inclusion of 1-2 year bonds)	Until December 2017 + SAPI	€2260 bln
26 October 2017	Reduction in PSPP monthly pace to €30 bln	Until September 2018 + SAPI	€2530 bln
13 September 2018	Reduction in PSPP monthly pace to €15 bln and announced end of PSPP by December 2018	End of December 2018	€2575 bln
13 December 2018	End of net purchases within PSPP	End of December 2018	€2575 bln
Interest rate decisions			
3 December 2015	Reduce the deposit facility rate (DFR) to -0.3%		
10 March 2016	Reduce the deposit facility rate (DFR) to -0.4%	Forward Guidance on DFR and APP	

Note: SAPI - sustained adjustment in the path of inflation consistent with the ECB's inflation aim.

The Eurosystem's purchases are conducted by national central banks (90%) and the ECB (10% of purchases). The ECB communicates ex ante an aggregate volume target (for the APP) and publishes each month purchase volumes disaggregated by jurisdiction and by subprogram, to inform market participants about the distribution of conducted purchases. The allocation of purchases over different jurisdictions is conducted - to the extent possible - according to national central banks' capital key. The capital key is each national bank's stake in the ECB and reflects population and GDP size (equally weighed) of each country in the euro area. National central banks buy bonds issued by their domestic governments and supranational institutions, while the ECB conducts purchases in all markets. Purchases per country are in practice not perfectly aligned with the distribution by the capital key. Typically this occurs

when market liquidity does not allow for purchases or when there are insufficient bonds satisfying the eligibility criteria.[7]

Following the intention of market neutral implementation, national central banks take into account liquidity conditions of specific market segments. Purchases in our sample took place almost on the entire spectrum of outstanding government bonds with remaining maturities ranging from two years (at a later stage one year) up to more than 30 years. Until 2016, purchases did not take place if bonds traded below the deposit facility rate (DFR). As a result, in several jurisdictions the minimum maturity of purchasable bonds in practice was much higher than two years. In December 2016 the ECB lifted the DFR-restriction and allowed bond purchases below the DFR to the extent necessary.

4. Data

4.1. Data description

Our sample period covers the first phase of net purchases conducted under the PSPP and runs from 9 March 2015 until 31 December 2018. We use monthly data on PSPP purchases of individual government bonds. We merge these with end-of-the-month data from Bloomberg on individual government bond yields across all euro area (EA) countries and data on individual bond characteristics from the Centralized Securities Database (CSDB). The latter include quarterly data on issuer country, issuer sector, outstanding amount, issuance date, maturity date, and coupon type. Additionally, we collect information from Standard & Poor's on credit ratings of EA countries.

We exclude purchases of government agencies and supranational institutions from our sample. Thus, we keep only bonds issued by the government (central and regional) in each country. In addition, we drop the data for 9 EA countries that had no or few purchases within the PSPP and/or whose markets are relatively illiquid (Cyprus, Estonia, Greece, Latvia, Lithuania, Luxembourg, Malta, Slovakia, and Slovenia). This results in a sample which comprises 10 EA countries (Austria, Belgium, Finland, France, Germany, Ireland, Italy, the Netherlands, Portugal, and Spain). These countries account for over 98% of the PSPP net sovereign debt purchases during the sample period.

[7] For example, Greek government bonds could not be bought because the credit rating of Greece was too low.

As additional data cleaning steps, we drop observations for bonds with a maturity of less than 90 days and apply winsorizing (95%) of bond yields to prevent outliers related to technical aspects (such as end-of-year effects, inflation-linked features and other non-plain vanilla bonds) from distorting the regressions.

4.2. Construction of purchases variables

In order to examine the effects of domestic and foreign purchases on bond yields, we use net monthly purchases, measured as the nominal amount (in mln EUR) of central bank purchases. We then scale these monthly purchases by the total nominal outstanding amount (in mln EUR) of all issued bonds by the EA countries in the sample. More formally:

$$total\ purch_{jt} = \frac{total\ purchases\ of\ ALL\ countries_t}{total\ outstanding\ amount\ for\ ALL\ countries_t} \times 100, \quad (1)$$

This variable is used to capture the '**total effect'** of all net purchases conducted in month *t* by all analyzed EA countries of all bonds, on a bond yield *b* issued in country *j*.

Next, we decompose total purchases into two terms – domestic and foreign – to separate the effect of '**domestic purchases'** (all purchases by country *j*'s domestic central bank of bonds issued by country *j*) from the effect of '**foreign spillovers'** (all purchases by the rest of the Eurosystem, i.e. without country *j*'s central bank) in month *t*:

$$total\ purch_{jt} = domestic\ purch_{jt} + foreign\ spillovers_{jt} =$$
$$\left(\frac{domestic\ purchase_{jt}}{total\ outst.\ amount\ for\ ALL\ countries_t} \times 100\right) + \left(\frac{foreign\ purchase_{jt}}{total\ outst.\ amount\ for\ ALL\ countries_t} \times 100\right), \quad (2)$$

We further disaggregate domestic purchases into **direct purchases** (all purchases by country *j*'s domestic central bank of a specific bond *b* issued by country *j*) and **other domestic purchases** (all purchases by country *j*'s domestic central bank of bonds other than bond *b* issued by the same country *j*), described in the following formula:

$$domestic\ purch_{jt} = direct\ purch_{bjt} + other\ domestic\ purch_{bjt} =$$
$$\left(\frac{direct\ purchase_{bjt}}{total\ outst.\ amount\ for\ ALL\ countries_t} \times 100\right) + \left(\frac{other\ domestic\ purchase_{bjt}}{total\ outst.\ amount\ for\ ALL\ countries_t} \times 100\right) \quad (3)$$

Other domestic purchases are further split into close and distant substitutes. For this purpose, we group bonds in each country into six mutually exclusive maturity segments based on the bond's remaining time to maturity in years, using the following intervals: 0-1 year, 1-2 years, 2-5 years, 5-10 years, 10-20 years, and over 20 years. The upper bounds of the intervals (except for the last one) are closed, so that the same bond cannot appear in two segments at the

same time. Domestic purchases by country *j* of **close substitutes** are defined as all purchases by country *j*'s central bank of all bonds, except bond *b*, located in the same maturity segment as bond *b*. Domestic purchases by country *j* of **distant substitutes** are defined as all purchases by country *j*'s central bank of all bonds located in different maturity segments than bond *b*:

$$other\ domestic\ purch_{bjt} = close\ substitutes_{bjt} + distant\ substitutes_{bjt} = \left(\frac{close\ substitutes\ purchases_{bjt}}{total\ outst.\ amount\ for\ ALL\ countries_t} \times 100\right) + \left(\frac{distant\ substitutes\ purchases_{bjt}}{total\ outst.\ amount\ for\ ALL\ countries_t} \times 100\right) \quad (4)$$

We decompose foreign spillovers into three dimensions: credit rating, risk group, and bond's maturity segment. First, foreign spillovers are split into same rating and different rating groups, using S&P ratings of individual EA countries during 2015-2018. We distinguish five credit rating categories, namely: 1) AAA (Germany, the Netherlands); 2) AA (Austria, Belgium, Finland, France); 3) A (Ireland); 4) BBB (Italy, Spain); and 5) BB (Portugal). **Same rating (SR) spillovers** include all purchases by other countries than country *j* which have the same credit rating as country *j*. **Different rating (DR) spillovers** include all purchases by other countries with a different credit rating than country *j:*

$$foreign\ spillovers_{jt} = SR\ spillovers_{jt} + DR\ spillovers_{jt} = \left(\frac{SR\ foreign\ purchases_{jt}}{total\ outst.\ amount\ for\ ALL\ countries_t} \times 100\right) + \left(\frac{DR\ foreign\ purchases_{jt}}{total\ outst.\ amount\ for\ ALL\ countries_t} \times 100\right) \quad (5)$$

The drawback of using spillovers based on countries' credit rating is that in a sample of just ten EA countries, some countries (namely, Ireland and Portugal) do not have any same rating 'partners'. An alternative approach is to distinguish lower/higher credit risk groups and assign each country to one of them. This basically implies collapsing credit rating categories, distinguished in previous decomposition, into bigger country groups. The lower credit risk group comprises rating categories 1-2 with six countries (Austria, Belgium, Finland, France, Germany, and the Netherlands); the higher credit risk group includes rating categories 3-5 and consists of the four remaining countries (Ireland, Italy, Portugal, and Spain). We use this distinction to construct **same group (SG) spillovers** (all purchases by other countries within the same risk group as country *j*) and **different group (DG) spillovers** (all purchases by other countries in the different risk group than country *j*), which sum up to total spillovers as follows:

$$foreign\ spillovers_{jt} = SG\ spillovers_{jt} + DG\ spillovers_{jt} = \left(\frac{SG\ foreign\ purchases_{jt}}{total\ outst.\ amount\ for\ ALL\ countries_t} \times 100\right) + \left(\frac{DG\ foreign\ purchase\ _{jt}}{total\ outst.\ amount\ for\ ALL\ countries_t} \times 100\right) \quad (6)$$

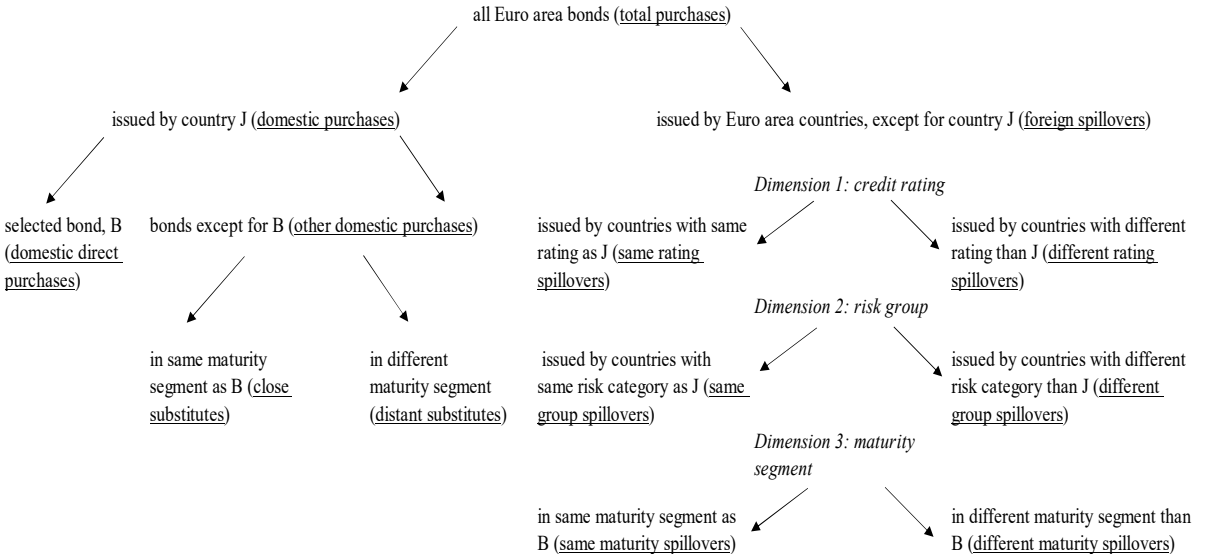
Finally, we use the grouping of bonds by maturity segments, as described above, and decompose foreign spillovers into **same maturity (SM) spillovers** (all purchases of bonds

issued by other countries and located in same maturity segment as bond *b* issued by country *j*), and **different maturity (DM) spillovers** (all purchases of bonds issued by other countries and located in different maturity segments than bond *b* issued by country *j*), shown in formula (7):

$$foreign\ spillovers_{jt} = SM\ spillovers_{bjt} + DM\ spillovers_{bjt} = \left(\frac{SM\ foreign\ purchase_{bjt}}{total\ outst.\ amount\ for\ ALL\ countries_t} \times 100\right) + \left(\frac{DM\ foreign\ purchase_{bjt}}{total\ outst.\ amount\ for\ ALL\ countries_t} \times 100\right) \quad (7)$$

Note that all purchases variables are normalized by the total outstanding amount of all issued bonds across all analyzed countries. This allows controlling for a general scale effect of purchases under the PSPP on bond yields.

Figure 1. The purchase volumes which are used as explanatory variables to estimate the effect on the yield of bond *b*, are decomposed in the following breakdowns



As a robustness check, we use duration risk-weighted net purchases instead of unweighted purchases, in order to test if purchases of government bonds with a higher duration risk have a stronger effect on yields than purchases of bonds with a lower duration risk. We construct risk-weighted variables by multiplying net purchases with the remaining time to maturity in years (divided by 10 for comparability) and subsequently construct all the purchases variables using formulas (1)-(7). Our findings show that using the duration risk-weighted purchases does not affect the main conclusions (results available upon request).

4.3. Descriptive statistics

Table 2 presents descriptive statistics for bond yields and monthly net purchases for the full sample. Total monthly purchases were on average 0.44% of the total amount outstanding

of government bonds issued by the 10 EA countries. For the average bond, domestic monthly purchases amounted to 0.06% of the total outstanding amount, while monthly foreign purchases were equal to 0.38% of the total outstanding amount[8].

Domestically, monthly *direct* purchases of a specific bond by individual EA central banks constituted on average 0.0005% of the total outstanding amount. Monthly purchase volumes of distant substitutes were the largest within the domestic purchases (0.049% compared to 0.009% for close substitutes), as they were conducted across several maturity segments. Regarding foreign purchases, on average the largest in terms of the relative volume were monthly purchases by countries with a different credit rating than country *j* and monthly purchases by other countries of bonds within different maturity segments than bond *b* purchased by country *j*'s national central bank.

The univariate unit-root Fisher-type tests for unbalanced panel data show that all analyzed variables – bond yields and monthly net purchases - are stationary (results available on request).

Table 2. Descriptive statistics for 10 EA countries over March 2015 – December 2018

Variable	Mean	St. dev.	25th percentile	75th percentile
Bond yield (in %)	0.722	1.124	-0.172	1.442
Total purchases	0.437	0.343	0.258	0.603
Domestic purchases	0.058	0.070	0.014	0.106
Domestic direct purchases	0.0005	0.002	0.000	0.0002
Other domestic purchases	0.058	0.070	0.013	0.105
Domestic close substitutes	0.009	0.061	0.000	0.022
Domestic distant substitutes	0.049	0.082	0.010	0.086
Foreign spillovers	0.378	0.300	0.223	0.537
Same rating spillovers	0.051	0.437	0.012	0.132
Different rating spillovers	0.327	0.470	0.188	0.433
Same risk group spillovers	0.165	0.154	0.088	0.253
Different risk group spillovers	0.213	0.175	0.110	0.312
Same maturity spillovers	0.061	0.301	0.017	0.137
Different maturity spillovers	0.318	0.371	0.178	0.449

Note: All purchases are measured in percent of the total amount outstanding of all bonds issued by all EA countries in the sample. N=40,672.

5. Methodology

We use our panel dataset for 10 euro area countries with information on individual bonds issued by these countries at the monthly frequency over the period from March 2015 until

[8] Purchases conducted abroad range between 0.34% and 0.43% of the total amount outstanding, from a perspective of an individual country in our sample.

December 2018. We then regress the yield of an individual bond b on monthly net relative purchases. Our methodological approach is similar to De Santis and Holm-Hadulla (2020) in terms of using panel regression techniques to analyze the effects of purchase volumes. The baseline model specification is as follows:

$$y_{bjt} = \alpha * y_{bjt-1} + \beta * purchases_{bjt} + \gamma_t + \mu_b + \varepsilon_{bjt}, \quad (8)$$

where y_{bjt} denotes the yield of a specific bond b in month t. The lagged dependent variable controls for the dependence of a bond yield on its past value.[9] $purchases_{bjt}$ is a vector of explanatory variables measuring monthly net purchases in percent of total outstanding amount issued by all analysed countries, constructed using formulas (1)-(7). We start from the aggregate and move to disaggregated variables in subsequent regressions. That is, we run regressions while including purchase variables in the various decompositions (see Figure 1 for possible components). In each specification all included purchase variables sum up to total purchases by construction. β is a vector of coefficients on purchase variables.

γ_t denotes time-fixed effects, capturing monthly time-specific common factors such as central bank announcements, market expectations, global and regional (European) financial conditions, and geopolitical events, among others. μ_b are unobserved time-invariant bond-specific fixed effects. ε_{bjt} is an idiosyncratic error term with mean 0 and variance $\sigma^2_{\varepsilon,bjt}$.[10] Standard errors are clustered at the bond level to account for heteroscedasticity and autocorrelation in the error term.[11]

Empirical studies on the effects of central bank asset purchase programs face a potential identification problem: the OLS method may produce inconsistent estimates if the allocation of overall purchase volumes to individual bonds by a purchasing central bank depends on the observed yields in the market on a given purchase day (De Santis and Holm-Hadulla, 2020). In this case, bond yields and purchases would be jointly determined, resulting in a simultaneity bias in the estimated relation between them. Several papers for the euro area attempt to solve

[9] Including a lagged dependent variable as a regressor may be a source of endogeneity. However, in our sample this is less likely to be a concern as we have a relatively large T=46, which reduces the Nickell bias. In addition, for a large T, the dynamic panel GMM-estimator converges to the fixed-effects panel regression estimator. As a robustness check, we applied the one-step system-GMM estimator where the lagged bond yield was instrumented with its further lagged levels in a first difference equation and with its lagged first differences in a level equation (we use the `collapse` option within the STATA command `xtabond2` to reduce the number of instruments). The results of this estimation are qualitatively similar to the ones we obtain using an OLS fixed-effects estimator (results are available upon request).

[10] The cross-sectional dimensions *b* (bond) and *j* (country) in our panel dataset are nested, i.e. multiple bonds are issued by one country. Therefore, bond-specific effects automatically control for country-specific effects.

[11] The post-estimation tests show that there is no remaining (second-order) serial correlation in the residuals.

this problem by using an instrumental variable approach (e.g.Arrata and Nguyen, 2017; Koijen et al., 2020). For instance, De Santis and Holm-Hadulla (2020) exploit a natural experiment using 'blackout periods' in the PSPP to identify exogenous variation in daily purchase volumes.

Compared to these studies, we opt for a different solution. We use monthly (instead of daily or intraday) purchases and monthly bond yields (based on their end-of-the-month level). This setting reduces a potential simultaneity bias since price differences are less likely to persist on a monthly basis; if they did, dealers would only be able to buy these bonds to a certain extent as they would need to fulfill a relatively large volume objective.

6. Estimation results

6.1. Main analysis

Table 3 presents our main estimation results for the full sample. The findings point to a statistically significant negative effect of all types of purchases on bond yields, in line with the related studies. That is, monthly net purchases under the PSPP are associated with a decline in government bond yields.

To interpret the economic size of the coefficient correctly, it is important to remember that all purchases variables are scaled by the total amount of outstanding bonds issued by all EA countries in our sample. When pooling all purchases together, Column (1) shows that, ceteris paribus, buying 1% of the total outstanding amount of all issued bonds results in a bond yield decrease of 35 basis points.[12] Based on our data and the estimated coefficient, the average monthly total purchases under the PSPP of about 0.44% of the total outstanding amount reduced an average bond yield by 15.43 basis points, ceteris paribus. The coefficient estimate of 0.85 on the lagged dependent variable implies a half-life of about 4 months. This means that the effect of the central bank bond purchases on the bond yield slowly dies out and is only half its original size after 4 months.[13]

Column (2) illustrates the regression results when total purchases are split into domestic and foreign purchases. The estimated coefficients are equal to -0.31 for domestic and -0.36 for

[12] Note that it is not possible to evaluate the cumulative effect of purchases over the entire sample period using our empirical setting. That is, the average monthly effects cannot be simply summed up over 46 months to produce the total effect of the PSPP on bond yields. In order to estimate a cumulative effect of the PSPP one would need a different model with cross-sectional data on total purchased stocks as of the end of 2018 and a bond yield change between the start and the end of the first phase of the PSPP implementation. Such analysis is beyond the scope of our paper as we investigate the market arbitrage due to the PSPP and not the total effectiveness of the PSPP.

[13] Half-life is the time that the yield needs to return to half of its pre-shock level, it is calculated as $\log(0.5)/\log(\alpha)$.

foreign purchases and are both significant at the 1% level. This implies that the average bond yield is significantly affected by both domestic and foreign purchases, which provides evidence for rebalancing within the EA government bond markets. In terms of the average effect calculated based on our data and coefficient estimates, the average monthly foreign purchases under the PSPP of 0.38% of total outstanding amount have a larger effect on a bond yield change (-13.49 basis points) than the average monthly domestic purchases of 0.06% of total outstanding amount (-1.80 basis points).

Table 3. Main estimation results – effects of PSPP on bond yields in EA countries

	(1)	(2)	(3)	(4)	(5)	(6)	(7)
Bond yield$_{bjt-1}$	0.850***	0.851***	0.851***	0.851***	0.850***	0.851***	0.851***
	(0.008)	(0.008)	(0.008)	(0.008)	(0.008)	(0.008)	(0.008)
Total purchases	-0.353***						
	(0.025)						
Domestic purchases		-0.310***					
		(0.027)					
Domestic direct purchases			-2.545***	-2.487***	-2.549***	-2.555***	-2.538***
			(0.520)	(0.523)	(0.524)	(0.521)	(0.521)
Other domestic purchases			-0.298***		-0.282***	-0.302***	-0.298***
			(0.027)		(0.027)	(0.026)	(0.027)
Close substitutes				-0.317***			
				(0.031)			
Distant substitutes				-0.294***			
				(0.027)			
Foreign spillovers		-0.357***	-0.357***	-0.356***			
		(0.025)	(0.025)	(0.025)			
Same rating spillovers					-0.339***		
					(0.025)		
Different rating spillovers					-0.361***		
					(0.025)		
Same group spillovers						-0.362***	
						(0.023)	
Different group spillovers						-0.349***	
						(0.031)	
Same maturity spillovers							-0.357***
							(0.025)
Different maturity spillovers							-0.356***
							(0.025)
Constant	0.117***	0.116***	0.116***	0.116***	0.117***	0.116***	0.116***
	(0.008)	(0.008)	(0.008)	(0.008)	(0.008)	(0.008)	(0.008)
Bond-specific fixed effects	yes	yes	yes	yes	yes	yes	yes
Time fixed effects	yes	yes	yes	yes	yes	yes	yes
R-squared	0.817	0.817	0.817	0.817	0.818	0.817	0.817
N of observations	40,672	40,672	40,672	40,672	40,672	40,672	40,672
N of bonds	1,290	1,290	1,290	1,290	1,290	1,290	1,290
N of time series observations per bond (average)	31.5	31.5	31.5	31.5	31.5	31.5	31.5

Notes: The table reports the estimation results from a fixed effects panel regression where a bond yield is a dependent variable. Standard errors in parentheses are clustered on the bond-level. ***, **, * indicate statistical significance at 1%, 5%, and 10% levels, respectively.

Column (3) focuses on domestic bond purchases and distinguishes between direct purchases of a bond *b* and other purchases in domestic bonds. While the magnitude of the estimated effect is the largest for direct purchases - the estimated coefficient of other domestic purchases is about a factor 10 smaller – the average value of the purchase variables should be taken into account. The average monthly direct purchases of an individual bond *b* in our dataset amounts to 0.0005% of total outstanding amount issued by all countries and is relatively small in comparison to the average value of 0.06% for other domestic purchases. Using the estimated coefficients, the average monthly effect on a bond yield is therefore estimated to be -0.13 basis points for domestic direct purchases and -1.73 basis points for other domestic purchases (see Table 4). Note that the coefficient estimate on foreign purchases remains very stable.

Next, we investigate whether the effects on a bond yield are different for close substitute domestic purchases, i.e. bonds with a similar maturity, compared to distant substitute domestic purchases, i.e. bonds with a very different maturity. Column (4) shows that close substitutes have a somewhat larger estimated coefficient in absolute value (-0.32) than distant substitutes (-0.29). However, both coefficients are smaller than for foreign or direct purchases of bond *b*.

We calculate the average effects on bond *b*'s yield during a typical month of the PSPP by taking the average monthly direct purchases of bond *b* (0.0005% of total outstanding amount), purchases of close substitutes of bond *b* (0.01%), distant substitutes of bond *b* (0.05%) and foreign purchases from bond *b*'s perspective (0.38%). Based on the estimated results shown in Table 3 (Column 4), we find that during a typical month domestic direct purchases reduced the bond *b*'s yield by 0.13 basis points, close substitute purchases by further 0.29 basis points, distant substitutes by 1.44 basis points and foreign purchases by 13.49 basis points. In total the effect of all purchases is roughly -15.4 basis points (see Table 4).

Several observations can be made based on these calculations. First, the size of the average monthly effect of direct purchases on the yield of a specific purchased bond is negligible. Second, purchases of distant substitutes have a larger average monthly effect on a bond yield compared to close substitutes. Third, the size of the coefficient for foreign spillovers is about 8 times smaller than for domestic direct purchases. However, in economic terms, purchases conducted by other central banks – foreign spillovers – seem to matter much more for an individual bond yield than domestic purchases. These findings suggest that the general purchase pace under the PSPP across all involved euro area countries is of greater relevance for the effect on a bond yield than the actual purchase in a single bond itself. Moreover, it points to the important role of arbitrage in the euro area government bond markets.

Distinguishing spillovers by different dimensions does not change our conclusions about their importance. We observe that foreign purchases by countries with a different credit rating or by countries from a different risk group reduce the yield of a domestic bond *b* stronger than same rating or same group spillovers, which is visible from the calculated average monthly effect (see Table 4). The estimated coefficients for foreign spillovers by maturity segment are similar in absolute value. However, in terms of economic size the average monthly foreign purchases in a different maturity segment reduce a bond yield much more (-11.32 basis points) than foreign purchases in the same maturity segment (-2.18 basis points). Table 4 summarizes all estimated results and calculated average monthly effects of purchases.

Table 4. Average monthly effects of purchases under the PSPP during 2015-2018

	Estimated coefficient (Table 3)	Average monthly purchases in % of total amount outstanding (Table 2)	Average monthly effect = coefficient * average monthly purchases, in basis points
Total purchases	-0.353	0.437	-15.43
Domestic purchases	-0.310	0.058	-1.80
Domestic direct purchases	-2.545	0.0005	-0.13
Other domestic purchases	-0.298	0.058	-1.73
Close substitutes	-0.317	0.009	-0.29
Distant substitutes	-0.294	0.049	-1.44
Foreign spillovers	-0.357	0.378	-13.49
Same rating spillovers	-0.339	0.051	-1.73
Different rating spillovers	-0.361	0.327	-11.80
Same group spillovers	-0.362	0.165	-5.97
Different group spillovers	-0.349	0.213	-7.43
Same maturity spillovers	-0.357	0.061	-2.18
Different maturity spillovers	-0.356	0.318	-11.32

6.2. Extensions: maturity segments

The effects of central bank asset purchases on bond yields may vary across maturity segments, for instance due to preferred habitat investors. In order to test this prior we split the sample into three groups of government bonds based on their remaining time to maturity at time *t.* We distinguish short-term (remaining maturity up to 5 years), medium-term (5-10 years), and long-term bonds (over 10 years) and re-estimate all model specifications for each of the three subsamples.

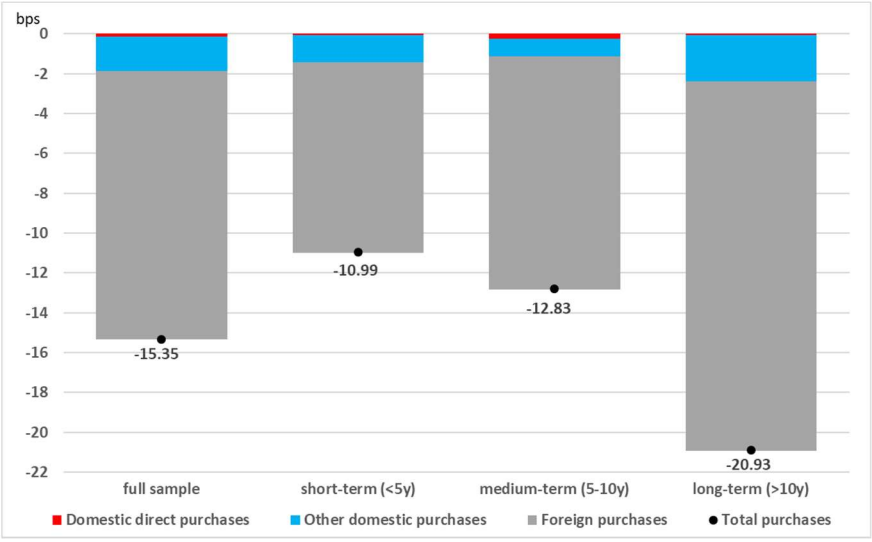
The results (see Tables A2-A4 in the Appendix) offer several insights. First, the estimated effects of purchases on bond yields are more pronounced – both in absolute value and statistical significance – for longer-term bonds, in line with the higher duration risk that is extracted from this market segment. This holds for both domestic purchases as well as foreign spillovers. Figure 2 shows that the average monthly effect of total purchases on the average bond yield in

the long-term maturity segment (equal to -20.9 basis points) is twice as large as for the bond yield in the short-term maturity segment (-11.0 basis points) and about 1.5 times larger than for the bond yield in the medium-term segment (-12.8 basis points). Similar proportions hold for the average monthly effect of foreign purchases. Figure 2 shows that spillovers, in particular those for foreign purchases (grey bar), account for the largest portion of the yield impact.

Second, domestic direct purchases do not have an effect on the yield of short-term bonds but are significant for the medium- and long-term bonds.

Third, domestic purchases of close and distant substitutes have a comparable impact (in terms of the coefficient's magnitude) on the yields of bonds up to 10 years of the remaining maturity. Purchases of substitutes matter strongly for the long-term bond yields: the impact of domestic purchases of other long-term bonds (close substitutes) is twice the size of the effect of domestic purchases in short- and medium-term bonds (distant substitutes). A similar result is found for foreign purchases distinguished by maturity – same maturity spillovers have a larger effect on the yield of an average bond *b* in the long-term segment compared to different maturity spillovers. This finding is in line with the literature on the portfolio rebalancing channel, suggesting that the effect of central bank asset purchases is stronger for bonds that are located in the same maturity segment, because they are considered as superior substitutes for preferred habitat investors compared to bonds from other maturity segments.

Figure 2. Average monthly effects of purchases for different maturity segments



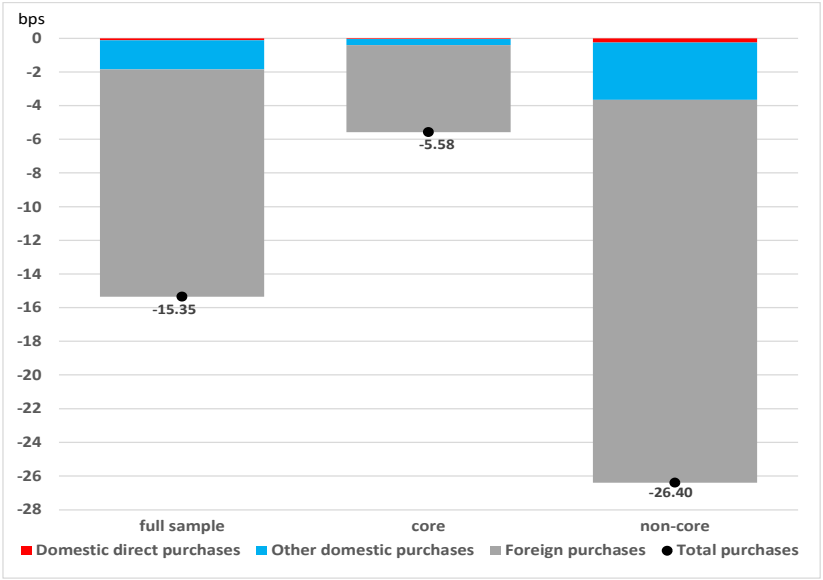
Notes: The figure plots the average monthly effects (in basis points) of domestic direct, other domestic, foreign, and total purchases under the PSPP on a bond yield, calculated as coefficient estimate * average monthly net purchases. The coefficient estimates are based on column (3) in Tables A2-A4 in the Appendix.

6.3. Extensions: core versus non-core countries

As another extension, we analyze whether the impact of bond purchases under the PSPP differs between country groups by estimating the models separately for the core (Austria, Belgium, France, Finland, Germany, the Netherlands) and the non-core EA countries (Italy, Ireland, Portugal, Spain). The results (Tables A5-A6 in the Appendix) show that the estimated effects of purchases are larger for the non-core group than for the core one. This result holds for all categories of purchases variables, both domestic and foreign.

In particular, larger volumes of domestic direct purchases of bond *b* issued by countries in the non-core group are associated with a much stronger reduction of bond yields in this country group, compared to what we find for the core group. Such outcome may be related to the larger credit risk component of bonds issued in the non-core countries, which increases the impact of direct purchases of a particular bond. Moreover, lower market liquidity can also contribute to stronger downward effects on the yield of bonds that are being purchased.

Figure 3. Average monthly effects of purchases in different country groups



Notes: The figure plots the average monthly effects (in basis points) of domestic direct, other domestic, foreign, and total purchases under the PSPP on a bond yield, calculated as coefficient estimate * average monthly net purchases. The coefficient estimates are based on column (3) in Tables A5-A6 in the Appendix.

Figure 3 compares the average effects of purchases for two country groups. While the pace of average monthly total purchases is comparable between the two country groups, their average monthly impact on a bond yield is strikingly different: it is almost five times larger for the non-core group (-26.4 basis points) than for the core group (-5.6 basis points). Large

differences in the average monthly effects are observed for foreign spillovers as well as for domestic purchases. These results suggest that the PSPP has been most effective in lowering bond yields in the EA non-core economies, in line with the observed data. This is also plausible from a theoretical point of view. When risk-free rates decrease, risk premia are likely to decrease as well, for instance because of improved debt sustainability. Since risk premia are larger for non-core countries, the potential for decreasing yields is larger in these jurisdictions. The already low yields in the core countries may therefore trigger investors to rebalance their portfolios towards higher yielding sovereign bonds issued by the non-core countries, thereby creating additional demand for those bonds. In addition, the non-core jurisdictions may benefit relatively more than the core countries from the improved market liquidity and anticipation of increasing European risk sharing due to the PSPP.

6.4. Extensions: time periods

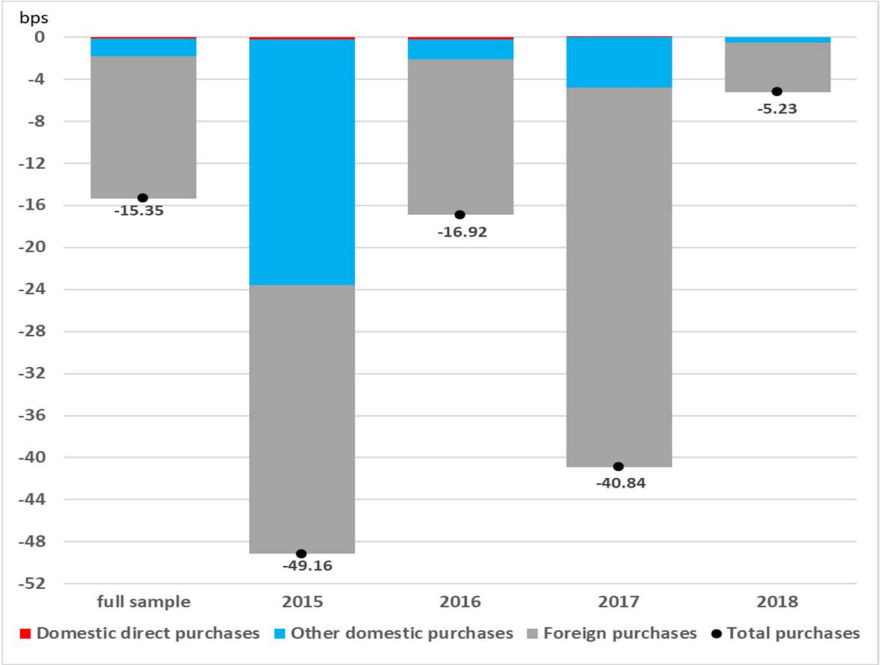
Finally, we investigate the differences in the impact of the PSPP on bond yields over time by slicing the analyzed time period into yearly subsamples. The findings (see Tables A7-A10 in the Appendix) suggest that the estimated effects of purchases on the bond yield were the largest in 2015, i.e. during the first ten months of the PSPP.

Looking at the average monthly effects (Figure 4), we observe the largest impact of the PSPP in 2015: average monthly total purchases reduced the bond yield by around -50 basis points, with half of this decrease due to foreign spillovers and the other half due to domestic purchases of substitutes. The average monthly effect was much smaller during 2016 and equaled -17 basis points, while the effect in 2017 was again substantial with -41 basis points.

The observed patterns are somewhat surprising. The reduction of the average monthly effects over time, with the smallest (in absolute value) calculated for 2018, could be explained by the relatively low purchase pace in 2018. This might indicate that the level of the general purchase pace is of a greater importance than the decreasing stock of assets available in the market (which have not been bought by the central bank yet). The average monthly effects in 2016 are, however, much smaller than in 2017, while during 2016 the purchase pace was increased to its highest level of €80 bln per month. Moreover, technical modifications of the PSPP (see Table 1) cannot fully explain this pattern. Potentially, external factors could be at play which are not captured by time-fixed effects. This could be related to the spikes in bond yields and other asset prices around the timing of the Brexit referendum and the U.S. elections,

which might have somewhat heterogeneous (and, therefore, not captured by time-fixed effects) impact on the EA bond markets and which could have weakened the PSPP impact in that year.

Figure 4. Average monthly effects of purchases for different time periods



Notes: The figure plots the average monthly effects (in bps) of domestic direct, other domestic, foreign, and total purchases under the PSPP on a bond yield, calculated as coefficient estimate * average monthly net purchases. The coefficient estimates are based on column (3) in Tables A7-A10 in the Appendix.

7. Conclusions

This paper investigates cross-border spillover effects from the Eurosystem's Public Sector Purchase Programme (PSPP) on euro area government bond yields. We provide evidence on how PSPP purchases of an individual bond, of bonds with a similar or different maturity, as well as of domestic and foreign bonds affect bond yields. The overall findings show that all purchases have a significantly negative effect on yields. These results hold not only for direct purchases of a specific bond, but also for other bond purchases within a particular country or across other euro area countries.

The finding that the impact of bond purchases spreads across countries and maturity segments complements earlier research by showing the important role that arbitrageurs play in the euro area government bond markets. If these markets were completely fragmented, bond purchases in one country would have no effect on bond yields in other countries, ceteris

paribus. The large cross-border effects, documented in this paper, provide evidence of a strong integration of the euro area government bond markets.

Our results have several policy implications. First, PSPP purchases have been effective in pushing down yields, which is an important criterion for conducting central bank purchase programs in the first place. The effect appears to be most pronounced for bonds with longer maturities and lower ratings, which can be explained by the larger duration and credit risk extraction in these cases. The relatively large impact of purchases in these market segments can be attributed to spillovers from higher-rated low-maturity bonds due to investors rebalancing their sovereign bond portfolio towards higher yielding sovereign bonds.

Second, the distribution of government bond purchases over different countries may have a limited impact on the overall transmission of the ECB's monetary policy across euro area countries as long as the arbitrage functions well in the bond markets. With arbitrageurs at work, it appears to be less relevant which bonds are being bought – as long as the overall volume is purchased. While not explicitly tested in this paper, the effect of the distribution of bond purchases might, however, also have an impact via an expectations channel. Moreover, the transmission of bond purchases across countries may be dependent on market liquidity and may be hampered in times of financial stress. There could also be limitations when purchases are concentrated in a few bond issues or in one particular maturity segment. In particular, price distortions would arise when purchases crowd out arbitrageurs and preferred habitat investors fully dominate these bond holdings. Preventing these potential market distortions can justify spreading bond purchases across a large number of bonds when conducting the PSPP.

Finally, our empirical framework can be applied for evaluating other (ongoing and future) asset purchase programs in the euro area. The important aspect that we add to the literature – i.e., considering spillover effects from bond purchases in other euro area countries - potentially matters for the effectiveness of central bank purchase programs and, therefore, needs to be taken into account. In this sense, the Eurosystem's Pandemic Emergency Purchase Programme (PEPP) is an important testing ground for new research on the effectiveness of asset purchase programs in the euro area.

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Appendix

Table A1. Effects of PSPP in the euro area: empirical evidence

Study	Time period	Country sample	Empirical approach	Estimated effect
PSPP announcements – effect on 10-year bond yield				
Altavilla et al. (2015)	9/2014-3/2015	euro area	event study daily data	-30 to -50 bps
Andrade et al. (2016)	3-12/2015	euro area	event study daily data	-45 bps
Eser et al. (2019)	1/2015-6/2018	euro area	term structure model monthly data	-50 bps (initial announcement) -95 bps (overall)
De Santis (2020)	9/2014-10/2015	10 euro area countries	panel error correction model daily data	-72 bps
PSPP actual purchases – effect on 10-year bond yield				
Arrata and Nguyen (2017)	3/2015-3/2016	France	OLS, IV regressions cross-sectional data	Per 10% of amount outstanding purchased: -13 bps (OLS) -26 bps (IV)
Koijen et al. (2020)	2015q1-2017q4	euro area	2-stage LS regressions quarterly data	Per 10% of amount outstanding purchased: -63 bps on average; between -37bps and -77bps across countries
PSPP actual purchases – effect on average bond price				
De Santis and Holm-Hadulla (2020)	3/2015-6/2016	euro area	2-stage LS regressions daily data	Per €100 mln purchased: +7.5 bps
Schlepper et al. (2020)	9/2015-10/2016	Germany	panel regressions intraday and daily data	Per €100 mln purchased: between +3.8 and +8.9 bps

Table A2. Estimation results – short-term bonds (up to 5 years)

	(1)	(2)	(3)	(4)	(5)	(6)	(7)
Bond yield$_{bjt-1}$	0.794***	0.794***	0.794***	0.794***	0.793***	0.794***	0.794***
	(0.018)	(0.018)	(0.018)	(0.018)	(0.018)	(0.018)	(0.018)
Total purchases	-0.252***						
	(0.049)						
Domestic purchases		-0.222***					
		(0.056)					
Domestic direct purchases			-1.022	-1.013	-1.017	-1.025	-1.017
			(0.743)	(0.747)	(0.746)	(0.745)	(0.744)
Other domestic purchases			-0.218***		-0.200***	-0.222***	-0.218***
			(0.056)		(0.057)	(0.055)	(0.057)
Close substitutes				-0.221***			
				(0.057)			
Distant substitutes				-0.217***			
				(0.057)			
Foreign spillovers		-0.257***	-0.256***	-0.256***			
		(0.050)	(0.050)	(0.050)			
Same rating spillovers					-0.242***		
					(0.049)		
Different rating spillovers					-0.263***		
					(0.050)		
Same group spillovers						-0.265***	
						(0.046)	
Different group spillovers						-0.245***	
						(0.058)	
Same maturity spillovers							-0.257***
							(0.049)
Different maturity spillovers							-0.256***
							(0.050)
Constant	-0.071***	-0.071***	-0.071***	-0.071***	-0.072***	-0.072***	-0.072***
	(0.011)	(0.011)	(0.011)	(0.011)	(0.011)	(0.011)	(0.011)
Bond-specific fixed effects	yes	yes	yes	yes	yes	yes	yes
Time fixed effects	yes	yes	yes	yes	yes	yes	yes
R-squared	0.738	0.738	0.738	0.738	0.739	0.738	0.738
N of observations	15,602	15,602	15,602	15,602	15,602	15,602	15,602
N of bonds	653	653	653	653	653	653	653
N of time series observations per bond (average)	23.9	23.9	23.9	23.9	23.9	23.9	23.9

Notes: The table reports the estimation results from a fixed effects panel regression where a bond yield is a dependent variable. Standard errors in parentheses are clustered on the bond-level. ***, **, * indicate statistical significance at 1%, 5%, and 10% levels, respectively.

Table A3. Estimation results – medium-term bonds (5-10 years)

	(1)	(2)	(3)	(4)	(5)	(6)	(7)
Bond yield$_{bjt-1}$	0.872***	0.874***	0.873***	0.873***	0.872***	0.874***	0.873***
	(0.013)	(0.013)	(0.013)	(0.013)	(0.014)	(0.013)	(0.013)
Total purchases	-0.305***						
	(0.050)						
Domestic purchases		-0.176***					
		(0.046)					
Domestic direct purchases			-2.519***	-2.493***	-2.519***	-2.508***	-2.521***
			(0.856)	(0.854)	(0.863)	(0.851)	(0.856)
Other domestic purchases			-0.156***		-0.147***	-0.142***	-0.153***
			(0.046)		(0.047)	(0.044)	(0.046)
Close substitutes				-0.171***			
				(0.057)			
Distant substitutes				-0.152***			
				(0.045)			
Foreign spillovers		-0.308***	-0.307***	-0.310***			
		(0.050)	(0.050)	(0.052)			
Same rating spillovers					-0.295***		
					(0.050)		
Different rating spillovers					-0.309***		
					(0.050)		
Same group spillovers						-0.291***	
						(0.043)	
Different group spillovers						-0.325***	
						(0.059)	
Same maturity spillovers							-0.301***
							(0.050)
Different maturity spillovers							-0.305***
							(0.050)
Constant	0.056***	0.051***	0.051***	0.051***	0.051***	0.050***	0.050***
	(0.013)	(0.013)	(0.013)	(0.013)	(0.013)	(0.013)	(0.013)
Bond-specific fixed effects	yes	yes	yes	yes	yes	yes	yes
Time fixed effects	yes	yes	yes	yes	yes	yes	yes
R-squared	0.862	0.862	0.862	0.862	0.862	0.862	0.862
N of observations	10,016	10,016	10,016	10,016	10,016	10,016	10,016
N of bonds	454	454	454	454	454	454	454
N of time series observations per bond (average)	22.1	22.1	22.1	22.1	22.1	22.1	22.1

Notes: The table reports the estimation results from a fixed effects panel regression where a bond yield is a dependent variable. Standard errors in parentheses are clustered on the bond-level. ***, **, * indicate statistical significance at 1%, 5%, and 10% levels, respectively.

Table A4. Estimation results – long-term bonds (over 10 years)

	(1)	(2)	(3)	(4)	(5)	(6)	(7)
Bond yield$_{bjt-1}$	0.872***	0.872***	0.872***	0.872***	0.869***	0.872***	0.872***
	(0.011)	(0.011)	(0.011)	(0.011)	(0.012)	(0.011)	(0.011)
Total purchases	-0.485***						
	(0.031)						
Domestic purchases		-0.446***					
		(0.030)					
Domestic direct purchases			-1.848*	-1.721*	-1.895*	-1.978**	-1.819*
			(0.945)	(0.930)	(0.965)	(0.956)	(0.946)
Other domestic purchases			-0.442***		-0.423***	-0.455***	-0.434***
			(0.030)		(0.030)	(0.030)	(0.030)
Close substitutes				-0.798***			
				(0.048)			
Distant substitutes				-0.378***			
				(0.031)			
Foreign spillovers		-0.488***	-0.487***	-0.461***			
		(0.032)	(0.032)	(0.033)			
Same rating spillovers					-0.460***		
					(0.032)		
Different rating spillovers					-0.491***		
					(0.032)		
Same group spillovers						-0.506***	
						(0.029)	
Different group spillovers						-0.459***	
						(0.041)	
Same maturity spillovers							-0.511***
							(0.033)
Different maturity spillovers							-0.478***
							(0.032)
Constant	0.290***	0.288***	0.289***	0.281***	0.293***	0.289***	0.287***
	(0.021)	(0.021)	(0.021)	(0.021)	(0.022)	(0.021)	(0.021)
Bond-specific fixed effects	yes	yes	yes	yes	yes	yes	yes
Time fixed effects	yes	yes	yes	yes	yes	yes	yes
R-squared	0.883	0.883	0.883	0.884	0.884	0.883	0.883
N of observations	15,054	15,054	15,054	15,054	15,054	15,054	15,054
N of bonds	516	516	516	516	516	516	516
N of time series observations per bond (average)	29.2	29.2	29.2	29.2	29.2	29.2	29.2

Notes: The table reports the estimation results from a fixed effects panel regression where a bond yield is a dependent variable. Standard errors in parentheses are clustered on the bond-level. ***, **, * indicate statistical significance at 1%, 5%, and 10% levels, respectively.

Table A5. Estimation results – core countries

	(1)	(2)	(3)	(4)	(5)	(6)	(7)
Bond yield$_{bjt-1}$	0.783***	0.783***	0.783***	0.783***	0.783***	0.783***	0.783***
	(0.011)	(0.011)	(0.011)	(0.011)	(0.011)	(0.011)	(0.011)
Total purchases	-0.115***						
	(0.019)						
Domestic purchases		-0.074***					
		(0.020)					
Domestic direct purchases			-0.753**	-0.718**	-0.762**	-0.691*	-0.743**
			(0.353)	(0.355)	(0.351)	(0.352)	(0.354)
Other domestic purchases			-0.071***		-0.075***	-0.010	-0.071***
			(0.020)		(0.021)	(0.014)	(0.020)
Close substitutes				-0.082***			
				(0.022)			
Distant substitutes				-0.069***			
				(0.020)			
Foreign spillovers		-0.134***	-0.134***	-0.134***			
		(0.019)	(0.019)	(0.019)			
Same rating spillovers					-0.141***		
					(0.025)		
Different rating spillovers					-0.130***		
					(0.022)		
Same group spillovers						-0.073***	
						(0.012)	
Different group spillovers						0.177***	
						(0.018)	
Same maturity spillovers							-0.135***
							(0.019)
Different maturity spillovers							-0.134***
							(0.019)
Constant	0.055***	0.057***	0.057***	0.057***	0.057***	0.015***	0.057***
	(0.005)	(0.005)	(0.005)	(0.005)	(0.005)	(0.004)	(0.005)
Bond-specific fixed effects	yes	yes	yes	yes	yes	yes	yes
Time fixed effects	yes	yes	yes	yes	yes	yes	yes
R-squared	0.830	0.830	0.830	0.830	0.830	0.830	0.830
N of observations	23,524	23,524	23,524	23,524	23,524	23,524	23,524
N of bonds	721	721	721	721	721	721	721
N of time series observations per bond (average)	32.6	32.6	32.6	32.6	32.6	32.6	32.6

Notes: The table reports the estimation results from a fixed effects panel regression where a bond yield is a dependent variable. Standard errors in parentheses are clustered on the bond-level. ***, **, * indicate statistical significance at 1%, 5%, and 10% levels, respectively.

Table A6. Estimation results – non-core countries

	(1)	(2)	(3)	(4)	(5)	(6)	(7)
Bond yield$_{bjt-1}$	0.895***	0.897***	0.896***	0.896***	0.896***	0.896***	0.896***
	(0.008)	(0.008)	(0.008)	(0.008)	(0.008)	(0.008)	(0.008)
Total purchases	-0.645***						
	(0.047)						
Domestic purchases		-0.526***					
		(0.078)					
Domestic direct purchases			-5.164***	-5.164***	-5.168***	-4.663***	-5.170***
			(1.019)	(1.022)	(1.019)	(1.020)	(1.020)
Other domestic purchases			-0.500***		-0.500***	0.001	-0.500***
			(0.079)		(0.079)	(0.041)	(0.079)
Close substitutes				-0.499***			
				(0.081)			
Distant substitutes				-0.500***			
				(0.079)			
Foreign spillovers		-0.625***	-0.618***	-0.618***			
		(0.050)	(0.050)	(0.050)			
Same rating spillovers					-0.622***		
					(0.051)		
Different rating spillovers					-0.618***		
					(0.050)		
Same group spillovers						-0.118**	
						(0.048)	
Different group spillovers						-0.519***	
						(0.036)	
Same maturity spillovers							-0.618***
							(0.050)
Different maturity spillovers							-0.618***
							(0.050)
Constant	0.159***	0.149***	0.149***	0.149***	0.149***	0.081***	0.149***
	(0.016)	(0.016)	(0.016)	(0.016)	(0.016)	(0.012)	(0.016)
Bond-specific fixed effects	yes	yes	yes	yes	yes	yes	yes
Time fixed effects	yes	yes	yes	yes	yes	yes	yes
R-squared	0.863	0.863	0.863	0.863	0.863	0.863	0.863
N of observations	17,148	17,148	17,148	17,148	17,148	17,148	17,148
N of bonds	569	569	569	569	569	569	569
N of time series observations per bond (average)	30.1	30.1	30.1	30.1	30.1	30.1	30.1

Notes: The table reports the estimation results from a fixed effects panel regression where a bond yield is a dependent variable. Standard errors in parentheses are clustered on the bond-level. ***, **, * indicate statistical significance at 1%, 5%, and 10% levels, respectively.

Table A7. Estimation results for year=2015

	(1)	(2)	(3)	(4)	(5)	(6)	(7)
Bond yield$_{bjt-1}$	0.555***	0.562***	0.562***	0.563***	0.562***	0.561***	0.563***
	(0.034)	(0.034)	(0.034)	(0.034)	(0.034)	(0.033)	(0.034)
Total purchases	-0.920***						
	(0.042)						
Domestic purchases		-3.288***					
		(0.319)					
Domestic direct purchases			-3.282*	-2.950*	-3.555**	-5.073***	-2.967*
			(1.777)	(1.783)	(1.773)	(1.577)	(1.762)
Other domestic purchases			-3.288***		-3.489***	-5.245***	-3.299***
			(0.318)		(0.323)	(0.349)	(0.318)
Close substitutes				-3.394***			
				(0.332)			
Distant substitutes				-3.257***			
				(0.315)			
Foreign spillovers		-0.549***	-0.549***	-0.552***			
		(0.036)	(0.036)	(0.036)			
Same rating spillovers					-1.565***		
					(0.216)		
Different rating spillovers					-0.269***		
					(0.073)		
Same group spillovers						-2.665***	
						(0.125)	
Different group spillovers						1.581***	
						(0.124)	
Same maturity spillovers							-0.596***
							(0.039)
Different maturity spillovers							-0.538***
							(0.037)
Constant	0.867***	0.860***	0.860***	0.861***	0.860***	0.874***	0.860***
	(0.021)	(0.021)	(0.021)	(0.021)	(0.021)	(0.022)	(0.021)
Bond-specific fixed effects	yes	yes	yes	yes	yes	yes	yes
Time fixed effects	yes	yes	yes	yes	yes	yes	yes
R-squared	0.645	0.649	0.649	0.649	0.650	0.662	0.650
N of observations	7,319	7,319	7,319	7,319	7,319	7,319	7,319
N of bonds	880	880	880	880	880	880	880
N of time series observations per bond (average)	8.3	8.3	8.3	8.3	8.3	8.3	8.3

Notes: The table reports the estimation results from a fixed effects panel regression where a bond yield is a dependent variable. Standard errors in parentheses are clustered on the bond-level. ***, **, * indicate statistical significance at 1%, 5%, and 10% levels, respectively.

Table A8. Estimation results for year=2016

	(1)	(2)	(3)	(4)	(5)	(6)	(7)
Bond yield$_{bjt-1}$	0.617***	0.617***	0.617***	0.617***	0.615***	0.616***	0.617***
	(0.028)	(0.027)	(0.027)	(0.027)	(0.028)	(0.028)	(0.027)
Total purchases	-0.252***						
	(0.041)						
Domestic purchases		-0.231***					
		(0.059)					
Domestic direct purchases			-2.952***	-2.937***	-3.122***	-2.992***	-2.927***
			(0.827)	(0.828)	(0.831)	(0.832)	(0.828)
Other domestic purchases			-0.216***		-0.314***	-0.266***	-0.216***
			(0.059)		(0.064)	(0.086)	(0.059)
Close substitutes				-0.225***			
				(0.063)			
Distant substitutes				-0.213***			
				(0.059)			
Foreign spillovers		-0.255***	-0.258***	-0.258***			
		(0.047)	(0.047)	(0.047)			
Same rating spillovers					-0.519***		
					(0.075)		
Different rating spillovers					-0.172***		
					(0.049)		
Same group spillovers						-0.299***	
						(0.076)	
Different group spillovers						-0.212***	
						(0.061)	
Same maturity spillovers							-0.263***
							(0.048)
Different maturity spillovers							-0.257***
							(0.047)
Constant	0.309***	0.309***	0.312***	0.312***	0.312***	0.312***	0.312***
	(0.041)	(0.041)	(0.041)	(0.041)	(0.041)	(0.042)	(0.041)
Bond-specific fixed effects	yes	yes	yes	yes	yes	yes	yes
Time fixed effects	yes	yes	yes	yes	yes	yes	yes
R-squared	0.653	0.653	0.654	0.654	0.654	0.654	0.654
N of observations	9,957	9,957	9,957	9,957	9,957	9,957	9,957
N of bonds	983	983	983	983	983	983	983
N of time series observations per bond (average)	10.1	10.1	10.1	10.1	10.1	10.1	10.1

Notes: The table reports the estimation results from a fixed effects panel regression where a bond yield is a dependent variable. Standard errors in parentheses are clustered on the bond-level. ***, **, * indicate statistical significance at 1%, 5%, and 10% levels, respectively.

Table A9. Estimation results for year=2017

	(1)	(2)	(3)	(4)	(5)	(6)	(7)
Bond yield$_{bjt-1}$	0.750***	0.753***	0.753***	0.753***	0.744***	0.755***	0.753***
	(0.028)	(0.028)	(0.028)	(0.028)	(0.027)	(0.028)	(0.028)
Total purchases	-0.821***						
	(0.042)						
Domestic purchases		-0.698***					
		(0.038)					
Domestic direct purchases			1.020**	0.952*	0.975*	1.020**	1.014**
			(0.504)	(0.498)	(0.500)	(0.511)	(0.503)
Other domestic purchases			-0.707***		-0.720***	-0.669***	-0.707***
			(0.038)		(0.038)	(0.037)	(0.038)
Close substitutes				-0.682***			
				(0.040)			
Distant substitutes				-0.712***			
				(0.038)			
Foreign spillovers		-0.848***	-0.847***	-0.847***			
		(0.045)	(0.045)	(0.045)			
Same rating spillovers					-0.871***		
					(0.044)		
Different rating spillovers					-0.836***		
					(0.044)		
Same group spillovers						-0.813***	
						(0.044)	
Different group spillovers						-0.893***	
						(0.046)	
Same maturity spillovers							-0.846***
							(0.045)
Different maturity spillovers							-0.848***
							(0.045)
Constant	0.655***	0.657***	0.656***	0.656***	0.661***	0.658***	0.656***
	(0.025)	(0.025)	(0.025)	(0.025)	(0.024)	(0.025)	(0.025)
Bond-specific fixed effects	yes	yes	yes	yes	yes	yes	yes
Time fixed effects	yes	yes	yes	yes	yes	yes	yes
R-squared	0.674	0.675	0.675	0.675	0.679	0.675	0.675
N of observations	11,458	11,458	11,458	11,458	11,458	11,458	11,458
N of bonds	1,052	1,052	1,052	1,052	1,052	1,052	1,052
N of time series observations per bond (average)	10.9	10.9	10.9	10.9	10.9	10.9	10.9

Notes: The table reports the estimation results from a fixed effects panel regression where a bond yield is a dependent variable. Standard errors in parentheses are clustered on the bond-level. ***, **, * indicate statistical significance at 1%, 5%, and 10% levels, respectively.

Table A10. Estimation results for year=2018

	(1)	(2)	(3)	(4)	(5)	(6)	(7)
Bond yield$_{bjt-1}$	0.670***	0.671***	0.671***	0.671***	0.661***	0.665***	0.671***
	(0.009)	(0.009)	(0.009)	(0.009)	(0.008)	(0.009)	(0.009)
Total purchases	-0.394***						
	(0.025)						
Domestic purchases		-0.329***					
		(0.031)					
Domestic direct purchases			-1.053	-0.978	-1.522	-1.393	-1.057
			(1.771)	(1.773)	(1.789)	(1.792)	(1.778)
Other domestic purchases			-0.327***		-0.253***	-0.335***	-0.327***
			(0.032)		(0.031)	(0.030)	(0.032)
Close substitutes				-0.350***			
				(0.040)			
Distant substitutes				-0.323***			
				(0.032)			
Foreign spillovers		-0.400***	-0.400***	-0.399***			
		(0.026)	(0.026)	(0.026)			
Same rating spillovers					-0.360***		
					(0.026)		
Different rating spillovers					-0.414***		
					(0.027)		
Same group spillovers						-0.474***	
						(0.028)	
Different group spillovers						-0.309***	
						(0.031)	
Same maturity spillovers							-0.400***
							(0.026)
Different maturity spillovers							-0.400***
							(0.026)
Constant	0.311***	0.310***	0.310***	0.309***	0.317***	0.311***	0.310***
	(0.008)	(0.008)	(0.008)	(0.008)	(0.008)	(0.008)	(0.008)
Bond-specific fixed effects	yes	yes	yes	yes	yes	yes	yes
Time fixed effects	yes	yes	yes	yes	yes	yes	yes
R-squared	0.514	0.514	0.514	0.514	0.529	0.516	0.514
N of observations	11,938	11,938	11,938	11,938	11,938	11,938	11,938
N of bonds	1,078	1,078	1,078	1,078	1,078	1,078	1,078
N of time series observations per bond (average)	11.1	11.1	11.1	11.1	11.1	11.1	11.1

Notes: The table reports the estimation results from a fixed effects panel regression where a bond yield is a dependent variable. Standard errors in parentheses are clustered on the bond-level. ***, **, * indicate statistical significance at 1%, 5%, and 10% levels, respectively.

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