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The Liquidity Effects of Official Bond Market Intervention

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Abstract

To "ensure depth and liquidity," the European Central Bank intervened in sovereign debt markets through its Securities Markets Programme (SMP), providing a unique opportunity to estimate the effects of large-scale asset purchases on sovereign bond liquidity premia. From reduced-form estimates, we find robust, economically significant impact and lasting reductions in sovereign bonds' liquidity premia in response to official purchases. We develop a search-based asset-pricing model to understand our empirical results. The theory implies that bond liquidity premia fall in response to both official purchases and rising sovereign default probabilities, as seen in the data.

I. Introduction

In response to the global financial crisis of 2007–2009, major central banks enacted nonstandard monetary policy programs. These were instituted because reducing policy rates to the effective lower bound, at an unprecedentedly large and broad scale, was seemingly insufficient to counteract the effect of the crisis. Most of the nonstandard programs involved some form of large-scale asset purchases. For example, the Federal Reserve conducted three large-scale asset purchase programs and a maturity extension program; similarly, the Bank of England purchased hundreds of billions of pounds in government securities through its Asset Purchase Facility. Empirical evidence of asset purchase programs'

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effects on financial markets is substantial, but there has been considerable debate over the channels through which the programs work.

In May 2010, the European Central Bank (ECB) began large-scale asset purchases of substantial quantities of sovereign debt from member nations via its Securities Markets Programme (SMP).[1] This official intervention had the explicit goal of ensuring "depth and liquidity" in "dysfunctional" markets that were perceived to be increasingly fragmented. SMP purchases of varying sizes occurred in dozens of weeks in several European sovereign bond markets over the course of almost 2 years. Purchases were not preannounced to the market, in contrast to Federal Reserve and Bank of England programs. Furthermore, throughout the program, the ECB never announced the timing, size, or allocation of its purchases during any given week. Therefore, as market commentary at the time expressed, the official purchases involved some surprise to market participants whenever they occurred. These SMP operations provide a unique opportunity to learn about large-scale asset purchase programs' effects, specifically on sovereign bond liquidity premia.

We estimate that SMP purchases had impact and lasting effects that are economically and statistically significant. An official purchase of 1% of 5-year sovereign debt outstanding decreases the liquidity premium by 32–40 basis points (bps) on impact. Some of this effect is temporary, but about 13–17 bps of the liquidity premium's decrease is lasting. Meanwhile, a 1-percentage-point increase in the probability of sovereign default lowers the liquidity premium by about 4.2–4.7 bps. We find these results to be robust to a variety of alternative specifications and to be similar in nearby maturities.

To understand the mechanism through which both ECB purchases and the varying probability of default influence liquidity premia, we develop a search-based asset-pricing model. Our theory includes default in the model of Duffie, Garleanu, and Pedersen (DGP) (2005), (2007). The model produces a liquidity premium that compensates buyers for the risk that they may become eager to sell the bond in the future but are not able to do so immediately because of search frictions. By affecting the probability that a bondholder is stuck searching for a buyer in the future, increases in the default probability lower liquidity premia in the model. Then we model official intervention as an exogenous reduction in the supply of bonds traded among investors, which is caused by the official sector instantaneously purchasing bonds from bond sellers. We show that this exogenous shock affects the model's steady state and, in the process, creates transition dynamics in simulations mimicking the impact and lasting effects on liquidity premia that we estimate in the data.

In our empirical analysis, we use a measure of bond liquidity refining the well-known credit default swap (CDS)-bond basis, the difference between the CDS spread and the sovereign yield spread, for a given country and maturity. Because the SMP interventions were conducted for countries with

[1] See http://www.ecb.europa.eu/press/govcdec/otherdec/2010/html/gc100521.en.html, which reports the ECB May 2010 monetary policy decision. The ECB's stated goal for the SMP was clearly different from the more traditional sovereign bond purchases that the ECB began in Mar. 2015 under its Public Sector Purchase Programme.

well-functioning, liquid CDS markets, sovereign bonds and CDSs should, in theory, reflect the same default premium. As a result, and because CDS prices are not necessarily tied to liquidity conditions in the bond market, the difference between CDS spreads and yield spreads allows us to isolate a noisy measure of the liquidity component of yields.[2]

This article is related to the large literature on search in asset markets. DGP (2005) introduced a search-based asset-pricing model with risk-neutral investors. DGP (2007) simulated the model and showed how it approximated to first-order the behavior of risk-averse investors. Lagos and Rocheteau (2009) generalized DGP (2005) to allow for multiple types of risk-averse investors who could make continuously valued purchases. Feldhutter (2012) implements an empirical version of DGP (2005) to obtain maximum-likelihood estimates of selling pressure in U.S. corporate bonds from 2004 to 2009, using the detailed TRACE data set that allows the structural parameters to be identified. Closer to our paper, He and Milbradt (2014) embed DGP's model in Leland and Toft's (1996) framework to endogenize the firm's default decision and link bond liquidity conditions to the firm's distance-to-default. In He and Milbradt (2014), a corporate default leads to a recovery process where investors hold on to very illiquid claims, and so an increased default probability *increases* the liquidity premium. In contrast, in our model, a sovereign default immediately pays out a recovery value, as in Duffie (1998), and so an increased default probability *decreases* the liquidity premium. These contrasting assumptions reflect empirical differences between recovery value payouts for corporate versus sovereign defaults. He and Milbradt (2014) focus on the theoretical properties of their model and provide no estimation. However, we find empirical support for our model's prediction that sovereign bonds' liquidity premia fall along with the distance-to-default.

A growing literature investigates the SMP's effects. Eser and Schwaab (2016) use daily data and model the factor structure of European sovereign risk in order to identify SMP purchase impact effects separately by country. Their more sophisticated econometric framework also concludes that there were both impact and lasting effects on the total bond yield from SMP purchases. Their baseline impact estimates (also at the 5-year maturity) are a reduction of 30 bps per percentage-point purchase, and they also find that liquidity conditions were improved when the ECB intervened. This combines with our results to suggest that changes in liquidity premia were the significant driver of total bond yield changes coming from SMP purchases.

Ghysels, Idier, Manganelli, and Vergote (2014) look at intraday data to investigate the impact effects of SMP purchases and separate them from other high-frequency events. Trebesch and Zettelmeyer (2014) recently used novel data on the particular Greek bonds purchased under the SMP to find significant yield declines in response to ECB purchases. Finally, in order to determine the drivers

[2]In addition, because the ECB sterilized these operations, the effect of SMP purchases on the euro-wide discount rate (as measured by relevant-maturity German bund yields) should be negligible. That is, we should not expect these operations to influence either the expected path of short rates or the rate of overall European growth. In any case, we are able to control for changes in German rates directly. This highlights a difficulty with performing our analysis on, say, Federal Reserve large-scale asset purchases because there the official intervention *must change the U.S. discount rate*.

of the CDS-bond basis in euro-area countries between 2007 and 2012, Fontana and Scheicher (2016) also examine the impact of SMP purchases on the CDS-bond basis for euro-area countries. However, they only consider aggregate SMP purchases and do not examine the difference between immediate impact versus lasting effects as we do here, nor do they consider the impact of time variation in the probability of sovereign default. Our empirical estimates dovetail with the average effect seen in Eser and Schwaab's (2016) time-series results, the benchmark results from Trebesch and Zettelmeyer's (2014) cross-sectional analysis, and the positive impact of SMP purchases on the CDS-bond basis that Fontana and Scheicher (2016) find.

The four aforementioned papers fit into a larger literature that estimates the effects of large-scale asset purchases. Joyce, Lasaosa, Stevens, and Tong (2011) estimate the effects of the Bank of England's asset purchases in the United Kingdom. Most other literature focuses on the United States, including, among others, Gagnon, Raskin, and Sack (2011), Hamilton and Wu (2011), Krishnamurthy and Vissing-Jorgensen (2011), Christensen and Rudebusch (2012), and D'Amico, English, Lopez-Salido, and Nelson (2012). Noteworthy are the findings of D'Amico and King (2013), who use a preferred-habitat motivation to find *stock* and *flow* effects of Federal Reserve large-scale asset purchases. They find significant effects from the purchases, identifying the effects primarily through the real term premium. Our findings complement theirs and suggest an economic friction that causes the effects to come via the real term premium channel.

The article is organized as follows: Section II presents the data sources. Section III provides estimation results and robustness checks of our findings. Section IV presents the search-based asset-pricing model and then reports theoretical and numerical results illustrating its mechanisms and showing the liquidity effects of official bond purchases. Section V concludes. Proofs are relegated to the Internet Appendix (available at www.jfqa.org), which also contains some additional model discussion and details on how we extract default probabilities from CDS spreads.

II. Data

We collect data for four European countries: Portugal, Ireland, Italy, and Spain.[3] These are countries for which the ECB confirmed to have purchased sovereign debt under its SMP. For each country, we collect daily CDS spreads and bond price data between Jan. 2010 and Mar. 2012, when the SMP program effectively ended.

Because the ECB bought bonds of different maturities, we examine the impact of SMP purchases on the liquidity component of bonds across the yield curve. This requires constructing the CDS-bond basis for different maturities. We use term structure methods to estimate zero-coupon curves over time for each country in our sample, allowing us to construct reliable yield spreads at any maturity. We use similar curve-estimation techniques to fit the curve of CDS spreads, only now

[3]We exclude Greece from our main analysis because its bond and CDS prices are outliers to those countries included here. For an in-depth analysis of the unique Greek experience, see Trebesch and Zettelmeyer (2014).

to extract the term structure of cumulative default probabilities because this is a key input in our regression specification.

A. Sources

Bond prices are from Datastream, and for each country, we collect sovereign bond prices for all bonds that are outstanding for each day in our sample. With the full set of characteristics of each available bond (maturity date, coupon rate, and coupon payment frequency), we use the popular, and by now standard, Nelson and Siegel (1987) curve-estimation methodology to estimate zero-coupon yield curves for each day in our sample. When doing so, we apply the usual filters to the data: We delete any bonds that have option-like features or floating coupon payments, we do not include any bills or bonds that are denominated in nondomestic currencies, and we exclude any bond in the estimation as soon as it has less than 3 months left to maturity (see Gürkaynak, Sack, and Wright (2007) for details and a similar approach to estimating zero-coupon yield curves for the United States).[4] In order to account for any potential on-the-run versus off-the-run liquidity differences, we only first include bonds in the estimation 1 year after they are issued.[5] We use German zero-coupon yields as our underlying euro-zone discount rates, constructed using the Bundesbank's estimated Svensson–Nelson–Siegel parameters obtained from the Bundesbank Web site (available at www.bundesbank.de/statistik/statistik_zeitreihen.en.php).

Our source for sovereign CDS spreads is Markit Partners, and we collect midquotes on eight CDS contract maturities: 6 months and 1, 2, 3, 4, 5, 7, and 10 years. All contracts are denominated in U.S. dollars, even though these are designed to offer default risk protection on euro-denominated sovereign bonds. The reason behind this currency mismatch is that the overwhelming majority of CDS trading on euro-area sovereign bonds occurs in U.S. dollar-denominated contracts.[6] Finally, we obtain 6-month euro-area London Interbank Offered Rate (LIBOR) and euro-swap rates from Bloomberg, and we use these in our methodology of computing CDS-based default probabilities, as described in the Internet Appendix.

The data on the ECB's SMP purchases mainly come directly from the SMP entry on the ECB's balance sheet, which is publicly available on a weekly

[4]However, whereas they use the Svensson–Nelson–Siegel method, we use the more parsimonious Nelson–Siegel (1987) method because we only estimate curves out to 15 years (although we only use a maximum maturity of 10 years in our regressions) and because the number of outstanding bonds for any given day can be relatively small, especially for the countries in our sample that have smaller bond markets, such as Ireland and Portugal.

[5]Contrary to the pronounced liquidity differences that have been identified for U.S. Treasury securities, from our conversations with market participants and empirical work such as Ejsing and Sihvonen (2009), it appears that liquidity differences in euro-area sovereign bond markets are less prevalent. Excluding bonds until 1 year after issuance (which also accounts for initial reopenings which are common in euro area bond markets) should sufficiently account for any liquidity mismatches that do exist.

[6]Chen, Fleming, Jackson, Li, and Sarkar (2011) analyzed all the trades entered into the Depository Trust & Clearing Corporation (DTCC) warehouse between May and July 2010 and found that only a small fraction of the sovereign single-name trades used euros. The outstanding volume of European sovereign CDS is relatively small compared to the stock of outstanding European debt, even though the European CDS market has grown substantially since the onset of the financial crisis (see the data available at www.dtcc.com).

frequency (see www.ecb.int/press/pr/wfs/). In addition, the ECB provides some information as to which bonds were purchased and when. For instance, early purchases under the program, beginning in 2010, were only of Greek, Portuguese, and Irish bonds. The expansion of the SMP to Spain and Italy began in Aug. 2011. In Feb. 2013, the ECB released a snapshot of how much debt it was holding for each country at the end of Dec. 2012 (see www.ecb.europa.eu/press/pr/date/2013/html/pr130221_1.en.html). This snapshot accords with the country-level weekly purchase data we obtain from Barclays (described in the following paragraph). To date, the ECB has not publicly released any further details on its SMP purchases.[7]

Barclays, which was a significant counterparty to ECB transactions during our data sample, has published weekly country breakdowns of SMP purchases. We use these estimates to allocate total SMP purchases across countries at each point in time.[8] The estimates, plotted in Figure 1, primarily reflect a rule of proportionality (buying that is proportionate to nations' bond market size) but additionally adjust according to differential market pressures (week by week), as was observed by the Barclays' trading desk.

B. Measuring Variation in Bond Liquidity

From our data on bond yields and CDS spreads, we construct a measure of bond liquidity akin to the well-known CDS-bond basis, which is defined as a country's CDS spread minus the spread of its corresponding sovereign yield over the yield on a German bond, all of comparable maturity. This measure is an empirical proxy for the liquidity premium that we model in Section IV, and it serves as the dependent variable in our empirical analysis in Section III. As demonstrated by Duffie (1999), an exact arbitrage pricing relation exists among a risky floating-rate bond trading at par, a risk-free par floater of the same maturity, and a CDS contract of the same maturity on the risky bond. Consequently, the CDS-bond basis should theoretically be 0 at all times.[9]

From Duffie and Singleton (1999), we know that bonds are subject to default and liquidity premia, and as a result, euro-area bond yields will be the sum of at least three components: i) the euro-wide risk-free discount rate, ii) a default risk premium, and iii) a liquidity risk premium. As shown by Beber, Brandt, and Kavajecz (2009) and Monfort and Renne (2014) the latter two components play a significant role in the determination of the level and dynamics of euro-area yields, especially during the height of the euro-area crisis.

[7]The appendix in De Pooter, DeSimone, Martin, and Pruitt (2015) contains a detailed timeline of SMP purchases and market beliefs about purchase timing.

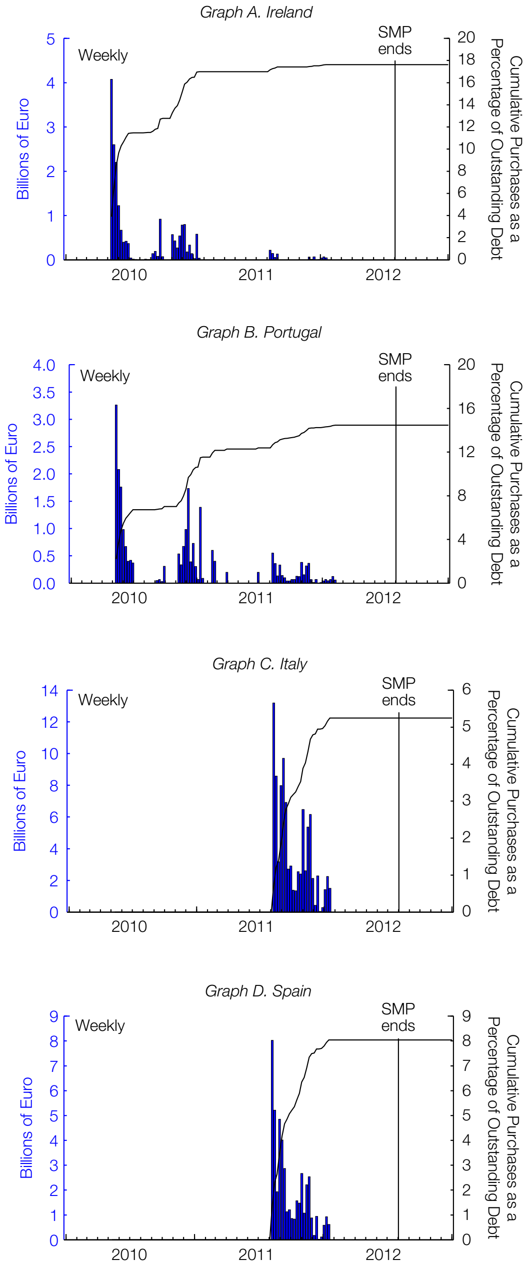
[8]We thank Laurent Fransolet for kindly sharing these data with us.

[9]In practice, however, this is not always the case, and in normal times, the basis can be either positive or negative for a variety of reasons. Some commonly stated reasons include one market leading the other in terms of price discovery, the "cheapest-to-deliver" option that is part of standard CDS contracts, liquidity premiums in either the CDS or bond market, counterparty risk, flight-to-safety flows, or an exchange rate effect when the CDS contract is written in a different currency than the reference bonds. We refer readers interested in analyses of this nonzero basis to articles such as Ammer and Cai (2011) and Coudert and Gex (2010). During the time the ECB's SMP was active, the magnitudes by which euro-area CDS-bond bases had moved away from 09 were much more extreme, and as we argue later, we see impaired liquidity in the bond market as the key factor driving these nonzero bases.

FIGURE 1

Securities Markets Programme Purchases: By Country

Figure 1 shows the sovereign bond purchases of the European Central Bank (ECB) under the Securities Markets Programme (SMP), by country, from Barclays data. Bars show the amount purchased each week (in billions of euros). The solid line shows the cumulative amount of debt purchased through the SMP as a percentage of each country's outstanding debt, by aggregating each weekly purchase divided by total outstanding debt at that time.



Although taking German yields as the risk-free rate as we do here allows us to identify the first component of yields, we cannot uniquely separate the remaining yield spread into its default and liquidity components just from bond price data alone. However, CDS spreads also embed an estimate of the compensation that investors require to guard against the sovereign defaulting on its debt. Because bonds and CDSs on the same sovereign should theoretically reflect the same default event, the probability of default priced by bonds and CDSs should be identical. Therefore, by taking the difference between the CDS spreads and the yield spread (i.e., the CDS-bond basis), we can identify a measure of the relative liquidity premium that is embedded in bonds and CDSs.

Bond liquidity premia exist because sovereign bonds are traded over the counter (OTC). Typically, sovereign bonds (outside of the very liquid U.S., U.K., and German bond markets) embed a substantial liquidity premium, capturing the difficulty involved with selling and buying the bonds in an illiquid market. The search-based model of DGP (2005), (2007) describes an important mechanism for bond illiquidity: the search involved in securing a successful transaction.

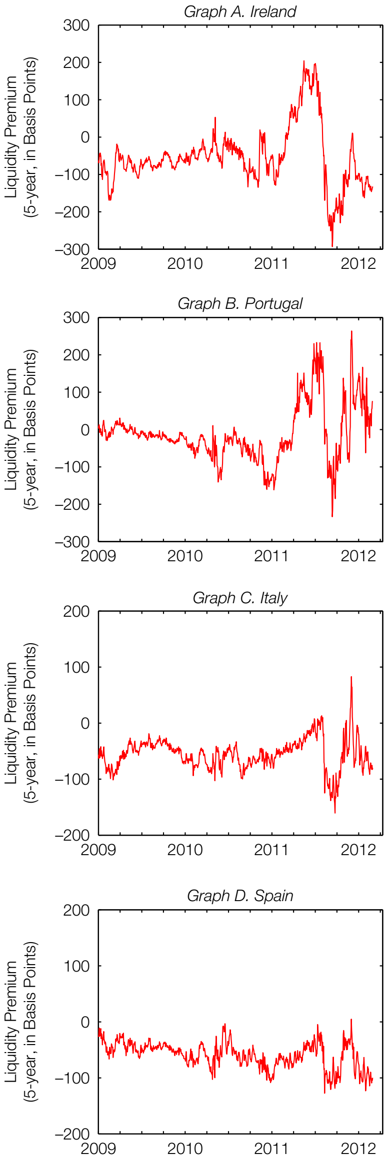
How about the liquidity in the CDS market? CDSs trade differently from bonds: They exist as contacts offered by large transnational banks. "Buying" CDSs means getting bond protection in that contract; "selling" CDSs means offering bond protection in that contract. We would argue that SMP *bond* purchases, by nature, have a negligible effect on CDS "liquidity." Anecdotally, several well-known banks continued to "sell" and "buy" CDSs throughout the period we study. So, the availability of both sides of these CDS contracts did not disappear, despite SMP purchases and a sharp uptick in default probabilities.

Empirically, we evaluate if bond market liquidity is correlated with our two main regressors: SMP bond purchases and the country's probability of default. It seems sensible a priori that our two key regressors are negligibly correlated with CDS "liquidity." From here on, we therefore drop the qualifier "relative" for the sake of exposition; we view our liquidity premium as measuring, with noise, the liquidity conditions in the bond market. Fontana and Scheicher (2016) also examine the CDS-bond basis for euro-area countries and find that bond liquidity is indeed a key driver of the nonzero basis. To aid the interpretation of the estimated effect of SMP purchases on peripheral euro-area yields, we use the *negative* of the CDS-bond basis as our measure of relative liquidity. This way, an increase in a sovereign bond's liquidity risk premium that raises its yield, all else equal, raises our liquidity measure by the same amount. Figure 2 shows the time series of our liquidity measure at the 5-year horizon.

Other studies, such as that by Fontana and Scheicher (2016), typically focus on the CDS-bond basis at just a single maturity, often using benchmark yields to construct the yield spread. Doing so makes results and conclusions dependent on the quality of quotes at exactly that maturity, and a single bad quote could have a substantial impact on results. We opt instead to use the *entire* term structure of bonds and CDS spreads in an effort to reduce that noise. To that end, we use our estimated zero-coupon curves described in Section III.A. Although in our empirical results we will focus predominantly on the 5-year maturity, we also examine the impact of SMP purchases on bond liquidity at the 3-, 4-, 7-, and 10-year maturities.

FIGURE 2
Bond Liquidity at the 5-Year Maturity

Daily time-series estimates of our measure of bond liquidity at the 5-year maturity, expressed in basis points by country.



We now turn to discussing our estimation procedure for extracting sovereign default probabilities from CDS spreads, one of the key variables in our regression analysis in Section III.

C. Estimating Default Probabilities from CDS Spreads

Using the framework of Pan and Singleton (2008), we estimate from CDS spreads the time-varying implied probability that the sovereigns in our sample will default on their outstanding debt. We exploit the fact here that CDS contracts have known cash flows, and we follow the majority of the literature in assuming a known and identical recovery value of 40% in order to estimate these default probabilities. We take euro-area swap rates as our risk-free asset in our CDS calculations and assume a quarterly CDS payment frequency. We specify the hazard rate as a continuous and flexible functional form. In particular, we assume the hazard rate to be equal to the exponential of a Nelson–Siegel (1987) function, the parameters of which we estimate by minimizing the squared differences between the CDS contracts' premium and protection legs across maturities. We refer the reader to the Internet Appendix for the granular details of the estimation. Furthermore, Figure A1 shows our estimated cumulative default probabilities under the assumption of a 40% recovery rate, as well as under several alternative recovery rates.[10]

III. Empirical Results

This section describes our empirical results. The reduced-form linear specification we employ is simple and could accommodate various theoretical predictions. Our baseline estimates come from ordinary least squares (OLS) and (feasible) generalized least squares (GLS). We find both significant impact and persistent effects of official bond purchases and a significant negative relationship between default probabilities and liquidity premia. We then review the sensitivity analyses of these main findings and find that they hold in a variety of alternative specifications.

A. Specification

With our panel data, we estimate the pooled regression equation

$$(1) \qquad \Delta y^j_{L,t} = \beta^j_{\text{FIX}} + \beta_0 \text{FLOW}^j_t + \beta_1 \text{FLOW}^j_{t-1} + \beta_{\text{DEF}} \Delta \text{DEFPROB}^j_t + \beta_{\text{AR}} \Delta y^j_{L,t-1} + \epsilon^j_t .$$

Nations are indexed by the superscript j. We estimate equation (1) in first differences due to evident nonstationarity in the data. The dependent variable $y^j_{L,t}$ is the negative of the CDS-bond basis, reported in units of yield basis points, which we take as a noisy measure of the liquidity premium embedded in bond yields. Of note, we find that our assumption of pooling data across countries is accepted by the data (see Section III.C).

We primarily evaluate if bond market liquidity is correlated with SMP bond purchases and the country's probability of default. This appears reasonable: The existence of a new buy-and-hold investor and the enhanced probability of an

[10]Figure A1 suggests that our estimates of the default probability mainly shift parallel for alternate recovery-rate values. However, the time-series variation is essentially unchanged over a wide range of recovery rates, and our empirical estimates are indeed robust to alternate recovery-rate assumptions.

imminent debt restructuring likely affect bond liquidity conditions. The model in Section IV suggests one mechanism for how this is so.

We measure SMP purchases in week t by FLOW_t^j, converted to a percentage of the amount of country j bonds outstanding.[11] One might argue for instead using total euro-area debt as the denominator, but we do not for at least two reasons.[12] First, the amount of total euro-area debt is dominated by the debt of Germany and France, two countries that were not part of the SMP. Second, the amount of total euro-area debt would be the proper denominator if all European bonds were perfect substitutes, but the CDS and pricing data clearly demonstrate that they are not. Furthermore, the SMP was initiated in part due to the increasingly fragmented nature of peripheral European bond markets at the time. Therefore, we see our choice of country-specific denominators as preferable.

We include the contemporaneous and the first-order lagged effect of FLOW_t^j. This enables us to distinguish temporary and permanent effects. In sensitivity analyses, we explore using additional lags beyond the first, but we find them to be insignificant. We report the Wald statistic testing the null hypothesis $\beta_0 + \beta_1 = 0$ that there are no lasting effects on bond liquidity from official purchases.

$\Delta\text{DEFPROB}_t^j$ is the change in the default probability (in percentage) for country j as derived from CDS prices. It is noteworthy that some previous empirical studies on the effects of official bond purchases have not included this variable, for a couple of good reasons: i) The periods or countries on which the previous research focuses often include little variation in conventional measures of this variable, and therefore its effects may have been negligible. ii) Without a structural model to rely on, one might reasonably assume that the CDS-bond basis does not systematically respond to the default probability because the default premia in bonds and CDS should approximately cancel one another out. Nevertheless, we want to control for this variable in our empirical exercise, particularly because the liquidity premium responds to the probability of default in our theoretical model.

We also include the past change in bond liquidity $\Delta y_{L,t-1}^j$. It could be that bond liquidity itself is a signal used by the ECB to conduct bond purchases in the first place, the purchases have no effect, but bond liquidity tends to improve after a large degradation. If this is the case, we would expect β_{AR} to be significantly negative and β_0, β_1 to be insignificant. Previewing our results, β_{AR} is uniformly insignificant.

Finally, we include country fixed effects, by means of the $\beta_{\text{Fix},j}$ coefficients, to pick up differential trends in y_L over our sample. Our first set of baseline results comes from OLS. However, the error terms ϵ_t^j are likely to be correlated in a cross-sectional manner. In this case, the maximum-likelihood estimator is given by (feasible) GLS. To implement this, we estimate the residuals' covariance matrix by the residuals from the OLS estimation. The residuals exhibit negligible autocorrelation, and so we report White (1980) standard errors and t-statistic p-values.

[11]Note that by computing purchases over outstanding debt, we take into account bond issuance and redemptions by euro-area sovereigns.

[12]We thank an anonymous referee for making this point.

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B. Baseline Results

Table 1 reports our baseline results using OLS and GLS: These agree with one another for all our main qualitative results, and the quantities are usually statistically close as well. We use weekly data from Jan. 2010 through Mar. 2012 for Ireland, Portugal, Italy, and Spain, taken as Friday closing values. We focus on the 5-year maturity so that our coefficient estimates tell us the average response of the 5-year sovereign bond yield. We consider the 5-year maturity because market participants report that official purchases are heaviest around this tenor, 5-year sovereign CDSs are the most liquidly traded, and it roughly captures the maturity preference of ECB purchases reported by market participants at the time. In the following sensitivity analyses, however, we find our results to be qualitatively similar for nearby maturities.

TABLE 1
Baseline Results

Table 1 shows weekly data for Jan. 2010–Mar. 2012 for Ireland, Portugal, Italy, and Spain. We use the credit default swap (CDS)-bond basis at the 5-year maturity. Coefficients β_0, β_1, and β_{DEF} reflect basis-point responses to percentage-point changes. Country fixed effects are included. Under the point estimates, heteroskedasticity-robust standard errors are reported in square brackets, and p-values from t-statistics based on the standard normal are reported in parentheses. Below the Wald statistic in parentheses is its p-value based on a $\chi(1)$ distribution.

β_0	β_1	β_{DEF}	β_{AR}	$\beta_0+\beta_1=0$ Wald Statistic	R^2 (%)	Notes
−31.89	19.06	−4.18	−0.06	9.97	13.15	OLS
[4.89]	[4.94]	[0.87]	[0.09]			
(0.000)	(0.000)	(0.000)	(0.492)	(0.001)		
−39.57	22.76	−4.67	−0.03	14.70	14.58	GLS
[5.78]	[5.88]	[0.97]	[0.08]			
(0.000)	(0.000)	(0.000)	(0.733)	(0.000)		

The estimates of β_0 and β_1 give our main finding. From the highly significant estimates for β_0, we find a negative "impact effect" of 32–40 bps on the liquidity premium due to a purchase of 1% of debt outstanding. From the estimates for β_1, we find that 19–23 bps of this impact effect is temporary. To calculate the "lasting effect," we should technically account for autocorrelation of changes to the liquidity measure $((\beta_0+\beta_1)/(1-\beta_{AR}))$, but because β_{AR} is statistically insignificant, we take it to be exactly 0 and report the lasting effect as $\beta_0+\beta_1$. The lasting effect of a purchase of 1% of debt outstanding is a reduction in the liquidity premium of approximately 13–17 bps. The Wald tests says it is statistically significant at the 0.1% level.

Of note, we find a significantly *negative* estimate for β_{DEF}. For a 1-percentage-point increase in the country's 5-year cumulative default probability, the liquidity premium falls about 4.2–4.7 bps. This result might be surprising. Because bonds and CDSs written on those bonds price the same default event, why should the CDS-bond basis not "difference out" the effects of a varying default probability? Should we expect no systematic relationship to remain? Indeed, we do expect the default premium to be approximately differenced out; thus, this significant empirical relationship must come via different channels. Our model in Section IV describes how such a negative relationship arises via the channel of bond liquidity.

Altogether, our estimates say that ECB intervention had a significant effect on bond market liquidity. An official purchase of 1% of a country's debt outstanding leads liquidity premia to fall on impact by 32–40 bps. Some of this effect reverses, but a significant impact of 13–17 bps is lasting. Furthermore, we find a strong negative relationship between sovereign bond liquidity premia and the probability of default. A 1-percentage-point rise in the 5-year default probability decreases the liquidity premium by 4.2–4.7 bps.

C. Sensitivity Analysis

An important first check of our empirical results is to evaluate whether or not our pooled (across country) regression specification is appropriate. To this end, we estimate a generalization of equation (1) that includes as additional regressors $\sum_{k=2}^{4} \mathbb{1}(j=k)\left(\gamma_0^k \text{FLOW}_t^j + \gamma_1^k \text{FLOW}_{t-1}^j\right)$. This specification now estimates country-specific SMP purchase coefficients. Therefore, the test of $\gamma_0^2 = \gamma_1^2 = \gamma_0^3 = \gamma_1^3 = \gamma_0^4 = \gamma_1^4 = 0$ embodies the null hypothesis that our pooled regression is correctly specified. For this joint test, the Wald statistic p-value is 0.67, far from statistically significant. Moreover, none of the country-specific γ values are individually significant. Hence, we find that the data are compatible with our pooled specification.

1. Other Specifications at the 5-Year Maturity

Table 2 reports the results for a variety of sensitivity analyses of our pooled regression. Rows 1 and 2 include additional variables to control for financial stress conditions in each nation, to separately control for general financial distress apart from shifts in the default probability or the existence of SMP purchases. We include the euro-wide discount rate (the German yield, in differences) because it could reflect anticipated monetary policy actions or flight-to-safety pressures stemming from the crisis. We also include country-specific financial stress indexes constructed by the Federal Reserve Board (in differences), taken as a principal component of equity market, corporate bond market, term spread, and funding market condition variables. One can see from an increase in R^2 (the adjusted R^2 rises too) that these variables are indeed explanatory. Nevertheless, the impact and lasting effects are only modestly changed. Meanwhile, separately controlling for financial stress actually increases the estimated negative effect of the default probability.

Rows 3 and 4 of Table 2 include 3 lags of the purchases. Now the Wald statistic is for $\sum_{\tau=0}^{3} \beta_\tau = 0$ for β_τ the coefficient on $\text{FLOW}_{t-\tau}^j$. Each of the further lags is statistically insignificant, and the Wald test continues to reject. Our results are essentially unchanged.

Rows 5 and 6 of Table 2 use a CDS-bond basis employing a step-wise parametric function for the CDS curve, instead of the smooth function we use throughout (see the Internet Appendix for more detail on these parametric functions). Virtually nothing in the results is changed.

Rows 7–10 of Table 2 consider throwing out the first weeks of SMP purchases, in two ways, for the following rationale. It is quite apparent that the first SMP purchases were complete surprises to the market. But it could be argued that subsequent "after-first" SMP purchases were less surprising and perhaps

TABLE 2
Sensitivity Analysis: 5-Year Maturity

Table 2 shows weekly data for Jan. 2010–Mar. 2012 for Ireland, Portugal, Italy, and Spain. Coefficients β_0, β_1, and β_{DEF} reflect basis-point responses to percentage-point changes. Estimates include country fixed effects. Under the point estimates, heteroskedasticity-robust standard errors are reported in square brackets, and t-statistic p-values based on the standard normal are reported in parentheses. Below the Wald statistic in parentheses is its p-value based on a $\chi(1)$ distribution ($\chi(3)$ for rows 3 and 4). Specifications vary as follows: Rows 1 and 2 control for the lagged change in the German yield and country-specific financial stress indexes. Rows 3 and 4 include 3 lags of Securities Markets Programme (SMP) purchases. Rows 5 and 6 use a credit default swap (CDS)-bond basis employing a step function for the CDS curve. Rows 7–10 throw out the first SMP purchases in two ways defined in the text. In rows labeled "Memo," we repeat our baseline point estimates from Table 1.

Specification	β_0	β_1	β_{DEF}	β_{AR}	$\beta_0+\beta_1=0$ Wald Statistic	R^2 (%)	Notes
Memo:	−31.89	19.06	−4.18	−0.06	9.97	13.15	OLS
Memo:	−39.57	22.76	−4.67	−0.03	14.70	14.58	GLS
1	−31.04	18.84	−5.45	−0.06	9.87	15.57	Stress controls
	[5.72]	[5.24]	[1.55]	[0.09]			OLS
	(0.000)	(0.000)	(0.000)	(0.491)	(0.002)		
2	−39.38	23.12	−6.67	−0.03	16.26	19.11	Stress controls
	[6.19]	[5.64]	[1.97]	[0.08]			GLS
	(0.000)	(0.000)	(0.001)	(0.667)	(0.000)		
3	−31.58	16.31	−4.18	−0.06	3.00	13.95	Additional lags
	[4.85]	[5.44]	[0.83]	[0.09]			OLS
	(0.000)	(0.002)	(0.000)	(0.470)	(0.083)		Wald: $\sum_{\tau=0}^{3}\beta_\tau=0$
4	−39.64	17.83	−3.63	−0.03	4.23	15.61	Additional lags
	[5.91]	[5.64]	[0.96]	[0.08]			GLS
	(0.000)	(0.002)	(0.000)	(0.689)	(0.040)		Wald: $\sum_{\tau=0}^{3}\beta_\tau=0$
5	−31.52	19.05	−4.19	−0.06	10.27	13.64	Step CDS
	[4.81]	[4.91]	[0.83]	[0.09]			OLS
	(0.000)	(0.000)	(0.000)	(0.498)	(0.001)		
6	−39.62	22.60	−4.69	−0.03	15.26	15.20	Step CDS
	[5.66]	[5.81]	[0.96]	[0.08]			GLS
	(0.000)	(0.000)	(0.000)	(0.748)	(0.000)		
7	−32.68	20.19	−4.54	−0.07	6.36	12.73	After-first:
	[9.83]	[7.32]	[0.93]	[0.09]			2010
	(0.001)	(0.006)	(0.000)	(0.406)	(0.012)		OLS
8	−35.83	20.38	−4.77	−0.03	6.66	11.31	After-first:
	[11.44]	[7.91]	[1.13]	[0.09]			2010
	(0.002)	(0.010)	(0.000)	(0.737)	(0.009)		GLS
9	−22.07	13.37	−4.63	−0.07	2.71	12.15	After-first:
	[11.55]	[8.31]	[0.95]	[0.09]			2010 and 2011
	(0.057)	(0.108)	(0.000)	(0.410)	(0.099)		OLS
10	−32.09	19.01	−5.07	−0.04	4.77	12.41	After-first:
	[12.03]	[8.24]	[1.14]	[0.09]			2010 and 2011
	(0.008)	(0.022)	(0.000)	(0.789)	(0.029)		GLS

somewhat expected (although, we note, the ECB throughout the SMP never announced the timing, size, or allocation of its purchases during any given week). The goal of rows 7–10 is to investigate whether or not the estimates change drastically once we focus only on after-first SMP purchases, which might have been somewhat expected.

Rows 7 and 8 of Table 2 throw out the first week of SMP purchases made in May 2010, which were only of the Irish and Portuguese bonds in our sample. Because before this week the ECB had neither engaged in SMP purchases nor discussed the possibility of starting SMP purchases, this week is the most obvious surprise in our data. After the ECB began buying sovereign bonds, one could argue that it may have been expected to make purchases subsequently, and therefore that such after-first SMP purchases were to some extent expected. Qualitatively, nothing changes in our main results. We continue to find a statistically significant impact and lasting effect of SMP purchases and the default probability. The Wald statistics drop by about half, now rejecting at the 1% level (instead of the 0.1% level in the baseline). The effect of default probability is unchanged. The point estimates change a bit, but in large part, the differences from our baseline have to do with the decrease in statistical precision created by throwing away informative observations.

Rows 9 and 10 of Table 2 go a step further and throw away more data. In particular, these rows additionally throw out the first Italian and Spanish bond purchases in Aug. 2011. Perhaps one could argue that although Irish and Portuguese purchases were expected after May 2010, purchases of Italian and Spanish bonds were totally unexpected until the ECB actually made them in Aug. 2011. By ignoring these important observations, we do see the point estimates attenuate: The GLS estimates of the impact and lasting effects are reduced by about 25%. However, the impact effect remains significant at the 1% level, and the lasting effect remains significant at the 5% level. Meanwhile, the default probability effect is increased modestly.

Altogether, rows 7–10 of Table 2 suggest that even if we throw away the SMP purchases that were i) the largest and ii) the most plausible surprises, we continue to see significant impact and lasting effects of the ECB's official intervention in the after-first observations. This suggests that even subsequent purchases were somewhat of a surprise to the market; otherwise, we would see no effect of these after-first purchases because forward-looking prices would have adjusted to account for the expected future official intervention.

In summary, significant impact and lasting effects of official purchases are a robust feature of the data. Moreover, we find that an increased probability of default decreases the liquidity premium embedded in sovereign bonds, and this relationship is robust across various specifications.

2. The Baseline Specification at Other Maturities

We now consider how our results change as we look across different maturities. We cannot really know which maturities the ECB purchased, and so we investigate our main findings' robustness to the choice of maturity. Qualitatively, our main results hold for maturities near the 5-year point. In Table 3, we continue to see a large impact effect of SMP purchases, which is not fully reversed subsequently. We continue to see a negative response of the liquidity premium to rises in the default probability.

Relative to our baseline 5-year point estimates (repeated from Table 1), shorter maturities (3- and 4-year) see slightly larger estimates of impact and lasting effect, but the differences are not statistically significant. The point estimates for the default probability effect attenuate and become less statistically significant.

Moving to the longer maturities (7 and 10 years), the impact and lasting effects attenuate but remain highly statistically significant. Meanwhile, the effect of the default probability actually increases and becomes more precisely estimated: For the 10-year sovereign bond, we estimate that a 1-percentage-point increase in default probability lowers the liquidity premium by about 7–8.4 bps.[13] Moreover,

[13]This accords nicely with the theoretical model to come, which for simplicity views the asset as infinitely lived conditional on nondefault. For long-lived assets in that model, the liquidity premium

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TABLE 3
Sensitivity Analysis: Other Maturities

Table 3 shows weekly data for Jan. 2010–Mar. 2012 for Ireland, Portugal, Italy, and Spain. Coefficients β_0, β_1, and β_{DEF} reflect basis-point responses to percentage-point changes. Estimates include country fixed effects. Under the point estimates, heteroskedasticity-robust standard errors are reported in square brackets, and t-statistic p-values based on the standard normal are reported in parentheses. Below the Wald statistic in parentheses is its p-value based on a $\chi(1)$ distribution. Specifications vary by what maturity is used: 3, 4, 7, and 10 years. The 5-year maturity estimates are repeated from Table 1.

Maturity	β_0	β_1	β_{DEF}	β_{AR}	$\beta_0+\beta_1=0$ Wald Statistic	R^2(%)	Notes
3	−35.39	17.58	−2.32	−0.10	10.98	5.61	OLS
	[5.88]	[6.66]	[1.78]	[0.10]			
	(0.000)	(0.009)	(0.194)	(0.290)	(0.001)		
3	−41.58	18.52	−2.22	−0.07	15.01	5.76	GLS
	[7.15]	[7.91]	[1.89]	[0.09]			
	(0.000)	(0.020)	(0.239)	(0.431)	(0.000)		
4	−33.04	19.18	−2.78	0.03	9.50	6.93	OLS
	[5.45]	[5.67]	[1.27]	[0.09]			
	(0.000)	(0.001)	(0.029)	(0.727)	(0.002)		
4	−40.45	22.20	−3.00	0.02	12.15	8.02	GLS
	[6.74]	[7.16]	[1.41]	[0.09]			
	(0.000)	(0.002)	(0.033)	(0.865)	(0.000)		
5	−31.89	19.06	−4.18	−0.06	9.97	13.15	OLS
5	−39.57	22.76	−4.67	−0.03	14.70	14.58	GLS
7	−28.92	18.44	−6.08	−0.14	12.34	33.80	OLS
	[3.99]	[3.68]	[0.58]	[0.07]			
	(0.000)	(0.000)	(0.000)	(0.041)	(0.000)		
7	−36.07	21.65	−6.95	−0.13	21.27	37.56	GLS
	[3.98]	[3.77]	[0.69]	[0.07]			
	(0.000)	(0.000)	(0.000)	(0.066)	(0.000)		
10	−25.38	19.04	−7.03	−0.11	5.77	47.72	OLS
	[3.97]	[3.32]	[0.58]	[0.08]			
	(0.000)	(0.000)	(0.000)	(0.172)	(0.016)		
10	−33.02	23.84	−8.38	−0.09	7.75	52.22	GLS
	[5.00]	[4.28]	[0.72]	[0.08]			
	(0.000)	(0.000)	(0.000)	(0.222)	(0.005)		

our simple empirical specification now accounts for half of the variation in the CDS-bond basis.

D. Interpreting the Estimates

A difficulty with much of the empirical literature on official bond purchases is that these purchases are taken to measure the program's implementation success, even though markets *should have already adjusted* to the official intervention once they formed expectations of its existence and size.[14] Therefore, should we interpret our empirical results as point estimates, or should we view them as some sort of lower bound on the liquidity effect that does not take into account market expectations?

We have some hope that the particulars of this policy experiment might bring our results closer to "point estimates" than "lower bounds." The ECB did not make detailed announcements about the SMP, either beforehand or after the fact. During the program, the ECB did not even acknowledge whose bonds it was buying. Purely anecdotally, markets did not seem to have consensus views (at the

has a clear negative relationship to the probability of default. Inspecting the mechanism, we would expect this relationship to vanish for short-maturity assets, just as these empirical results suggest.

[14]We thank an anonymous referee for making this point.

time) as to whether or not the ECB would be "in the market" on the following day, let alone the following week. This stands in stark contrast to the U.S. experience, where details down to the Committee on Uniform Securities Identification Procedures (CUSIP) identifiers were given to the market in advance of the actual purchases (D'Amico and King (2013)). Hence, we have some hope that treating each purchase as a surprise (as we implicitly do in the empirical exercise) is a reasonable assumption. But we acknowledge that our estimates may be attenuated by market movements we cannot confidently measure.

As evidence that our stylized view is not at odds with the data, recall the robustness check using after-first SMP purchases. Our empirical results might have changed drastically if we were taking away the only surprising SMP purchases by taking away the first SMP purchases. But our results remain. This suggests that SMP purchases, after the first, still constitute substantive surprises to the market. This offers some support for the way we represent official intervention in the model of the next section.

Our estimates of the default probability's effect do not suffer from this issue. The default probability itself comes from a market price, and so its movements reflect market news.

IV. A Search-Based Model of Liquidity

Our empirical results strongly suggest that official bond purchases have both impact and lasting effects. Furthermore, we find that the default probability has a negative effect on liquidity premia that is robust across specifications and measures. How do these effects arise? How could isolated periods of official purchases give rise to a lasting effect? Why might purchases temporarily decrease liquidity premia below what is ultimately sustainable? Why should an increased probability of default decrease liquidity premia?

To answer these questions, we present an asset-pricing model following DGP (2005), (2007). The model explains liquidity premia by the risk that an agent cannot immediately sell an asset when he or she wants to, due to search frictions. We explicitly include default in the model. We then interpret official intervention as an exogenous reduction in the supply of bonds, caused by instantaneous official purchases of bonds from agents wishing to sell. The model predicts that these purchases change the steady state (a persistent effect) and induce dynamics on the transition path to that new equilibrium (an impact effect). Finally, the model predicts that an increasing probability of default, all else equal, reduces liquidity premia.

Our model hinges on the assumption that sovereign default entails a payment to bondholders that is equal to the bond's "recovery value." This is a typical assumption in the sovereign bond literature and reflects features of recent sovereign defaults actually seen. For example, in the Greek restructuring of 2012, the outstanding bonds were swiftly swapped for new bonds (of greatly reduced face value). This stands in contrast to corporate defaults, which might take months or years to litigate. Such a tie-up of value, motivated, for instance, by the Lehman Brothers' bankruptcy proceedings, is an assumption of He and Milbradt's (2014) corporate bond model (also based on DGP) that gives rise to a *positive* relationship between default probabilities and liquidity premia. Our data strongly suggest a *negative* relationship, and so we make a contrasting assumption that is also consistent with sovereign default experience.

A. Model

Our search-based asset-pricing model adapts DGP's (2005) framework, which in turn rests on Diamond's (1982) seminal work. Our development mirrors theirs except for the addition of an exogenous default arrival process. As in DGP (2007), we neglect the consideration of market-makers analyzed in DGP (2005); this does not affect any of our pricing conclusions and just abstracts from bid and ask prices about which we do not have data. Our primary measure of liquidity y_L, resembling our empirical measure described previously, is the spread between the equilibrium yield and a frictionless yield that would prevail if the asset were exchanged in Walrasian spot markets.

We set agents' time preference by a constant discount rate $r>0$ and assume they are risk-neutral. DGP (2007) show that this framework is a first-order approximation of a model with risk-averse agents and stochastic endowments. An investor is distinguished by whether or not he or she owns the asset and whether or not his or her intrinsic type is "high" or "low."[15] A low-type investor experiences a holding cost of $\delta>0$ per time unit, whereas a high-type investor has no such holding cost. A low-type investor switches to being a high-type investor with intensity $\lambda_u>0$, whereas a high-type investor switches to being a low-type investor with intensity $\lambda_d>0$, each as a result of an exogenous Poisson process. DGP (2005) discuss several possible motivations for this construct. In the context of the European debt crisis, we prefer a motivation tied to exogenous liquidity needs: Exogenous to this particular asset market, a private-sector agent may need to liquidate his or her asset holdings to raise funds, shifting from a high to a low type.

Therefore, the four types of agent in the model are indexed by $\{ho, hn, lo, ln\}$, where h denotes high type, l denotes low type, o indicates an asset owner, and n indicates an asset non-owner. By definition, shares μ of each type of agents sum to 1, so that $\mu_{ho}(t)+\mu_{hn}(t)+\mu_{lo}(t)+\mu_{ln}(t)=1$ for all t. The supply of the asset $s\in(0,1)$ is determined outside the model and restricts the mass of asset owners according to $\mu_{ho}(t)+\mu_{lo}(t)=s$ for all t. Later in the article, official intervention is modeled as exogenous changes to s.

The asset is infinitely lived conditional on being in nondefault, but we introduce into the model an exogenous default Poisson process with intensity $\lambda_D\geq 0$. Upon default, the asset market closes, and owners receive the recovery value $R(t)\geq 0$.

Investors meet other investors according to an exogenous Poisson process with intensity $\lambda>0$. The search is nondirected, and therefore the other investor comes from a uniform distribution across the investor population. Reasonable parameterizations admit equilibrium private-market transactions only when

[15] We analyze a model with only one asset, which implicitly embeds the idea of fragmented bond markets that we employed by using country-specific debt denominators in our estimation. It would be interesting, but beyond the scope of this article, to consider a multi-asset version of the model where bonds are imperfect substitutes by reason of either technology or investor preference.

low-type owners (lo) meet high-type non-owners (hn): lo investors wish to sell, whereas hn investors wish to buy. Assuming a law of large numbers applies (see Duffie and Sun (2007)), the masses' rates of change are identical to those in DGP (2007) because the default process does not alter the evolution of agent types in the model.[16]

However, the introduction of default does affect the value function of every agent. Asset owners take account of the possibility of default and associated recovery rate, whereas non-owners take account of the possibility that they will never be able to buy the asset. We put the value functions for each agent in the Internet Appendix and here present the first-order conditions obtained:

$$\begin{aligned}
\dot{V}_{ln} &= rV_{ln} - \lambda_u(V_{hn} - V_{ln}) + \lambda_D V_{ln},\\
\dot{V}_{lo} &= rV_{lo} - \lambda_u(V_{ln} - V_{lo}) - 2\lambda\mu_{hn}(V_{ln} + P - V_{lo}) - \lambda_D(R - V_{lo}),\\
\dot{V}_{hn} &= rV_{hn} - \lambda_d(V_{ln} - V_{hn}) - 2\lambda\mu_{lo}(V_{ho} - P - V_{hn}) + \lambda_D V_{hn},\\
\dot{V}_{ho} &= rV_{ho} - \lambda_d(V_{lo} - V_{ho}) - \lambda_D(R - V_{ho}) - 1.
\end{aligned}$$

For simplicity, we subsume the dependence on t of $\dot{V}_{(\cdot)}, V_{(\cdot)}, \mu_{(\cdot)}$ and assume R is constant. These equations reduce to those in DGP (2007) when $\lambda_D = 0$. For price determination, we use the surplus-splitting rule $P = (1-q)(V_{lo} - V_{ln}) + q(V_{ho} - V_{hn})$, where $q \in [0,1]$.[17] In general, $P < V_{ho}$, manifesting the earlier statement that equilibrium private-market transactions happen only between lo and hn.

Lemma 1. Assume $s < (\lambda_u)/(\lambda_u + \lambda_d)$ and $R \in (0, 1/r)$. For any given initial distribution $\mu(0)$, there exists a unique steady-state equilibrium. The price is given by

$$(2)\quad P = \frac{1 + R\lambda_D}{r + \lambda_D} - \frac{\delta}{r + \lambda_D}\frac{r(1-q) + \lambda_d + 2\lambda\mu_{lo}(1-q) + (1-q)\lambda_D}{r + \lambda_d + \lambda_u + 2\lambda\mu_{lo}(1-q) + 2\lambda\mu_{hn}q + \lambda_D}.$$

Proof. See the Internet Appendix.[18]

Our analytical focus is on assets whose market value decreases when search frictions increase.[19] To ensure this intuitive feature of the model, we adopt DGP's (2005) condition 1: $s < (\lambda_u)/(\lambda_u + \lambda_d)$. This assumption ensures that in steady state, there is less than 1 unit of asset per high-type agent, and therefore the asset's discounted cash flow equals the frictionless price (defined next). Furthermore, we are interested in situations where the present value of the default-free asset's cash flow is greater than the recovery value obtained upon default; this is ensured by assuming $R \in (0, 1/r)$.

The equilibrium price equation (2) can be rewritten $P = P_f - P_f L$. Both P_f and L are functions of λ_D. The quantity P_f represents the present value of the asset's cash flow, taking into account the possibility of default, which should be

[16]These equations are relegated to the Internet Appendix.

[17]DGP (2007) discuss how this rule can emerge from various bargaining setups, notably Nash bargaining.

[18]As noted previously, default risk does not affect the steady-state distribution of agent types. Hence, when $\lambda_D = 0$, equation (2) reduces to DGP's (2007) price.

[19]DGP (2007) note that an asset, for instance, U.S. Treasuries, might experience a "scarcity value" instead of a liquidity risk premium.

the price were there no search frictions. The quantity $P_f L$ represents the cost of search frictions as dictated by what we call the liquidity discount, L:

$$(3)\qquad L=\frac{P_f-P}{P_f}=\frac{\delta}{1+R\lambda_D}\frac{r(1-q)+\lambda_d+2\lambda\mu_{lo}(1-q)+(1-q)\lambda_D}{r+\lambda_d+\lambda_u+2\lambda\mu_{lo}(1-q)+2\lambda\mu_{hn}q+\lambda_D}.$$

This discount expresses the cost of search frictions as a proportion of the frictionless price. For instance, a liquidity discount $L=0.1$ says that agents must be compensated in order to hold the asset's liquidity risk, and this risk weighs down on the price by 10%.

It is useful to transform the discount L in equation (3) into a liquidity premium that looks like what we have measured in the data. Define the yield $y_L=(P_f/P)-1$: the present value of the asset's future cash flows divided by its market price, minus 1. The yield y_L is equivalently a spread, different from 0 to the extent that the liquidity discount is different from 0, relative to the yield on the theoretical frictionless asset (whose yield so defined is trivially $P_f/P_f-1=0$). Algebraically,

$$(4)\qquad y_L=\frac{L}{(1-L)}.$$

It is clear from equation (4) that y_L is an increasing function of L. The following proposition describes the two key properties of the liquidity premium y_L:

Proposition 1. Assume $s<(\lambda_u)/(\lambda_u+\lambda_d)$ and $R\in(0,1/r)$. Also assume that $\lambda_d/(1-q)+\lambda\mu_{lo}>(1/\zeta-1)r$ for $\zeta\in(0,1)$. Then y_L is increasing in s and decreasing in λ_D.

Proof. See the Internet Appendix.[20]

The proposition's statement about s provides our theoretical understanding of the lasting effect of SMP purchases on bond liquidity.[21] It captures the intuition that increases in the supply of bonds rest more and more in the hands of low-type agents. This increases the compensation agents' demand for the increased risk that they fall in this undesirable pool of agents. Conversely, a reduction in supply limits the steady-state mass of these agents desperate to sell, meaning that search frictions bear less on the present value of the asset, leading the liquidity premium to fall. The channel through which we model official purchases as having an effect is a permanent reduction in s. Therefore, the proposition predicts that SMP purchases permanently decrease the steady-state liquidity premium in euro-area bond yields.

The proposition also says that the liquidity premium falls as the default intensity increases. The cost of liquidity in this model stems from the risk that an asset owner might be unable to sell the asset when he or she wants to in the future. As the asset's default becomes increasingly likely, the "future" over which

[20]The condition $\lambda_d/(1-q)+\lambda\mu_{lo}>(1/\zeta-1)r$ is hard to interpret but generally applies in all but pathological parameterizations of the model (see the Internet Appendix for an argument). We take it as given in order to show that y_L is *everywhere* decreasing in λ_D. Even if the condition does not hold, then we still know that there exists some $\bar{\lambda}_D>0$ such that for all $\lambda_D\geq\bar{\lambda}_D$, y_L is decreasing in λ_D.

[21]This is equivalent to DGP's (2007) first proposition result for the effect of s on the price.

the asset owner reckons this liquidity risk shrinks, and hence the premium falls. This is because, as in Duffie (1998) and consistent with the Greek default in early 2012, we assume the recovery value is paid out immediately upon default.

B. Simulations

We model official intervention as exogenous shocks to the supply of bonds s. Officials (without search) purchase bonds from bond owners, reducing the overall supply of bonds in the private market. This resembles DGP's (2007) formulation of a liquidity shock, in that a mass of agents instantaneously switches states. Our shock differs in that an exogenous central bank agent has taken bond supply out of the system to create this instantaneous switch, which leads our liquidity shock to have permanent effects. We calibrate the amount of SMP purchases to mimic the average amount purchased of Irish and Portuguese bonds in 2010. To make such purchases, the ECB in our model must buy from both lo and ho investors, and therefore the ECB must offer a price that is generally above the equilibrium price (see the Internet Appendix for more discussion).

There are at least three reasons for our conception of a liquidity shock. First, the ECB's objective function is not that of the representative investor. The central bank optimizes different criteria and is not subject to the liquidity pressures we have represented by low-type and high-type investors. Therefore, we regard SMP purchases as exogenous to the model, not undertaken for the profit motives that are captured by our investors' first-order conditions. Second, the ECB is evidently a buy-and-hold investor.[22] This suggests the particular manner in which official intervention should be modeled: An exogenous reduction in the supply of bonds that are available for private market transactions. Third, we assume that the ECB's buying is special: There is no searching required for its purchases. The institution is large and visible, and it can buy as many bonds as it wishes. This is an admittedly simplistic way of modeling ECB purchases, but it captures the same qualitative model features as a more sophisticated modeling strategy (see the Internet Appendix for more discussion).

The ECB initiates the SMP because liquidity conditions exogenously deteriorate; we model this as an exogenous fall in λ, the intensity at which investors meet each other. This amounts to a "search friction shock," making it more difficult for bondholders to meet each other OTC. In Table 4, this is visible in the first row, where "matches per day" drops from 8 to 1.

In Table 4, we report three sets of steady-state values. Column 1 values are prior to the liquidity shock. Column 2 values are after the liquidity shock, *assuming the ECB did not intervene*. Column 3 values are after the liquidity shock *when the ECB intervenes with SMP purchases*, taking supply out of the private market.

To be concrete, we space SMP purchases 5 days apart and conduct 9 purchases that equal (on average) the amount of Irish and Portuguese bonds we actually saw the ECB buy each week. This results in about 8% of outstanding debt being purchased by this 2-month-long simulated intervention. There is anecdotal

[22]This was confirmed by the ECB's Feb. 2013 release in which it classified the SMP holdings as "held-to-maturity."

TABLE 4
Steady-State Values

Column 1 of Table 4 reports important characteristics of the initial steady state prior to the liquidity shock. Column 2 reports the shocked steady state after the liquidity shock with no official intervention. Column 3 reports the steady state after the liquidity shock but when officials intervene. The official intervention is 9 purchases each spaced 5 days apart of an amount of bonds roughly equal to the average amount bought in Ireland and Portugal.

Steady-State Type	Initial 1	Shocked 2	Official Intervention 3
Matches per day (no. of agents)	8	1	1
Wait time (days)	0.9	8.3	6.7
Yield (bps)	310	571	447
Liquidity premium (bps)	25	286	162
Misallocation (%)	0.3	3.0	2.5

evidence that the ECB was not in the market every weekday of the SMP period, and so our assumption is a rough approximation to what actually occurred (see the appendix of De Pooter et al. (2015)). Finally, for simplicity, we model these purchases as surprises to the market, in keeping with the anecdotal evidence at the time and our empirical sensitivity analyses that suggested that after-first SMP purchases had similar effects to the first purchases (see the Internet Appendix for more discussion on this modeling choice).

In our initial steady state (column 1 of Table 4), the sovereign bond has a yield of 310 bps, roughly around the yield on Irish and Portuguese 5-year bonds a month before the SMP began in 2010. The matching intensity is high: Every day, each agent comes into contact with 8 other agents. Because of this frequent matching, the average wait time for the seller is a little less than 1 day.[23] Only one-third of 1% of the market is looking to sell at any time (the misallocation number). Therefore, the liquidity premium is a modest 25 bps.[24]

Assume the search friction exogenously increases: Every day each agent comes into contact with only 1 agent. Suppose the ECB does not intervene. In this new steady state (column 2 of Table 4), the average wait time for the seller shoots up to a little more than 8 days, and now 3% of the market is looking to sell at any time. In this new steady state, the yield shoots up to about 570 bps, about 285 bps of which is the liquidity premium. Figure 3 shows this transition in yields as the gray squares in Graph A.

Now suppose the ECB sees deteriorated market conditions and begins its SMP purchases a week after the search friction increases. Figure 3 plots the daily yields as black dots in Graph A. The black bars in Graph B plot the size of the ECB's 9 consecutive purchases, calculated as the average amount of Irish and Portuguese bonds actually bought, which constitute the proportionate changes in s used in the simulations.[25]

[23] With little to guide these values, we set λ_d, λ_u in line with DGP (2007) such that a high-type stays such for about 1 year, and a low-type stays such for about 6 months.

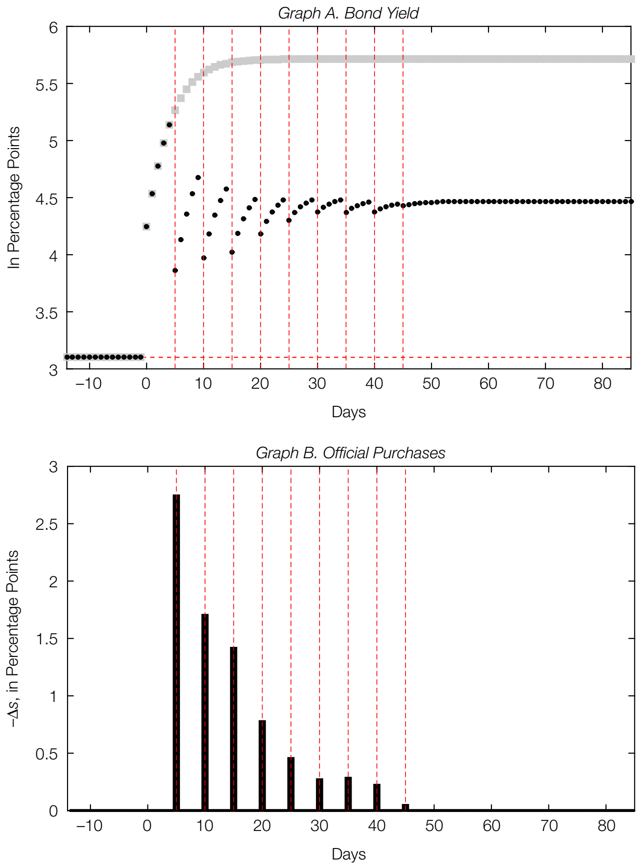
[24] We take the risk-free rate to be 200 bps, roughly where the German 5-year yield was at the beginning of May 2010; therefore, the default premium is 85 bps.

[25] For simplicity, we only consider Irish and Portuguese purchases because they happened first. Italian and Spanish purchases give the same qualitative message.

FIGURE 3

Simulated Bond Yields and Official Purchases

Graph A of Figure 3 shows transition dynamics for bond yields as the model transitions from the "Initial" steady state (prior to day 0) to the "Shocked" or "Official Intervention" steady state of Table 4. "Shocked" yields are shown as gray squares, and "Official Intervention" yields are shown as dots. The search friction shock occurs on day 0. The first official purchase of bonds occurs on day 5. The initial bond yield level is marked by a horizontal dashed line. In both graphs, days of official purchases are marked by vertical dashed lines. Graph B reports the size of each official purchase as a percentage of debt outstanding.



When the ECB buys, yields fall. This comes from two effects, one temporary and one permanent. The permanent effect is that the SMP purchase takes bonds out of the market. We know that this reduces the steady-state liquidity premium. The temporary effect is that the lo pool is reduced by the SMP purchase below its new steady-state level. Because of this, the liquidity premium is temporarily below its new steady-state level. This follows because the liquidity premium is in large part compensation to bond buyers for the risk that they will someday want to sell but not be able to, in other words, that they will someday be in the lo pool. The smaller is the lo pool, the shorter is the time a potential bond buyer expects to be in the lo pool: Because they will be one of the few agents selling bonds, they expect to sell the bond quickly. As the lo pool fills back up to its new steady-state value, this temporary reduction in the liquidity premium goes away.[26] All that is left is the permanent effect.

Figure 3 shows both of these effects. Whenever a purchase occurs, the yield falls and then moves back up in subsequent days. The impact effect is not exactly linear in the model, but it is approximately so. We can find it by dividing the change in yields (the jump between a dot on the thin dashed vertical line and the dot just before in Graph A) by the purchase size (the bar in Graph B). The simulated effects, in basis points, are −46, −41, −39, −39, −39, −39, −38, −38, and −38 for the 9 purchases; they are neither very different from one another nor very different from the effect of −32 to −40 bps estimated in Table 1.

The permanent effect is visible, in that after the ECB has taken out about 8% of the bonds outstanding, the yield is around 445 bps (where the black dots settle down to on the right side of Graph A of Figure 3). This is far below the approximately 570 bps it otherwise would have been (where the gray squares settle down to on the right side of Graph A). The reduction in outstanding bonds reduces sellers' wait times by 1.5 days and reduces the liquidity premium by about 125 bps lower than it otherwise would have been. This is in line with the permanent effect of 105 to 135 bps implied by our estimates in Table 1.

V. Conclusion

We investigate how the ECB's purchases of sovereign debt through its Securities Markets Programme affect peripheral European bond yields, particularly the liquidity premium embedded therein. Bonds' (relative) liquidity premia are measured by comparing prices for sovereign bonds and CDSs written on those bonds. Across a range of specifications, we find strong evidence for the effect of default probability and the effects of SMP purchases on sovereign bond liquidity premia. We find that a 1-percentage-point rise in default probability lowers the liquidity premium on European 5-year sovereign bonds by 4.2–4.7 bps. We find that an official purchase of 1% of sovereign bonds outstanding lowers liquidity premia by 32–40 bps on impact, 13–17 bps of which is lasting.

We include default in the search-based asset pricing model of DGP (2005), (2007) to make sense of our empirical findings. The model predicts that the liquidity premium declines as the probability of sovereign default rises because the risk of needing to search for a buyer falls as the bond's default (and recovery-value payout) becomes more imminent. Meanwhile, official purchases lower the liquidity premium by reducing the outstanding amount of bonds held by the private market and, in the process, reducing the amount of market misallocation.

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[26]This overshooting occurs whenever the reduction in s is larger than the change in steady-state μ_{lo}. Matching the model with the data, purchases are relatively big, and the changes to steady-state μ_{lo} are small, and so this overshooting behavior always happens in our simulations.

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