Quantitative easing and the price-liquidity trade-off *

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We consider the effects of quantitative easing on liquidity and prices of bonds in a theoretical model. Asset purchases initially improve liquidity, but subsequently as the central bank buys and holds bonds to maturity, the bonds become scarcer. The purchases also crowd out other buyers, eventually leading to lower liquidity of the bonds. The effect depends on the share of preferred habitat investors holding the bonds. Lower share of preferred habitat holdings is associated with more elastic demand so that liquidity improves more initially, but then falls more than with high share of preferred habitat holdings. Price impact is larger in case of high share of preferred habitat bond holdings. We calibrate the model to the Eurozone and construct an index measuring the prevalence of preferred habitat investors in each Eurozone country.

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1 Introduction

There is still something to be said for Ben Bernanke's observation in 2014 that while quantitative easing (QE) works in practice, it does not work in theory.[1] The number of empirical studies on the effectiveness of central banks asset purchase programmes as an unconventional monetary instrument when policy rates reach the lower zero bound has grown significantly. The theoretical understanding of QE remains less developed, especially when it comes to the effects of QE on market liquidity.

Interest in QE has increased particularly after the 2008/2009 financial crisis when all major central banks embarked on asset purchases as a means of monetary accommodation after the interest-rate lower bound was reached. Evidence suggests that the programmes had significant short-term effects on targeted and other bond yields in the United States (Krishnamurthy and Vissing-Jorgensen, 2011; Gagnon, Raskin, Remache and Sack, 2011; Swanson, 2017), in the United Kingdom (Kapetanios, Mumtaz, Stevens and Theodoridis, 2012; Joyce, McLaren and Young, 2012a; McLaren, Banerjee and Latto, 2014; Meaning and Warren, 2015), the euro area (Altavilla, Carboni and Motto, 2015; Altavilla, Canova and Ciccarelli, 2016; Andrade, Breckenfelder, De Fiore, Karadi and Tristani, 2016; Blattner and Joyce, 2016; Eser and Schwaab, 2016) and in Sweden (De Rezende, 2017; De Rezende and Ristiniemi, 2018). The studies on the effects of QE on market liquidity have less consistent findings. Some point to increased liquidity (Christensen and Gillan, 2013; De Pooter, Martin and Pruitt, 2015), while others point to declining liquidity, or increased scarcity (Kandrac, 2013; Coroneo, 2015; Schlepper, Riordan, Hofer and Schrimpf, 2017).[2]

At the same time, theoretical models of QE continue to reply on *ad hoc* assumptions rather than providing a "robust theoretical basis" (Woodford, 2012). In standard models, bond prices are unaffected by the open-market operations because of the neutrality of the government's consolidated balance sheet (Wallace, 1981; Eggertsson and Woodford, 2003). For QE to be effective, this assumption has to be loosened to allow for private sector portfolios to be imperfect substitutes. For example, the term structure model is extended by preferred habitat investors that have preferences for specific maturities and are unwilling to exploit arbitrage opportunities (Vayanos and Vila, 2009; Hamilton and Wu, 2012). The

[1] "The problem with QE is that it works in practice, but it doesn't work in theory." Ben Bernanke during a panel discussion at the Brookings Institution, 'Central Banking after the Great Recession: Lessons Learned and Challenges Ahead', Washington D.C., 16 January 2014.

[2] QE programmes are also found to have positive effects on output, consumer prices and labour market performance (Baumeister and Benati, 2013; Weale and Wieladek, 2016; Gambacorta, Hofmann and Peersman, 2014; Luck and Zimmermann, 2018).

models set up a framework in which asset purchases can affect the price of the bonds, but the actual purchases by central banks are not modelled explicitly.

This paper provides an alternative approach to modelling the impact of central bank asset purchases on market prices and liquidity. Our model predicts that QE has a stronger downward effect on yields in countries with relatively more preferred habitat investors. At the same time, we expect liquidity effects of QE on bond markets to be more pronounced in countries with relatively fewer preferred habitat investors.

More specifically, we model sovereign bond markets in a search-theoretic framework of over-the-counter debt with arbitrageurs and preferred habitat investors based on Duffie et al. (2005). That is, financial market rigidity is introduced – analogous to wages in a standard labour market search model – by means of search friction. Empirically, this reflects the practice of some large investors in sovereign bond markets, particularly central banks, to scout the market, which delays the time to transaction.

We model central bank asset purchases explicitly. In a standard asset pricing model, a bond price depends only on the bond characteristics such as face value, coupon payments, maturity, default probability, recovery rate, and the discount factor. In our model, in addition, the price depends a liquidity premium. Bond prices and liquidity are thus not only affected by the pricing kernel, but also by market demand and supply. In this way, the central bank intervention in the bond market impacts prices and liquidity by two channels; it increases/reduces the number of buyers in the market when in starts/stops selling bonds (demand effect), and it reduces the number of sellers in the market when it holds bonds on its balance sheets (supply effect). These two effects are akin to the 'flow effect' and 'stock effect' described in D'Amico and King (2013).

The model explains the market impact of QE in different phases of an asset purchase programme; (i) the announcement and early intervention phase, (ii) the mature intervention phase, and (iii) the tapering/reinvestment phase. In the early phase of an asset purchase programme, an increase in demand for bonds by the central bank results in falling yields. The increase in the number of transactions results in an improvement of liquidity. Once the central bank purchases a significant asset portfolio, the reduction in the supply of bonds on the secondary market results in a further reduction of yields. However, as the stock of bonds is depleted on the secondary market, it becomes harder for buyers to find a seller. The number of transactions fall and liquidity declines. Finally, the central bank tapers its purchases but holds the bonds on its balance sheets. As the central bank exits the bond market, yields increase. However, yields remain below original levels as long as the central bank holds on to its asset portfolio. In this phase, market liquidity deteriorates further as the central bank exits the market as a buyer. This is the price-liquidity trade-off of QE. By purchasing a larger stock of the bonds, yields fall more but at the expense of liquidity.

In our framework the effectiveness of QE does not depend on the presence of preferred habitat investors *per se*. Even purchases of short-term assets can be effective. However, preferred habitat investors determine the magnitude of the effect of the QE programme on prices and liquidity. A larger share of preferred habitat investors implies a smaller share of sellers on the secondary market. Given fewer willing sellers, it is relatively harder for a buyer like the central bank to acquire bonds. As a result, the impact of the QE programme on prices will be higher. At the same time, liquidity reacts more strongly in a market with relatively fewer preferred habitat investors. Given the relatively higher number of willing sellers, the entry/exit of a large additional buyer has a relatively stronger positive/negative impact on bond market liquidity.

Where buyers enter the asset market endogenously (as in Afonso 2011), QE crowds out demand from the market. In this case, the effect of the asset purchase programme on yields is muted. Liquidity initially improves if the central bank demand outweighs the crowding out effect. Once the central bank tapers its purchases and holds on to the asset portfolio, however, liquidity falls below the initial level. This is because – with higher prices – fewer buyers are willing to enter the market than in the pre-QE period. These effects are expected to be stronger in bond markets with relatively fewer preferred habitat investors, as preferred habitat investor are less likely to be crowded out by the central bank purchases.

We calibrate the search-theoretic model for the European Central Bank's (ECB) Public Sector Purchase Programme (PSPP). The PSPP provides a unique environment to explore the effect of QE, which remains underutilised by economic research into the effects of quantitative easing. Namely, the ECB has conducted broadly symmetric asset purchases in a number of national sovereign bond markets, which are very heterogeneous with regard to size and structure. To calibrate the model, we construct a new Preferred Habitat Index (PHI) for the euro area from the ECB Securities Holdings Database. Our PHI shows significant differences across euro area countries with regard to the sovereign debt holdership by preferred habitat investors. The calibrated model illustrates how the originally announced ECB asset purchase programme affected yields and liquidity in euro area countries with a relatively high and low PHI score.

Our model is closest to De Pooter et al. (2015), which studies the liquidity effects ECB's Securities Market Programme (SMP). This is, to the best of our knowledge, the only other study of asset purchase programmes to employ a search-theoretic framework. The paper finds that central bank asset purchases lead to a decrease in the bond liquidity premium by alleviating search friction. However, the purchases by the central bank are not modelled explicitly, so that the model considers only an exogenous reduction in the stock of bonds. The model is closed in the spirit of Duffie et al. (2005), and does not consider endogenous entry of buyers and crowding out of other buyers.

Our paper relates to the empirical work on liquidity effects of QE. Empirical studies of the effects of quantitative easing on liquidity have not been conclusive. For example, Christensen and Gillan (2013) find that liquidity improved as a result of the Federal Reserve's purchases of Treasury Inflation Protected Securities (TIPS). By contrast, Coroneo (2015) finds that TIPS improved liquidity, but this effect was dominated by increased scarcity in the market. D'Amico and King (2013) analyse the repo market in the US and show that there is a considerable and highly persistent scarcity premium on the government bonds, especially at short maturities, traced back partly to the Fed's QE programme. Kandrac (2013) – studying the mortgage-backed securities market during the period of Federal Reserve purchases – finds that purchases negatively affected volumes, trade-sizes, and implied financing rates in dollar roll transactions, but sees no effect on bid-ask spreads. Our model would suggest that these inconclusive results are at least partly due to the fact that asset purchases initially improve liquidity through the demand effect. Only as bonds are withdrawn from the market, they lead to scarcity. [3]

More broadly, our paper also relates to the theoretical and empirical literature exploring the transmission channels through which QE may affect market interest rates (Bernanke and Reinhart, 2004; Joyce et al., 2012b). First, our model relates most closely to the 'liquidity channel' described in the QE literature. As the central bank adds a large and price-desensitive buyer to the asset market, liquidity increases and thus reducing the liquidity

[3] Liquidity concerns were also raised by policy-makers. The Bank of England observed that the government bond market became 'dislodged' during its QE programme, and began to lend back a proportion of the gilts it had bought (Paul Fisher, 2010). In the case of the euro area, Corradin and Maddaloni (2015) show that during the SMP, the government bonds that were purchased became 'special', meaning that their price contained a scarcity premium. This effect was reversed as the ECB began selling purchased bonds back to on the repo market (European Securities and Market Authority, 2016). The International Capital Markets Association (2016) released a study warning of reduced liquidity in the European repo market due to regulation and QE. Analysing high frequency German Bund data, Schlepper et al. (2017) show that ECB's asset purchases led to an increased scarcity of Bunds and this effect has increased over time.

premium and yields (Gagnon et al., 2011). The literature gives relatively less importance to this channel compared to, in particular, the portfolio rebalancing channel (Joyce et al., 2011; Krishnamurthy and Vissing-Jorgensen, 2011). In this regard and second, our model provides a description of the mechanism underlying the effect of QE on the local supply of securities of a particular maturity range. Where individual investors have a preferred range of asset maturity, falling yields of bonds targeted by the central bank will result in investors rebalancing their portfolio and shifting investments towards asset substitutes with higher expected returns. Although the effect is not modelled explicitly, this 'scarcity channel' will result in a drop of yield across assets in this maturity class through changes in demand and supply of assets (Schlepper et al., 2017).[4]

This paper proceeds as follows. In Section 2 we lay out the search-theoretic model of over-the-counter debt and the effect of QE on prices and liquidity. Section 3 provides a brief description of the PSPP, presents the new Preferred Habitat Index for the euro area and presents the results of the model calibrated with the PHI.

2 A micro-founded model of over-the-counter debt markets

The following section describes the search-theoretic model used to illustrate government bond purchases by central banks. We first describe the agents, and their endowments, and solve the model. Then we show some of the results on bond prices and liquidity in a simple version where the masses of investors are exogenously determined. In the last part we allow the masses of investors vary, and illustrate a model solution when buyers enter endogenously.

Model set-up

The model is based on a search theoretic model of over-the-counter debt by Duffie, Garleanu and Pedersen (2005) that first showed how over-the-counter market could be modelled through search frictions. Lack of centralised exchange for bonds leads agents

[4]An alternative version of the portfolio rebalancing channel emphasises the increasing bond premium with increasing risks of unexpected future changes in policy interest rates. When the central bank extracts assets with longer maturity, duration risk decreases in investor portfolios and yields fall across the maturity spectrum ('duration channel'). The exact mode of operation and the relative importance of these individual channels have been subject of much academic debate. Against the sovereign debt crisis in the euro area, empirical evidence suggests that the 'default risk channel' may play a role in non-risk free asset markets (Krishnamurthy et al., 2018). Here, central banks are expected to hold securities to maturity and where monetary policy stimulus is expected to improve the economic outlook and reduce default risks.

to search for a counterparty for their trade. For sovereign bonds, it often means going sequentially from trader to trader to request quotes for the bonds. Organised trading platforms exist for government bonds, especially for large countries, however, investors, and central banks tend to scout the market to get a view on order books across dealers, which adds to the time to transaction. Trades can be made based on theoretical prices posted on the trading platform by bond holders, but these often deviate enough from the traded prices, so that scouting of the market is necessary.

The bond prices are dependent on this search friction, which can be decomposed to demand (flow) and supply (stock) effects, both of which quantitative easing affects. A larger supply of bonds leads to improved search alternatives for the buyers, leading to a decline in the price of the bond. Similarly, higher demand for bonds leads to an increase in the price. The central bank purchases reduce the supply of bonds for a given stock supplied by the government, since the central bank buys the bonds for a long holding period.[5]

The model is set in continuous time with a continuous flow of meetings subject to the search friction. The agents meet each other randomly, with uniform probability of meeting a certain type of agent. The search intensity is represented by the Poisson parameter λ, such that the mean time to meet a new agent is $1/\lambda$. We study the steady state of the model to draw conclusions about final prices, and liquidity, abstracting from the dynamics to arrive at the equilibrium.

In order to study the effects of quantitative easing, we add a central bank as an additional buyer, debt that matures stochastically, and preferred habitat investors who hold debt to maturity. The share of preferred habitat investors holding the bonds is crucial to the results. The supply, and demand effects are non-linear and depend on the initial share of the bonds held by the preferred habitat investors. Large holdings by preferred habitat investors, whom we assume to be hold-to-maturity investors imply that the number of sellers active on the market is smaller. That reduces the buyers' probability of meeting an active sellers, inducing the buyers to pay a higher price for the bonds.

There is a continuum of six types of agents: high, and low type sellers, high type buyers,

[5]D'Amico and King (2013) define flow effects as temporary, and stock effects as permanent effects on prices of bonds. Stock effects are in their words "persistent changes in prices that result from movements along Treasury demand curves", while they define flow effects "the response of prices to the ongoing purchase operations and could reflect, on top of portfolio rebalancing activity due to the outcome of the purchases, impairments in liquidity and functioning that lead to sluggish price discovery". Given the differing persistence of these effects, we map them such that flow effects are equal to demand effects in our model, and stock effects are equal to supply effects in the model. The demand effects persist only during the purchases, while stock effects last as long as the central bank holds the balance sheet.

central bankers, preferred habitat investors, and outside investors. Low type denotes low liquidity, those agents want to liquidate their holdings for cash to finance consumption. In the model those agents have a low discount rate.

Each bond holder holds just one bond. Once those bonds mature, or the investors sell the bond, they consume a unique good available to them, which is used as a numeraire. On the buyer side, the agents: buyers, central bankers, and outside investors all hold an endowment of 1 unit of an asset, which they can use to purchase the bond from the sellers. We now go through each of the agents in turn.

Sellers, low type with mass α_{sl}, are impatient, looking to liquidate their bond holding in order to consume. They hold one bond, which they would like to sell either to a buyer, or a central banker. The probability that they meet a buyer depends on the mass of buyers on the market, i.e. the probability of meeting one. Once a low-type seller finds a buyer, he receives a price P for the bond, exits the market, and consumes 1 unit of the consumption good.

Sellers, high type, with mass α_{sh}, each hold one bond. Because they are patient, they do not trade when they meet buyers. They do however, receive a liquidity shock with probability θ, and become low type sellers, at which point they trade with a buyer when they meet them. The liquidity shock in this case is a funding liquidity shock, as opposed to a market liquidity shock.

Buyers, high type, whose measure is α_b hold a transaction asset in value of 1, which they would like to use to buy a bond from a seller. Buyers are patient, with a discount factor of zero. For this reason, they become high rather than low type sellers after the transaction.

Preferred habitat investors, with mass α_{phi} are hold-to-maturity investors, holding the bonds at quantity of one each. They withdraw the mass of bonds they hold from the secondary market exogenously, and do not participate in the search process.

Central bank is represented by a measure α_{cb}. They buy bonds off the secondary market, and add to the stock of preferred habitat investors by holding the bonds to maturity. Therefore, central bank purchases reduce the number of bonds on the market, with implications on yields and liquidity. For simplicity, we model the central bank as a many central bankers each holding one bond, rather than one central bank holding many bonds. This does not change the results of the paper.

Investor flows are shown in figure 1. Investors in the model are high, and low type sellers, preferred habitat investors, buyers, and central bankers with measures $\alpha_{sh}, \alpha_{sl}, \alpha_{phi}, \alpha_b, \alpha_{cb}$ respectively. They meet each other randomly and trade if there are benefits to trade for both. Investor flows are shown in figure 1.

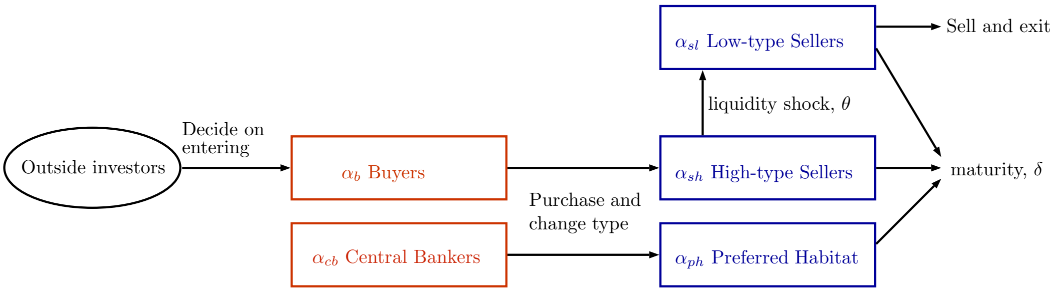

Figure 1: Flows of investors

Government is passive in the model, having supplied a stock D of bonds to the secondary market. Those bonds mature stochastically at rate δ. That means that the bonds held by impatient, low-type sellers may mature before they find a buyer, while the bonds of high-type sellers might mature before they receive a liquidity shock. When a bond matures, the government will return a face value of 1 to the investor holding the maturing bond. With a default probability q, the government does not honour its repayments and investors receive a recovery value $\gamma < 1$ for the bond.

Matching on the market depends on the relative measures of investors. The probability that any of the agents meets another, depends on the measures of those investors on the market, such that larger presence makes meetings more likely. This search friction makes supply and demand for bonds relevant for price, and price no longer depends only on the bond characteristics.

Market tightness is equivalent to the ratio of active buyers to active, low-type sellers, or equivalently demand to supply, $\frac{\alpha_b+\alpha_{cb}}{\alpha_{sl}}$. This is similar to the ratio of unemployed to vacancies in job search literature. Tightness is two-sided in this model. If the tightness ratio is low, the market is tight due to low liquidity in a traditional sense, while if the ratio is large, bonds are scarce due to a low supply of bonds.

2.1 Model solution with exogenous masses of investors

We now set up the expected utilities, and the bargaining process required to solve the model and to reach the first results. We show that the price in the market is affected by

QE in two ways. Firstly, the central bank purchases add a buyer to the market, increasing demand. Secondly, the central bank buys bonds from active, low-type sellers, and by holding them to maturity, reduces the supply of bonds on the secondary market.

The expected utility of a low-type seller is shown in equation 1. These low-type sellers are the only impatient agents in the model, and have a discount factor ρ. The other agents in the model have a discount factor of zero.

The first two terms of the low-type sellers' value function inside the brackets show returns from the bond maturing. The bonds mature stochastically with probability δ, paying 1 as long as the government does not default on its obligations. The government defaults with probability q, in which case the bondholders recover γ.

The probability of meeting a counterparty depends on the mass of those counterparties on the market. With probabilities $\lambda\alpha_b$, and $\lambda\alpha_{cb}$, the seller meets a buyer, and a central bank respectively, and gets a price P for the bond when the transaction succeeds. λ is the Poisson probability of meeting a counterparty, so that $1/\lambda$ reflects the time it takes to find one.

$$V_{sl} = \frac{1}{(1+\rho)} \left[\delta(1-q) + \delta\gamma q + (\lambda\alpha_b + \lambda\alpha_{cb})P + (1 - \delta - \lambda\alpha_b - \lambda\alpha_{cb})V_{sl}\right] \tag{1}$$

Buyers pay a flow search cost of e while they are actively searching for a seller. They meet a seller with probability $\lambda\alpha_{sl}$, in which case they purchase a bond for a price P, and become high-type sellers with expected return of V_{sh}.

$$V_b = -e + \lambda\alpha_{sl}(V_{sh} - P) + (1 - \lambda\alpha_{sl})V_b \tag{2}$$

High-type sellers' bond matures with the same probability δ as low-type sellers'. The repayments in case of a default and non-default are also the same. The high-type seller can be hit by a funding liquidity shock that arrives with probability θ, after which they switch type to impatient sellers.

$$V_{sh} = \delta(1-q) + \delta\gamma q + \theta V_{sl} + (1 - \delta - \theta)V_{sh} \tag{3}$$

We describe the expected returns of the central bank, and the preferred habitat investors in the next section.

2.2 Bargaining over price

When low-type sellers meet a buyer, or a central banker, they bargain through Nash bargaining, and trade. The bargaining process is set up to match the process for government bond purchases by the European Central Bank. The key features are that the purchases are designed to be market neutral, and that the bonds are bought over the counter.

Market neutrality in this model means that the central bank is paying the same price for the bond as any other buyer. In practice this requires making an assumption in the value function of the central bank to ensure that the expected return of the central banker does not differ from the expected return of the buyer.

Following Nash bargaining, we solve for the price using the expected surpluses of each of the bargaining party. The expression for price is in equation 4 for the bargaining between a low-type seller and a buyer, and in equation 5 for bargaining between a low-type seller and a central banker. We denote the bargaining power of a buyer, or a central banker by β. In order to ensure that the price does not differ between a buyer and a central banker, V_{sh} has to equal V_{phi} and V_b has to equal V_{cb}.

$$P = \beta V_{sl} + (1-\beta)(V_{sh} - V_b) \tag{4}$$

$$P = \beta V_{sl} + (1-\beta)(V_{phi} - V_{cb}) \tag{5}$$

We start by writing out the value functions of a buyer and a central bank explicitly:

$$V_b = -e + \lambda\alpha_{sl}(V_{sh} - P) + (1 - \lambda\alpha_{sl})V_b$$
$$V_{cb} = -e + \lambda\alpha_{sl}(V_{phi} - P) + (1 - \lambda\alpha_{sl})V_{cb}$$

A central banker pays the same search cost as the buyer, e. If it meets a seller, it pays a price P for the bond. After trading, the central banker becomes a hold-to-maturity investor, which is equivalent to being a preferred habitat investor. We therefore denote their continuation utility by that of the preferred habitat investors, V_{phi}. The only difference between these two agents is in the continuation utilities they receive following a trade. For the trading price to not differ, those utilities will have to be equal. The expressions for them are shown in equations 6, and 7.

$$V_{sh} = \delta(1-q) + \delta\gamma q + \theta V_{sl} + (1-\delta-\theta)V_{sh} \tag{6}$$

$$V_{phi} = \delta(1-q) + \delta\gamma q + \theta V'_{phi} + (1-\delta-\theta)V_{phi} \tag{7}$$

High-type sellers have a probability θ of being hit by a funding liquidity shock, and becoming a low-type seller with a lower return of V_{sl}. While the preferred habitat investors do not change type, we assume that they are subject to similar shocks that lower their return by the same amount, such that $V_{sl} = V'_{phi}$. One way to think about these shocks is in terms of aggregate negative demand shocks for example, which make the high-type sellers want to liquidate their holdings. Simultaneously, while the preferred habitat investors do not change type, and are less responsive to price changes, they never-the-less bare the cost of these reductions in the valuation of the assets.

Following this assumption, we return to the bargaining process. The bargaining process collapses to solving for the price in a trade between a low-type seller, and buyer. The price paid by a low-type seller, and a central banker will be equal to that.

With the pricing equation 4, we can solve for all the value functions, and the price:

$$V_b = -\frac{e}{\lambda\alpha_{sl}} + \frac{(\delta(1-q)+\delta\gamma q)\rho - \theta k(\rho+\delta) - \delta k(\rho+\delta+\lambda\alpha_b+\lambda\alpha_{cb})}{(\delta+\theta)(\rho+\delta)} \tag{8a}$$

$$V_{sl} = \frac{(\delta(1-q)+\delta\gamma q) + k(\lambda\alpha_b+\lambda\alpha_{cb})}{\rho+\delta} \tag{8b}$$

$$V_{sh} = \frac{(\delta(1-q)+\delta\gamma q)(\rho+\delta+\theta) + \theta k(\lambda\alpha_b+\lambda\alpha_{cb})}{(\delta+\theta)(\rho+\delta)} \tag{8c}$$

$$P = \underbrace{\frac{\delta(1-q)+\delta\gamma q}{\rho+\delta}}_{\text{fundamental value}} + \underbrace{\frac{(1-\beta)}{\beta}\frac{e(\lambda\alpha_b+\lambda\alpha_{cb}+\rho+\delta)}{\lambda\alpha_{sl}(\rho+\delta)}}_{\text{liquidity premium}} \tag{8d}$$

where $k = \frac{(1-\beta)}{(\beta)}\frac{e}{\lambda\alpha_{sl}}$

Price is a sum of two components, *fundamental value*, and *liquidity premium.* The fundamental value is a function of bond characteristics: maturity δ, default probability q, recovery rate γ, and the discount factor ρ. These are factors that enter a typical bond pricing equation, where quantitative easing has no effect on the price.

The second part of the pricing equation contains the liquidity premium that is a function of the supply (α_{sl}), and demand (α_b, and α_{cb}) for the asset. A higher liquidity premium implies that investors pay a higher premium for the bond.

Tightness here is a broader concept than liquidity. Liquidity is about having deep enough markets, with enough buyers so that an investor is able to sell a bond without affecting its price. In terms of the measure of tightness, it means that the ratio of buyers to sellers is large enough. The measure captures also tightness on the sellers side, that is, scarcity of bonds, when the ratio of buyers to sellers is large.

Bond purchases can affect market tightness from both sides. On one hand, they increase the demand for bonds, by increasing the measure of central bankers, leading to improved liquidity. On the other hand they crowd out sellers as the central bank holds the bonds to maturity, incresasing scarcity. When we endogenise the model, we also show that central bank purchases can crowd out other buyers, lowering α_b.

2.3 Results with fixed measures of investors

We explore the key results of the model below in a simple version of the model where we assume that both α_{sl}, and α_b are exogenous. We show that the price of the bond depends on demand and supply, and that central bank bond purchases improve liquidity of the bonds.

2.3.1 Impact of asset purchases on yields

Proposition 1. *Price increases with increasing demand, and declines with increasing supply*

Proof. A partial derivative of price in equation 8d in terms of demand is:

$$\frac{\partial P}{\partial \alpha_b} = \frac{(1-\beta)e}{\beta(\rho+\delta)\lambda\alpha_{sl}} \tag{9}$$

Since $\beta < 1$, the derivative is positive and price increases with demand.

A partial derivative of price in equation 8d in terms of supply of bonds on the secondary market is:

$$\frac{\partial P}{\partial \alpha_{sl}} = -\frac{(1-\beta)}{\beta}\frac{e(\lambda\alpha_b + \lambda\alpha_{cb} + \rho + \delta)}{\lambda\alpha_{sl}^2(\rho+\delta)} \tag{10}$$

which is negative for $\beta < 1$. Therefore, price falls with an increase supply.

□

Proposition 2. *Central bank purchases increase price*

Proof. Central bank purchases increase price through both demand and supply channels. As a central bank announces its intention to purchase the bonds, it in effect decides to enter the market as a buyer, increasing demand through an increase in α_{cb}. This is the stock effect of asset purchases. Price increases as a result of increasing central bank demand, as is seen in equation 11

$$\frac{\partial P}{\partial \alpha_{cb}} = \frac{(1-\beta)e}{\beta(\rho+\delta)\lambda\alpha_{sl}} \tag{11}$$

Asset purchases also affect price through a reduction in the stock of bonds. Given our assumption of a fixed stock of bonds, when central bank purchases the bonds, its holdings of bonds increase and the holdings by active sellers fall[6]. A reduction in the measure of sellers leads to an increase in price given the derivative in equation 10.

We can also see this below in equation 12. The total amount of debt in the economy is the sum of bonds held by all the investors: $D = \alpha_{sl} + \alpha_{sh} + \alpha_{ph}$. We can replace the measure of sellers in the equation for price 8d to see that the increase in the mass of preferred habitat investors (central bankers become hold-to-maturity investors) leads to a higher price.

$$P = \frac{(\delta(1-q) + \delta\gamma q)}{\rho+\delta} + \frac{(1-\beta)}{\beta}\frac{e}{\lambda(D - \alpha_{sh} - \alpha_{ph})}\frac{(\rho + \delta + \lambda\alpha_b + \lambda\alpha_{cb})}{\rho+\delta} \tag{12}$$

□

[6]We assume that the central bank buys only from low-type sellers. This is consistent with micro data evidence in (Koijen, Koulischer, Nguyen and Yogo, 2017) who show that preferred habitat investors do not reduce their holdings as a result of central bank purchases

The effects of QE in this model arise solely from the search friction. Therefore the presence of preferred habitat investors is not necessary for QE to have an effect, in contrast to other models of QE, such as (Hamilton and Wu, 2012; Chen, Cúrdia and Ferrero, 2012). There is also no portfolio substitution because the model has just one bond. However, the supply, or stock effect in the model is similar to the portfolio channel of QE, as it is based on the reduction in the supply of bonds.

2.3.2 Impact of asset purchases on liquidity

We now extend the analysis to the impact of asset purchases on liquidity of the bonds.

Proposition 3. *Liquidity improves initially as the central bank increases demand for bonds. It worsens subsequently when the central bank withdraws bonds off the secondary market.*

Proof. Liquidity is modelled as a measure of transactions, or meetings on the market:

$$L = \lambda\alpha_{sl}\alpha_b + \lambda\alpha_{sl}\alpha_{cb} \tag{13}$$

When the central bank increases demand for bonds, increasing α_{cb}, it becomes easier for sellers to match with a buyer, increasing the number of transactions on the market. Therefore liquidity improves at the start of the purchases. Subsequently, as the central bank purchases bonds and withdraws them off the secondary market, the mass of active sellers shrinks and liquidity declines. □

2.3.3 Impact depends on the mass of preferred habitat investors

The magnitude of the results depends on the share of preferred habitat investors holding the bonds

Proposition 4. *Price increases more as a result of central bank demand when the share of preferred habitat investors holding the bonds is larger.*

Proof. The partial derivative in equation 9, depends on the share of bonds held by preferred habitat investors, α_{ph}. Since the amount of bonds issued by the government, D is held fixed, we can write that $D = \alpha_{sl} + \alpha_{sh} + \alpha_{ph}$. Using this relation, we can write the partial derivative as:

$$\frac{\partial P}{\partial \alpha_b} = \frac{(1-\beta)e}{\beta(\rho+\delta)\lambda(D-\alpha_{ph}-\alpha_{sh})} \tag{14}$$

Equation 14 shows that the impact of increase in demand for bonds by the central bank is larger, for a larger share of the bonds held by preferred habitat investors α_{ph}. This can also be seen in Figure 2

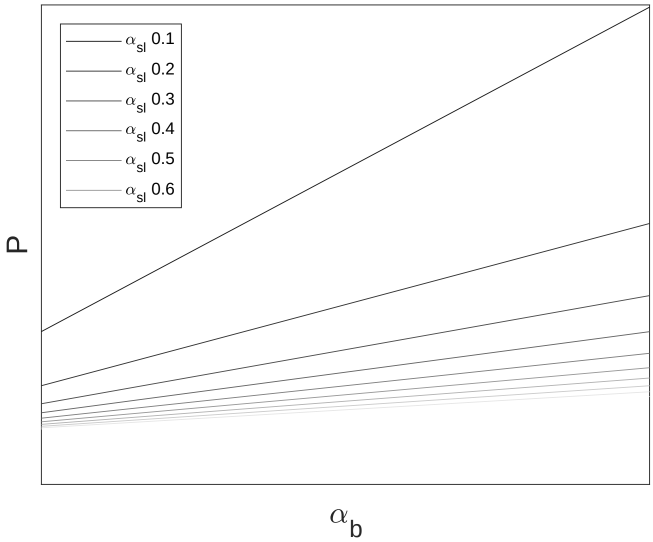

Figure 2: Price is positively related to the mass of buyers. The strength of that relationship depends on the mass of sellers, which is inversely related to the preferred habitat holdings.

□

Proposition 5. *Price increases more as a result of central bank reduction of supply of bonds, when the share of preferred habitat investors is larger*

Proof. Purchasing bonds from active sellers, and holding them to maturity reduces the mass of active sellers α_{sl}. This reduction leads to an increase in the price, and that increase is larger for a larger mass of preferred habitat investors (smaller mass of sellers) on the market. This can be seen in the partial derivative in equation 15.

Figure 3 plots price as a function of the mass of sellers. When the mass of preferred habitat investors is large, and hence the mass of sellers is low, then a reduction in the mass of sellers following central bank purchases, will lead to a larger increase in price, than in the case where the mass of preferred habitat investors is low.

$$\frac{\partial^2 P}{\partial \alpha_{sl}^2} = \frac{(1-\beta)}{\beta} \frac{2e(\lambda\alpha_b + \lambda\alpha_{cb} + \rho + \delta)}{\lambda(D - \alpha_{ph} - \alpha_{sh})^3(\rho + \delta)} \tag{15}$$

□

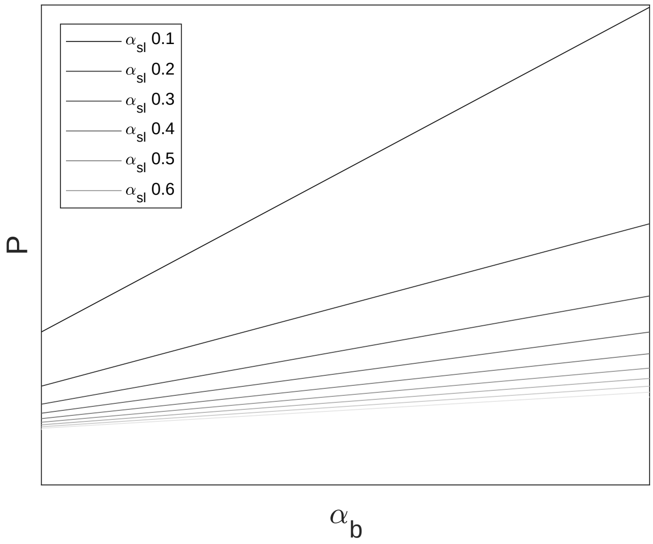

Figure 3: Price is positively related to a decline in the mass of sellers (increase in mass of preferred habitat investors). The strength of that relationship depends on the mass of sellers, which is inversely related to the mass of preferred habitat investors.

Proposition 6. *The increase in central bank demand leads to a larger improvement in liquidity when the mass of preferred habitat investors is low.*

Proof. A partial derivative of liquidity 13 in equation 16 depends on the share of sellers, and substituting that by $D - \alpha_{ph} - \alpha_{sh}$ we can see that the improvement in liquidity from increase in central bank demand is larger the fewer preferred habitat investors there are.

$$\frac{\partial L}{\partial \alpha_{cb}} = \lambda \alpha_{sl} \tag{16}$$

□

Bonds with a large preferred habitat holdings are characterised by high demand and low supply. Central bank purchases exacerbate the situation by further increasing demand and reducing supply. Therefore search frictions become more binding and price moves more as a result.

In the case of low share of preferred habitat holdings, there are few buyers, but many sellers, and when a central bank increases demand, the search friction is instead alleviated. It is easy to match with the sellers, and liquidity improves as the number of buyers increases.

2.4 Model solution with endogenous entry of buyers

We now add outside investors to the model, who compare the value of their outside option to the value of a buyer to decide whether to enter the market as a buyer. When the value function of a buyer declines, fewer outside investors find it profitable to enter the market. The value function of buyers is in equation 8a. It depends negatively on the mass of central bankers demanding bonds, and positively on the supply of bonds, α_{sl}. Therefore, when the central bank increases demand, and reduces supply, the value function of the buyers declines, leading outside investors to reduce entry to the market. Through this mechanism, quantitative easing *crowds out other buyers.*

We now endogenise the entry of buyers in the model.[7] The entry flows of outside investors are denoted by g. Those outside investors compare the value of their outside option K, to the value of becoming a buyer, V_b. If the value of the outside option V_K is lower than the value of a buyer, the investor decides to enter the market and becomes a buyer. Each outside investor is heterogeneous in their outside option K_i. For simplicity, we assume that the value of the outside option V_{Ki} of each outside investor equals K_i. The value of the outside option of a marginal investor, the one that is indifferent to entering, is denoted by K_m. Every outside investor with a value of the outside option less than or equal to K_m enters, and every outside investor with a value of the outside option greater than K_m does not enter. Therefore we get that:

$$g = \int_{\underline{K}}^{K_m} f(K)dK = F(K_m) \tag{17}$$

At equilibrium, $V_K = V_b$, and given our assumption that $V_K = K_m$, it follows that $K_m = V_b$. We can write the above condition therefore as $g = F(V_b)$. This is the equilibrium condition. We call g the entry flows and $F(V_b)$ the buyer return.

Equilibrium solution involves solving both the function g, and V_b for the share of active sellers α_{sl} and looking for the α_{sl} that solves the system. In order to do that, we need to specify the investor flows. In steady state the inflows of outside investors to the economy g, must equal the outflows, the matches between sellers and buyers, and the central bank, i.e.

$$g = \lambda\alpha_{sl}\alpha_b + \lambda\alpha_{sl}\alpha_{cb} \tag{18}$$

[7] We follow closely Afonso (2011) in modelling the equilibrium with endogenous entry.

The flows of patient, high-type sellers, α_{sh} can be written out explicitly. The first term of this flow equation in 19 has the inflows of buyers who are matched a seller, $\lambda\alpha_{sl}\alpha_b$. A share $\lambda\alpha_{sl}$ of the buyers meet a seller and become a high-type seller. With probability θ, the high-type sellers receive a liquidity shock, and with probability δ, their debt matures and they exit the market:

$$\dot{\alpha}_{sh} = \lambda\alpha_{sl}\alpha_b - \theta\alpha_{sh} - \delta\alpha_{sh} \tag{19}$$

At equilibrium $\dot{\alpha}_{sh} = 0$, which gives $\lambda\alpha_{sl}\alpha_b = (\theta+\delta)\alpha_{sh}$. We can substitute this into the equation 18 describing the inflows of outside investors, g and get that $g = (\theta+\delta)\alpha_{sh} + \lambda\alpha_{sl}\alpha_{cb}$.

The flows of preferred habitat investors are similar to the flows of high-type sellers. Inflows consist of central bankers that have met a low-type seller and now become a hold-to-maturity investor. The only way these investors leave their position is through their bond maturing, which happens with probability δ:

$$\dot{\alpha}_{ph} = \lambda\alpha_{sl}\alpha_{cb} - \delta\alpha_{ph} \tag{20}$$

Setting the preferred habitat investor flows to zero, the equation can again be substituted to the equation for g, together with the condition that the total amount of debt in the economy consists of bonds held by the high-, and low-type sellers, and preferred habitat investors, $D = \alpha_{sl} + \alpha_{sh} + \alpha_{ph}$. Finally, we get the first of the equilibrium conditions, the entry flows:

$$g = (\theta+\delta)(D - \alpha_{sl}) - \theta\alpha_{ph} \tag{21}$$

Solving this system of flow equations, we get α_b as a function of α_{sl}, exogenously determined α_{ph}, and parameters only[8]

$$\alpha_b = \frac{(\theta+\delta)(D - \alpha_{sl} - \alpha_{ph})}{\lambda\alpha_{sl}} \tag{22}$$

[8]Later on we calibrate the initial share of preferred habitat investors. The share of bonds purchased by the central bank are similarly calibrated and we know the probability with which the debt held by the preferred habitat investors matures. Hence α_{ph} is predetermined.

Substituting α_b into the equation for V_b in 8a, we get V_b that enters the second equilibrium condition as a function of α_{sl} and parameters only:

$$V_b = \frac{\rho(\delta - (1-\gamma)\delta q)}{(\delta+\theta)(\rho+\delta)} - \frac{(1-\beta)}{\beta}\frac{e}{\lambda\alpha_{sl}}\left[2 + \frac{\delta\lambda\alpha_{cb}}{(\delta+\theta)(\rho+\delta)} + \frac{\delta(D-\alpha_{sl}-\alpha_{ph})}{\alpha_{sl}(\rho+\delta)}\right] \tag{23}$$

We can now search for the α_{sl} that solves for the intersection of the entry flows in equation 21 and buyers value function $F(V_b)$ where V_b is described in equation 23. The intersection of $F(V_b)$ and g give us the equilibrium α_{sl} with which we can derive all the other variables of the model.

Rest of the results follow from the solution to these two key equations. The buyers' value function is upward sloping in α_{sl}. An increasing share of active sellers makes it easier for buyers to be matched and thereby alleviates the search friction from the buyer's side. This improves the expected return of becoming a buyer.

The entry flow condition, g in 21 is downward sloping for α_{sl}, as can be seen easily in equation 21.

Figure 4 plots the equilibrium conditions, entry flows, g, and buyer return $F(J_b)$ for mass of sellers, α_{sl}. Since the buyer value function is upward sloping for α_{sl}, and the entry condition of buyers is downward sloping, we can solve the equilibrium in the model by searching for the α_{sl} where the two curves intersect.

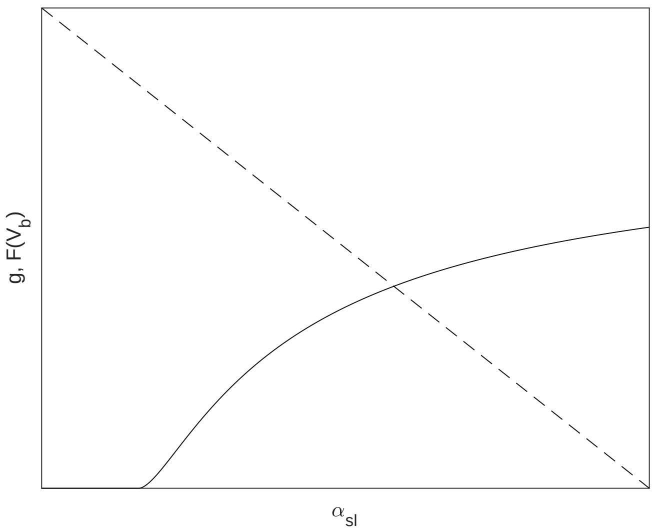

Figure 4: Equilibrium condition

There is no closed form solution to the model. For this reason we firstly explore some of the properties of the solution and then simulate it with a calibration to the Eurozone.

2.5 Results with endogenous entry of buyers

Impact of asset purchases on yields

Below we show some of the results that are different from those presented in the above section with exogenous entry of buyers. The results are mostly dampened through the effect crowding out has on price. We start by analysing the impact of central bank bond purchases on the price of bonds.

Proposition 7. *Central bank demand increases the price of the bond, but the effect is partially muted by changes in the measure of sellers and buyers.*

Proof. As was shown in the case with exogenous α_{sl} and α_b, the demand from central bank, i.e. an increase in α_{cb} leads to an increase in price. However, now also the measures of both sellers and buyers adjust.

The increase in central bank demand affects only the buyer value function $F(V_b)$. The derivative of V_b with respect to the purchases is:

$$\frac{\partial V_b}{\partial \alpha_{cb}} = -\frac{1-\beta}{\beta}\frac{e}{\lambda\alpha_{sl}}\frac{\delta}{(\delta+\theta)(\rho+\delta)} \tag{24}$$

As a result, the buyer value function $F(V_b)$ shifts down as α_{cb} increases, since the price increase from the central bank purchases lowers the value function of the buyers. When $F(V_b)$ shifts down, the intersection of the equilibrium shifts to the right, meaning that equilibrium values of both g and $F(V_b)$ are lower, and that the equilibrium mass of sellers is higher. By equation 22, mass of buyers, α_b then decreases. These two effects put a counteracting downward pressure on price (equation 8d. Therefore, price rises by less when the entry of buyers is endogenous. □

Proposition 8. *Central bank purchases, the reduction in stock of bonds increases the price, and that effect is exacerbated by the increase in the measure of buyers.*

Proof. When the central bank purchases the bonds and withdraws them off the market, the measure of preferred habitat investors increases. As seen in the equilibrium conditions, equation 23 for V_b shifts upward, while equation 21 for g shifts downward. Both of these effects lead to a decline in the measure of sellers, α_{sl}. By equation 22 the mass of buyers, α_b increases. Both the increase in the mass of buyers, and in mass of preferred habitat investors lead to an increase in price. □

Proposition 9. *Central bank asset purchases crowd out other buyers.*

Proof. As was shown above, the central bank demand for bonds lowers the equilibrium inflows of outside investors g. This is the crowding out effect. With endogenous entry of buyers, the outside investors can now decide whether to enter the market, depending on the central bank purchases' effect on their entry condition. Central bank purchases lead to a higher price, which reduces the value of becoming a buyer. Since the value of the outside option does not change, there are more investors for whom the value of their outside option is higher than the value of becoming a buyer. Fewer investors therefore enter the market.

Because the measure of buyers is also now lower, the price impact of the purchases is more muted. The central bank purchases increase the price impact, while the decline in the number of other buyers reduces it.

□

Impact of asset purchases on liquidity

Proposition 10. *Response of liquidity ($\lambda\alpha_{sl}(\alpha_b + \alpha_{cb}$ to central bank purchases is smaller with endogenous entry of buyers.*

Proof. Liquidity improves as a response of central bank demand, increase in α_{cb}, but the effect is dampened by the crowding out effect, a decline in α_b. α_{sl} increases, but the increase in α_{sl} is smaller than the decline in α_b in most situations. This can be seen by taking a derivative of the equation for α_b, 22 in terms of α_{sl}.

$$\frac{\partial \alpha_b}{\partial \alpha_{sl}} = -\frac{(\theta + \delta)(D - \alpha_{ph})}{\lambda \alpha_{sl}^2} \tag{25}$$

The derivative is less than 1 for most realistic calibrations. This is because λ is a large number, except when it takes a very long time to trade, which is at least not the case in Eurozone bond markets. We have assumed a value of 600 in the calibrations, meaning that it takes about

□

3 Model simulations with a preferred habitat index for the euro area

Section 3.1 starts with a short description of the ECB's Public Sector Asset Purchase Programme (PSPP). It then presents the calculation of a a preferred habitat index for the euro area in Section 3.2. This index is employed for the calibration of this paper's model in Section 3.3 and its subsequent simulation in Section 3.4.

3.1 The ECB's Public Sector Asset Purchase Programme and euro area sovereign bond markets

The ECB was the last major central bank to announce in January 2015 a large-scale QE programme in the aftermath of the Great Recession 'in order to address the risks of a too prolonged period of low inflation'.[9] This extended Asset Purchase Programme (EAPP) consists of four elements, namely the Covered Bond Purchase Programme (CBPP3) since October 2014, the Asset-Backed Securities Purchase Programme (ABSPP) since November 2014, the Public Sector Purchase Programme (PSPP) since March 2015 and the Corporate Sector Purchase Programme (CSPP) since June 2016.[10] In the context of the EAPP the ECB purchased around EUR 60 billion per month until March 2016, around EUR 80 billion from March 2016 to March 2017, around EUR 60 billion per month until December 2017 and further reduced purchases to EUR 30 billion per month since then. Total asset holds of the from the EAPP amounts to almost EUR 2.5 trillion in July 2018. Given that the PSPP amounts to more than 80% of these holdings, we will focus on this programme in the following.

Following its announcement in January 2015, the Eurosystem started purchasing public

[9] 'ECB announces expanded asset purchase programme', ECB press release, 22 January 2015.

[10] The portfolio of ECB asset purchase programmes also include the completed Covered Bond Purchase Programmes 1 and 2 (CBPP1 and CBPP2), the Securities Markets Programme (SMP), and the Outright Monetary Transactions Programme (OMT). It should be noted, however, that these asset purchase programmes have a different monetary policy objective. In particular, the CSPP was launched against the background of global financial crisis. It was intended to stabilise the securities market and address bank refinancing problems. The SMP and OMT where launched against the background of the sovereign debt crisis in the euro area. Purchases of government bonds in the secondary market under the SMP were launched with the aim to address problems in the monetary policy transmission mechanism. Until the end of the programme in February 2012 a volume of EUR 210 billion was purchased. The OMT replaced the SMP in September 2012. It aims to safeguard the monetary transmission process and preserve the integrity of the euro area by addressing redenomination risks where they emerge. Purchases of government bonds under the OMT programme require governments to agree to a financial assistance programme. Also, the ECB 'sterilised' asset purchases under the SMP and OMT by withdraw money from the money market.

sector securities under the Purchase Program (PSPP) in March 2015. The PSPP is guided by a number of rules and ECB Governing Council decisions. For example, government bond purchases are only conducted on the secondary market, given that primary market purchases would violate the monetary financing prohibition under Art. 123 of the Treaty on the Functioning of the European Union. The ECB conducts the purchases in national government bond markets on the basis of its capital key. This implies that ECB purchases of are approximately the same as a percentage of GDP cross euro area countries.[11] Originally set to 25% of each bond issuance, in September 2015 the Governing Council decided to increase the issuance limit to 33%. The aim of this limit is to 'to safeguard market functioning and price formation as well as to mitigate the risk of the ECB becoming a dominant creditor of euro area governments'. Finally, the distribution of possible losses on purchased securities is subject to different rules than the other Eurosystem monetary policy operations. Only 20% of PSPP purchased are subject to joint liability, while the remaining risks are borne by the national central banks.

While the asset purchases under the ECB's PSPP are broadly symmetric across euro area countries, national sovereign bond markets are very heterogeneous in terms of their liquidity as well as in terms of riskiness. First, the sovereign bond markets – in line with the size of the economies – are of very different size. At the start of the PSPP, the outstanding debt of Estonia, Malta and Cyprus was only between EUR 2 and 10 billion (2015, source: Eurostat). At the same time, the size of the government debt market is over EUR 2 trillion in Italy, Germany and France. Second, debt sustainability is not the same in all euro area countries. In 2015, gross public debt was above 100% of GDP in Belgium, Cyprus, Portugal, Italy and Greece. At the other end of the spectrum, the debt-to-GDP ratio was only around 10% in Estonia. Accordingly, in late 2015, only three euro area sovereigns maintained a triple-A rating. At the other end of the spectrum, three countries were considered low investment grade (BBB) and three were rated speculative (BB or worse).[12]

Bond purchases by the Eurosystem are expected to be subject to search friction more so than other financial market transactions. This is on account of the relatively small size of many of the sovereign bond markets in the euro area. In any case, although electronic trading volumes have increased significantly, little less than half of bond transactions are

[11] The shares of the NCBs in the ECBs capital key are calculated based in equal parts according to the shares of the respective Member States in the total population and gross domestic product of the European Union (EU) in accordance with Art. 29 its statutes.

[12] December 2015 Strandard & Poors rating.

arranged by 'voice'.[13]

3.2 A Preferred Habitat Index (PHI) for the euro area

We develop a preferred habitat index (PHI) by measuring the prevalence of preferred habitat investors from the ECB's securities holding statistics. We show that there are large differences in the shares of preferred habitat investor holdings, ranging from less than 2% to just under 50% (See Figure 9 in the Appendix). The model is calibrated to core and periphery euro area countries with 42% and 21% of bonds held by preferred habitat investors, respectively.

We construct an index of preferred habitat investors from the ESCB securities holdings statistics (SHS).[14] This relatively new database contains quarterly data on the holdings of securities, including government debt securities, at a security-by-security level. Compared to the more standard aggregate data, it allows for an overview of the holders and issuers of securities by economic sectors at a very granular level of detail (excluding Eurosystem holdings), including their interdependencies. Previously, this kind of detailed data was in the Euro area only available for deposits and loans, or more recently only at the macro level in the "who-to-whom" tables in National Accounts statistics. We describe the database in more detail in Appendix A

Our index of preferred habitat investors is a composite indicator, consisting of the holdings of investors that are likely to be preferred habitat investors. In particular, we consider central banks, general governments outside the euro area, insurance companies, and pension funds (both in and outside the Euro area) to be more likely to preferred habitat investors than other investors in Euro area sovereign bonds.[15] Index measures the preferred habitat investors as a share of the total government debt securities issued by euro area countries (excluding Eurosystem holdings

Our euro area index of preferred habitat investors is new. To our knowledge, there exists no comparable cross-country data on the holders of government debt nor a measure for preferred habitat investors at this level of detail. Blattner and Joyce (2016) is one of the few papers to construct a proxy measure of preferred habitat investors by estimating the amount of "free floating" debt (i.e. excluding foreign official holdings) on the basis of

[13]Morgan Stanley

[14]For more information on the SHS database, see (Rousov and Caloca, 2015; European Central Bank, 2015; Boermans and Vermeulen, 2016)

[15]For examples of papers that model preferred habitat investors in a macro model, see Andrés, López-Salido and Nelson (2004); De Graeve and Iversen (2016).

IMF data of official holdings. The method is based on Arslanalp and Poghosyan (2014). Given public data limitations, their measure contains information on foreign official holdings of debt and does not consider holdings by pension funds, and insurance companies. Andritzky (2012) develops a measure of institutional investors from public sources for the G20 countries, which includes a breakdown to domestic banks, pension funds and insurance companies, and domestic central bank, but excludes foreign central bank holdings.[16]

In Figure 5 the index is presented by (unweighted) country groupings, separating between the larger and higher rated countries and the other Eurozone countries, and the (weighted) Eurozone average, while showing the three components of the index. It is clear that the large difference in the index between the two sets of countries is particularly due to the differences in holdings by central banks, and general governments outside the Euro area, whereas the distribution is less dispersed for insurance companies and pension funds. However, at the individual country level, there is more dispersion that is partly evened out in the country groupings.

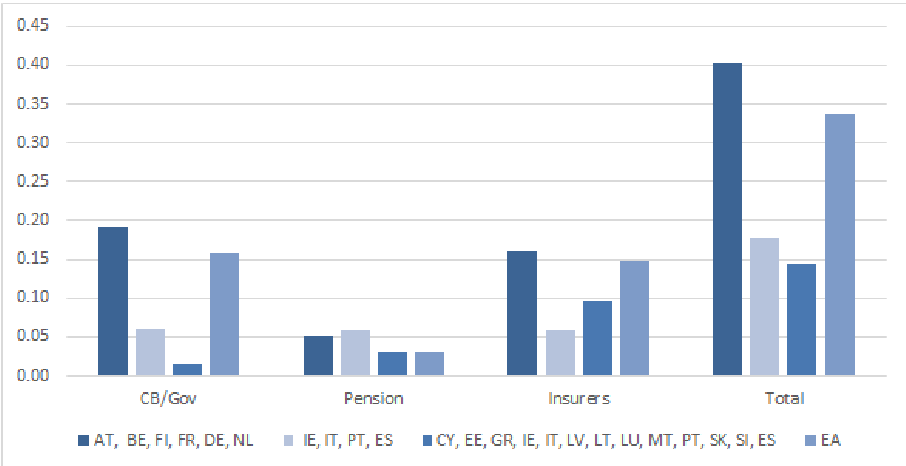

Figure 5: Preferred habitat investors index per sector, 2014 average, for (unweighted) country groupings and the (weighted) euro area average.

The share of preferred habitat investors is a key to results also in New Keynesian models with QE. For example, Chen et al. (2012) estimate the share of preferred habitat investor

[16]There are a few other papers that use the security holdings database, but with a different approach to ours. Boermans, Frost and Steins Bisschop (2016) use the security holdings data base at a security-by-security level to study the effect of market liquidity and ownership on bond price volatility, but focus on concentration of ownership rather than investor characteristics. Koijen, Koulischer, Nguyen and Yogo (2017) do focus on investor characteristics and use security level holdings data to construct a measure of risks exposures across major investor sectors and countries. Studying portfolio flows and the dynamics of risk exposures during the PSPP programme from 2015Q2 to 2015Q4, they find that foreign investors, banks and mutual funds sell the bonds that the central banks buy, whereas euro area insurers and pension funds purchase those same bonds.

holdings of US treasuries to be only 3%. As a result, they get very small effects from central bank asset purchase programme on yields. Burlon et al. (2017) calibrate their model with a higher 25% share of preferred habitat investors and obtain a more significant effect of QE on yields. De Graeve and Iversen (2016) show that the results in this type of model are highly sensitive to the share of preferred habitat investors. Given our finding of around 40% preferred habitat investors in a country with a similar rating to the US, the effects of QE would likely increase substantially in the model.

3.3 Calibration of the model

We simulate the model numerically by looking for the measure of sellers, α_{sl} that solves the equilibrium condition presented in Section 2.5. That is, the point where the entry flows of outside investors equal the expected return of becoming a buyer. The model is calibrated to the Eurozone.

Calibration of the model is shown below in table 1. Bargaining power of the buyers, β is set to 0.5. Correspondingly, the bargaining power of the sellers, $(1-\beta)$ is also 0.5. The average sovereign debt maturity in the Eurozone is 7 years, and the value is quite similar for most of the countries. We therefore set δ, the probability of debt maturing in any given year to 0.14. The high-type sellers are the only agents in the model with a discount factor, and that is set to 0.05. As is common in literature, we set the recovery value to 0.4. The Poisson intensity of the search process, λ is a constant in this model. We set it to 600, which means that if the measure of sellers is one, it takes about a half of a business day on average to find a seller. The probability of liquidity shock is harder to calibrate, and we set it to 0.10. In each year there is a 10% probability of getting hit by a liquidity shock. It should not be too unreasonable given that it is an annual probability. e the buyer search cost is set very low at 0.001. We assume that $F(J_b)$ follows a general beta distribution, and set the parameters of the distribution α and β to 1 and 2 respectively.

Table 1: Calibration

Buyers bargaining power	β	0.5	Probability of a liquidity shock	θ	0.1
Probability of debt maturing	δ	0.14	Buyers' search cost	e	0.001
Sellers' discount factor	ρ	0.05	α of the beta distribution		1
Recovery rate	γ	0.4	β of the beta distribution		2
Search intensity	λ	600			

We calibrate the model to the Eurozone to see how the impact of QE on yields and liquidity differs among the Eurozone countries. The difference in response in the model comes from the different shares of preferred habitat investors in each country, therefore this information is essential for the calibration.

Ideally we would calibrate the model to each country separately, but due to confidentiality of the data used to compute the preferred habitat investor index, we cannot reveal its values for each individual country. We therefore split the sample in two groups of larger Eurozone countries with high and low share of preferred habitat bondholders. The group of countries with a higher share of preferred habitat investors consists of Austria, Belgium, Germany, Finland, France, and Netherlands, while the group with a lower share consists of Ireland, Italy, Portugal, and Spain. The shares of preferred habitat investors in these countries can be seen in figure 6. Inside the box are the countries in the high preferred habitat holdings group and outside those in the low preferred habitat group.

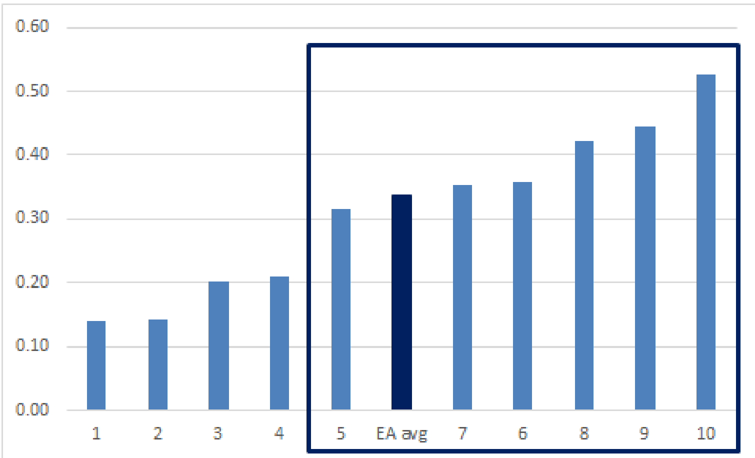

Figure 6: Preferred habitat investor index per Eurozone country, 2014. Countries used in calibration.

Statistics used in the calibration for these country groups are shown below in table 2. The difference in the share of preferred habitat investors between the groups is quite large. In the high group, 42% of debt is held by preferred habitat investors, while in the low group the figure is 21%. The amounts purchased as a share of long-term bonds are very similar in both groups.

Table 2: Calibration of groups

	Preferred habitat	Default probability	Purchases as a share of long-term bonds	Average maturity
High preferred habitat	0.42	0.23	13.29	6.68
Low preferred habitat	0.21	2.14	13.81	7.48

The default probabilities are computed from benchmark 10 year sovereign yields on 1st of December 2014, 3 days before the ECB press conference where Draghi hinted about the upcoming asset purchases programme. As an approximation for a risk-neutral default intensity that we use is $\frac{y-r}{1-RR}$ where y is the yield on 1st of December 2014, r is the risk free rate, German benchmark yield in this case and RR is the recovery rate that we set to 40% as in the calibration.

The average maturity of loans in both groups is very similar, and it is even longer in the low rating group. This is mostly due to the low rating groups having official loans with very long maturities. We calibrate the average maturity to be 7 years for both of these groups.

3.4 Simulation of the model

We simulate the model using the calibration in section 3.3. The model was solved for the bond price, but it is more convenient to look at the impact on yields. We therefore solve for the yield with the following bond pricing formula, where y is the yield, and maturity is $1/\delta$:

$$y = (1/P)^{\delta} - 1 \tag{26}$$

Graph 7 shows the results of the simulation. We show four artificial periods of simulation. The periods are not related to time necessarily, but rather show the effects of central bank bond demand increase (stock effect), and supply reduction (flow effect). In the first period purchases are zero and the share of preferred habitat investors is set to the initial levels we find in data for each group.

The demand and supply side of purchases are analysed separately in the following two periods, such that in period two central bank demand for the bonds increases, and in period three demand remains at the previous period's level, and additionally supply falls. More specifically, in period two, the central bank announces purchases of 13% of the bonds in. In period three those bonds are purchased from low-type sellers and added to the stock of preferred habitat investors. The period three value can be understood as the combined supply and demand effect on yields and liquidity. Note that in both periods we keep the measure of buyers constant in order to show the effect of crowding out separately. In period four the central bank stops the purchases, while it holds the share of bonds it purchased in the previous period on its balance sheet. In this last period we allow the measure of buyers to adjust endogenously in order to show the crowding out effect. The period four effect is therefore the effect of ending the asset purchases that leads to an increase in yields due to the fall in central bank demand.

In period two, as central bank demand for the bonds increases, yields fall, 6.6% in the group with a low share of preferred habitat bond holdings. This can be compared to the 9.7% decline in yield in the group with a high share of preferred habitat holdings of the bonds. The demand element of the model explains approximately two thirds of the decline in yields observed on the announcement day of the first PSPP programme.

Yields decline further in period three as the supply effects of the central bank purchases are added. Period three decline in the yield is therefore the combined effect of increase in demand, and reduction in supply. The combined effect in the group with high share of preferred habitat holdings is 10.8 compared to 9.7 in the group with low share of preferred habitat holdings.

In the last, fourth period of the simulation, central bank tapers the purchases, i.e. it stops buying the bonds but holds the balance sheet. We also allow the number of buyers to vary now, which means that some of the outside investors are allowed to determine whether to enter the market. Yields increase in this case, but especially in the countries with a low share of preferred habitat holdings. This is because demand by buyers falls due to the crowding out effect.

Liquidity improves more in the countries with fewer preferred habitat investors as the central bank increases demand where it is scarce. Eventually, as the central bank stops the purchases but keeps holding the purchased bonds, liquidity falls to a lower level than it was initially. This is because we allow the entry of buyers to adjust endogenously in the last period, and the central bank holdings in that case crowd out potential buyers.

The magnitude of the decline in liquidity depends on how much the measure of buyers is allowed to vary. Since demand by preferred habitat investors is typically less elastic to price, countries with high share of preferred habitat investor holdings of bonds can be thought to have a higher remaining demand, in which case liquidity would not fall as much. Therefore, the liquidity decline is mostly a concern for countries with low preferred habitat demand.

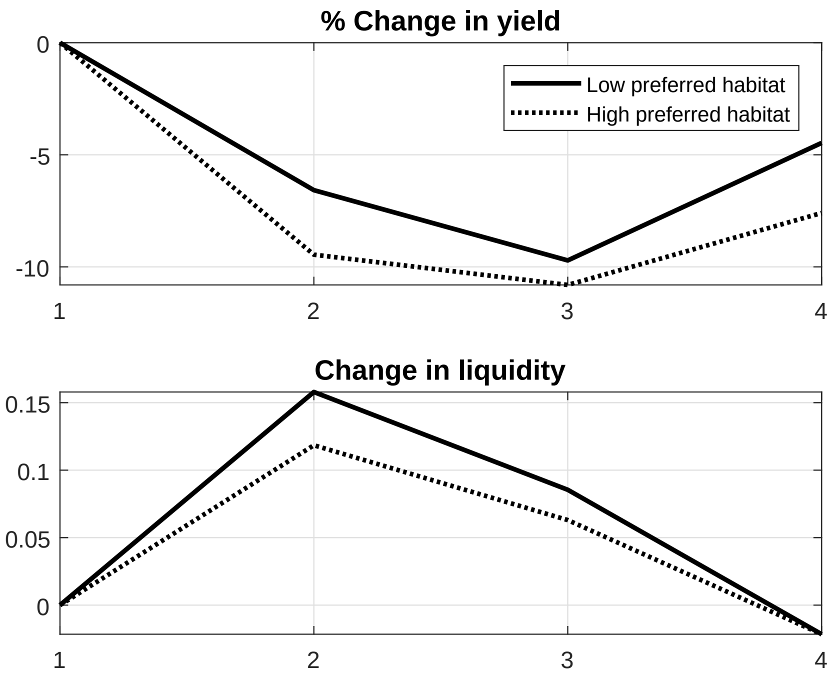

Figure 7: Price and liquidity impact from the calibrated model

3.4.1 Effects of increasing government debt

In many of the countries where central banks have been purchasing government bonds, the size of the issuance has not stayed constant. It has decreased in some countries, and increased in others. We can analyse the effects of those policies in the model.

The price, and liquidity impact of government debt issuance depends on the distribution of the issuances. If the bonds were purchased by the same investors from whom central bank purchases displaced, in the model, the effects of QE would be exactly undone. However, (Koijen et al., 2017) show that it is foreign investors - low-type sellers in our model who sell the bonds, while preferred habitat investors buy the same bonds as the central bank buys. In that case, search frictions would continue to bind at the same intensity and yields would continue to be low.

4 Conclusion

We presented a search-theoretic model of over-the counter debt that allows us to analyse the impact of central bank purchases on yields. The impact is predominantly determined by tightness on the bond market, the ratio between sellers and buyers. In turn, the tightness of the market is influenced by the share of preferred habitat investors. These investors are unwilling to sell their bonds to the central banks and for this reason, prices and yields move more in markets with a higher share of preferred habitat investors, i.e. markets that are tighter.

With data from the ECB securities and holding statistics, we construct a new index for the share of preferred habitat investors in Eurozone countries. This index varies strongly across Eurozone countries, and is positively correlated with sovereign debt ratings. We calibrate the model to the share of preferred habitat investors for two groups of higher and lower rated larger Eurozone countries, and show that yields decline more in countries with larger preferred habitat holdings while liquidity improves more in countries with less preferred habitat holdings of bonds.

The model also predicts a liquidity trade-off effect. The impact on liquidity depends also on the tightness of the bond market. Asset purchases by the central bank improve liquidity initially, as they represent the addition of another large buyer to the market. However, as the central bank reduces the stock of bonds on the secondary market available for sale by holding the bonds to maturity, it subsequently reduces liquidity. Liquidity at the end of purchases is lower than before the start of the purchases.

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Appendix A : Preferred habitat investor index

Securities Holding Statistics (SHS)

Securities Holding Statistics data are collected on a security by security level (based on Regulation ECB/2012/24, as amended by ECB/2015/18) for four security types: short- and long-term debt securities, quoted shares and investment funds shares/units, and subsequently linked with reference data on individual securities from the Centralised Securities Database (CSDB) with additional attributes referring to individual securities and their issuers. The data cover holdings of securities aggregated by selected investor sectors of each Euro area country, excluding the holdings by the eurosystem. The main holding sectors available are (i) deposit-taking corporations, (ii) money market funds, (iii) investment funds, (iv) financial vehicle corporations, (v) insurance corporations, (vi) pension funds, (vii) other financial corporations, (viii) general government, (ix) non-financial corporations, (x) households and (xi) non-profit institutions serving households. For holdings by non-Euro area investors, the mandatory sector breakdown is more restricted and distinguishes only between holdings by General Government and NCBs and the remaining investors.

For our purpose, we focus on the debt securities issues by Eurozone general governments that are held by (i) central banks and governments outside the Eurozone; (ii) insurance companies, both inside and outside the Eurozone, and (iii) pension funds, both inside and outside the Eurozone.

A caveat to be taken into account concerns the collection of data of the holdings of Euro area securities by non-euro area investors, which is to a large extent collected indirectly via custodians and thus may not capture the country of the final investor (i.e., the data suffer from custodial bias). This custodial bias presents a potential risk of double-counting with euro area holdings, where they are held by euro area financial investors in custody outside the euro area (or of double counting euro area holdings, in case of chains of custodians).

Custodial bias would not be expected to significantly influence the data on the holdings of non-euro area central bank and general government, insurance companies and pension funds. If at all, there could be a potential undercounting of the holdings of euro area securities by these sectors ,in particular those by insurance corporations and pension funds. Given the larger than average contribution of holdings outside the euro area to the index of the countries with the highest share of preferred habitat investors in our index, this would likely imply an even larger dispersion across countries.

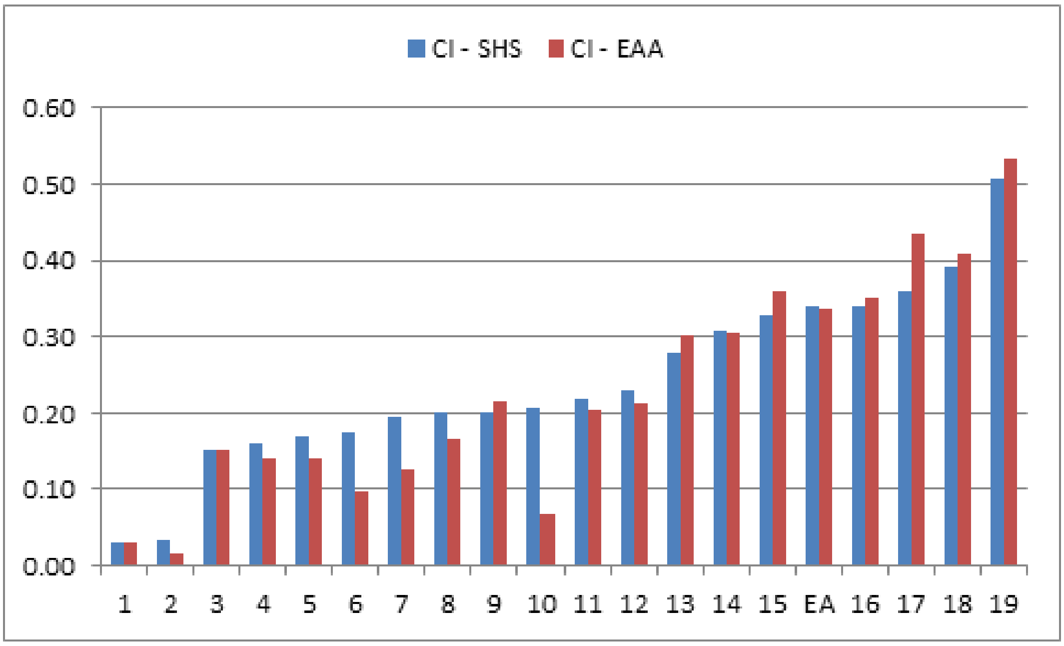

Figure 8: Preferred habitat index (CI) as a share of securities in the SHS and EEA databases

Through the potential double counting, custodial bias could influence the total amount of securities held, which is covered in the data base. Since we express our index as a share of total securities issued, we investigate this potential bias by comparing the total amount of securities included with the amount of general government debt issued by EA countries according to a different data source, the Euro Area Accounts (EEA). This check also allows to address the lack of Eurosystem data in SHSS. While the total amount of debt covered by both databases is very similar (close to 100% for the euro area), there are some differences across countries. In particular, the SHS data base includes smaller amounts held of securities issued by smaller countries than the debt issued according to the EEA, whereas the amount attributed to larger countries with larger financial sectors is higher. Figure 8 shows the preferred habitat index calculated with denominator based on the SHS and on the EEA database. For most countries, the differences are limited, but if there are differences they increase the dispersion of the index across countries. Since the EEA database provides a full coverage of the issued securities, we base the denominator of our index on this database, with the numerator based on the SHS database.

Preferred habitat investor index

Our index of preferred habitat investors is a composite indicator, consisting of the holdings of economic sectors that are likely to be preferred habitat investors, as a share of the total government debt securities issued by euro area countries (excluding Eurosystem holdings). In particular, we consider central banks and general government outside the Euro area, insurance companies, and pension funds (both in and outside the Euro area) to be more likely to preferred habitat investors than other investors in Euro area sovereign bonds.

Central banks hold government bonds of other countries as foreign reserves, assets that can be easily sold in distress. This gives them a special preference for liquid and safe assets and is considered as a particular form of preferred habitat investment (see for instance in Krishnamurthy and Vissing-Jorgensen (2011) for the US Treasuries). While there are few detailed statistics about the holdings of central banks, the ones that do publish show a clear preference for higher-rated and more liquid sovereigns. See table 3 For example, the Riksbank mostly holds German bonds, and more Austrian than Italian bonds. Likewise, the Swiss National Bank, which does not publish a country breakdown, holds most of its foreign currency fixed income assets in securities of AAA-rated countries.

Table 3: Fixed income assets in foreign reserves, end 2014

Riksbank		**Swiss National Bank**	
Germany	68%	AAA -rated	60%
France	12%	AA -rated	25%
Netherlands	9%	A -rated	10%
Belgium	5%	Other	5%
Austria	4%		
Italy	2%		

Riksbank: holdings of foreign currency bonds in the Eurozone`http://www.riksbank.se/en/The-Riksbank/The-Riksbanks-asset-management/Gold-and-foreign-currency-reserve/` Swiss National Bank: holdings of foreign currency fixed income assets: `http://www.snb.ch/en/iabout/assets/id/assets_reserves`.

General government holdings outside the Euro are aggregated together with central banks in the SHS database. However, we consider it likely that the entities in general government that hold foreign sovereign bonds, such as social security funds or sovereign wealth funds, display the same preferred habitat investor characteristics as pension funds and insurers.

According to the preferred habitat theory, institutional factors and regulations influences the behaviour of certain investors, which determines the maturity and asset classes in which they will invest. We consider this to primarily be the case for insurers and pension funds, which both have long-term obligations and are subject to supervision and regula-

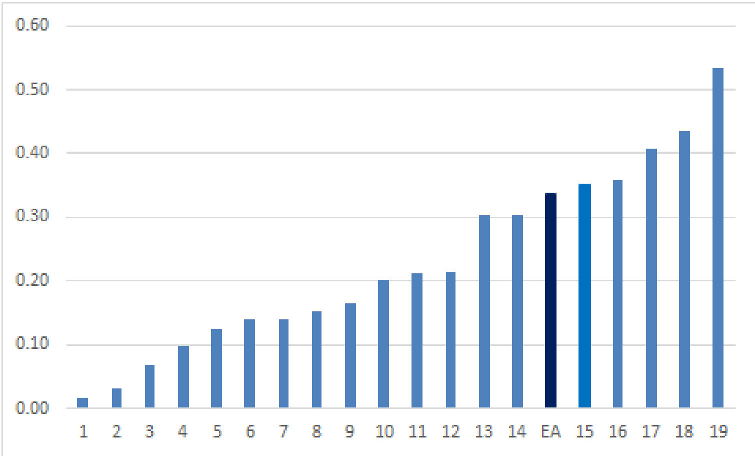

Figure 9: Preferred habitat investor index per Eurozone country, 2014. All Eurozone countries.

tions, including sometimes restrictions on the geographical area or rating of instruments to invest in. For example, held to maturity accounting rules discourage insurance companies, and other long-term investors of selling bonds on the secondary market. These rules state that if an entity sells and therefore marks to market more than an insignificant amount of bonds it holds, it will not be able to account any financial assets as held to maturity in the current and the following two financial years, including all assets in its portfolio. (International Accounting Standards 39 (n.d.))

Our index is a proxy index, based on the characteristics of the investor, rather than the actual behaviour. It is of course possible that for example pension funds act as arbitrageurs with all or part of their sovereign debt holdings, or that other investor sectors act as preferred habitat investors. It is also a broad proxy as the SHS database limits the level of disaggregation of investor sectors that can be considered. In particular, the holding of insurers cannot be broken down in different types of insurers (e.g. life insurers), which might be relevant for the type of maturity that is preferred.

Due to confidentiality of the data we are unable to identify individual countries. However, we can mention some broad characteristics and present country groupings. First, there is a strong correlation between the size of the country and the preferred habitat index. For example, the nine Eurozone countries with the lowest preferred habitat index represent cumulatively less than 10% of the ECB capital key (which reflects the respective country's share in the total population and gross domestic product, and is the basis for the distribution of the ECB asset purchase programme). Second, there is a strong correlation between the rating of the sovereign and the preferred habitat index, with higher

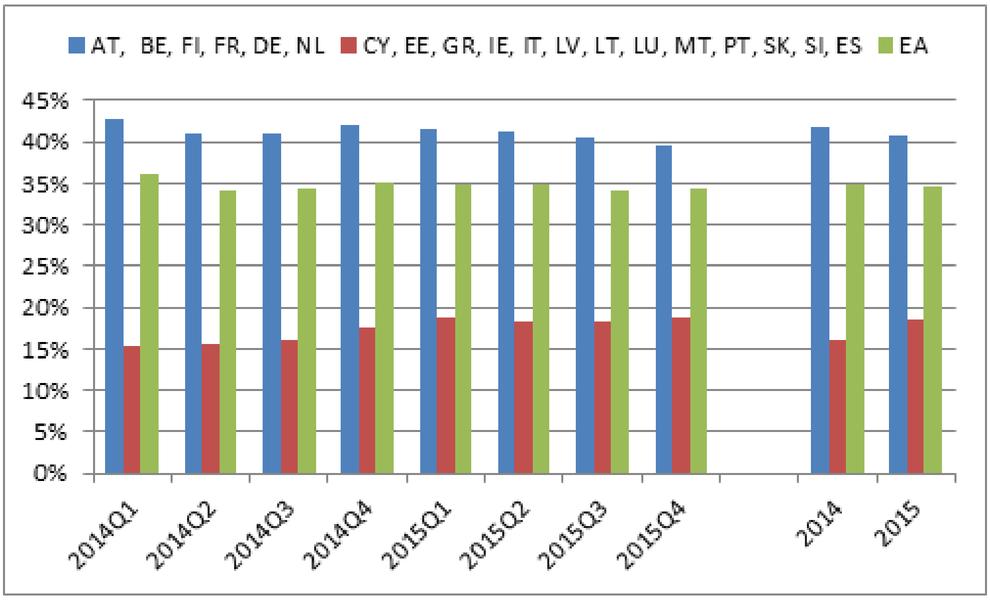

Figure 10: Evolution of the preferred habitat investors index

rated countries having a higher share of preferred habitat investors. Thirdly, when we consider the different components of the index, it is noteworthy that countries with a large second-pillar pension system or a large insurance sector also have a high share of sovereign holdings by these sectors.

Our preferred habitat investor index is relatively stable over time. In figure 10, the quarterly evolution of the index in 2014 and 2015 is shown for the Euro area average and selected country groupings, as well as the annual averages. [17] While there has been some convergence in this period between higher and lower rated sovereigns, the different score on the index remain pronounced, both before and after the start of QE. It should be noted that the index might be influenced by various factors, e.g. the sale of foreign reserves by central banks outside the Euro area, the emergence of some Euro area countries out of EU/IMF financial adjustment programmes, etc.

[17] The SHS data base contains only experimental data before 2013-Q4.