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# 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 search- and matching model. The model explicitly distinguishes between demand and supply effects of central bank asset purchases. Both are shown to lead to a decline in yields, while they have opposite effects on market liquidity. This results in a price-liquidity trade-off. Initially, liquidity improves in reaction to central bank demand. As the central bank buys and holds bonds, supply becomes scarcer and other buyers are crowded out. As a result, liquidity can fall below initial levels. The magnitude of the effects depend on the presence of preferred habitat investors. In markets with a higher share of these investors, bonds are scarcer and central bank asset purchases lower yields more. With a lower share of preferred habitat investors and a relatively illiquid market, central bank demand has a stronger positive effect on liquidity. We are the first to construct an index from bond holding data to measure the prevalence of preferred habitat investors in each euro area country. Subsequently, we calibrate the model to the euro area and show how yields and liquidity are affected by the European Central Bank's asset purchase programme.

**Keywords:** Asset purchases, liquidity, search and matching
**JEL Classification:** E52, E58, G12

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# 1 Introduction

The amount of empirical work on the effects of central banks' asset purchase programmes has grown significantly. The theoretical understanding of the mechanisms by which these programmes affect bond prices and market liquidity remains less developed. In the standard term structure model – the most widely applied theoretical framework – bond supply and demand play no role and the empirical findings of QE for bond prices remain unexplained.[1] At the same time, theoretical work to understand the effect of QE on market liquidity is scare and not conclusive. None of the theoretical contributions model purchases by central banks explicitly.

We model QE in a search-theoretic framework of over-the-counter debt with a central bank, arbitrageurs and preferred habitat investors based on Duffie et al. (2005). This approach focusing on the micro-structure of the bond market is necessary to understand how central bank asset purchases affect prices and liquidity. The effects are determined by the supply and demand for assets that arise from the micro-structure of the bond market. More specifically, in our model asset purchases affect bond prices and liquidity due to a search friction. Such search-and-bargaining frictions are relevant for bond markets, which are largely over-the-counter markets that require investors to scout the market and incur costs before achieving a transaction. To our knowledge, De Pooter et al. (2018) provide the only other search-theoretical model of QE.

We contribute to the literature by being the first to model central bank asset purchases explicitly and show how QE lowers yields through both demand and supply effects. Central bank purchases are typically modelled by an exogenous extraction of bonds from the market, which affects only their supply. We model central banks as an additional buyer in the market and can also analyse the demand effect of QE. In this way, the central bank intervention in the bond market impacts prices and liquidity by two mechanisms; it increases the number of buyers in the market when it starts buying bonds (demand effect), and it reduces the number of sellers in the market when it holds bonds on its balance sheets (supply effect).

Second, we find that demand and supply effects of QE have opposite effects on liquidity. The initial increase in asset demand by the central bank makes it easier for sellers to find a buyer, and hence leads to an increase in market liquidity. However, as central bank asset purchases reduce the free-float of bonds over time, liquidity declines. This creates a price-liquidity trade-off of QE. It also provides an explanation for the inconsistent empirical findings of the effect of asset purchases on liquidity. Liquidity improves initially, but declines as the central bank holdings become larger.

Third, in our model the effectiveness of QE does not depend on the presence of preferred habitat investors *per se*. However, the share of these investors determines the magnitude of both yield and liquidity effects. Assuming a fixed stock of bonds, a larger share of preferred habitat investors with inelastic demand implies a relatively smaller share of sellers vis-à-vis buyers in the secondary bond market. As central bank purchases increase bond demand and reduce supply, sellers can bargain for a higher price. This effect is stronger in countries with a large share of preferred habitat holdings. Similarly, as central bank asset holdings reduce the supply of

[1] Typically, a bond price depends on the bond characteristics such as face value, coupon payments, maturity, default probability, recovery rate, and the discount factor, which are not affected by QE. For QE to be effective, the models are typically extended by preferred-habitat investors with preferences for specific maturities, such that the supply of bonds affects their price (Vayanos and Vila, 2009; Hamilton and Wu, 2012; Chen, Cúrdia and Ferrero, 2012)

bonds, a large share of preferred habitat investors aggravate liquidity shortfalls. In reverse, QE improves liquidity more when the share of preferred habitat investors is initially smaller. Here, there are more active sellers who benefit from a presence of a large, additional buyer. In short, the share of preferred habitat investor holdings has implications for the way QE affects yields and liquidity.

Fourth, we show that market liquidity can even fall below levels prevailing prior to the onset of the asset purchase programme. When buyers enter the asset market endogenously, the decline in the expected return of holding the bonds due to QE crowds out demand from the market. In this case, the effect of the asset purchase programme on yields is muted. At the same time, liquidity initially improves as long as 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 can fall below initial levels. With lower yields, 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 investors are less likely to be crowded out by the central bank purchases.

Fifth, we calibrate the search-theoretic model to the European Central Bank's (ECB) Public Sector Purchase Programme (PSPP). The PSPP provides a unique environment to explore the effects of QE. 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. We construct a new Preferred Habitat Index (PHI) for the euro area from the ECB Securities Holdings Database to calibrate the model. Our PHI shows significant differences across euro area countries in terms of preferred habitat investor holdings. 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 share.

The literature on transmission channels of QE, starting with Krishnamurthy and Vissing-Jorgensen (2011), has evolved quickly over the past years. However, terminology and delineation between the different transmission channels in the literature is not always clear. For example, it may be useful to distinguish between channels with a direct impact on firm and household's borrowing rates – the ultimate objective of the asset purchase programme – and intermediate or indirect channels. The former prominently include the communication channel and the portfolio rebalancing channel.[2] However, much of the literature focuses on intermediate channels, i.e. those that lower yields of the assets targeted by the central bank. This, in turn, results in portfolio rebalancing, where investors shift their investments from the targeted assets towards assets with higher returns.[3] The intermediate channels most widely discussed are the duration risk channel and the local supply or scarcity channel.

This paper contributes to the literature on the indirect transmission channels of QE by explicitly modelling the supply and demand effect of central bank asset purchases. These two effects arise endogenously from the micro-structure of the bond markets. They are akin to the 'stock effect' and 'flow effect' described in D'Amico and King (2013). First, the stock effect

[2]The communication channel itself includes two distinct mechanisms: First, market interest rates may be affected by an announcement channel when the central bank impacts the expectations about future monetary policy (mechanism described in Bauer and Rudebusch (2014)). The signalling channel credibly commits central banks to low levels of interest rates (Clouse et al., 2000).

[3]The literature distinguishes 'narrow' channels, that affect only the price of the targeted asset, and 'broad' channels of QE, which affect also assets not targeted by the central bank directly (Buraschi and Whelan, 2015).

results from a local supply or scarcity channel, whereby central bank asset purchases reduce the free float of assets and increase yields. Second, the central bank adds a large buyer to the asset market (demand or flow effect). The demand or 'flow' effects persist only during the purchases, while supply or 'stock' effects last as long as the central bank holds the balance sheet.

In line with many empirical studies, our model simulations show how central bank asset purchases have been effective in lowering yields in the euro area (Altavilla et al., 2015; Blattner and Joyce, 2016; Eser and Schwaab, 2016; Andrade et al., 2016). Also in line with most of this literature, our model shows that these effects can potentially be stronger in periphery countries than in the core countries at the time of the programme announcement. However, the model suggests that over time the effects of asset purchases are expected to be larger in countries with more preferred habitat investors, which are typically core euro area countries. The supply or scarcity effects become more pronounced and tend to outweigh the demand effects, which have a more pronounced effect in countries with fewer preferred habitat investors. Similarly, most empirical studies show that stock effects are expected to be larger than flow effects (Arrata and Nguyen, 2017; De Santis and Holm-Hadulla, 2019). This effect is confirmed in Arrata et al. (2018) who look at scarcity in the euro area repo market. Consistently with our results, the decline of repo rates following ECB asset purchases has been much larger for German and French sovereign bonds than for Italian and Spanish ones.

This paper also contributes to the scarcer literature on the liquidity effects of QE. De Pooter et al. (2018) find that central bank asset purchases lead to a decrease in the bond liquidity premium replacing the agents who benefit from trade the most, i.e. impatient sellers. 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.

Empirical studies on the effects of quantitative easing on liquidity have not been conclusive. Some studies find that QE improves liquidity (Beirne et al., 2011; Steeley, 2015; Coroneo, 2015; Eser and Schwaab, 2016). For the U.S., Christensen and Gillan (2017) find, for example, that liquidity improved as a result of the Federal Reserve's purchases of Treasury Inflation Protected Securities (TIPS). For the UK, Boneva et al. (2019) show that the Bank of England Corporate Bond Purchase Scheme improves the liquidity of bonds. Other studies find that QE deteriorated liquidity (D'Amico and King, 2013; Kandrac, 2013). For example, Kandrac (2018) shows that the Federal Reserve mortgage-backed securities purchases adversely affected market liquidity. Our model would suggest that these inconclusive results are at least partly explained by the fact that asset purchases initially improve liquidity through the demand effect. Only as bonds are withdrawn from the market, they lead to scarcity. In line with this finding, Pelizzon et al. (2018) distinguish between two opposing effects of QE on the liquidity of Japanese government bonds, namely the increase of demand for bonds which improves liquidity and a scarcity effect with a negative impact, due to the shrinkage in the available supply of bonds. Studies on euro area, such as Corradin and Maddaloni (2019) show that the government bonds that were purchased became 'special', meaning that their price contained a scarcity premium. 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.

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 the effects of QE. We first describe the agents and their endowments in Section 2.1. In Section 2.2 we then solve a simple version where the number of private investors is exogenously determined. In Section 2.3 we present a model where investor flows are endogenous, including flows of outside investors.

## 2.1 Model set-up

Many assets, including government bonds, are traded predominantly in over-the-counter (OTC) markets (Duffie et al., 2007). The defining feature of over-the-counter markets is the lack of a centralised exchange for bonds. Agents need to search for counterparties to trade with, which often means going sequentially from trader to trader requesting quotes for bonds. Organised trading platforms exist for government bonds, especially for large countries. However, investors and central banks tend to scout the market prior to buying to get a view on order books across dealers, which adds to the time to transaction.[4](de Rourea et al., 2019) show that large parts of sovereign bonds are traded OTC.

Our model is based on a search theoretic model of OTC debt by Duffie, Garleanu and Pedersen (2005). We follow Duffie et al. (2005) in that there is only one bond in the market that infinitely-lived agents trade. In order to study the effects of quantitative easing, we add a central bank as an additional buyer. We also add preferred habitat investors who hold a stock of bonds off the market.

There is a continuum of six types of agents in the model: (i) impatient bondholders, who we term low-type sellers, (ii) patient bondholders, who we term high-type sellers, (iii) private buyers seeking to buy the asset, who we term high-type buyers, (iv) central bankers, (v) preferred habitat investors, who hold their bond to maturity and do not search for buyers, and (vi) outside investors. Each bondholder holds just one bond. Once a bond matures, or is sold, bondholders exit the market and consume. Active buyers on the market are the sum of private buyers and central bankers. Central bankers, buyers, and high- and low-type sellers meet each other randomly in the market.

**Low-type sellers**, with measure $\alpha_{sl}$, their bond either to a high-type buyer or a central banker to finance consumption. These low-type sellers are the only impatient agents in the model with a positive discount factor. All other agents in the model have a discount factor of zero. Once a seller finds a buyer, he receives a price $P$ for the bond and exits the market.

**High-type sellers**, with measure $\alpha_{sh}$, are patient. Therefore, a contact with a buyer does not result in a trade. The high-type seller may, however, switch type and become impatient, through experiencing a funding liquidity shock. He then becomes a low-type seller, seeking to make trade with a buyer when they make contact.

**Preferred habitat investors**, with measure $\alpha_{ph}$, are hold-to-maturity investors. Each preferred habitat investor holds one bond. The agent withdraws the bond from the secondary

[4]Trades can be made based on theoretical prices posted on the trading platform by bondholders, but these often deviate enough from the realised prices, so that scouting the market is necessary (Duffie, 2012).

market exogenously, and does not participate in the search process.

**High-type buyers**, whose mass is $\alpha_b$, hold a transaction asset in value of 1 and would like to use this to invest in a bond. They are patient, with a discount factor of zero. For this reason buyers become high-type rather than low-type sellers after the transaction.

**Central bankers** are represented by a measure $\alpha_{cb}$. They buy bonds off the secondary market, and add to the stock of preferred habitat investors by holding the bonds to maturity. Therefore, central bankers' purchases reduce the number of bonds in the market, with implications on yields and liquidity. [5]

**Outside investors** consider whether to enter the market as high-type buyers. They compare their outside purchasing option to the gains from buying a bond.

Government bonds have the following characteristics in the model. The government is passive in the model, having supplied a stock $D$ of bonds to the secondary market. The bonds mature stochastically at rate $\delta$. When a bond matures, the government will return a face value of 1 to the bondholder. With a probability $q$, the government defaults and bondholder receives a recovery value $\gamma < 1$.

Buyers and sellers meet each other randomly and trade if there are benefits to trade. Investor flows are shown in Figure 1.

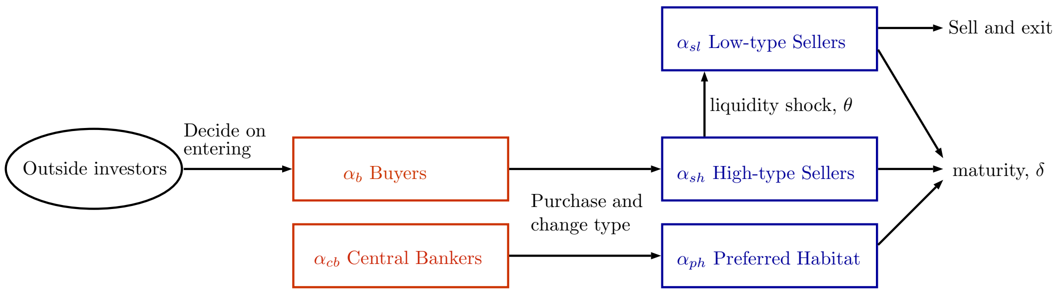


Figure 1: Flows of investors

The model is set in continuous time with a continuous flow of meetings over time. The rate at which the investors find each other, depends on the measure of counterparties on the secondary market, such that each buyer meets a seller with mean intensity $\lambda\alpha_s$, each seller meets a buyer at intensity $\lambda\alpha_b$, and each central banker meets a seller at mean intensity $\lambda\alpha_{cb}$. The total rate of meetings is $\alpha_s(\lambda\alpha_b + \lambda\alpha_{cb})$. [6] We can also think of this as a matching function of the form $M(\alpha_s, \alpha_b, \alpha_{cb}) = \lambda\alpha_s(\alpha_b + \alpha_{cb})$ with increasing returns to scale, as is typical in these types of models.

Market tightness is defined here as a measure of the ease with which buyers and sellers match. It is described as the ratio of active buyers to willing sellers, or – equivalently – demand to supply $(\frac{\alpha_b+\alpha_{cb}}{\alpha_{sl}})$. This measure of market tightness is similar to the ratio of unemployed

[5] For simplicity, we model a central bank as a mass of central bankers, each holding one bond, rather than one central bank holding many bonds. This does not change the results of the paper.

[6] Duffie and Sun (2012) provide the microfoundations for this result. They show how using the law of large numbers on a continuum of agents, the total rate of meetings from independent random matching converges almost surely to $\lambda\alpha_s\alpha_b$ in a model without central bankers.

workers to job vacancies in search-theoretic models of the labour market.

Market tightness has implications for both prices of the bonds as well as for liquidity of the bond market. First, the price of bonds in the model is not only determined by the bond characteristics, but also depends on the matching cost, which is directly related to the tightness ratio. Bonds with high tightness ratio, i.e. many buyers compared to sellers, have a higher price than bonds with a low tightness ratio.

Second, liquidity in the model is defined as the measure of transactions $(\lambda\alpha_{sl}\alpha_b + \alpha_{sl}\alpha_{cb})$. Here both a low measure of sellers, as well as a low measure of buyers leads to a decline in the probability that counterparties meet each other, instead of their own type. Third, market tightness is also influenced by the prevalence of preferred habitat investors. Markets with many preferred habitat investors are typically tighter; there are more buyers relative to sellers, as a larger percentage of the bond holders are hold-to-maturity investors. Markets with few preferred habitat sellers tend to be less tight; there are more sellers relative to buyers.

In the following, we study the steady state of the model to draw conclusions about prices and liquidity, abstracting from the dynamics to arrive at the equilibrium.

## 2.2 Model with exogenous masses of investors

### 2.2.1 Value functions of the agents

The probability of meeting a buyer – a private investor or the central bank – depends on the measure of those counterparties in the market. With probabilities $\lambda\alpha_b$ and $\lambda\alpha_{cb}$, the low-type seller meets a private investor or a central banker respectively, and gets a price $P$ for the bond when the transaction succeeds.

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

The expected pay-off for an impatient, **low-type seller** is given in Equation 1. The first two terms of the low-type sellers' value function inside the brackets show returns from the bond maturing or from the case of a default. The bonds mature stochastically with probability $\delta$, 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 $\gamma$. With probability $1-\delta-\lambda\alpha_b-\lambda\alpha_{cb}$ he remains a seller in the next period. The discount rate of the low-type seller is $\rho$.

$$V_{sh} = \delta(1-q) + \delta\gamma q + \theta V_{sl} + (1-\delta-\theta)V_{sh} \tag{2}$$

The expected pay-off for a patient bondholder, the **high-type seller**, is given in Equation 2. The high-type sellers' bond matures with the same probability $\delta$ as the low-type sellers' bond. 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 $\theta$, after which he switches type and becomes a low-type seller. Alternatively, he remains a high-type seller in the next period.

$$V_{phi} = \delta(1-q) + \delta\gamma q + \theta V'_{ph} + (1-\delta-\theta)V_{ph} \tag{3}$$

The expected pay-off for a **preferred habitat investor** is given in Equation 3. Compared to the high-type seller, the preferred habitat investor does not change type. However, we assume that preferred habitat investors are subject to similar shocks that lower their return by the same amount, such that $V_{sl} = V'_{ph}$. One way to think about these shocks is in terms of aggregate negative demand shocks for example, which act like a funding liquidity shock in case of high-type sellers. Simultaneously, while the preferred habitat investors do not change type, and are less responsive to price changes, they nevertheless bare the cost of these reductions in the valuation of the assets.

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

The expected pay-off for a **high-type buyer**, is given in Equation 4. 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 $V_{sh}$.

$$V_{cb} = -e + \lambda\alpha_{sl}(V_{ph} - P) + (1 - \lambda\alpha_{sl})V_{cb} \tag{5}$$

The expected pay-off for a **central banker**, which is similar to that of a high-type buyer is given in Equation 5. A central banker pays the same search cost as the buyer, $e$. If he meets a seller, he pays a price $P$ for the bond. After trading, however, 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, $V_{ph}$. The only difference between central bank and private buyers is in the continuation utilities they receive following a trade.

Note that we assume market neutrality of central bank asset purchases. That is, the central bank is paying the same price for the bond as private investors. The bargaining process is set up to match the process for government bond purchases by the European Central Bank. A key feature is that the purchases are designed to be market neutral and that the bonds are bought OTC (see Section 3.1 for details).[7] In practice, market neutrality 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. In order to ensure that the purchase price does not differ between a buyer and a central banker, $V_{sh}$ has to equal $V_{ph}$ and $V_b$ has to equal $V_{cb}$. This holds given our assumption that preferred habitat investors bear a cost $V'_{ph} = V_{sl}$.

#### 2.2.2 Bargaining over price

When low-type sellers meet a private buyer or a central banker they Nash-bargain and trade. We model the euro area purchases in particular, where Nash bargaining is the relevant process. The purchases are primarily conducted on a trading platform or by voice by the ECB or the national central banks who ask for several quotes and choose the best price.[8] In any case, since the ECB conducts the purchases in market neutral way, the price of the purchase will be the

[7] If auctions are used to purchase bonds, as some central banks do, the price formation process needs to be modelled differently.

[8] As such, the sellers cannot direct their search to approach the central bank.

same whether the seller would sell to the ECB or a private buyer. The equilibrium bond price will still adjust however as a result of the change in the measure of investors and the resulting change in market tightness.

We solve for the price using the expected surpluses of each of the bargaining parties.

$$P = \beta V_{sl} + (1-\beta)(V_{sh} - V_b) \tag{6}$$

$$P = \beta V_{sl} + (1-\beta)(V_{ph} - V_{cb}) \tag{7}$$

Equations 6 and 7 show the bargaining process for price between a low-type seller and a buyer and a central banker, respectively. We denote the bargaining power of a buyer, or a central banker by $\beta$.

Given the market neutrality assumption described above, the bargaining process collapses to solving for the price in a trade between a low-type seller and private buyer. As a result, we can solve Equation 6 using the value functions of buyers, low-type sellers and high-type sellers.

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

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

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

where (8d)

$$k = \frac{(1-\beta)}{(\beta)}\frac{e}{\lambda\alpha_{sl}} \tag{8e}$$

We also solve for the market price.

$$P = \underbrace{\frac{\delta(1-q)+\delta\gamma q}{\rho+\delta}}_{\text{fundamental value}} + \underbrace{\frac{(1-\beta)}{\beta}\frac{e(\lambda\alpha_b+\lambda\alpha_{cb}+\rho+\delta)}{\lambda\alpha_{sl}(\rho+\delta)}}_{\text{matching premium}} \tag{9}$$

This provides the first substantial result of the model: The bond price is a sum of two components, *fundamental value* and a *matching premium*. The fundamental value is a function of bond characteristics: maturity $\delta$, default probability $q$, recovery rate $\gamma$, and the discount factor $\rho$. These are factors that enter a typical bond pricing equation, where quantitative easing usually has no effect on the price. The second part of the pricing equation, the matching premium, is a function of the market tightness, i.e. the ratio of demand ($\alpha_b$, and $\alpha_{cb}$) to supply ($\alpha_{sl}$). A higher premium implies that investors pay a higher price for the bond.

It should be noted that the effects of QE in this model arise solely from the search friction.

Therefore and in contrast to other bond market models such as (Hamilton and Wu, 2012; Chen, Cúrdia and Ferrero, 2012), the presence of preferred habitat investors is not necessary for QE to have an effect. However, the magnitude of the price impact depends on the share of preferred habitat investors holding the bonds. Given a fixed amount of bonds on the market, a higher measure of preferred habitat investors implies a lower share of sellers relative to buyers. This implies a stronger impact of QE purchases on bond prices.

We now prove that all meetings between buyers and central bankers with high-type sellers lead to trade.

**Proposition 1** *All meetings between buyers or central bankers and high-type sellers result in trade.*

Since the value function of a buyer and a central banker are the same, it suffices to prove that all meetings between buyers and high-type sellers lead to trade. Buyers and high-type sellers will benefit from the trade as long as gains from it are positive. The gains to the seller are $S_{sl} = P - V_{sl}$, while the gains to the buyer are $S_b = V_{sh} - P - V_b$. The total gains therefore are:

$$S_{sl} + S_b = -V_{sl} + (V_{sh} - V_b) \tag{10}$$

Solving this with the definitions of the value functions in (8) gives us the following, which is positive:

$$S_{sl} + S_b = \frac{1}{\beta} \frac{e}{\lambda \alpha_s} \tag{11}$$

#### 2.2.3 Impact of asset purchases on yields

Central bank purchases increase the bond price through both demand and supply channels. First, the central bank purchases add a buyer to the market, increasing demand ('flow effect'). Price increases as a result of increasing central bank demand. Second, 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 ('stock effect').

**Proposition 2** *QE increases the bond price by increasing demand.*

The partial derivative of the price equation 9 with respect to central bank demand is given by:

$$\frac{\partial P}{\partial \alpha_{cb}} = \frac{(1-\beta)e}{\beta(\rho+\delta)\lambda\alpha_{sl}} \tag{12}$$

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

**Proposition 3** *QE increases the bond price by reducing supply.*

A partial derivative of price in Equation 9 in terms of supply of bonds on the secondary market is:

$$\frac{\partial P}{\partial \alpha_{sl}} = -\frac{(1-\beta)}{\beta}\frac{e(\lambda\alpha_b + \lambda\alpha_{cb} + \rho + \delta)}{\lambda\alpha_{sl}^2(\rho+\delta)} \tag{13}$$

This is negative. Therefore, price increases with a reduction supply.

The effect of central bank asset purchases on supply, shown in Proposition 3, can also be seen in a variation of the price equation, shown in Equation 14. 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 9 to see that the increase in the measure of preferred habitat investors (central bankers becoming hold-to-maturity investors) leads to a higher price.

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

**Proposition 4** *QE increases the bond price more through the demand effect when the share of preferred habitat investors is relatively large.*

The partial derivative in Equation 12, depends on the share of bonds held by preferred habitat investors, $\alpha_{ph}$. For a fixed stock of bonds, we can use $D = \alpha_{sl} + \alpha_{sh} + \alpha_{ph}$ to substitute for $\alpha_{sl}$ and get:

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

Equation 15 shows that the impact of an increase in demand for bonds by the central bank is larger, for a larger share of the bonds held by preferred habitat investors $\alpha_{ph}$ (equivalently, smaller share of low-type sellers, $\alpha_{sl}$). This can also be seen in Figure 2.

**Proposition 5** *QE increases the bond price more through the supply effect when the share of preferred habitat investors is relatively large.*

Purchasing bonds from active sellers, and holding them to maturity reduces the mass of active sellers $\alpha_{sl}$. This reduction leads to an increase in the price, and that increase is larger for a larger mass of preferred habitat investors on the market. This can be seen in the second partial derivative in Equation 16. The derivative is positive, which means that the relationship between price and mass of low-type sellers is convex. The fewer sellers there are, the bigger is the change in price for a given reduction in stock (reduction in the mass of low-type sellers).

$$\frac{\partial^2 P}{\partial \alpha_{sl}^2} = \frac{(1-\beta)}{\beta}\frac{2e(\lambda\alpha_b + \lambda\alpha_{cb} + \rho + \delta)}{\lambda(D - \alpha_{ph} - \alpha_{sh})^3(\rho+\delta)} \tag{16}$$

Figure 3 plots price as a function of the mass of sellers. When the measure of preferred habitat investors is large and hence the mass of sellers is low, then a reduction in the mass of

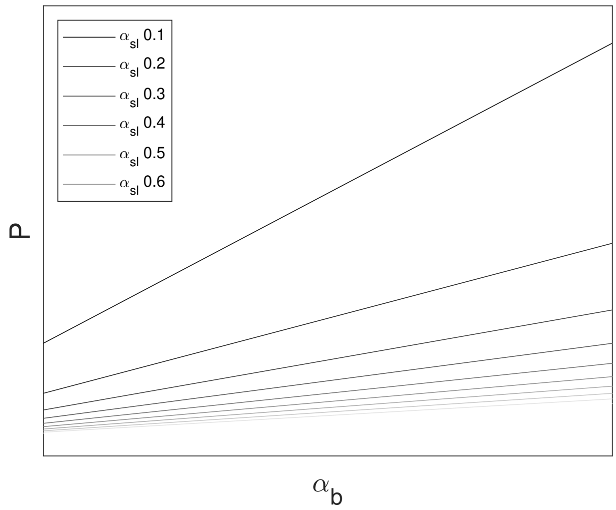


Figure 2: Price is positively related to the mass of buyers. The strength of that relationship depends on the mass of sellers, which is inversely related to the preferred habitat holdings. Darker lines reflect higher share of preferred habitat holdings.

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.

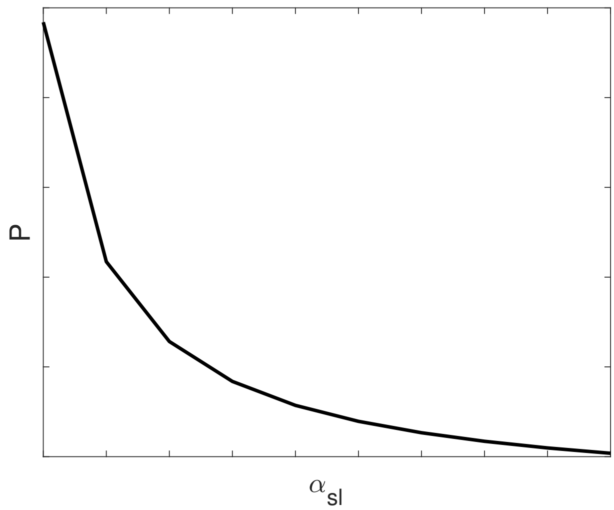


Figure 3: Price is positively related to a decline in the mass of sellers (increase in mass of preferred habitat investors). The strength of that relationship depends on the mass of sellers, which is inversely related to the mass of preferred habitat investors.

### 2.2.4 Impact of asset purchases on liquidity

We extend the analysis to the impact of QE on bond market liquidity. As in the case of bond yields, a QE programme affects market liquidity through demand and supply.

**Proposition 6** *Liquidity improves initially as the central bank increases demand for bonds. It worsens subsequently when the central bank withdraws bonds from the secondary market.*

Liquidity is modelled as a measure of transactions, or meetings on the market, where the inverse of this measure is equivalent to time to transaction:

$$L = \lambda \alpha_{sl} \alpha_b + \lambda \alpha_{sl} \alpha_{cb} \tag{17}$$

When the central bank increases demand for bonds, increasing $\alpha_{cb}$, 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 $\alpha_{sl}$ shrinks and liquidity declines.

As is the case for yields, the relative share of preferred habitat investors will also impact bond market liquidity.

**Proposition 7** *QE increases market liquidity more when the share of preferred habitat investors is relatively small.*

A partial derivative of liquidity in Equation 18 depends on the share of sellers. Substituting this by $D - \alpha_{ph} - \alpha_{sh}$ shows that the improvement in liquidity from an increase in central bank demand is larger, the fewer preferred habitat investors there are.

$$\frac{\partial L}{\partial \alpha_{cb}} = \lambda \alpha_{sl} \tag{18}$$

## 2.3 Model solution with endogenous entry of buyers

### 2.3.1 Equilibrium entry of investors into the market

We now extend the model by adding outside investors following Afonso (2011). When deciding on whether to enter the bond market as buyers, outside investors compare the expected return of the buyer to the expected return of their outside investment option. [9] More specifically, 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 $V_b$, the investor decides to enter the market and becomes a buyer. Outside investors are heterogeneous in their outside option $K_i$. For simplicity, we assume that the value of the outside option $V(K_i)$ of each outside investor equals $K_i$. The entry flow of outside investors is denoted by $g$, and the flows are described in Equation 19. 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.

$$g = \int_{\underline{K}}^{K_m} f(K) dK = F(K_m) \tag{19}$$

In equilibrium, the marginal investor is indifferent between entering and not entering, that is, the value of the outside option is equal to the value of becoming a buyer $(V(K_m) = V_b)$.

[9] This mechanism is similar to the portfolio rebalancing channel in the QE literature. When assets targeted by central bank purchases become relatively expensive, investors turn to other assets, raising demand for these bonds and lowering their yields.

Given our assumption that $V(K_m) = K_m$, it follows that $K_m = V_b$ . As a result we can write the above as the equilibrium condition:

$$g = F(V_b) \tag{20}$$

We now solve for the flows of investors. In steady state the in- and outflows of buyers must be equal, such that $\dot{\alpha_b} = 0$ . The investor inflows consist of the outside investors who decide to become buyers. Investor outflows are the buyers who meet a seller and become patient investors. Solving the flows we get the measure of buyers:

$$\begin{aligned} \dot{\alpha_b} &= g - \lambda \alpha_{sl} \alpha_b \\ \alpha_b &= \frac{g}{\lambda \alpha_{sl}} \end{aligned} \tag{21}$$

The flow of patient, high-type sellers $\alpha_{sh}$ is specified as follows. The first term of Equation 22 has the inflow of active buyers who have found a seller and have become patient sellers. With probability $\theta$, the patient sellers receive a liquidity shock and turn into impatient sellers. With probability $\delta$ debt matures and with probability $q$ the bond goes into default, and patient bondholders exit the market. In order to keep debt levels constant, however, we assume that government rolls over the bonds and the investors that exited are exactly replaced.[10] In equilibrium, the in- and outflows of patient sellers are equal, such that $\dot{\alpha}_{sh} = 0$. Equation 22 then solves as follows:

$$\begin{aligned} \dot{\alpha}_{sh} &= \lambda \alpha_{sl} \alpha_b - \theta \alpha_{sh} - \delta \alpha_{sh} + (1-q)\delta \alpha_{sh} \\ \lambda \alpha_{sl} \alpha_b &= (\theta + q\delta)\alpha_{sh} \end{aligned} \tag{22}$$

Since total debt, $D$ is equal to the holdings by high- and low-type sellers, and preferred habitat investors, we can substitute $\alpha_{sh}$ out and get that $\lambda \alpha_{sl} \alpha_b = (\theta + q\delta)(D - \alpha_{ph} - \alpha_{sl})$. Together with Equation 21 we get an expression for $g$, the first of the equilibrium conditions.

$$g = (\theta + q\delta)(D - \alpha_{ph} - \alpha_{sl}) \tag{23}$$

Using the expression for inflows of outside investors, $g$, we can write the mass of buyers in Equation 21 as follows. Now $\alpha_b$ is a function of $\alpha_{sl}$, exogenously determined $\alpha_{ph}$, and parameters only.[11]

$$\alpha_b = \frac{(\theta + q\delta)(D - \alpha_{ph} - \alpha_{sl})}{\lambda \alpha_{sl}} \tag{24}$$

[10] If different types of investors would return to the market, it would affect the relative holdings and therefore the effects of QE. We abstract from such effects here.

[11] In Section 3 we calibrate the initial share of preferred habitat investors and the share of bonds purchased by the central bank. Also, all the bonds held by the preferred habitat investors are rolled over when they mature. Hence $\alpha_{ph}$ is known.

Substituting $\alpha_b$ into Equation 8a, we get $V_b$. This provides us with the second equilibrium condition as a function of $\alpha_{sl}$, predetermined $\alpha_{ph}$ and parameters only.

$$V_b = -\frac{e}{\lambda\alpha_{sl}} + \frac{(\delta(1-q)+\delta\gamma q)\rho}{(\delta+\theta)(\rho+\delta)} - \frac{(1-\beta)e}{\beta\lambda\alpha_{sl}}\left(1+\frac{((\theta+q\delta)(D-\alpha_{ph}-\alpha_{sl})}{\alpha_{sl}(\delta+\theta)(\rho+\delta)}+\frac{\lambda\alpha_{cb}}{(\delta+\theta)(\rho+\delta)}\right) \tag{25}$$

There is no analytical solution to the system. Therefore, we use a numerical approach by doing a grid search of $\alpha_{sl}$ to find its value where $g$ is equal to $F(V_b)$. Given the equilibrium values of $\alpha_{sl}$, $g$, and $F(V_b)$ we can solve for all the other variables in the model, such as the measures of other investor, as well as price and liquidity.

Figure 4 plots the equilibrium conditions – namely the entry flows $g$ and buyer return $F(V_b)$ – for different values for the mass of sellers $\alpha_{sl}$. The buyer value function is upward sloping in $\alpha_{sl}$. An increasing mass of active sellers makes it easier for buyers to be matched and thereby alleviates the search friction from the buyers. The entry flow condition, $g$ is downward sloping for $\alpha_{sl}$.

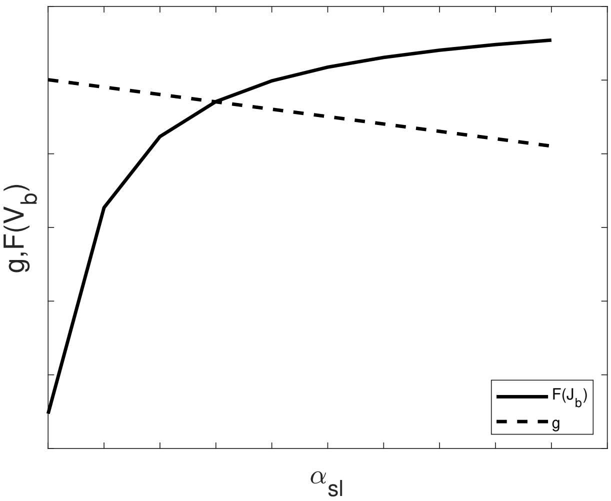


Figure 4: Equilibrium condition

In the absence of an analytical solution to the model, one can approximately trace out the mechanism. An increase in central bank demand leads to more matches between low-type sellers and central bankers, which leads to a decline in the measure of those sellers. A reduction in the supply of bonds has a similar effect. The bond price increases as before following an increase in $\alpha_{cb}$ and $\alpha_{ph}$. Liquidity increases with higher demand, but declines with the subsequent reduction in supply. Now with endogenous masses of investors, also the measures of buyers and sellers adjust. The decline in mass of low-type sellers increases the price and leads to reduced liquidity. Potential buyers are discouraged from entering the market, and as the mass of buyers declines, they find it more difficult to match with sellers. It is only possible to see the final effect on the mass of buyers through a simulation. The simulation of the calibrated model is shown in Section 3.

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

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

In the context of the extended Asset Purchase Programme (EAPP) the ECB purchased around EUR 60 billion euro area government bonds per month until March 2016, around EUR 80 billion from March 2016 to March 2017, around EUR 60 billion until December 2017 and EUR 30 billion until the end of the net purchases in December 2018. Total bond holdings from the EAPP were EUR 2.65 trillion at the end of December 2018. Given that the PSPP amounts to more than 80% of these holdings, we will focus on this programme in the following.

The Eurosystem started purchasing public sector securities under the Purchase Program (PSPP) in March 2015. The purchases are conducted in national government bond markets on the basis of ECB's capital key. This implies that ECB purchases of are approximately the same as a percentage of GDP across euro area countries.[12] The purchases were originally limited to 25% of each bond issuance, but in September 2015 the Governing Council decided to increase the limit to 33%.

While the asset purchases under the ECB's PSPP are broadly symmetric across euro area countries, national sovereign bond markets are very heterogeneous. 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).[13]

Transactions in euro area sovereign bond markets, including the bond purchases by the Eurosystem, are primarily executed in over-the-counter (OTC) markets in which search frictions are relevant Rocheteau and Weill (2011). In addition, the ESCB purchases were done in a decentralised manner by the ECB and all the national central bank, with "the majority of APP purchases were executed by bilateral trades with counterparties [...] via electronic platforms and by voice" (Hammermann et al., 2019). Arrata and Nguyen (2017) describe how the ECB purchased bonds primarily by bilateral trading and by small instalments across the maturity spectrum, implying relatively large search frictions. Although electronic trading volumes have increased significantly, little less than half of bond transactions are arranged by 'voice'.

PSPP purchases are conducted in a market neutral way. The ECB states that "the concept of market neutrality means that, while we do want to affect prices, we do not want to suppress the price discovery mechanism."[14]

[12] The shares of the NCBs in the ECB's capital key are calculated according to the shares of the respective Member States in total population and gross domestic product of the European Union (EU).

[13] December 2015 Strandard & Poors rating.

[14] 'Embarking on public sector asset purchases', Speech by Benoît Cœuré, Member of the Executive Board of

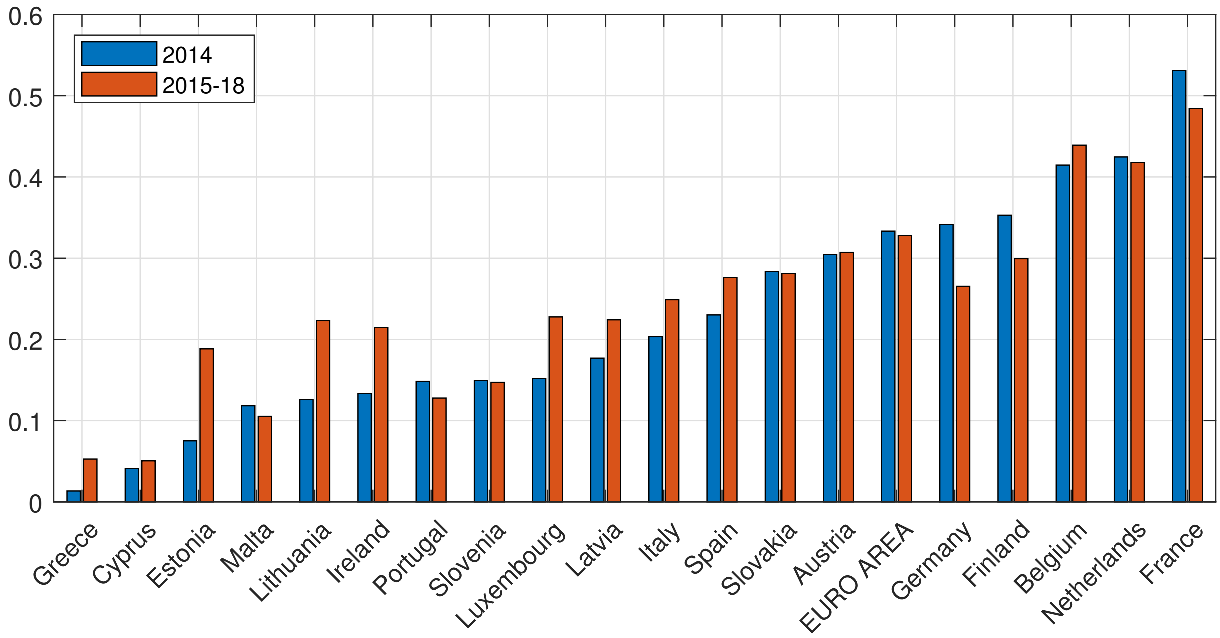


Figure 5: Preferred habitat index, calculated as the share of holdings by ICPFs + non-euro area central banks and general government (SHS), in government debt securities issued by each euro area country with maturity above 1 year (QSA), average over 2014 and over 2015-18 (1 = 100 percent)

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

We present a new index for the share of preferred habitat investors in euro area countries based on the securities holding statistics (SHS) of the European System of Central Banks. This database contains quarterly data on the ownership of securities, including government debt securities. Compared to the more standard, aggregate data, the database has information on issuers and holders at a security-by-security level and by economic sectors. (For a more detailed description of the database, see Appendix A)

Our preferred habitat investor index (PHI) consists of the share of euro area sovereign bond holdings held by categories of investors that are likely to have a preference for certain maturities or certain type of sovereign bonds. These investor categories are insurance companies and pension funds (both in and outside the Euro area) and central banks and general governments outside the euro area.

For the euro area as a whole, the PHI remains stable at around 33% of outstanding government debt from 2014 onwards, the period for which reliable SHS data is available (see Figure 5). There are, however, considerable differences in the PHI across euro area countries, which varies from less than 5% to above 50% of outstanding government debt. While there has been some convergence over time between countries with higher and lower scores, the differences in the index remain pronounced. Changes in the index might be influenced by various factors, e.g. sovereign bond rating upgrades for countries exiting EU/IMF adjustment programmes, the issuance behaviour of governments etc.

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the ECB, at the Second International Conference on Sovereign Bond Markets, Frankfurt, 10 March 2015

Using the same SHS data, but at a security-by-security level, Koijen, Koulischer, Nguyen and Yogo (2017) study portfolio flows and the dynamics of risk exposures across holding sectors during the PSPP programme. They find that foreign investors, banks and mutual funds sold the bonds that the ECB bought, whereas euro area insurers and pension funds purchased the same bonds. Eser, Lemke, Nyholm, Radde and Vladu (2019) apply the same classification of preferred habitat investors as we do, but aggregate SHS-holdings for the four largest euro area countries only. They also include holdings of the intra-euro area general government sector and Eurosystem portfolios. Based on a gravity model using SHS granular data, Boermans and Vermeulen (2018) find practically unchanged demand functions for euro area bond holders following the start of QE, across different sectors, in contrast to a stronger response by non-euro area investors.

Other papers have previously estimated preferred habitat holdings from more aggregated data. Blattner and Joyce (2016) use IMF data of official holdings to construct a proxy measure of preferred habitat investors, which is methodologically based on Arslanalp and Poghosyan (2016). This measure estimates the amount of "free floating" debt (i.e. excluding foreign official holdings of debt), but due to data limitations 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 pension funds and insurance companies, domestic banks and the domestic central bank (but excludes foreign central bank holdings).

The PHI is related to both the size of the sovereign bond market and the bond rating, with a higher PHI for larger markets and higher rated bonds. In Figure 6 the index is presented by (unweighted) country groupings, separating between the larger and higher rated countries and the other euro area countries, and the (weighted) euro area average, while showing the three components of the index. The large difference in the index between the two country groups 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.

### 3.3 Calibration of the model

We simulate the model by looking for the measure of sellers, $\alpha_{sl}$ that solves the equilibrium condition presented in Section 2.3. The equilibrium is defined by the fixed point where the measure of entry flows of outside investors equals a function of the expected return of becoming a buyer The model is calibrated for the euro area, with annual values shown below in Table 1. Bargaining power of the buyers, $\beta$, 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 euro area is 7 years, and the length is quite similar for most of the countries. We therefore set $\delta$, 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 rate after a default to 0.4. The Poisson intensity of the search process, $\lambda$, is a constant in this model. We set it to 1000, which means that if the measure of sellers is one, it takes less than a quarter of a business day, on average, to find a seller. The probability of liquidity shock is harder to calibrate, and we set it to 0.24. In each month there is a 2% probability of getting hit by a liquidity shock. $e$ the buyer search cost is set low at 0.001. We assume that $F(J_b)$ follows a general beta distribution, and set the parameters of the distribution $\alpha$ and $\beta$ to 1.5 and 2.7

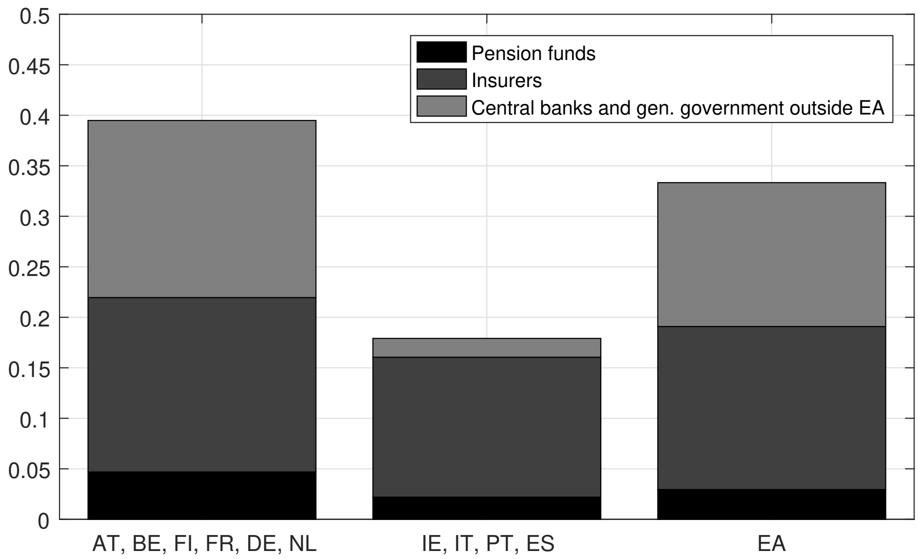


Figure 6: Preferred habitat investors index per sector, 2014 average, for (unweighted) country groupings and the (weighted) euro area average (1 = 100 percent).

respectively.

| | | | | | |
|---|---|---|---|---|---|
| Buyers bargaining power | $\beta$ | 0.5 | Probability of a liquidity shock | $\theta$ | 0.24 |
| Probability of debt maturing | $\delta$ | 0.14 | Buyers' search cost | $e$ | 0.001 |
| Sellers' discount factor | $\rho$ | 0.05 | $\alpha$ of the beta distribution | | 1.5 |
| Recovery rate | $\gamma$ | 0.4 | $\beta$ of the beta distribution | | 2.7 |
| Search intensity | $\lambda$ | 1000 | | | |

Table 1: Calibration

We calibrate the model to the euro area to see how the impact of QE on yields and liquidity differs among the euro area countries that have different shares of preferred habitat investors.

We split the sample in two groups of larger euro area countries based on the share of preferred habitat investors in 2014. 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 5.

Statistics used in the calibration for these country groups are shown in Table 2. The difference in the share of preferred habitat investors between the groups is quite large. In the high group, 39% of debt is held by preferred habitat investors, while in the low group the figure is 18%. The amounts purchased as a share of long-term bonds are very similar in both groups.

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 we use $\frac{y-r}{1-RR}$ 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.

| | Preferred habitat, % of long-term bonds | Default probability, % | Purchases, share of long-term bonds, % | Average maturity, years |
|---|---|---|---|---|
| High PHI | 39 | 0.23 | 13.29 | 6.68 |
| Low PHI | 18 | 2.14 | 13.81 | 7.48 |

Table 2: Calibration of groups. High (low) PHI are countries with high (low) share of preferred habitat investor holdings of long-term bonds

### 3.4 Simulation of the model

We simulate the model for two groups of euro area countries, with a high and a low share of preferred habitat holdings. We compare the differences in the asset purchases' impact on yields and liquidity.[15] The impact can be divided in different phases in terms of timing; (i) the announcement and early intervention phase, (ii) the course of the intervention phase, including announcement of additional purchases, and (iii) the reinvestment phase without new net purchases.

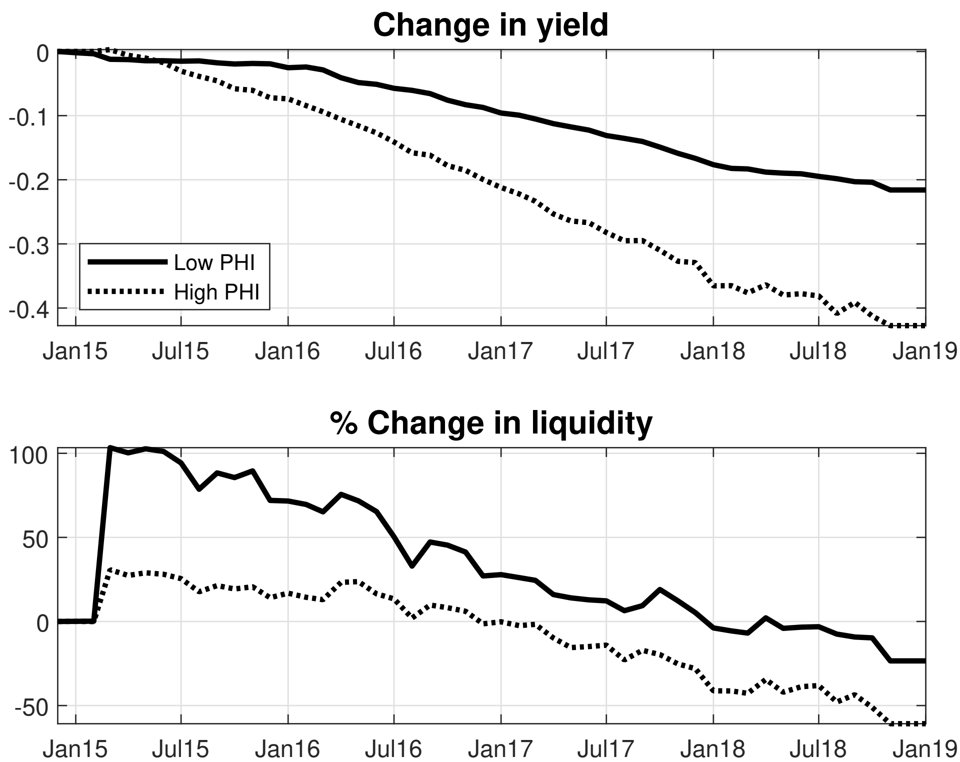


Figure 7: Effect of ECB purchases on yields (percentage points) and liquidity (per cent) in countries with low and high shares of preferred habitat investors

[15]The model was solved for the bond price, but – in line with the literature – we show model simulations with the impact on yields. We solve for the yield with the following bond pricing formula, where $y$ is the yield and maturity is $1/\delta$:

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

In the first phase, yields decline slightly more in the markets with a lower share of preferred habitat investors than in higher-preferred-habitat markets (solid and dotted line, respectively, in top panel of Figure 7). Demand for government bonds is lower in lower-preferred-habitat markets and they therefore especially benefit from the increase in demand by the central bank purchases. The supply effects of the asset purchases only materialise over time.

By similar reasoning, liquidity initially improves more in lower-preferred-habitat countries (solid line in the bottom panel of Figure 7). The number of transactions increases as sellers find it easier to find a buyer with the increased demand of the central bank asset purchase programme. There is a much smaller improvement in liquidity in the higher-preferred-habitat countries (dotted line), where the additional effect of the central bank demand is less relevant as demand was already relatively strong.

In the second phase and over the course of the purchase programme, yields fall more in markets with a higher share of preferred habitat investors (dotted line in top panel of Figure 7). As the central bank purchases accumulate and are held to maturity, the share of the free float decreases. This effect is stronger in markets where there are fewer sellers relative to buyers, i.e. a high share of preferred habitat investors. The decline of the free float through an increase in central bank holdings and the associated decline in the number of sellers also deteriorates liquidity in the market.

In the third phase and by the end of the purchase programme, yields of lower-preferred-habitat bonds decline by around 20 basis points on average, and by around 50 basis points on average in the higher-preferred-habitat countries. In this phase, liquidity falls below the pre-purchase levels, as buyers are discouraged from entering the market.

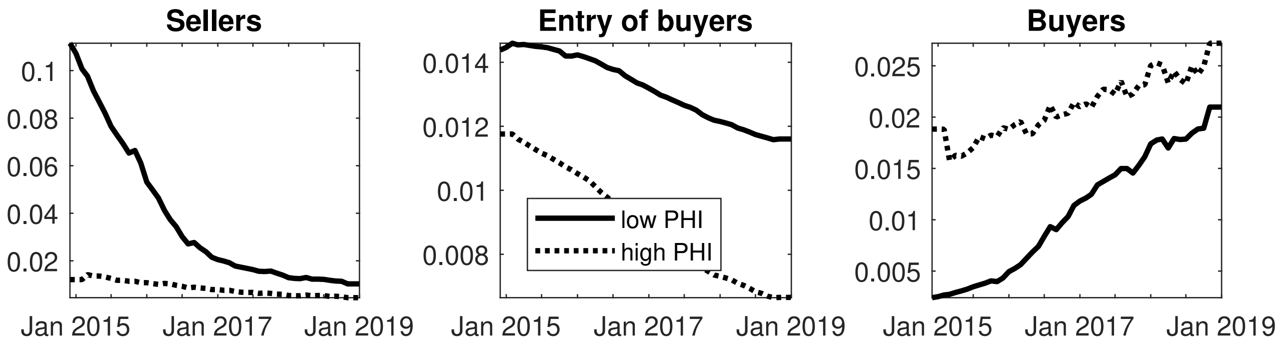


Figure 8: Investors flows following central bank asset purchases

Figure 8 shows that there is a distinct difference in the initial measure of sellers and buyers across countries with higher and lower preferred habitat bond holdings. There are relatively more sellers in lower-preferred-habitat countries (left panel), and relatively more buyers in higher-preferred-habitat countries (right panel). When a smaller share of the bonds is held by preferred habitat investors, more of the stock remains free float. It is easier for buyers to find a seller, resulting in relatively strong outflows. In higher-preferred-habitat countries, by contrast, it is harder for buyers to find a seller and they remain in the market.

Figure 8 also shows investor flows on account of central bank asset purchases. First, the number of sellers declines in both groups of countries (left panel). Given that the central bank holds bonds to maturity similarly to preferred habitat investors, sellers that sell to the central bank are not replaced when they exit and their measure declines. Second, the measure of buyers increases in the model (right panel). As the free float declines, the probability that a buyer meets a willing seller declines. More and more buyers fail to meet a trading partner. Third, outside investors are discouraged from entering the market to become buyers (centre panel). Higher prices due to the asset purchases reduce the value of entering the market, while the value of the outside option is assumed to be unchanged.[16]

Overall, the results of the simulation are broadly in line with the range of empirical findings on the PSPP effect on yields in the euro area. In particular, event studies have shown that the announcement of the PSPP in January 2015 significantly lowered yields. Estimates of the effect of the ECB asset purchase programme on the euro area 10 year sovereign bond yield vary between about 30 basis points and about 70 basis points (Altavilla et al., 2015; De Santis, 2016; Blattner and Joyce, 2016; Bulligan and Monache, 2018).

However, the simulation results of this paper appear to contradict some findings that the PSPP had a stronger effect on periphery, lower-preferred-habitat euro area bonds than on core, higher-preferred-habitat bonds (Altavilla et al., 2015, 2016; Andrade et al., 2016; Blattner and Joyce, 2016; Eser and Schwaab, 2016; De Santis, 2016, 2019). This difference may be related to the event study approach that these papers rely on.[17] As our simulations show, the effect of PSPP may initially be larger in periphery countries with fewer preferred-habitat bond holders when the effect of additional central bank demand outweighs the effect of a reduction in supply. However, this effect may be reversed over the course of the purchase programme. In line with our argument, Koijen et al. (2019) suggest that the effect of the PSPP is particularly large in countries where the central bank purchases led to a stronger depletion of the stock of bonds, that is the supply of government bonds was most reduced. In their analysis, the effect of the PSPP is larger in Finland and Germany than in Italy, for example. Similarly, in their study of the repo markets during the PSPP, Arrata et al. (2018) show that following QE, the spread between the special and general collateral rates of German and French government bonds increased more than the spread of Italian and Spanish bonds, indicating higher levels of scarcity of German and French bonds due to QE. Even the general collateral rate of German and French bonds gradually fell below the deposit facility rate, pointing to an increased overall scarcity of these bonds. In contrast, the general collateral rate of Italian and Spanish bonds has remained close to the deposit facility rate.

Another difference with many empirical papers is that the supply effects of the PSPP in our model materialise over time, not with the announcement of the programme. It is typically expected that market participants immediately price in the entire effect of the asset purchase envelope. This allows empirical studies to focus on the announcement window of the programme to measure the overall effect of programme on yields. In our model, agents are not forward-looking. Supply effects thus only have an effect on yields at the time of the purchase and materialise over duration of the purchase programme as the central bank purchases absorb free float. While part of the supply effect would be expected to the priced by market agents at the time of the announcement of the programme, a number of recent papers point to a more protracted materialisation of this effect (Schlepper et al., 2017; Pelizzon et al., 2018; Arrata et

[16]In practice, the yields of the outside investment option could fall with buyers being crowded out of the sovereign bond market and seeking alternative investment opportunities. This effect would be the portfolio rebalancing effect of QE.

[17]At the same time, other intermediate channels that are not endogenously modelled in our framework may also be at play. These include the credit risk channel. Altavilla et al. (2015) suggest that this channel in particular had a stronger impact on periphery countries of the euro area.

al., 2018). Following the intuition of this paper, Pelizzon et al. (2018) separate the effects of QE on demand (spotlight effects) and supply (scarcity effects). Analysing the Bank of Japan's asset purchases, they find that the spotlight effects materialise not when the bonds are included in the target list of purchases but at the day of purchases.[18] Corradin and Maddaloni (2019) and Arrata et al. (2018) further point out the purchased bonds cannot become scarce relative to other bonds even in terms of expectations before it is revealed which bonds will be purchased.

[18]Consistent with our results, they find that both demand, and supply effects lead to a decline in yields, while liquidity improves due to demand effects, but deteriorates over time due to the supply effects.

## 4 Conclusion

We present a search-theoretic model of over-the counter debt that allows us to analyse the effect of central bank purchases on bond yields and market liquidity. In our model, central bank purchases are modelled explicitly. They affect yields and liquidity through a demand and supply channel, i.e. changes in the ratio between sellers and buyers.

The model suggests that there is a trade-off for monetary policy makers between reducing yields on the one hand and maintaining market liquidity on the other hand. This trade-off originates in the supply channel of QE: While the reduction of asset supply through the central bank increases yields, smaller free float in the market deteriorates market liquidity.

The effect of QE in our model depends on the search frictions in the market and does not depend on the presence of preferred habitat investors. However, there is an important interaction between central bank asset purchases and the share of preferred habitat investors in the market, as this determines the free float of assets in the market that are available for purchase. We calibrate the model using a novel preferred habitat index for the euro area, which shows strong variation across euro area countries. Our simulations show that yields decline more in countries with larger preferred habitat holdings, while liquidity initially improves more in countries with smaller preferred habitat holdings of bonds.

Our model provides an intuition for the developments of market liquidity in euro area sovereign bond markets since the start of QE. Initially QE should improve liquidity in the markets with few preferred habitat investors. However, rising yields on account of the asset purchase programme crowd out buyers, which can eventually outweigh these positive liquidity effects. At the same time, scarcity has become an issue for sovereign bonds favoured by preferred habitat investors. The ECB acknowledged that its asset purchases may have had a negative impact on liquidity in some markets (Cœuré, 2017), and adjusted announced purchasing profiles because "limitations were experienced in the availability of bonds for purchase, which arose, for instance, as bonds were held by hold-to-maturity investors or because of the overall size of the eligible universe in some jurisdictions" (Hammermann et al., 2019).[19]

QE has become part of the toolbox of monetary policy makers. The impact of central bank asset purchases on market liquidity may gain increasing prominence over time and with a renewed increase in the use of this policy tool. It is therefore important to understand the policy implications of the effect of asset purchases on price and liquidity. First, it is important that safe assets remains in sufficient supply to ensure the smooth functioning of both the asset market and the monetary policy instrument itself. This may be more challenging in fragmented sovereign debt markets such as the euro area, or where falling public debt levels reduce the supply of safe assets. Second, the central bank can employ flanking measures, such as repurchasing and swap operations, to ensure that a sufficient supply of the safe assets is available in the market.[20] Third, maintaining a broad investor base in the sovereign bond market is essential to avoid costs of re-attracting investor groups at the end of QE.

[19]Similarly, 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).

[20]For example, European Securities and Market Authority (2016) shows that liquidity concerns were alleviated when the ECB began selling purchased bonds back to on the repo market.

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# Appendix A A preferred habitat investor index based on the Securities Holding Statistics (SHS)

According to the preferred habitat theory, certain investors have a preference for specific maturities or asset classes, due to the maturity of their liabilities, regulations or other factors, which make them less price sensitive than other investors (Modigliani and Sutch (1966)). For example, held-to-maturity accounting rules discourage insurance companies from 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.)).

We develop an index of the share of preferred habitat investors in Euro area sovereign bond markets, based on the ECB Securities Holding Statistics. Our index 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. In particular, we consider as preferred habitat investors: (i) central banks and governments outside the Eurozone; (ii) insurance companies, both inside and outside the euro area, and (iii) pension funds, both inside and outside the euro area.

Securities Holding Statistics cover holdings of securities aggregated by selected investor sectors of each Euro area country, excluding the holdings by the Eurosystem. The 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 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 sector breakdown is more restricted and distinguishes only between holdings by central banks and general government and NCBs and the remaining investor sectors, including pension funds and insurers. 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.

To avoid the risks of double counting due to custodial bias, the holdings of the preferred habitat sectors are divided by the total amount of general government debt issued by EA countries according to a different data source, the Euro Area Accounts (EEA). Data of the holdings of euro area securities by non-euro area investors is to a large extent collected indirectly via custodians, and thus may not capture the country of the final investor. This custodial bias presents a potential risk of double-counting with euro area holdings, if bonds are held by euro area financial institutions in custody for investors outside the euro area (or a risk of double counting euro area holdings, in case of chains of custodians). The total amount of securities covered in the SHS data base might be overestimated due to this double counting, which is makes the total amount less suitable to use as denominator of our index. Custodial bias would not be expected to significantly influence the data on the holdings of non-euro area central banks and general government, insurance companies and pension funds, and thus not influence the numerator of our index. 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.

The dispersion of the preferred habitat index across euro area countries is not random. There is a strong correlation between the size of the country and the preferred habitat index. For example, the nine euro area countries with the lowest preferred habitat index in 2014 represent cumulatively less than 10% of the ECB's 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). There is also a strong correlation between the rating of the sovereign and the preferred habitat index, with higher rated countries having a higher share of preferred habitat investors. Finally, when considering the different components of our 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 Table 3, the quarterly evolution of the index is shown since 2014 for individual countries and the euro area average.

| Issuer | 2014 | | | | 2015 | | | | 2016 | | | | 2017 | | | | 2018 | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Issuer | Q1 | Q2 | Q3 | Q4 | Q1 | Q2 | Q3 | Q4 | Q1 | Q2 | Q3 | Q4 | Q1 | Q2 | Q3 | Q4 | Q1 | Q2 | Q3 | Q4 |
| Austria | 0.30 | 0.29 | 0.30 | 0.33 | 0.32 | 0.32 | 0.33 | 0.30 | 0.32 | 0.31 | 0.32 | 0.29 | 0.30 | 0.30 | 0.30 | 0.31 | 0.30 | 0.30 | 0.30 | 0.31 |
| Belgium | 0.41 | 0.40 | 0.42 | 0.43 | 0.44 | 0.43 | 0.44 | 0.42 | 0.44 | 0.44 | 0.45 | 0.44 | 0.42 | 0.45 | 0.44 | 0.45 | 0.44 | 0.45 | 0.44 | 0.44 |
| Cyprus | 0.05 | 0.04 | 0.04 | 0.04 | 0.04 | 0.03 | 0.03 | 0.03 | 0.04 | 0.05 | 0.07 | 0.07 | 0.07 | 0.07 | 0.07 | 0.06 | 0.06 | 0.04 | 0.04 | 0.04 |
| Estonia | 0.06 | 0.07 | 0.09 | 0.08 | 0.10 | 0.09 | 0.10 | 0.12 | 0.12 | 0.13 | 0.14 | 0.15 | 0.14 | 0.14 | 0.13 | 0.34 | 0.20 | 0.20 | 0.36 | 0.55 |
| Finland | 0.36 | 0.35 | 0.35 | 0.34 | 0.34 | 0.34 | 0.36 | 0.32 | 0.31 | 0.30 | 0.30 | 0.28 | 0.28 | 0.28 | 0.29 | 0.28 | 0.26 | 0.28 | 0.29 | 0.27 |
| France | 0.53 | 0.53 | 0.53 | 0.53 | 0.52 | 0.52 | 0.51 | 0.51 | 0.49 | 0.48 | 0.48 | 0.48 | 0.48 | 0.48 | 0.48 | 0.47 | 0.46 | 0.47 | 0.46 | 0.46 |
| Germany | 0.41 | 0.33 | 0.32 | 0.31 | 0.29 | 0.30 | 0.28 | 0.27 | 0.27 | 0.26 | 0.26 | 0.26 | 0.25 | 0.25 | 0.27 | 0.26 | 0.26 | 0.26 | 0.26 | 0.25 |
| Greece | 0.01 | 0.01 | 0.02 | 0.02 | 0.01 | 0.01 | 0.02 | 0.02 | 0.02 | 0.05 | 0.06 | 0.07 | 0.07 | 0.08 | 0.08 | 0.06 | 0.07 | 0.07 | 0.07 | 0.08 |
| Ireland | 0.12 | 0.13 | 0.14 | 0.15 | 0.18 | 0.18 | 0.18 | 0.19 | 0.21 | 0.22 | 0.22 | 0.22 | 0.22 | 0.22 | 0.22 | 0.23 | 0.23 | 0.23 | 0.23 | 0.23 |
| Italy | 0.20 | 0.20 | 0.21 | 0.21 | 0.22 | 0.23 | 0.23 | 0.25 | 0.27 | 0.27 | 0.27 | 0.26 | 0.26 | 0.25 | 0.24 | 0.24 | 0.24 | 0.24 | 0.24 | 0.24 |
| Latvia | 0.16 | 0.18 | 0.18 | 0.19 | 0.20 | 0.20 | 0.19 | 0.20 | 0.20 | 0.21 | 0.20 | 0.19 | 0.23 | 0.25 | 0.26 | 0.25 | 0.26 | 0.25 | 0.25 | 0.25 |
| Lithuania | 0.11 | 0.12 | 0.13 | 0.15 | 0.18 | 0.18 | 0.19 | 0.21 | 0.22 | 0.22 | 0.21 | 0.23 | 0.23 | 0.24 | 0.26 | 0.24 | 0.26 | 0.24 | 0.24 | 0.23 |
| Luxembourg | 0.15 | 0.15 | 0.15 | 0.14 | 0.15 | 0.13 | 0.15 | 0.14 | 0.15 | 0.14 | 0.13 | 0.14 | 0.13 | 0.12 | 0.11 | 0.12 | 0.12 | 0.11 | 0.11 | 0.10 |
| Malta | 0.12 | 0.11 | 0.13 | 0.12 | 0.11 | 0.12 | 0.12 | 0.12 | 0.12 | 0.12 | 0.11 | 0.12 | 0.12 | 0.12 | 0.12 | 0.12 | 0.12 | 0.12 | 0.01 | 0.01 |
| Netherlands | 0.42 | 0.41 | 0.43 | 0.43 | 0.44 | 0.44 | 0.45 | 0.42 | 0.43 | 0.43 | 0.41 | 0.41 | 0.42 | 0.41 | 0.42 | 0.41 | 0.41 | 0.41 | 0.39 | 0.38 |
| Portugal | 0.16 | 0.15 | 0.14 | 0.15 | 0.15 | 0.15 | 0.14 | 0.14 | 0.14 | 0.14 | 0.14 | 0.15 | 0.15 | 0.14 | 0.15 | 0.15 | 0.14 | 0.15 | 0.15 | 0.16 |
| Slovakia | 0.27 | 0.27 | 0.29 | 0.30 | 0.31 | 0.28 | 0.28 | 0.28 | 0.28 | 0.28 | 0.27 | 0.27 | 0.27 | 0.27 | 0.28 | 0.29 | 0.29 | 0.28 | 0.28 | 0.29 |
| Slovenia | 0.14 | 0.16 | 0.15 | 0.16 | 0.15 | 0.15 | 0.15 | 0.16 | 0.19 | 0.20 | 0.21 | 0.25 | 0.25 | 0.26 | 0.27 | 0.28 | 0.27 | 0.28 | 0.28 | 0.28 |
| Spain | 0.23 | 0.22 | 0.23 | 0.25 | 0.26 | 0.26 | 0.26 | 0.27 | 0.28 | 0.29 | 0.29 | 0.29 | 0.28 | 0.28 | 0.27 | 0.27 | 0.27 | 0.28 | 0.29 | 0.29 |
| Euro area | 0.34 | 0.33 | 0.33 | 0.34 | 0.33 | 0.34 | 0.33 | 0.33 | 0.34 | 0.34 | 0.33 | 0.33 | 0.33 | 0.33 | 0.32 | 0.32 | 0.32 | 0.32 | 0.32 | 0.32 |

Table 3: Preferred habitat index, calculated as the share of holdings by ICPFs + non-euro area central banks and general government (SHS), in government debt securities issued by each euro area country with maturity above 1 year (QSA), 2014Q1 – 2018Q4, by country and euro area average (1 = 100 percent).

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