THE TRANSMISSION OF UNCONVENTIONAL MONETARY POLICY IN UK GOVERNMENT DEBT MARKETS

Jack Meaning and James Warren*

Through its quantitative easing programme the Bank of England has looked to manage the supply of nominal UK government securities in order to lower interest rates. In doing so it has removed more than 25 per cent of the overall supply of those securities from the publicly accessible market. The benchmark New Keynesian model suggests this should only have an impact on interest rates insofar as it affects expectations of future policy rates, whilst alternative theoretical frameworks imply a direct effect of changes in supply onto yields. Our aim is to test for the existence of these potential transmission mechanisms. We find empirical evidence to support the existence of both channels. Our analysis suggests the Bank's quantitative easing programme reduced yields by around 25 basis points through the supply channel alone. Importantly, we find that such supply effects have remained significant in recent years, suggesting that as quantitative easing is unwound the increase in publicly available supply will put upward pressure on interest rates. Lastly we highlight the monetary-fiscal interaction inherent in our result and discuss some of the issues it raises for policymakers.

Keywords: quantitative easing; unconventional monetary policy; asset purchases; monetary-fiscal

JEL Classifications: E520; E580; E630

Introduction

Since March 2009, the Bank of England's quantitative easing programme has seen the UK's central bank purchase £375bn worth of assets from the private sector, funded by the creation of reserves. These purchases have predominantly been of UK government securities. In fact, the Bank of England, via the Asset Purchase Facility (APF), has bought and now holds over 25 per cent of the total outstanding supply of nominal gilts. This has expanded the Bank's balance sheet dramatically, but also represents a substantial reduction in the quantity of those securities available to the private sector.

One important aim of the policy has been to lower medium and longer-term interest rates and thus stimulate economic activity through the traditional Keynesian transmission mechanism.[1] However, exactly how such policies can achieve this aim has been a question of ongoing academic debate.

According to the expectations hypothesis, which lies at the centre of the benchmark finance model, interest rates on term bonds are determined by the expected sum of short-term interest rates over the life of the bond (equation 1). If they weren't, this would open up an arbitrage opportunity which perfectly functioning and complete financial markets would instantly exploit until it no longer existed. In its slightly weaker form a wedge is often introduced between this expectational term and the prevailing interest rate to represent a premium but this wedge is assumed to be constant.

$$R_t^n = \sum_{t=1}^{n} i_t + \rho \qquad (1)$$

where R_t^n is the interest rate on a bond with maturity n, i_t is the short-term nominal interest rate and ρ is the premium associated with the bond.

This assumption is at the heart of the canonical New Keynesian model and, along with assumptions that the representative household is infinitely lived and rational, allows the constellation of interest rates that exist in practice to be collapsed down to a single, one-period interest rate. As shown famously by Eggertson and Woodford (2003), under the assumptions of the baseline New Keynesian model central bank asset purchases are only effective insofar as they act as a signal of the future path of short-term policy rates. It is posited that they may do this by strengthening the incentive for the central bank to hold rates lower for longer, as increasing rates will impose a cost to the central bank's balance

*National Institute of Economic and Social Research. E-mail: j.meaning@niesr.ac.uk. The authors would like to thank Tony Yates, Oriol Carreras and Rebecca Piggott for their insightful comments and Michele Bernini for his invaluable technical assistance.

sheet, or by clarifying the central bank's commitment to accommodative policy.

Eggertson and Woodford's result is dependent on the no-arbitrage element of the New Keynesian model with which they work, and a second fundamental concept, that of Wallace neutrality. Laid out by Wallace (1981), this is a form of Ricardian equivalence for central bank asset purchases. It states that a transaction which moves assets between the private and public sectors should be inconsequential for prices. This is because the asset the private sector agent has given up is now held by the public sector, of which the private sector agent is the ultimate owner. Therefore the private sector agent is still exposed to the same payoffs as before in all states of the world, albeit that some will now be realised through taxation or reduced government spending as opposed to the direct impact of holding the asset. Knowing this, in order to counteract the increased exposure through the state, the private sector agent will reduce her demand for the asset sold, hedging and exactly offsetting the change in supply and leaving the price unchanged.[2]

It has long been widely accepted that Wallace neutrality fails with respect to money, at least away from the zero lower bound. This is because money provides a non-pecuniary benefit to the holder, for instance, utility emanating from its ability to pay taxes, or easily effect transactions. Private sector agents therefore do not perceive money held on their own balance sheet as equivalent to that held for them by the state as they do not receive the non-pecuniary benefit. This utility is itself subject to decreasing marginal returns and thus changes in the supply of money held by the public, for a given level of money demand, will affect the market clearing price, the short-term interest rate. This premise has been at the heart of the open market operations central banks have used to conduct policy for decades.

An argument against the effectiveness of recent quantitative easing put forward by Eggertson and Woodford is that, by definition, at the zero lower bound the non-pecuniary benefits of money have been exhausted and so the mechanism by which money violates Wallace neutrality is no longer operative. However, there is a growing body of empirical evidence that suggests changes in the supply of assets other than money can also have implications for their prices and yields. D'Amico and King (2010) and Meaning and Zhu (2011) both use individual bond level data to find significant changes in bond prices as a result of changes in the supply of government securities in recent central bank asset purchase programmes in the US and UK. Joyce *et al.* (2010) find similar evidence for the UK, as do Breedon *et al.* (2012) and Banerjee *et al.* (2012). The challenge has been developing a rigorous theoretical framework to explain such results, with ex-Federal Reserve Board Chairman Ben Bernanke describing asset purchases as policies which "work in practice, but not in theory" (Bernanke, 2014).

The theoretical arguments for such an effect have their roots in the work of Tobin (1963, 1969) and Culbertson (1957), who showed, relatively intuitively, that if there was imperfect substitutability between assets then changes in supply would induce movements in rates of interest. Modigliani and Sutch (1966) then began to develop a more rigorous theoretical explanation as to why imperfect substitutability may exist based on the idea that investors had a preference for certain assets or areas of the term structure. For instance, they may wish to hold assets with the same maturity profile as their liabilities or, in an extreme case, be mandated by law to hold assets with certain characteristics.[3] In the context of our earlier discussion about money, this imperfect substitutability between assets can be thought of as deriving from a non-pecuniary benefit which that asset provides to the holder and which other assets cannot perfectly replicate. More recently, the idea that investors have preferred-habitats, and that this gives rise to imperfect substitutability between assets, has been formalised in more complex economic models by authors such as Andrés *et al.* (2004) and Vayanos and Vila (2009) and has taken a prominent role in how the Bank of England has framed its quantitative easing policy (Benford *et al.*, 2009).

One way of modelling this is by modifying equation 1 such that ρ becomes a function of the supply both of the asset and its substitutes.

$$R_t^n = \sum_{t=1}^{n} i_t + \rho_t \text{ where } \rho_t = f[s_t, sub_t] \qquad (2)$$

The aim of our econometric investigation is to test for the existence of these two channels.

Uncovering potential transmission mechanisms

Using equation (2), the exercise then aims to identify each of these channels and their impact on interest rates. To do this we begin by building a data set of UK government securities at the individual bond level.

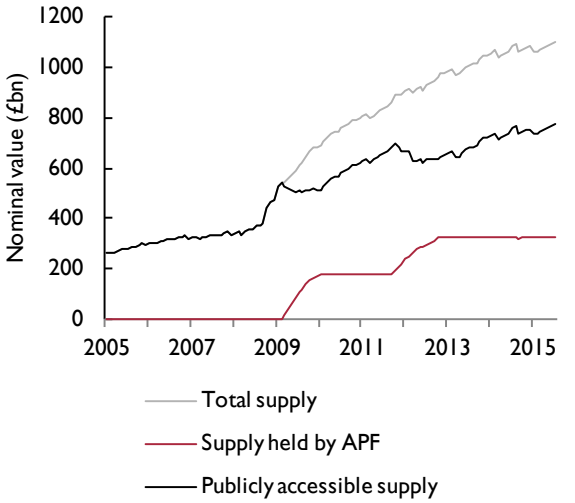
First we take data on the prices and total supply outstanding for each individual bond in the UK

government's debt portfolio. This raw data is sourced from the British Government Securities Database, constructed and maintained by David Wilkie and Andrew Cairns of Heriot-Watt University. We restrict our analysis to nominal securities only, and also to those with a remaining maturity of over three months. Our full sample period runs from January 2000 to July 2015 at a monthly frequency, although due to limitations in other data series we focus primarily on the period from January 2009 onwards. This leaves us with a sample of 103 securities.

From this, for each security we create a series of publicly available supply by subtracting the amount held on the Bank of England's balance sheet from the total. Figure 1 shows the aggregated series for publicly available supply as we have defined it plotted alongside total supply and supply held by the Bank of England on the APF. Since 2009, the publicly available supply of gilts has been considerably lower than the total gilt stock would imply, as the Bank of England has removed gilts through quantitative easing.

We then use these securities to construct series of publicly available substitutes, which we define as all securities in our sample with a remaining maturity within two years, or +/– 50 per cent of the remaining maturity of the security in question, whichever is greater. In other words, if security (i) has ten years left to maturity, all securities with a remaining maturity between five and fifteen years are considered substitutes and as such their supply is summed to generate the *sub* series for security (i).[4]

Figure 1. Publicly available nominal UK government securities



Source: Heriot-Watt British Government Securities database, authors' calculations.
Note: Series includes all nominal UK government securities with remaining maturity greater than three months.

To capture the expectations of future interest rate policy, consistent with the term $\sum_{t=1}^{n} i_t$ in equation (2), we use overnight index swap (OIS) rates. As discussed in Joyce *et al.* (2010) OIS rates serve as a reasonable proxy for markets' expectations of the path of Bank Rate as they are formed from geometric averages of overnight interest rates over the specified term. For each month we match the remaining maturity of each bond to the OIS rate with corresponding term, as measured by the Bank of England's fitted OIS curve. In this way we get a bespoke measure of the expectation of policy rates over the life of that bond in that month and thus should have an accurate representation of the expectations component of term rates.[5] It should be noted here that expectations of the short-term nominal interest rate will move in response to many things which are themselves considered determinants of bond prices, such as expectations of inflation or future output growth. The key for our analysis is that by using OIS rates we can isolate the extent to which these factors change agents' perceptions about the future path of monetary policy and identify the impact associated with the expectations hypothesis-style arguments outlined earlier.

Monthly data on OIS rates in the UK is only available back to January 2009, which makes this the limiting variable in our main sample.

We then use this panel of data to estimate the following variant of equation (2)

$$p_t = \alpha + \beta_1 s_t + \beta_2 sub_t + \beta_3 OIS_t + \delta_{it} \qquad (3)$$

where p_t is the percentage change in the price of a security from the previous period, s_t is the publicly available supply of the security and sub_t is the supply of securities which are considered to be substitutes for that security. OIS_t is the overnight index swap rate which corresponds to the remaining maturity of the security and δ_{it} is a vector of control variables. We apply a fixed effects estimator to control for idiosyncratic features of any particular bond.

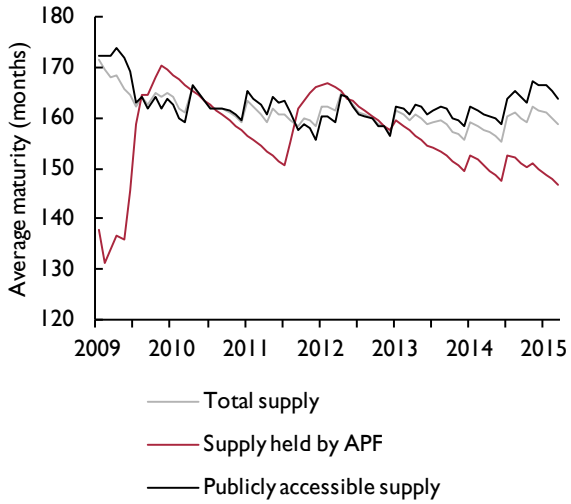
A potential concern is endogeneity between the dependent and explanatory variables, particularly between the supply variables and price changes. In theory, a prudent fiscal debt manager who is looking to issue a given quantity of debt at the lowest possible cost

to the government may find it optimal to issue more of that debt in the form of a particular bond when its price rises and so it becomes relatively cheaper to do so. This would imply that not only were bond prices responding to supply, but that supply was also responding to changes in price. For instance, Greenwood *et al*. (2014) show that in the United States, the US Treasury increased the maturity of their debt portfolio just as the Federal Reserve was removing maturity and raising the price of longer-dated bonds relative to shorter-dated ones. They show that this, at least partially, offset some of the efficacy of the Fed's policy and they highlight the inherent monetary-fiscal coordination issues such a result implies. A similar argument is made by D'Amico and King (2010), but from the monetary policy side, suggesting that the Federal Reserve may have been more likely to purchase bonds which were underpriced and thus would have expected an increase in their price anyway. To control for this they use an instrumented variable within their regression. In our framework, both these endogenous monetary and fiscal responses would be captured within the estimated relationship between price and our publicly available supply series.

However, within our study we do not consider such endogeneity to be a cause for concern for two reasons. The first is that the overall supply of debt which the UK Debt Management Office (DMO) has to issue is unlikely to be determined significantly by price. Rather it is determined primarily by the government's funding requirement. It could be argued that a government which sets its debt issuance optimally over time would seek to issue more debt when costs are low and the economy is weak, so financing through taxation is costly to economic activity. For the larger part of our sample however, the UK government has explicitly shunned this idea and sought to reduce the amount of debt it issues, making any such endogenous link improbable. Given the relative stability of the nominal gilt portfolio's characteristics over time (figure 2), it is these changes in total aggregate supply which are likely to drive changes in the total supply at the individual bond and substitute bond level, not changes in debt issuance practices.

What is more, in contrast to the US, the UK DMO was explicitly tasked with not setting its issuance to take advantage of the price changes brought about by the Bank of England's supply management over this period. The extent to which this commitment is credible is arguable, especially after such a long period of low rates when a counterfactual is hard to derive. However, as can be seen in figure 2, the average maturity of the nominal portfolio has been broadly constant over our sample period, indicating that the DMO has not issued particularly more longer-dated debt relative to short, despite the relative fall in longer-term yields.

Figure 2. Average maturity of publicly available nominal UK government securities



Source: Heriot-Watt British Government Securities database, authors' calculations.
Note: Series includes all nominal UK government securities.

Results

The results of our estimations are presented in table 1. Our baseline case is the estimation from January 2009 to July 2015, including all bonds with a remaining maturity of greater than three years, whose results are reported in the first column of table 1.[6]

The first point of note is that OIS rates have a significant impact on the price of bonds. An expectation that short-term interest rates will be higher over the life of the bond acts to reduce the price of that bond and thus increase the rate of interest it pays. Importantly, this result is estimated over a period when the short-term nominal interest rate itself was constrained by the lower bound and, bar the interest rate cut in March 2009, Bank Rate had been unwavering at 0.5 per cent per annum in the UK. Thus it supports the idea that it is not just current policy which determines longer rates, but rather the expectation thereof, implying that shaping these expectations in one manner or another represents a genuine channel by which monetary policy can gain traction, even when constrained by the lower bound on nominal rates.

Second, there is a significant influence from both changes in the supply of a security, and changes in the supply of its substitutes. Changes in both are correlated negatively

Table 1. Estimation results

	Jan 2009–July 2015 All bonds with RM>3 years	Jan 2009–July 2015 Bonds with RM>10 years	Jan 2000–Dec 2008 All bonds with RM>3 years	Jan 2000–July 2015 All bonds with RM>3 years	Jan 2013–July 2015 All bonds with RM>3 years
% change in supply	–0.0068**	–0.011**	–0.0041	–0.0032	–0.0065
	(0.041)	(0.03)	(0.16)	(0.12)	(0.48)
% change in supply of substitutes	–0.050***	–0.057*	–0.019*	–0.026***	–0.072***
	(0.005)	(0.08)	(0.01)	(0.002)	(0.005)
Corresponding OIS rate	–0.0065***	–0.008***	–	–	–0.0095***
	(0.00)	(0.00)			(0.00)
Bank Rate	–	–	–0.0026***	–0.0001	–
			(0.00)	(0.30)	
Remaining maturity	0.00017***	0.00017***	–0.00003***	–0.00001**	–0.00024***
	(0.00)	(0.00)	(0.00)	(0.03)	(0.00)
Constant	–0.013***	–0.028***	0.017***	0.004***	0.075***
	(0.00)	(0.00)	(0.00)	(0.00)	(0.00)
Adj-R2	0.017	0.017	0.011	0.010	0.074
Prob >F	0.00	0.00	0.00	0.01	0.00

Notes: *** denotes coefficient is significant at 1% level, ** at 5% level and * at 10% level. T-probabilities are presented in parentheses.

with prices, meaning that a policy such as quantitative easing, which reduced the publicly available supply of government securities, pushes up on prices and lowers interest rates. Given that our work is carried out in price space, the coefficients require some careful interpretation, but using the modified duration of the total nominal gilt portfolio over our sample period, our estimation implies that the removal of approximately 30 per cent of the publicly available supply of gilts, as has occurred through the Bank of England's quantitative easing, would lead to an average reduction in yields of between 20 and 25 basis points. This falls towards the lower end of the range of estimates within the literature, but it should be noted that it does not take account of any impact QE purchases have had through changing expectations of the future path of policy rates.[7,8] What is more, there is likely to be significant variation across bonds, with some segments of the yield curve where purchases were heavier and bonds more sensitive experiencing greater reductions in yields, while others moved very little. The same estimation over a sub-sample which includes only longer-dated bonds with a remaining maturity in excess of ten years shows they were more sensitive to changes in their supply, and also to changes in supply of substitutes. This would seem to make sense as the degree of market segmentation is likely to be higher further along the yield curve when compared to the shorter end where, for instance, the liquidity benefits of holding a 3-month bond are not dissimilar to holding a 6-month bond.

Quantitative easing in 'normal' times and exit

It could plausibly be argued that the period of recent financial crisis may be a special case. Heightened financial market stress may have elevated the degree of imperfection in substitutability between assets as investors came to value more the non-pecuniary benefits provided by specific asset types, such as safety or liquidity. In times of less financial stress then, it is possible that the degree to which assets are imperfect as substitutes for one another falls as markets become closer to the idealised no-arbitrage markets of theoretical models. If that were the case, then this would render quantitative easing largely irrelevant, other than as a tool in specific periods of extreme financial stress. As posited by Miles and Schanz (2014), it would also have implications for how a central bank should exit from asset purchase programmes. If the assets are purchased at a time of financial turmoil, then they would be expected to reduce rates. However, those assets could then be returned to the market when normal market functioning resumed with little to no impact on rates, other than their perceived informational content regarding the path of Bank Rate. This would simplify the exit process greatly, as the Bank of England could reduce its balance sheet without much impact on the monetary stance.

To test this hypothesis, we estimate the framework outlined above, but for the pre-crisis period of January 2000 to December 2008. Unfortunately data limitations

mean that we cannot include OIS rates as a control variable, as they are unavailable at maturities greater than two years over this sample period. Instead, we proxy their effect with the inclusion of Bank Rate. What our results show is that imperfect substitutability did exist over this pre-crisis sample, but that the coefficients on the two supply variables are reduced when compared to the post-2008 sample. This could be indicative of a change in the degree of imperfect substitutability between the two periods. However, we caution that Bank Rate amounts to an imperfect substitute for OIS rates as it has no forward looking component and cannot be matched to the maturity of the bond in question. Therefore it does not capture the theoretical principle of the expectations hypothesis in the same way. To see how much of an influence this fact has on the results, we run the same regression, which includes Bank Rate in place of OIS rates, for the full sample from January 2000 to July 2015, so encompassing the crisis period. The coefficients on the supply variables were broadly similar when compared to the pre-crisis sample, suggesting that at least some of the weakness in the pre-crisis estimation was due to the change in control variable.

Regardless, even prior to the financial turmoil of the recent crisis and the adoption of quantitative easing as an explicit policy tool, it appears there was enough market segmentation for changes in supply of assets to have significant effects on prices and yields. This result echoes that of D'Amico *et al*. (2012), who use a similar methodology on a pre-crisis sample for the US and find significant relationships between supplies and yields on US Treasury securities.

Addressing the point of Miles and Schanz (2014) on exit from QE, we estimate our original model over a sub-sample which runs from January 2013 to July 2015. In this period we should note that UK financial markets were operating without any particular stresses and largely as they may be expected to function when the Bank of England comes to unwind its asset purchase programme. We find from this sample that there is still a significant degree of imperfect substitutability between assets and, therefore, the return of bonds to the market would be expected to place downward pressure on prices and upward pressure on yields, equating to a monetary tightening. What is more, the implied magnitude of the effect is similar to that over the whole post-2008 sample, though the weighting has shifted somewhat between changes in the supply of a security itself and those of substitute securities.

Therefore, as the quantitative easing programme is unwound, we should expect to see upward pressure on UK sovereign bond yields in excess of those emanating solely from an increasing Bank Rate and expectations thereof.

An aside on expectation management

An interesting point of note is that in our later subsample, the coefficient on changes in the OIS rate is considerably larger than in the 2009– sample. This may be unsurprising, as over recent years the adoption of forward guidance as an explicit policy tool has meant that increased focus has been put onto markets' expectations of policy rates, and the Bank of England's attempts to shape them. What is more, with the prospect of rate tightening seemingly on the horizon, all financial markets are likely to be acutely aware of the possibility of an upcoming turning point in the monetary policy cycle. This may have led to an increased sensitivity of market behaviour, and thus prices, to changes in perceptions about the future path of policy. From the Monetary Policy Committee's point of view this could pose a potential problem, as it means that any volatility in market expectations of Bank Rate will transmit more heavily into volatility in bond prices and interest rates, something the MPC might wish to avoid. Clear and effective communication might be particularly valuable if the costs of uncertainty are particularly high.

All in all, our results suggest that changes in the supply of UK government securities have a significant impact on the prices and interest rates associated with those securities and securities which are close substitutes for them. This supports the existence of a channel by which the monetary authority can directly influence interest rates via quantitative easing in excess of any signalling of the future policy rate. Whilst the strength of this channel may be amplified by market turmoil, it remains significant in periods of relatively well-functioning markets. As we will discuss below, our results also raise a number of questions about how these monetary policy moves interact with fiscal policy.

Unconventional monetary policy and fiscal policy

We now turn to the monetary-fiscal interaction inherent in movements in the publicly available supply of government securities. Our discussion so far has been concerned with how the monetary authority can exploit the relationship between supply and prices through quantitative easing. However, manipulating the supply and composition of the publicly available government debt portfolio amounts to debt management, which has traditionally been the preserve of the fiscal authority. Referring back to figure 1, the same profile of publicly

available debt could also have been achieved by the UK Treasury simply issuing less debt.

So, does it matter which arm of policy – monetary or fiscal – acts to reduce the publicly available supply of government securities? The answer is that it clearly does. To achieve the reduction in supply from the fiscal side, the fiscal authority must reduce its debt issuance and, all else equal, tighten the stance of fiscal policy, either through increased taxation or less expenditure. This would be contractionary and would contribute to offsetting any stimulus which might come from lower interest rates.[9] This problem is likely to be even more pronounced when monetary policy is constrained by the zero lower bound, as the central bank cannot use its traditional instrument to loosen policy and offset the fiscal contraction.

Alternatively, if the changes in supply are effected by the monetary authority, the fiscal authority is free to provide a stimulus which works to reinforce the expansionary monetary policy. In essence, coordinating policy in this way both allows policymakers to pursue their own objectives independently of each other; the fiscal authority can set total debt in accordance with its funding requirements, conditioned on a set of macroeconomic and policy goals as well as the automatic stabilisers, whilst the monetary authority can manipulate the amount of that debt which is publicly available to be consistent with its own target for interest rates and thus inflation. Such a policy obviously raises questions about the appropriate degree of coordination and the safeguarding or otherwise of central bank independence, but it does not follow that there is no scope for welfare improving coordination between two independent policy arms, just perhaps an understanding that monetary policy decisions may have fiscal implications, and fiscal decisions may have consequences for the monetary authority.

Our result also serves to highlight an often overlooked, but important channel through which unconventional monetary policy may operate. By allowing the fiscal authority to issue an increased level of debt without the associated rise in interest rate burden, central bank purchases of government debt may help to create fiscal space which, if utilised, could stimulate activity and thus inflationary pressure in line with the monetary objective. This phenomenon is by no means new, or confined to unconventional monetary policy. In fact it occurs every time the central bank cuts the traditional policy rate. It is also far from a free lunch for the fiscal authority though, as the same mechanism will apply in reverse when the central bank tightens policy and unwinds its balance sheet. As discussed in Kirby and Meaning (2015), the fiscal benefits of central bank asset purchases therefore amount to an intertemporal transfer, the optimality and net benefit of which require deeper consideration.

Conclusions

Our analysis shows that both the expectations of short-term nominal interest rates and changes in supply of assets matter in determining the prices of UK government securities. This allows for the possibility of multiple transmission mechanisms for monetary policy at the zero-lower bound with the Bank of England seemingly able to shape expectations through forward guidance and signalling, whilst also able to change the publicly available supply of assets through quantitative easing.

Our estimates suggest that the roughly 30 per cent reduction in the publicly available supply of nominal gilts that has occurred as a result of the Bank of England's current quantitative easing programme would lead to an average of a 20–25 basis point fall in yields on those securities. This estimate is seen as a lower bound to the efficacy of the programme. The uncovered relationships are robust to various specifications and controls. Importantly, they are also relatively robust across time periods, suggesting there were significant supply effects prior to 2009, and that a significant relationship between the publicly available supply and the prices of gilts has persisted in recent years. Should this continue then as the Bank of England unwinds its expanded balance sheet, we can expect this to reinforce the monetary tightening associated with tighter expectations on the Bank Rate.

Our results also serve to demonstrate the interactions between monetary and fiscal policy when the former operates in sovereign debt markets. Managing supply, as was done through quantitative easing, in many ways amounts to debt management, leaving open the prospect that the same changes in the publicly available supply could have been effected by the fiscal authority. There may be important differences between the two approaches though and the correct balance between the two requires careful consideration.

NOTES

1 Alternative motivations, such as increasing the money supply and promoting bank lending, have also been discussed as possible transmission mechanisms of the policy, but the bulk of discussion in the UK has been on the impact on interest rates.

2 On a theoretical level, such an irrelevance proposition hinges

on the assumption of a representative agent.

3 Clear examples here are the UK pensions market which is legally required to hold long-term government securities, or the need to hold liquid assets under the latest Basel Liquidity Coverage Ratio.

4 We conducted our analysis using a range of different measures of substitute securities including just bonds with a remaining maturity within two years or less of a bond, those with a remaining maturity within 50 per cent of that of a bond, and those within 25 per cent. We found that the key results were little changed, but that when one tightened the definition of substitutes some of the magnitude of the subs effect waned as many longer-dated securities, where the substitution effect is found to be strongest, were by definition without substitutes as there were no bonds within two years of them.

5 The Bank of England's OIS curve only reports rates up to five years, so for all bonds in our sample with a remaining maturity over this term we apply the 5-year OIS rate.

6 It should be noted that we estimated a number of different specifications, including bonds of all maturities, bonds with maturity of between 5 and 25 years, which was the Bank of England's initial purchase range, and controlling for inflation and the exchange rate. Our core result was robust to all of these and so the results presented were chosen for their intuition and parsimonious nature.

7 Event studies such as Caglar *et al.* (2015) find this channel to be weak, but are limited in their methodology to a narrow window across which expectations might change, whereas in practice expectations may adapt significantly in advance of policy announcements if they are anticipated.

8 Estimates of the impact of QE in the United Kingdom in the existing literature vary between 20 and 150 basis points. For a summary of the empirical literature, see Joyce *et al.* (2012).

9 In fact, the impact on interest rates itself is ambiguous here, as the additional risks that a tighter fiscal stance might imply for the broader economy could potentially push up on rates by more than the change in supply lowers them.

REFERENCES

Andrés, J., Lopez-Salido, J.D. and Nelson, E. (2004), 'Tobin's imperfect asset substitution in optimizing general equilibrium', *Journal of Money, Credit and Banking*, 36(4), pp. 665–90.

Banerjee, R., Latto, D. and McLaren, N. (2012), 'Using changes in auction maturity sectors to help identify the impact of QE on gilt yields', *Bank of England Quarterly Bulletin*, Q2.

Benford, J., Berry, S., Nikolov, K. and Young, C. (2009), 'Quantitative easing', *Bank of England Quarterly Bulletin*, 49, 2, pp. 90–100.

Bernanke, B. (2014), 'Central banking after the Great Recession: lessons learned and challenges ahead', speech given at the Brookings Institute.

Breedon, F., Chadha, J.S. and Waters, A. (2012), 'The financial market impact of UK quantitative easing', *Oxford Review of Economic Policy*, Oxford University Press, 28(4), pp. 702–28, Winter.

Caglar, E., Chadha, J.S., Meaning, J., Warren, J and Waters, A. (2015), 'Central bank balance sheet policies: three views from the DSGE literature' in Chadha, J.S. and Holly, S. (eds), *Interest Rates, Prices and Liquidity*, Cambridge, Cambridge University Press.

Culbertson, J.M. (1957), 'The term structure of interest rates', *Quarterly Journal of Economics*, 71, pp. 485–517.

D'Amico, S., English, W., López-Salido, D. and Nelson, E. (2012), 'The Federal Reserve's large-scale asset purchase programmes: rationale and effects', *Economic Journal*, Royal Economic Society, 122(564), pp. F415–46, November.

D'Amico, S. and King, E. (2010), 'Flow and stock effects of large-scale treasury purchases', Federal Reserve Board Finance and Economics Discussion Series, 2010.52.

Eggertson, G. and Woodford, M. (2003), 'The zero bound on interest rates and optimal monetary policy', *Brookings Papers on Economic Activity*, 1, pp. 139–233.

Greenwood, R., Hanson, S.G., Rudolph, J.S and Summers, L. (2014). 'Government debt management at the zero lower bound', Hutchins Centre on Fiscal and Monetary Policy, Brookings. Working paper #5.

Joyce, M., Lasaosa, A., Stevens, I. and Tong M. (2010), 'The financial market impact of quantitative easing', Bank of England Working paper, No.393.

Joyce, M., Miles, D., Scott, A. and Vayanos, D. (2012), 'Quantitative easing and unconventional monetary policy – an introduction', *The Economic Journal*, 122 (November), F271–F288.

Kirby, S. and Meaning, J. (2015), 'Impacts of the Bank of England's asset purchases on the public finances', *National Institute Economic Review*, 232, May.

Meaning, J. and Zhu, F. (2011), 'The impact of recent central bank asset purchase programmes', *BIS Quarterly Review*, December.

Miles, D. and Schanz, J. (2014), 'The relevance or otherwise of the central bank's balance sheet', CESIFO Working paper, No. 4615.

Modigliani, F. and Sutch, R.C. (1966), 'Innovations in interest rate policy', *American Economic Review, Papers and Proceedings*, 56(2), pp. 178–97.

Tobin, J. (1963), 'An essay on the principles of debt management', in *Fiscal and Debt Management Policies*, Englewood Cliffs, N.J.; Prentice Hall, pp. 143–218.

—(1969), 'A general equilibrium approach to monetary theory', *Journal of Money, Credit and Banking*, 1, February, pp. 15–29.

Vayanos, D. and Vila, J. (2009), 'A preferred-habitat model of the term structure of interest rates', CEPR Discussion Paper 7547, LSE.

Wallace, N. (1981), 'A Modigliani-Miller theorem for open-market operations', American Economic Association, *American Economic Review*, 71(3), pp. 267–74, June.