Expectations about the Federal Reserve's Balance Sheet and the Term Structure of Interest Rates*

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This paper assesses the effects of the Federal Reserve's asset purchase programs on Treasury yields, and provides a framework to evaluate these effects both initially and over time as market expectations of the economy and the Federal Reserve's balance sheet evolve. Our framework suggests that the first purchase program had the largest initial impact on the ten-year Treasury yield, estimated to be about 34 basis points in early 2009. Although the effect of the first program waned considerably by the end of 2015, at that time all programs combined were depressing the ten-year yield by about 100 basis points, reflecting expectations of economic conditions and Federal Reserve policy.

JEL Codes: G1, E4, C5.

1. Introduction

Through the financial crisis and subsequent recession, the Federal Reserve introduced unconventional monetary policy actions in order to "promote a stronger pace of economic recovery" and to help ensure that "inflation, over time, is at levels consistent with its mandate."[1] To this end, the Federal Reserve embarked on a number of

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[1]Statement of the Federal Open Market Committee, November 3, 2010.

asset programs to purchase, sell, or reinvest securities that dramatically changed the Federal Reserve's securities holdings across all dimensions—size, composition, and maturity structure. Each asset program was implemented in part to put downward pressure on longer-term interest rates, aimed to support a stronger recovery.

But how much did these asset programs affect longer-term interest rates? There is a growing body of work on this subject, which can be divided into three broad categories. The first strand of research depends on event-study methodology to determine the effect of the asset programs on interest rates at the onset of the programs.[2] The second uses reduced-form regression analysis (either in a time series or using panel methods) to evaluate the effect of Federal Reserve purchases on interest rates over time.[3] Finally, the third strand incorporates changes in the net private supply of different assets into a structural model of the economy or the yield curve to evaluate the effect of these programs on interest rates at any point in time.[4] The dynamic nature of this third type of model requires one to incorporate information not only about the current level of System Open Market Account (SOMA) holdings but also about their expected future path for an accurate estimate on interest rates. In this paper, we take the third approach.

More generally, the third approach incorporates features that are key to understanding the overall impact of the asset purchase programs. Most studies model the Federal Reserve's asset purchases and sales as either occurring instantly or spread out evenly over a short window. In reality, the purchases and sales were announced ahead of time, followed a predetermined timetable where the pace sometimes varied, and were commonly expected to be unwound at a future point of time, resulting in changes not only to the contemporaneous level of the Federal Reserve's (Fed's) balance sheet and private holdings of Treasury securities and agency mortgage-backed securities (MBS) but also to expectations about their future dynamics. The dynamic pattern of the asset programs matters for the estimated impact on

[2]Refer to Gagnon et al. (2011), Krishnamurthy and Vissing-Jørgensen (2011), and Swanson (2011).

[3]Refer to D'Amico et al. (2012), Meaning and Zhu (2012), and D'Amico and King (2013).

[4]Refer to Chung et al. (2011), Hamilton and Wu (2012), and Li and Wei (2013).

interest rates. In addition, as the economy evolves, so do the expectations for the Fed's securities holdings (including issues such as how to invest proceeds from maturing securities and when to stop this reinvestment). Changing expectations have implications for how the Fed's actions affect yields on longer-term securities.

This paper develops a methodology that can be used to estimate the effect of asset purchases on interest rates both at the initial outset of a program and at any point in time thereafter. Importantly, this approach is consistent with contemporaneous and future investors' expectations for the macroeconomy and Federal Reserve policy, and therefore allows for a time-varying effect of a program on interest rates. Specifically, this paper demonstrates how estimates of interest rate effects can be derived from longer-term market expectations of interest rates, macroeconomic conditions, and the Federal Reserve's balance sheet. To capture the projected time-series patterns of Federal Reserve portfolio holdings at any point in time, we use the contemporaneous interest rate and macroeconomic projections from the Blue Chip Economic Indicators release and Treasury issuance projections by the Congressional Budget Office (CBO). In addition, we assume a possible path for the unwinding of monetary policy accommodation consistent with the most recent Federal Reserve communications regarding the removal of policy accommodation, or "normalization principles" at the date when the term premium effect of a program is estimated. In particular, for those purchases announced before 2014, we use those outlined in the minutes of the June 2011 Federal Open Market Committee (FOMC) meeting; for those after, we use the update provided in the Policy Normalization Principles and Plans released in 2014. We project private holdings of securities by recognizing that privately held securities are simply the total stock of the securities outstanding minus the Federal Reserve's holdings.[5] Taken together, these strategies ensure that our estimates are consistent with market participants' views of the evolution of the economy and removal of unconventional monetary policy.

[5]In this context (and as defined by the U.S. Treasury), all marketable Treasury debt that is not held by the Federal Reserve is considered to be "privately held," even if that debt is held by foreign official accounts. In addition, currently there is a small amount of marketable debt held by U.S. state and local governments; however, the level of these holdings relative to total marketable Treasury debt is small.

To construct our market-expectations-consistent projections of Federal Reserve holdings, and hence private holdings, we lean on the methodology outlined in Carpenter et al. (2015). Their study considers how the Federal Reserve's balance sheet evolves with respect to both the Federal Reserve's projected unwinding of unconventional monetary policy accommodation and the "natural" evolution of the balance sheet that accounts for increases in currency and growth in Federal Reserve bank capital.[6] The dollar amount of each asset purchase program and the maturity structure of the purchases and sales of securities also affect the expected evolution of the balance sheet, which is critical for determining the term premium effect (TPE). These characteristics are embedded in the estimates presented below and provide a view of how market participants perceived each asset program when it was implemented, as well as what is expected as of today.

When assessing the interest rate effects of the Federal Reserve's asset programs, we focus on the "duration" channel through which Federal Reserve purchases reduce the quantity and the average maturity of long-term safe assets held by private investors and lower the term premiums on these assets.[7] In particular, we adopt the model of Li and Wei (2013), which was motivated by empirical evidence that excess bond returns appear to be predictable by the amount and the average maturity of Treasury securities outstanding, as well as the theoretical work of Vayanos and Vila (2009), which shows how differences in maturity preferences of Treasury investors can generate supply effects in the government bond market.[8] In the Li and Wei (2013) model, Treasury yields are driven by both yield factors and Treasury and agency MBS supply factors. They use the model to evaluate the magnitude of supply effects on term premiums, and find that a 1 percentage point decline in the ratio of private

[6]One focus of that work was on the nature of the interest rate shocks that could lead to the Federal Reserve's remittances to Treasury ceasing for a period. This paper does not focus on that issue to the same extent; other papers, including Greenlaw et al. (2013) and Christensen, Lopez, and Rudebusch (2015), provide alternative views on the interest rate risk inherent in the Federal Reserve's portfolio.

[7]Other potential channels are discussed in the literature review section below.

[8]Greenwood and Vayanos (2014) illustrate that there are supply effects from overall Treasury debt outstanding on the term structure of interest rates.

holdings of Treasury ten-year equivalents to GDP ratio or the MBS par-to-GDP ratio would reduce the ten-year Treasury yield by about 10 basis points, while a one-year shortening of the average effective duration of private MBS holdings would lower the ten-year Treasury yield by about 7 basis points.

By combining estimates of market expectations for the Federal Reserve's portfolio, interest rates, and macroeconomic conditions constructed above with this term structure model, we are able to take a comprehensive view of both the term structure of interest rates and the size and composition of the Federal Reserve balance sheet. As a result, the estimated interest rate effects of the Federal Reserve's asset programs are consistent with market expectations about how private holdings of securities will evolve at any point in time with all asset programs in place at that date. This approach allows us to estimate the TPE at the onset of an asset program, to track the expected "decay" of the program, and to evaluate the TPE and its decay at any other point in time using updated market expectations.

The main contributions of this paper are twofold. First, we provide a time-varying, market-expectations-consistent estimate of the TPE as the economy evolves and expected FOMC policies adjust, while most other studies focus on the TPE at the onset of the asset programs. Second, we can estimate the expected decay of the TPE. The evolution of the TPE illustrates how past unconventional monetary policy will fade over the next several years, exerting downward pressure on longer-term interest rates even after the FOMC has raised the federal funds rate above zero.

Relative to other studies, this approach is more comprehensive and, therefore, provides a more complete estimate of the TPE. For example, Chung et al. (2012) use the par value of the Federal Reserve's Treasury and agency MBS holdings to estimate their TPE, and are therefore not equipped to provide TPE estimates for some of the asset programs that hold the level of securities constant but change the composition of holdings. Li and Wei (2013) use a rule-of-thumb proxy for the evolution of private holdings of securities and, therefore, focus only on the *contemporaneous* impact of the asset programs. Here, we align our projections of private holdings with market participants' views about the expected path of Treasury issuance and future Federal Reserve holdings of securities and, as a result, have

a contemporaneous estimate of the TPE of each asset program at implementation that is consistent with market expectations, have a projection of the expected *TPE over time (TPE path)* based on those expectations, and have the ability to reevaluate the TPE path with updated expectations at any future point in time.[9] Moreover, while this methodology requires constructing views on how the central bank's balance sheet evolves with and without a particular asset purchase program, and therefore is more complicated than an event-study approach, it is at the same time flexible and complete enough to produce estimates of monetary policy accommodation over time that are consistent with preferred-habitat models of asset purchases.

We evaluate the term premium effect of each of the seven asset programs conducted by the Federal Reserve from 2008 to 2014—the outright purchase programs announced on November 2008 and expanded in March 2009 (LSAP1); the reinvestment program announced in August 2010; the outright purchase program announced in November 2010 (LSAP2); the maturity extension program (MEP) announced in September 2011; the change to the reinvestment program announced in September 2011; the continuation of the MEP announced in June 2012; and the open-ended purchase program that commenced in the fall of 2012. We investigate how the ten-year Treasury term premium reacted at the time of each program's inception based on market expectations that were in place at the time, and we also examine how each program continues to affect interest rates today, using current expectations. Our estimates suggest that at inception, the first LSAP program resulted in the largest apparent reduction in the ten-year Treasury term premium of about 34 basis points in the second quarter of 2009, the maturity extension program taken as a whole held down the term premium by about 28 basis points, and the open-ended purchase program depressed the term premium by 31 basis points.

These estimates of the term premium effect are based on market participants' views of the evolution of the economy at the time that each asset program was implemented. However, through time, expectations changed. For example, the June 2009 Blue Chip Forecast expected that the federal funds rate would rise above 25 basis

[9]Engen, Laubach, and Reifschneider (2015) use our estimate in their paper.

points by June 2010 and that annual GDP growth would return to 3.1 percent by 2011, while in reality the federal funds rate stayed at the effective lower bound until end-2015 and annual GDP growth has yet to reach 3 percent. Also, the FOMC originally viewed MBS sales as part of the exit strategy but in 2012 announced that only residual sales could possibly be conducted at some point in the future. Importantly, our model allows us to update the TPEs of each program for current and evolving market expectations.

All of these asset purchases were completed as of the fourth quarter of 2014, and only the reinvestment programs were ongoing through 2015. Towards the end of 2015, after all purchases were completed and the FOMC was preparing to raise interest rates for the first time in many years, the TPEs of all programs combined is estimated to be about 100 basis points. We attribute about 5 basis points to the first large-scale asset purchase program, a negligible amount to the second; about 20 basis points each to the maturity extension program and its continuation; a little over 20 basis points to the third; and the remainder to the reinvestment programs. In addition, we present a measure of uncertainty around the term premium effect by calculating error bands around our point estimate. Overall, the results suggest about a wide 90 basis point confidence interval around our term premium effect. In the first quarter of 2015, the standard error on our TPE estimate is 27 basis points, representing roughly one-quarter of our estimate.

2. Background

This section reviews the purchase programs during the financial crisis that shaped the Federal Reserve's balance sheet and the theory behind our model. We discuss each in turn.

2.1 The Federal Reserve's Balance Sheet and the SOMA Portfolio

In order to have a comprehensive estimate of how the Federal Reserve's asset programs affected private-sector holdings of securities, one must consider how the SOMA evolves over time both with and without these programs. To help understand this point,

we briefly review a few key line items of the balance sheet; a more detailed discussion is in Carpenter et al. (2015).

For most of the postwar period, the largest asset on the Federal Reserve's balance sheet was the SOMA, and the largest liability was Federal Reserve notes (FR Notes), or paper currency, in circulation outside of reserve banks.[10] Growth of the Federal Reserve's balance sheet reflected growth in currency outstanding, as well as increases in Reserve Bank capital. As currency and capital grew, the Federal Reserve purchased Treasury securities in the open market to keep assets on the Federal Reserve's balance sheet equal to liabilities plus capital.

In addition to steady growth, the composition of the SOMA portfolio was fairly constant as well. Over time, the Federal Reserve held a few types of securities in the SOMA portfolio, and from 2004 through the financial crisis, the portfolio held only Treasury securities. The weighted-average maturity of the portfolio ranged from three to four years. In addition, as expressed in ten-year equivalents, or duration equivalents of the on-the-run ten-year note, the SOMA portfolio grew at a pace similar to the par growth rate of the portfolio, although it fluctuated some as the duration of the ten-year note changed.[11]

The Federal Reserve's balance sheet changed markedly with the start of the financial crisis, and in ways that both indirectly and directly affected the evolution of the Federal Reserve's securities holdings. The first actions were engaging in reserve-adding repurchase agreements and lowering the rate on discount window loans in August 2007. Subsequently, credit and lending facilities were introduced to aid with liquidity strains. These actions included the Term Auction Facility (TAF), which granted banks term loans of central bank funds, in the fall of that year. All of these actions expanded the asset side of the balance sheet. As a result, the Open Market Desk allowed some Treasury bills to mature and sold other securities in order to sterilize these reserve-adding actions. As a result of

[10]The remainder of the assets on the balance sheet—for example, borrowings from the discount window, other assets, and foreign exchange assets—was relatively small when compared with the SOMA portfolio.

[11]A Treasury security expressed in ten-year equivalents is the par value of security times the duration of security divided by the duration of the on-the-run ten-year Treasury note.

the sterilization, Treasury bill holdings in the SOMA dropped to a little less than $20 billion in June 2008.

After the collapse of Lehman Brothers in the fall of 2008, the Federal Reserve continued to lend funds through various facilities. The FOMC also decided to lower the target federal funds rate to its effective lower bound in December 2008. As the provision of additional accommodation through lowering the short rate was viewed as no longer an option, the Federal Reserve also started its first foray into actively changing the size and composition of the SOMA portfolio through purchase, sales, and reinvestment programs.[12] From that time to the present, the Federal Reserve announced seven different asset programs, summarized in table 1. In very broad terms, three changed the size of the balance sheet, and four focused mainly on composition, although all had some elements of both.

The next section discusses some theoretical models regarding the effect of asset purchases on rates and the macroeconomy, and also provides a general literature review.

2.2 The Effect of Treasury Supply on Yields: Theory and Literature Review

Vayanos and Vila (2009) formulated a modern arbitrage-free preferred-habitat term structure model. In their model, the existence of preferred-habitat investors provides a channel for relative supply factors to influence Treasury yields, while the existence of risk-averse arbitrageurs, who have no maturity preference but actively trade to take advantage of arbitrage opportunities, ensures that supply shocks are transmitted smoothly across the yield curve. Vayanos and Vila (2009) show that, under certain parameterizations, the yield impact of variations in relative supplies depends on the dollar duration of the supply shocks absorbed by the arbitrageurs, which implies a direct relationship between the term premium and the total duration risks faced by private investors. To the extent that LSAP programs remove duration risk from the market by withdrawing a portion of long-term securities, the risk premium built into the price of such assets should decline, and as a result, their yield should

[12] Bernanke and Reinhart (2004) discuss policy options at the effective lower bound for the short-term interest rate.

Table 1. Asset Programs

Program Name	Type of Securities Being Purchased	Program Effects on SOMA			Date Announced	Date Operations Began	Date Operations Ended
		Size of Program	Composition over Life of Program	Maturity			
LSAP1	Treasury securities, agency debt, agency MBS	"Up to" $200 billion in agency debt, $300 billion in Treasury securities, and $1.25 trillion in agency MBS	Share of agency securities increased from 0 to 68 percent	Maturity of portfolio lengthened	Nov. 2008	Nov. 2008	Jun. 2010
Reinvestments into Treasuries	Treasury securities	Maintained size of SOMA	30 percent increase in Treasury securities, share of agency MBS decreased 20 percent*	Treasuries remained steady, MBS maturity lengthened	Aug. 2010	Aug. 2010	Sep. 2011
LSAP2	Treasury securities	Increased size of SOMA by about $600 billion	Share of Treasury securities increased from 50 percent to 62 percent	Maturity slightly shortened	Nov. 2010	Nov. 2010	Jun. 2011
Reinvestments into Agency MBS	Agency MBS	Maintained size of SOMA	Share of agency MBS slightly increased	Maturity of portfolio lengthened	Sep. 2011	Sep. 2011	Oct. 2017

(*continued*)

Table 1. (Continued)

Program Name	Type of Securities Being Purchased	Program Effects on SOMA			Date Announced	Date Operations Began	Date Operations Ended
		Size of Program	Composition over Life of Program	Maturity			
MEP	Treasury securities	$400 billion of shorter-term Treasury securities sold, $400 billion of longer-term Treasury securities purchased	Weighted-average maturity of Treasury portfolio increased from 70 months in mid-2011 to 100 months by mid-2012	Maturity of portfolio lengthened	Sep. 2011	Sep. 2011	Jun. 2012
MEP2	Treasury securities	$267 billion of shorter-term Treasury securities sold or redeemed, $267 billion of longer-term Treasury securities purchased	Weighted-average maturity of Treasury portfolio increased from 70 months in mid-2011 to 120 months by the end of 2012	Maturity of portfolio lengthened	Jun. 2012	Sep. 2011	Dec. 2012
LSAP3	Treasury securities, agency MBS	$540 billion in Treasury securities, $520 billion in agency MBS	Share of agency securities increased from 36 percent to a peak of 42 percent	Maturity of portfolio slightly shortened	Sep. 2012	Sep. 2012	Dec. 2013

*Share of Treasury securities also includes reinvestments from agency debt.

decline. The removal of duration risk should generate reactions of yields across much of the maturity spectrum—not just on the yields of purchased securities but on those of adjacent maturities as well.

Motivated by this theory, Li and Wei (2013) propose and estimate an arbitrage-free term structure model with supply factors including the private holdings of Treasury and agency MBS securities. They show that these supply factors have important explanatory power on the term premium beyond that embedded in traditional yield-curve factors. They also derive a formula that links the term premium to current and expected future shocks to these supply factors. As a result, their model can be used to evaluate an asset purchase program's term premium effect based on the program's projected impacts over time on these supply factors.

Of course, there are other plausible modeling approaches that differ from the one we have chosen here. While the Li-Wei paper emphasizes the duration risk channel through which the Federal Reserve's asset programs work on reducing longer term rates, other papers have emphasized additional channels. For example, Krishnamurthy and Vissing-Jørgensen (2011) offer evidence that Treasury supplies could also affect interest rates through what they call "the safety premium channel." Another example is D'Amico and King (2013); their work emphasizes the "scarcity channel," or the available supply of nearby maturities. D'Amico et al. (2012) also focus on the scarcity channel in their analysis; they couple this channel with the duration channel to arrive at their final estimates of the term premium effects of the programs.

Finally, other approaches emphasize the "signaling" channel, whereby announcements of purchases by the central bank signal that accommodative federal funds rate policy would remain in place for some time. Researchers, including Bauer and Rudebusch (2014), illustrate the importance of this channel. Our modeling approach specifically abstracts from this channel, as we focus on the term premium effect of asset purchases. However, as will be explained further below, our modeling approach does indirectly incorporate market expectations for the federal funds rate. In particular, investors typically expect a link between the timing of any federal funds rate tightening and the timing when the Federal Reserve will allow securities to mature off its balance sheet. If any LSAP program announcement simultaneously lowered market expectations for the path of

the federal funds rate, our modeling approach would suggest that the balance sheet would remain larger for longer and, as such, the term premium effect would be magnified. All told, then, while our term premium effect estimate does not reflect a signaling channel, it does incorporate at least some of the effect on rates attributable to expectations for a lower federal funds rate path.

There are also alternative choices for modeling private holdings of securities. One example is in Chung et al. (2011), which uses the differences in the SOMA-to-GDP ratio from a long-run average as a proxy for changes in private holdings of securities due to LSAPs, and as such, uses balance sheet projections to evaluate LSAPs. That said, their approach has a few shortcomings. Specifically, they approximate the balance sheet contours by looking at the current par value of SOMA holdings and assume that SOMA holdings in excess of one year remaining maturity trend towards a long-run level of 5 percent of nominal GDP. This approximation is reasonable for a "rough estimate" of the TPE associated with the LSAP programs, but the results depend critically on the assumption for the steady-state SOMA-to-GDP ratio, which changes over time. In addition, while their methodology likely gives similar results to those presented here for the LSAP1 and LSAP2 purchase programs, it cannot evaluate the effect of the MEP or any asset purchase programs that change the duration of SOMA but not the nominal value of the portfolio. That methodology also fails to take into account any endogenous, cyclical variations in the SOMA-to-GDP ratio.

3. The Model

This section reviews the two aspects of our modeling efforts: the term structure model with supply factors, and the construction of the path of private-sector holdings of securities. We discuss each in turn.

3.1 Modeling the Term Premium Effect

Li and Wei (2013) assume that yields are driven by five state variables, denoted by f_t, that include two yield-curve factors (level and slope), one Treasury supply factor (total private holdings of Treasury securities in terms of ten-year equivalents and as a ratio of nominal

GDP), and two agency MBS supply factors (the par amount of total private holdings of MBS as a ratio of nominal GDP and average MBS duration), numbered 1 through 5.

The inclusion of these supply factors is motivated by the preferred-habitat term structure model as in Vayanos and Vila (2009). That model has two types of private participants in the Treasury market: preferred-habitat investors, who hold only a particular maturity segment of the Treasury yield curve and are risk neutral, and risk-averse arbitrageurs, who trade to take advantage of arbitrage opportunities and have no maturity preference. Vayanos and Vila (2009) show that in such a model, bond holdings of the arbitragers can affect the equilibrium bond risk premiums. The supply factors included in Li and Wei (2013) as well as in this paper can be justified by the additional assumption that the preferred-habitat investors consist of the U.S. Treasury and the Federal Reserve, while the arbitrageurs correspond to the entire private sector.[13]

The state variables are assumed to follow a first-order vector autoregressive process:

$$f_{t+1} = c + \rho f_t + \Sigma \varepsilon_{t+1}, \tag{1}$$

with the following restrictions:

$$\rho = \begin{bmatrix} \rho_{11} & \rho_{12} & 0 & 0 & 0 \\ \rho_{21} & \rho_{22} & 0 & 0 & 0 \\ 0 & 0 & \rho_{33} & 0 & 0 \\ 0 & 0 & 0 & \rho_{44} & 0 \\ \rho_{51} & 0 & 0 & 0 & \rho_{55} \end{bmatrix}, \sum = \begin{bmatrix} \sigma_{11} & 0 & 0 & 0 & 0 \\ 0 & \sigma_{22} & 0 & 0 & 0 \\ 0 & 0 & \sigma_{33} & 0 & 0 \\ 0 & 0 & 0 & \sigma_{44} & 0 \\ \sigma_{51} & 0 & 0 & 0 & \sigma_{55} \end{bmatrix},$$

where the non-zero ρ_{51} captures the feedback effect from the level of interest rates to average MBS duration. The restriction that Treasury and MBS holdings factors do not load on past yield factors ($\rho ij = 0, 3 \leq i \leq 4, 1 \leq j \leq 2$) reflects the empirical evidence that the *net* issuance of both Treasury securities and of agency MBS does not react strongly to interest rates in the short run.[14]

[13]The same assumption is used by Hamilton and Wu (2012).

[14]The Treasury's stated debt-management policy is that it does not "time the market"—or seek to take advantage of low interest rates—when it issues securities. Instead, the Treasury strives to lower its borrowing costs over time by

The one-period nominal short rate is assumed to be linear in the factors

$$y_{1t} = a_1 + b_1' f_t, \tag{2}$$

with the restriction that it only loads on the yield factors:

$$b_1 = \begin{bmatrix} b_{11} & b_{12} & 0 & 0 & 0 \end{bmatrix}'.$$

Under this restriction, shocks to supply factors do not affect interest rate expectations but can affect bond yields through the term premium channel only. This assumption captures the fact that the supply of Treasury and MBS securities is *not* an important consideration when the Fed determines the short-term interest rate.

The stochastic discount factor is conditionally log-normal,

$$\log M_t = -y_{1t} - \frac{1}{2}\lambda_t'\lambda_t - \lambda_t'\varepsilon_{t+1}, \tag{3}$$

with the market prices of risk also assumed to be affine in the factors:

$$\lambda_{\mathrm{t}} = \lambda_0 + \lambda_1 f_{\mathrm{t}}. \tag{4}$$

We impose the restriction that the supply factors do not carry their own risk premiums but can affect term premiums by changing the risk premiums on the yield factors. As a result, we can restrict the last three rows of b_1 to be zero. This assumption reflects our prior that Treasury and MBS supplies are unlikely to be a source of undiversifiable risk that should be priced on its own. Imposing these restrictions on the short rate and risk premiums also helps reduce the number of parameters that needs to estimated and avoid the overfitting problem.

Under all these assumptions, it is relatively easy to solve for the price P_t^n of an n-period zero-coupon bond at time t by recursively solving the relation

$$P_t^n = E_t(M_t P_{t+1}^{n-1}), \tag{5}$$

relying on a "regular and predictable" preannounced schedule of auctions. While the gross issuance of MBS responds strongly to the level of rates in a refinance boom sparked by declining interest rates, the net supply of MBS stays about unchanged as old mortgages and MBS are replaced with new ones.

with the terminal condition $P_t^0 = 1$. The resulting bond prices are exponential linear functions of the state vector:

$$P_t^n = \exp(A_n + B_n f_t), \tag{6}$$

with

$$A_{n+1} = A_n + B_n' (c - \Sigma\lambda_0) + \frac{1}{2} B_n' \Sigma\Sigma' B_n - a_1 \text{ and} \tag{7}$$

$$B_{n+1} = (\rho - \Sigma\lambda_1)' B_n - b_1, \tag{8}$$

and the initial conditions $A_1 = -a_1$ and $B_1 = -b_1$. Bond yields are then given by

$$y_t^n = a_n + b_n f_t, \tag{9}$$

where $a_n = -\frac{A_n}{n}$ and $b_n = -\frac{B_n}{n}$

Li and Wei (2013) estimate this model using monthly data on Treasury yields, private holdings of Treasury and agency MBS, and average MBS durations from March 1994 to July 2007, which provides model-implied loadings of yields on the factors b_n. Given these loading estimates, the impact of an asset purchase program can be easily estimated by first calculating the expected shocks to the first two supply factors—private holdings of Treasury securities and agency MBS—associated with each program, and then multiplying it by the term premium loadings; the MBS average duration factor is endogenously determined inside the model but not directly affected by the asset purchase programs.

This simple approach, however, treats the purchases as one-period shocks to these two supply variables with the implicit assumption that following the shocks, those supply variables will resume their evolution over time according to their historical dynamics. In contrast, the asset purchase programs are usually implemented over a period of time, resulting in *predictable or expected* changes to both the levels and the dynamics of the Treasury and MBS private holdings factors during and after the purchases. Therefore, the LSAP programs in practice represent a series of expected shocks to supply factors and are modeled as such in and Li and Wei (2013). In particular, they show that the cumulative effect of a series of expected

supply shocks on yields over the life of the bond can be measured by the following formula:

$$\tilde{y}_t^n - y_t^n = b_n^s u_t^s + \sum_{i=1}^{T-t} \frac{n-i}{n} b_{n-i}^s (u_{t+i}^s - \rho^{ss} u_{t+i-1}^s)$$

$$\approx b_n^s u_t^s + \sum_{i=1}^{T-t} \frac{n-i}{n} b_{n-i}^s (u_{t+i}^s u_{t+i-1}^s), \tag{10}$$

where $\tilde{y}_t^n - y_t^n$ is the difference in the bond yield with and without the expected supply shock to the Treasury and MBS private holdings, b_n^s denotes the loadings of yields on these two supply factors, $u_t^s = [u_t^{Tsy}, u_t^{MBS}]$ denotes the exogenous shocks to these two supply factors at time t, and ρ^{ss} denotes the autoregressive matrix of the supply variables. For Treasury securities, u_t^{Tsy} is the difference between Federal Reserve holdings of Treasury securities (in terms of ten-year equivalents and as a percentage of nominal GDP) in a scenario without the asset purchase program and a scenario with the program, while for agency MBS, u_t^{MBS} is the difference between Federal Reserve agency MBS holdings (in par amount and as a percentage of nominal GDP) in a scenario without the asset purchase program and a scenario with the program.[15]

As noted in equation (10), the term premium effect depends not only on the current supply shock u_t^s but also on the expected future path of u^s. In Li and Wei (2013), as an illustrative usage of the model, the u^s path is constructed simply as three phases for each asset program: a smooth increase during the program implementation phase, staying at this level for two years (the holding phase), and then a smooth decline over time that dissipates over five years (the unwinding phase). Here, we model the evolution of the u^s by making it consistent with market participants' views on the evolution of Treasury issuance and Federal Reserve holdings, with the latter accounting for the expected unwind of monetary policy accommodation provided by the balance sheet.[16]

[15]Keeping the total amount outstanding constant, the changes in private holdings are equal in magnitude but opposite in sign to changes in Federal Reserve holdings.

[16]More details of the construction of u^s are discussed below.

3.2 Modeling the Federal Reserve's Balance Sheet

As discussed above, the term premium effect relies on the projected path of shocks to private-sector holdings of securities. We construct this path by projecting the evolution of total Treasury issuance and Federal Reserve holdings of securities.[17] Both are critical to evaluate accurately the evolution of supply shocks discussed above.

The remainder of this section briefly reviews the construction of the Federal Reserve's holdings of securities; more specifics of the methodology can be found in Carpenter et al. (2015) and in the appendix.

To estimate the TPE for a given asset program upon implementation, we project how the SOMA portfolio evolved in two scenarios: (i) a projection of SOMA holdings immediately after the onset of the program (using expectations by market participants at that point in time) that includes the asset purchases to be studied; and (ii) a projection of SOMA holdings immediately prior to the announcement and implementation of the asset program under consideration but with no additional asset purchases (the counterfactual). An important counterfactual that we construct reflects the possible evolution of the balance sheet without any asset purchases at all. This counterfactual is a scenario where the economy evolved as market participants expected in October 2008; that is, without asset purchases and without a severe recession. This translated to a somewhat standard Federal Reserve balance sheet, with small asset holdings that primarily support currency in circulation.

For each scenario, we project the evolution of the balance sheet reflecting in part the maturity profile of the securities held in the portfolio. This evolution is based on the announced maturity structure of the asset purchase programs, the projection of the composition of total Treasury debt outstanding, and the growth in the size of the balance sheet attributable to factors other than the asset purchases.

Another key part of modeling the effect of asset purchase programs is the assumption surrounding the removal of balance sheet

[17]We assume that total securities outstanding are exogenous to the Federal Reserve's asset programs. This is consistent with the Treasury not altering their funding patterns after the initiation of the various Federal Reserve's asset purchase programs.

policy accommodation. For programs announced before 2013, we base our projections on the general principles for the exit strategy that the FOMC outlined in the minutes of the June 2011 FOMC meeting. At that time, the Committee stated that it intended to take steps in the following order:

(i) Cease reinvesting some or all payments of principal on the securities holdings in the SOMA.
(ii) Modify forward guidance on the path of the federal funds rate and initiate temporary reserve-draining operations aimed at supporting the implementation of increase in the federal funds rate when appropriate.
(iii) Raise the target federal funds rate.
(iv) Sell agency securities over a period of three to five years.
(v) Once sales begin, normalize the size of the balance sheet over two to three years.[18]

However, the Policy Normalization Principles and Plans released in September 2014 suggest that (i) ceasing reinvestment will not occur until after liftoff and (ii) MBS sales would not be a prominent part of the early stages of policy normalization. As such, we rely on these revised Principles and Plans for the open-ended asset purchase program and subsequent reinvestments. More broadly, the assumptions regarding the removal of policy accommodation affect the contour of the balance sheet and, therefore, the amount of accommodation provided: as the balance sheet with the asset purchases comes to resemble that without them, policy accommodation wanes.

To complete the normalization strategy, we make a few additional assumptions. We tie changes in the SOMA portfolio to the date the federal funds rate rises from its effective lower bound. For programs implemented prior to the open-ended purchases, we assume that the reinvestment of securities ends six months before this date and we assume that sales of agency securities begin six months after the federal funds rate begins to rise. For the open-ended purchase program implemented over 2012 to 2014 and for the estimate of the

[18]Minutes of the Federal Open Market Committee, June 21–22, 2011, available at http://www.federalreserve.gov/monetarypolicy/files/fomcminutes20110622.pdf.

Table 2. Assumptions

FOMC Policy	Date of Projection	Liftoff	Rolloff	MBS Sales
LSAP1				
Immediately Prior to LSAP1	Oct. 2008	N/A	N/A	N/A
Announcement of Extension of LSAP1	Apr. 2009	Jun. 2010	N/A	Dec. 2010
Treasury Security Reinvestments				
Immediately Prior to Reinvestments into Treasuries	Jun. 2010	Oct. 2010	N/A	Apr. 2011
Announcement of Reinvestments into Treasuries	Sep. 2010	Jun. 2011	Dec. 2010	Dec. 2011
LSAP2				
Announcement of LSAP2	Nov. 2010	Dec. 2011	Jun. 2011	Jun. 2012
MEP and MBS Reinvestments				
Immediately Prior to Reinvestments into MBS	Aug. 2011	Oct. 2013	Apr. 2013	Apr. 2014
Announcement of Reinvestments into MBS	Sep. 2011	Oct. 2013	Apr. 2013	Apr. 2014
Announcement of MEP	Sep. 2011	Oct. 2013	Apr. 2013	Apr. 2014
MEP2				
Immediately Prior to Extension of MEP	Jun. 2012	Dec. 2013	Jun. 2013	Jun. 2014
Announcement of MEP Extension	Jun. 2012	Dec. 2013	Jun. 2013	Jun. 2014
LSAP3				
Immediately Prior to LSAP3	Sep. 2012	Dec. 2013	Jun. 2013	Jun. 2014
Announcement of LSAP3	Sep. 2012	Sep. 2014	Mar. 2014	Mar. 2015
Normalization Principles				
Immediately Prior to Normalization Principles	Sep. 2014	Jun. 2015	Jun. 2015	Jun. 2016
Announcement of Normalization Principles	Sep. 2014	Jun. 2015	Dec. 2015	N/A

TPE of –100 basis points, we assume that reinvestment stops six months after liftoff (as in Carpenter et al. 2015) and that MBS sales never occur. We have the balance sheet contract over time until it hits a "normal size," which we mean is when reserve balances return to $25 billion, the average level before the crisis. The exit strategies and timing for each scenario are summarized in table 2.

One weakness of this approach is that it relies on whether market participants evolve their expectations for the balance sheet in a manner similar to our assumption. If market expectations for the size of the balance sheet were markedly different than our assumption, our estimates would be off. However, we use the same timing

assumptions as in the Federal Reserve Bank of New York publication "Domestic Open Market Operations in 2011." Furthermore, the Federal Reserve Bank of New York also posts its securities holdings at the CUSIP level on its website, making it possible for market participants to construct their own views on the evolution of the portfolio.

That said, because of the careful attention paid to the evolution of the balance sheet, the methodology used in this paper can incorporate an unanticipated change in the amount and/or composition of SOMA holdings that occurs while a program is ongoing and adjust the estimated path for balance sheet accommodation going forward accordingly. This is in sharp contrast to an event study, which cannot fully describe the evolution of a program over time and can only provide snapshots of expectations for policy accommodation. This distinction can be important when modeling programs that change over time, and we will see an example of this change in the discussion of LSAP3 below. In addition, the current methodology is able to estimate the downward pressure Federal Reserve policy is having on interest rates at any point in time, even after a LSAP program has been completed and conventional policy has moved the federal funds rate above zero.

In addition to these assumptions, we need assumptions on interest rates and debt outstanding in order to construct the Federal Reserve's and the private sector's holdings of Treasury securities in terms of ten-year equivalents, with the private-sector holdings being the supply input for the term structure model. For interest rates, we rely on the Blue Chip Survey of Professional Forecasters for their views on the paths of the federal funds and ten-year Treasury rates immediately before the implementation of the policy action we consider. The five-year long-run annual projections from this data source are released twice a year, in June and December. In addition, these projections include a five-year average for the selected variables for the years after the individual annual projections, resulting in a ten-year projection. As a result, for policy interventions announced in intervening months, we inspect the short-run projections that cover six quarters into the future that are produced monthly and interpolate these projections on a case-by-case basis, as described in table 3. Furthermore, for each of the balance sheet scenarios, we project total Treasury debt outstanding as well as the composition of

Table 3. Publication Dates of Data Sources

FOMC Policy	Blue Chip Interest Rates		Blue Chip Real GDP Growth		CBO Forecast
	Short Term*	Long Term	Short Term	Long Term	Fiscal Year
LSAP1					
Immediately Prior to LSAP1	Nov. 2008	Jun. 2008	Nov. 2008	Jun. 2008	2009
Announcement of Extension of LSAP1	Apr. 2009	Jun. 2009	Apr. 2009	Jun. 2009	2009
Treasury Security Reinvestments					
Immediately Prior to Reinvestments into Treasuries	Jun. 2010	Jun. 2010	Jun. 2010	Jun. 2010	2009
Announcement of Reinvestments into Treasuries	Sep. 2010	Dec. 2010	Sep. 2010	Dec. 2010	2010
LSAP2					
Announcement of LSAP2	Dec. 2010	Dec. 2010	Dec. 2010	Dec. 2010	2011
MEP and MBS Reinvestments					
Immediately Prior to Reinvestments into MBS	Sep. 2011	Dec. 2011	Sep. 2011	Dec. 2011	2011
Announcement of Reinvestments into MBS	Sep. 2011	Dec. 2011	Sep. 2011	Dec. 2011	2011
Announcement of MEP	Oct. 2011	Dec. 2011	Oct. 2011	Dec. 2011	2011
MEP2					
Immediately Prior to Extension of MEP	Jun. 2012	Jun. 2012	Jun. 2012	Jun. 2012	2012
Announcement of MEP Extension	Jun. 2012	Jun. 2012	Jun. 2012	Jun. 2012	2012
LSAP3					
Immediately Prior to LSAP3	Sep. 2012	Jun. 2012	Sep. 2012	Jun. 2012	2012
Announcement of LSAP3	Sep. 2012	Jun. 2012	Sep. 2012	Jun. 2012	2012
Normalization Principles					
Immediately Prior to Normalization Principles	Sep. 2014	Jun. 2014	Sep. 2014	Jun. 2014	2014
Announcement of Normalization Principles	Sep. 2014	Jun. 2014	Sep. 2014	Jun. 2014	2014

*Short term is defined as six quarters.

Treasury debt so we can project ten-year equivalents of both SOMA holdings and private-sector holdings. We use the Congressional Budget Office's deficit forecast close to the time of the inception of the program to project Treasury debt outstanding. For the construction of the maturity structure of Treasury debt, we rely on forecasts by Wrightson Research for Treasury issuance, as well as policy statements by the Treasury on the expected evolution of the maturity of Treasury debt over time.

4. The Effect of the Asset Programs

Given the models and assumptions outlined in section 3, we can construct the estimated term premium effect of each of the seven programs upon inception and at any other point of time. We illustrate the main points using three different types of programs: the first asset purchase program, which represented a change in the size and composition of the portfolio, with a calendar-based termination date; the maturity extension program, which represented a change in only the composition of the portfolio; and the open-ended asset purchase program, which represented a change in the size and composition of the portfolio, but the termination date was tied to macroeconomic outcomes and thus expectations for its ending could change over time. We compare our estimates to other studies, highlighting different assumptions that can be responsible for variations across the estimates. Then we consider the term premium effect as of November 2015 for all the programs and parse out the effect to the various programs. Finally, we discuss the confidence band around our estimates.

4.1 LSAP1: November 2008 and March 2009

Our first exercise demonstrates the use of our framework for a program that expands the Federal Reserve's portfolio, changes its composition, and has a known (even if updated) end date. The first large-scale asset purchase program, announced in November 2008 and expanded in March 2009, included purchases of $1.25 trillion of agency MBS, about $175 billion of agency debt, and $300 billion in

longer-dated Treasury securities.[19] Markets reacted to the announcements of these programs. Upon the first announcement of the program, as documented in Gagnon et al. (2011), the ten-year Treasury rate declined 7 basis points. The second announcement generated an even larger 40 basis point decline in the ten-year Treasury rate. These reductions in the ten-year rate may have reflected changes in investors' beliefs about the size and composition of the Federal Reserve's balance sheet, expectations for privately available securities in the future, and general improvement in market functioning. To estimate the TPE associated with LSAP1, we need two SOMA projections—the counterfactual scenario where no LSAP1 was implemented, and the scenario with LSAP1.[20] The difference between the paths of SOMA holdings in these two scenarios represents supposed supply shocks to private investors that were generated by the LSAP1 program, i.e., the u^s path in our term premium model. Finally, we plug the u^s path into our model for the estimated TPE.

4.1.1 LSAP1 Projection

The projection for the Federal Reserve's balance sheet at the time when the first LSAP occurred is constructed using expectations for interest rates and other key variables at the time of the implementation of the program. It is helpful to remember that at the inception of LSAP1, the Committee stated that all purchases would be completed by December 2009. As the program wore on, the Committee revised its estimate to the first quarter of 2010 "in order to promote a smooth transition in markets."[21] As a result, the projections here reflect the earlier completion date of the LSAP1 program. Another assumption at the time of LSAP1 was that as the agency securities

[19]Holdings of agency MBS actually peaked at a lower level than the $1.25 trillion, owing to prepayments on securities that were purchased earlier in the program.

[20]Projections for GDP, interest rates, and public debt use forecasts immediately prior to LSAP1.

[21]FOMC statement, December 19, 2009, available at http://www.federalreserve.gov/newsevents/press/monetary/20091216a.htm. This revision to the expected end date of the purchases would be captured in the time-varying LSAP of this model if we reestimated the TPE at that juncture.

prepaid or matured, these securities would roll off the portfolio, i.e., there was no expectation of reinvestment at this time.

As shown by the solid line in the top-left panel of figure 1, the SOMA rose dramatically between late 2008 and end-2009. Treasury holdings, shown in the top-right panel, moved up by $300 billion, while MBS holdings, shown in the bottom-left panel, jumped from zero to nearly $1.25 trillion.

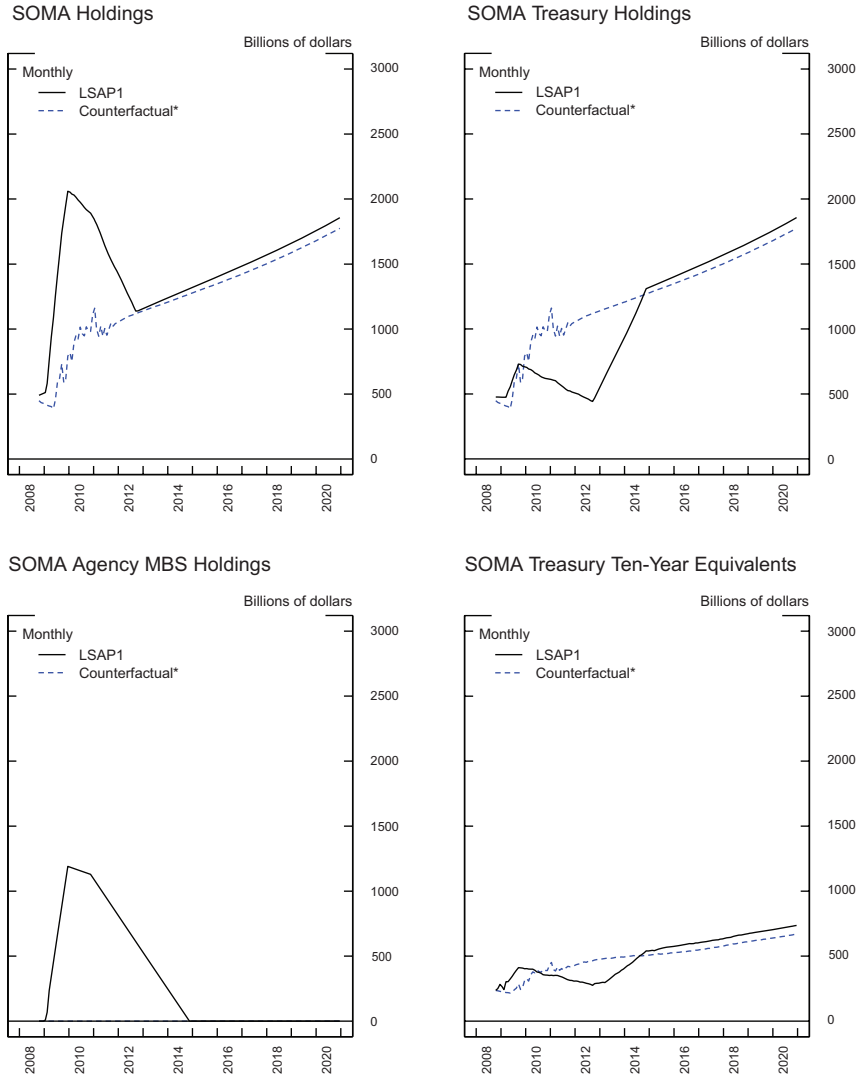
Our projection for how the Federal Reserve's balance sheet would have evolved after the purchases were completed depends critically on market expectations. There was no intention of further asset purchases, no expectation of reinvestment, and the assumed liftoff date of the funds rate was not that much later than when the purchases were completed. As shown in the top-left panel of figure 2, the liftoff of the federal funds rate—the date at which the federal funds rate was projected to rise above the 0 to 25 basis point range—was projected to occur in June 2010, about six months after the Committee had stated that the LSAP1 purchase programs would be finished. The ten-year yield, the top-right panel, was expected to fall a bit further from its April 2009 level but then slowly approach the same long-run average a few quarters later than investors projected in October.

The projection of the path of the federal funds rate affects the contours of the balance sheet projection, as we anchor our assumed exit from monetary policy accommodation off this date as noted in table 2. Under the Blue Chip projection, liftoff occurs in June 2010, and using the June 2011 exit principles as a guide, agency MBS sales begin in December 2010.[22,23] This assumption leads to a normalization of the size of the portfolio—defined as the size for which the

[22]Using the 2011 exit-principles approach admittedly has some weaknesses for estimating the effect of this program before their release. There was little public guidance before 2011 on the possible trajectory of the portfolio. As such, we use the first clear statement in the public record. Of course, if market expectations were different than those assumed here, our estimated term premium effects would differ as well. That said, the estimates provided in this paper are broadly in line with those found in other studies.

[23]Chairman Bernanke indicated at the June 2013 post-FOMC press conference that the Committee did not expect to sell agency MBS securities as part of its normalization strategy. Following that discussion, the FOMC revised its normalization principles in September 2014 such that the Committee currently does not anticipate selling agency MBS.

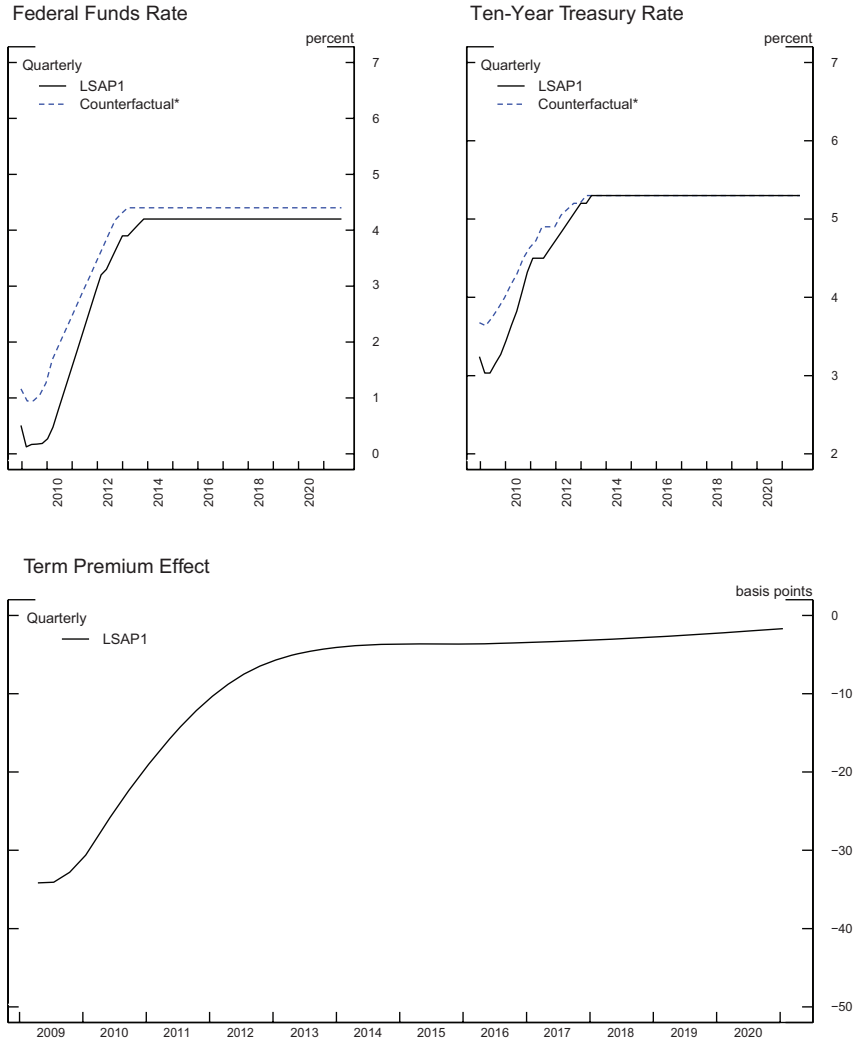
Figure 1. LSAP1: Selected Assets of the Balance Sheet



*Evolution of the Federal Reserve's balance sheet assuming no asset programs.

Note: The supply shock series can be heuristically interpreted as the difference between the counterfactual scenario and the program scenario.

Figure 2. LSAP1: Interest Rates



implied level of reserve balances is $25 billion—in October 2012, as listed in table 4. After that point, the portfolio grows in line with Federal Reserve notes and capital. Furthermore, when these purchases occur to increase the size of the portfolio, we propose that the purchases are at first only in Treasury bills until SOMA bills

Table 4. Dates for Key Balance Sheet Projections

FOMC Policy	Date	Reserves = $25 Billion	MBS = 0	Treasury Bills Are One-Third of Portfolio
LSAP1	Apr. 2009	Oct. 2012	Nov. 2014	Apr. 2013
Reinvestments into Treasury Securities	Sep. 2010	Jun. 2013	Nov. 2015	Feb. 2014
LSAP2	Nov. 2010	Jan. 2015	May 2016	Dec. 2015
Reinvestment into Agency MBS Securities	Sep. 2011	Apr. 2016	Mar. 2018	Feb. 2017
MEP	Sep. 2011	Jan. 2017	Mar. 2018	Jan. 2018
Extended MEP	Jun. 2012	Aug. 2017	May 2018	Aug. 2018
LSAP3	Sep. 2012	Sep. 2018	Feb. 2019	Aug. 2019
Normalization Principles	Sep. 2014	N/A*	N/A*	N/A*

*Occurs outside of the projection horizon.

reach one-third of total Treasury securities held in the portfolio—roughly in line with the composition of the portfolio before the start of the financial crisis. Once this ratio of one-third bills, two-third notes and bonds is reached, purchases continue so that this ratio stays constant. These assumptions are embedded in the projections shown in figure 1.

Putting the interest rate paths together with SOMA Treasury holdings gives us a path for SOMA Treasury ten-year equivalents, shown in the bottom-right panel of figure 1. This ten-year equivalents path and SOMA MBS (par value) holdings are the two inputs into the term premium model for LSAP1.

4.1.2 LSAP1 Counterfactual

To estimate the TPE associated with LSAP1, we need to look at how much larger projected SOMA holdings were with the asset purchases (LSAP1 projection) than in a scenario where no LSAP1 was implemented (LSAP1 counterfactual). In this counterfactual scenario we assume a counterfactual scenario that is close to what was expected by Blue Chip forecasters immediately prior to LSAP1. At that time, as indicated by the forecasters' projections, they assumed a quick

return to steady growth, perhaps reflecting their beliefs that the Federal Reserve was providing enough liquidity to financial markets that they anticipated these actions were enough to normalize conditions. We take the Federal Reserve's balance sheet as it appeared immediately prior to LSAP1, in October 2008, and make three assumptions regarding the evolution of the portfolio. First, because the SOMA portfolio comprised only Treasury securities, as had been the case for many years before the beginning of the crisis, we project a Treasury-only portfolio.[24] Second, we assume the balance sheet expands at roughly the growth rate of currency and capital, its historical pattern for many years. Third, we assume that the path of unwinding of the credit and lending facilities followed its actual path.[25] As shown by the dashed line in figure 1, because the level of securities in November 2008 was in fact lower than its long-run growth path as a result of the runoff of securities that occurred during the time when the credit and lending facilities were sterilized, we forecast that SOMA's holdings of Treasury securities begin to climb around October 2009.[26] After the unwinding of the credit and liquidity facilities, the SOMA portfolio grows at a constant rate, in line with growth of currency (which is in line with growth of nominal GDP) and capital.

To generate the projected supply shocks for this scenario, we use the interest rate forecasts shown in figure 2, which are the October

[24]Although there was some market commentary at the time that an LSAP might take place, we assume that those expectations were closer to the beginning of the program.

[25]While there is some question as to whether the credit and lending facilities would have unwound quite as quickly without the LSAP programs, we abstract from that issue in this paper.

[26]The forecast assumes that the Federal Reserve has perfect information regarding the amount outstanding in the credit and lending facilities. Therefore the projections for the facilities contain actual data through May 2012, which include repurchase agreements; Term Auction Facility (TAF) credit; central bank liquidity swaps; support to American International Group (AIG); the Primary Dealer Credit Facility (PDCF); primary, secondary, and seasonal credit; the Asset-Backed Money Market Mutual Fund Liquidity Facility (AMLF); the Term Asset-Backed Securities Loan Facility (TALF); Maiden Lane holdings; and the Commercial Paper Funding Facility (CPFF). Because some of the credit and lending facility activity was sterilized, after an initial runoff, Treasury holdings will necessarily increase one-for-one with the decline in credit and lending facilities.

2008 and June 2008 Blue Chip forecasts for the near term (six quarters) and longer term, respectively. The target federal funds rate was expected to decline 25 basis points from its level at the time, and bottom out at 1 percent. The funds rate was then expected to climb steadily to about 4.5 percent, near its long-run average and somewhat lower than it had been immediately preceding the crisis. As shown in the top-right panel, the ten-year rate was expected to climb as well, reaching a long-run value of about 5.25 percent by the end of 2012. Using these interest rates with the projected SOMA Treasury holdings path, the SOMA Treasury ten-year equivalents projection is shown in the bottom-right panel of figure 1.

4.1.3 LSAP1 Term Premium Effect

With the LSAP1 and LSAP1 counterfactual projections, we can construct our supply shocks for our TPE model as the counterfactual value minus the LSAP1 value for both SOMA MBS holdings and SOMA Treasury ten-year equivalents, displayed in the bottom panels of figure 1. Since the Federal Reserve never held MBS prior to the financial crisis, the projected value of u^{MBS} is just the negative of the amount of Federal Reserve holdings normalized by nominal GDP. For Treasury ten-year equivalents, one can see that projected Treasury holdings are actually lower in the LSAP1 scenario than those in the counterfactual from mid-2010 through mid-2014, reflecting the fact that LSAP1's purchases of MBS holdings boost the SOMA value, and Treasury holdings are not needed to offset growth in currency and capital. Looking at the long run, actual currency growth was much faster than what would have been projected in October 2008—likely a result of precautionary demand for dollar-denominated bank notes. Consequently, the balance sheet is permanently larger in the LSAP1 scenario than in the counterfactual.

As shown in the bottom panel of figure 2 and reported in row 1, column 1 of table 5, the initial impact of the LSAP1 program was to push down the ten-year Treasury yield by about 35 basis points. This estimate is almost identical to the announcement effect based on event studies, as discussed above, and our estimate is certainly well within confidence bands around other studies' estimates, as reported in table 6. In particular, D'Amico and King (2013) report a 20 basis point decline attributable to the Treasury portion of the

Table 5. TPE Estimates at Inception of the Asset Program

FOMC Policy	Marginal TPE from Program	Cumulate TPE at Onset of Program (Basis Points)	Expected TPE as of 2015:Q4
LSAP1	−34	−34	−4
Reinvestment into Treasury Securities	−8	−30	−5
LSAP2	−13	−40	−4
Reinvestment into Agency MBS Securities	−3	−48	−9
MEP	−17	−64	−15
Extended MEP	−11	−65	−22
LSAP3 ($1 Trillion)	−31	−97	−35
Normalization Principles (Reinvestment Ends Six Months after Liftoff)*	−20	−124	−100

*TPE estimates for "All Programs" reference this scenario.

LSAP, while Krishnamurthy and Vissing-Jørgensen (2011) estimate a 100 basis point fall for all types of securities purchased under this program. The similarity between the original announcement effect and our estimate suggests that our modeling approach captures the change in expectations for the balance sheet at that time, and gives us a reasonable estimate of the term premium effect of the program.

The bottom panel of figure 2 also shows the expected path of decay of the TPE. As the Federal Reserve's balance sheet is projected to slowly return to a more normal level over time, securities are returned to private investors and the TPE becomes less negative. As reported in column 3 of table 5, by end-2015 the estimated TPE associated with the first LSAP program is –4 basis points. This reduction primarily reflects two factors: first, the Federal Reserve was not reinvesting the proceeds from prepayments of agency securities, and so those securities were essentially returned to private investors; and second, markets expected the funds rate to rise above 25 basis points in June 2010, implying the unwinding of unconventional monetary policy well before this time.

Table 6. Term Premium Effect Estimates

	Estimated Decline in Ten-Year Treasury Yield (Basis Points)	Other Studies
LSAP Policies		
LSAP1	34	91 (Event Studies); 36 to 82 (Regressions) – Gagnon et al. (2011) 100 – Krishnamurthy and Vissing-Jørgensen (2011) 20 to 30 (Treasury Security Purchases Only) – D'Amico and King (2013) 35 (Treasury Security Purchases Only) – D'Amico et al. (2012)
LSAP2	12	25 – Krishnamurthy and Vissing-Jørgensen (2011) 55 – D'Amico et al. (2012) 21 Meaning and Zhu (2012) 15 – Swanson (2011)
Maturity Extension Program	28	22 – Hamilton and Wu (2012) 17 – Meaning and Zhu (2012)
LSAP3	31	60 – Engen, Laubach, and Reifschneider (2015)
Reinvestment Policies		
Start Reinestment into Treasuries	6	
Switch Reinvestment into MBS	4	
Change Stop of Reinvestment to after Liftoff	3	

4.2 Maturity Extension Program and Agency MBS Reinvestment Program

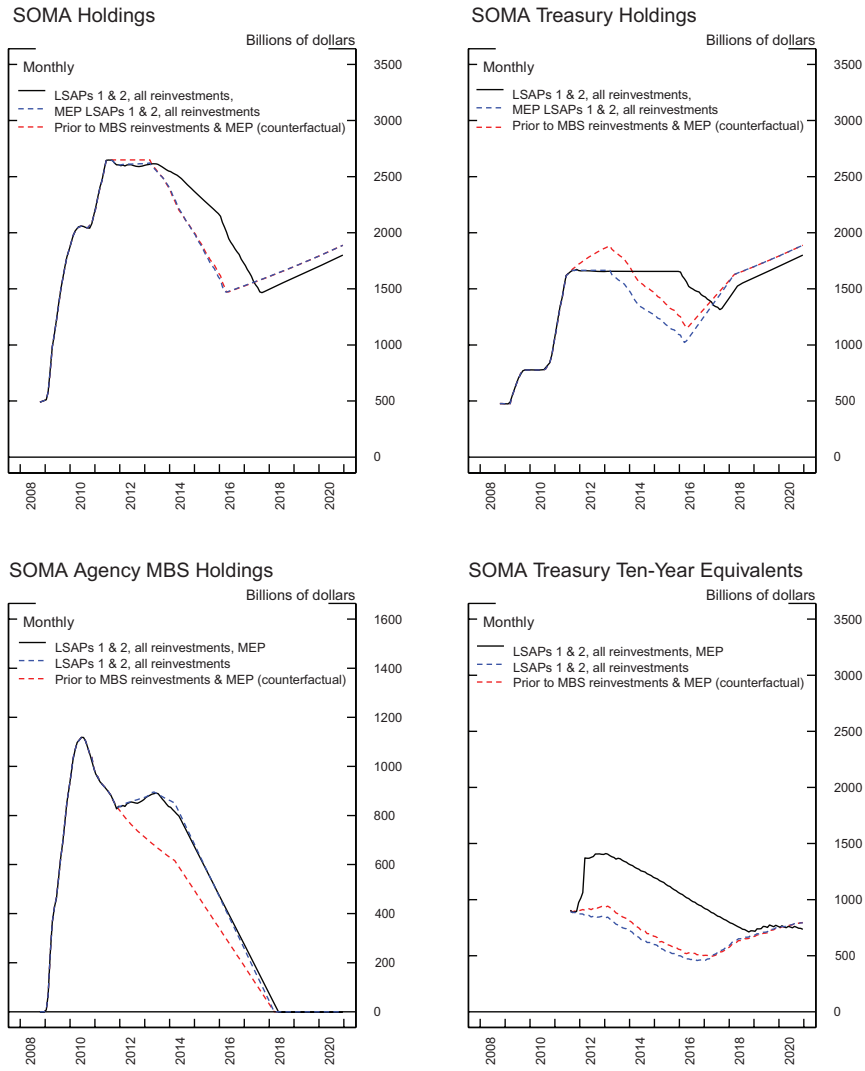
We now use our framework to demonstrate how programs implemented by the Federal Reserve that kept the size of the balance sheet the same but changed its composition and duration can be modeled. By the summer of 2011, the first two LSAP programs had increased the size of the balance sheet well above what would have

been expected by the growth rate of currency and capital, but the pace of economic recovery was not as fast as desired by the FOMC. On September 21, 2011, the Committee announced the MEP, under which the Desk was to sell $400 billion of shorter-dated Treasury securities and purchase an equal amount of long-dated Treasury securities, and the reinvestment of agency securities payments into MBS. On the announcement of the two programs, the ten-year yield dropped 7 basis points, even though a maturity extension program had been widely expected ahead of the announcement. As shown in the bottom panel of figure 3 and column 1 of table 5, the estimated maximum effect of the MEP and MBS reinvestment programs combined was –20 basis points. Although disentangling an announcement effect from the agency MBS reinvestment program from that of the MEP is not possible based on an event study, we can use our framework for an approximate estimate of each program's effect on the ten-year Treasury yield. We do this by projecting the balance sheet with and without the MEP, as shown in figure 4. Using this methodology, the vast majority of the effect of the programs, 17 basis points, is potentially attributed to the MEP. Therefore, although the par amount of the MEP program was less than the second LSAP program, the impact on the term premium is estimated to be about 1/2 times as large.

Estimates reported in other research for the interest rate effects of the MEP are fairly similar. Hamilton and Wu (2012) report a 22 basis point reduction in the ten-year yield of a swap program in similar size as the MEP, and Meaning and Zhu (2012) estimate a –17 basis point effect. The convergence of these results likely rests on the lack of anticipation of the MEP in markets, as well as a more structured methodology in each of these studies.

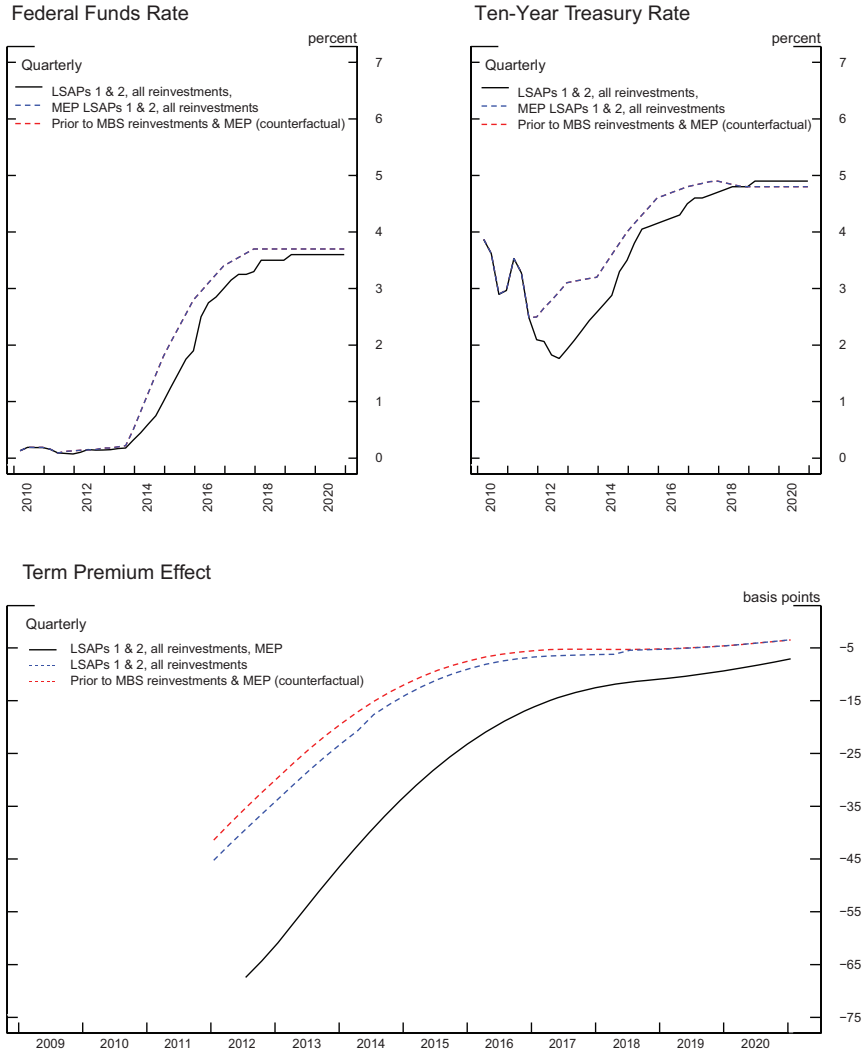
The near-term projection of total SOMA in par value terms with the extension to the MEP looks quite similar to the projection without it. However, in the bottom-right panel of figure 4, one can see that in terms of ten-year equivalents, the portfolio is estimated to be nearly $306 billion larger with the extension of the MEP. Also, the projected date of normalization is pushed out to August 2017, seven months later than prior to the extension. As shown in column 1 of table 5, the estimated maximum effect of extending the MEP program was –11 basis points.

Figure 3. MEP and MBS Reinvestments: Selected Assets of the Balance Sheet



Note: The supply shock series can be heuristically interpreted as the difference between the counterfactual scenario and the program scenario.

Figure 4. MEP and MBS Reinvestments: Interest Rates



4.3 LSAP3: September 2012

Our third exercise demonstrates how changes in expectations about the macroeconomy and Federal Reserve policy can alter the effects of a program. On September 13, 2012 the FOMC released its statement following the scheduled September policy meeting. The statement announced the third round of large-scale asset purchases by stating: "the Committee agreed today to increase policy accommodation by purchasing additional agency mortgage-backed securities at a pace of $40 billion per month. . . . These actions, which together will increase the Committee's holdings of longer-term securities by about $85 billion each month. . . should put downward pressure on longer-term interest rates." This statement incorporated the purchases included under the ongoing MEP program of $45 billion per month, which was scheduled to run through December. After the December FOMC meeting, the Committee released its statement stating "the Committee will continue purchasing additional agency mortgage-backed securities at a pace of $40 billion per month. The Committee also will purchase longer-term Treasury securities . . . initially at a pace of $45 billion per month." This continuation of Treasury asset purchases beyond the extension of the MEP marked the beginning of the full-scale LSAP3 asset purchase program.

Unlike LSAP1 and LSAP2, LSAP3 was announced as an open-ended program with no set size for the total amount of purchases. For our assumptions on the amount of purchases the market expected, we use the primary dealer survey released after the announcement of the program in September 2012. According to those reported estimates, which we assume for our projection, purchases were expected to commence in the month following the FOMC announcement (October 2012) and continue that pace through the end of 2013 before ceasing. Moreover, at the time of the announcement of the program, the Committee had maintained its commitment to sell agency MBS as part of the policy normalization process. Total purchases in our projection are $520 billion of MBS and $540 billion of Treasury securities. The actual size of the program far exceeds this amount.[27] The counterfactual for this program uses the Blue Chip

[27]In the September 2012 primary dealer survey, some dealers did indicate they expected a taper of asset purchases before the end of the program, but this was not a dominant view.

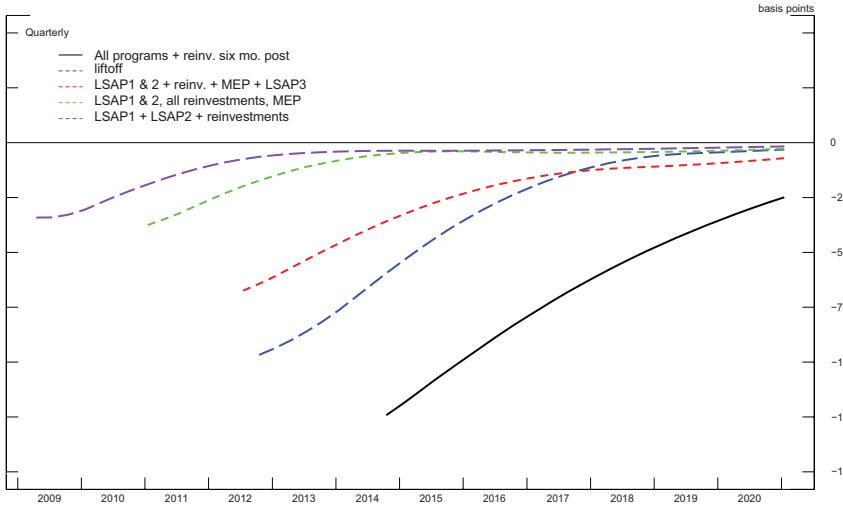
forecasts for macroeconomic variables and interest rates immediately before the program announcement, assumes reinvestment continues until six months before liftoff, and incorporates no additional purchases beyond those.

As reported in column 1 of table 5, the TPE resulting from the inception of LSAP3 is estimated to have been –30 basis points. One can see that the TPE was not projected to decay as quickly as some of the other purchase programs, in part reflecting market expectations for a funds rate increase being shifted out nine months from 2013:Q4 to 2014:Q3, as seen in table 2, column 2. Because the initial expected size of the LSAP3 program was significantly smaller than the actual size, and the communications on the method of normalizing the size of the balance sheet changed with the post-meeting press conference in June 2013 as well as the Policy Normalization Principles and Plans of September 2014, our estimate of the expected effect is likely smaller than the amount of accommodation provided by the ultimate program. In fact, Engen, Laubach, and Reifschneider (2015), who use our methodology to estimate the ultimate LSAP3 effect, find a decline of about 60 basis points, as reported in table 6. Taken together, these estimates demonstrate that not only the initial impact of a program but also the evolution of expectations are critical for understanding the overall effects of asset purchases.

4.4 All Programs (2015:Q4)

As discussed above, since the start of the asset purchase programs, expectations of how monetary policy accommodation will unwind have changed. This includes the manner by which MBS holdings decline—from sales to solely stopping reinvestments—as well as timing of halting reinvestments—from before liftoff to after the level of the federal funds rate normalization is well under way. As a result, the term premium effects associated with each of the asset programs may change over time. Consider what market participants thought at the time when LSAP1 was implemented. As reported in table 2, in April 2009, the Blue Chip forecast expected the federal funds rate to rise above 25 basis points by June 2010. Of course, the federal funds rate remained in the 0–25 basis point range until December 2015, more than five years later. Over time, therefore, the term premium effect associated with LSAP1 would have been adjusted for likely

Figure 5. Term Premium Effects



changes in market participants' views of the unwinding of monetary policy.

In order to control for the change in the normalization principles, we construct program-associated and counterfactual balance sheet projections for each program, shown in figure 5 using the Blue Chip forecast for interest rates as of the end of 2014. This allows us to decompose the term premium effect into the individual effect of each program, standardized by expectations for policy. In addition, we also used "realized" paths for items on the balance sheet through December 2014. For example, rather than agency MBS prepayments relying on an assumed model through December 2014, we use actual outstanding agency MBS balances outstanding; the same holds true for all other balance sheet items. The difference resulting from this change is relatively small; our estimates suggest it is not more than 5 basis points.

Figure 5 displays the estimated term premium effect associated with each program. As indicated by the solid black line, as of 2015:Q4, we estimate that the Federal Reserve's asset programs were depressing the ten-year Treasury yield by 100 basis points—about 5 basis points to the first large-scale asset purchase program,

a negligible amount to the second, about 20 basis points each to the maturity extension program and its continuation, a little over 20 basis points to the third, and the remainder to the reinvestment programs. Although one of the main drivers in differences of the programs is the change in expectations regarding interest rates, there are also differences that result from using realized balance sheet quantities instead of projected ones. For example, the projection at the time of LSAP1 had much slower agency MBS prepayments than what actually occurred, as interest rates declined much more than what was expected at the time of the implementation of LSAP1. Consequently, the realized term premium effect was likely a bit smaller than the projected term premium effect at the inception of the program.

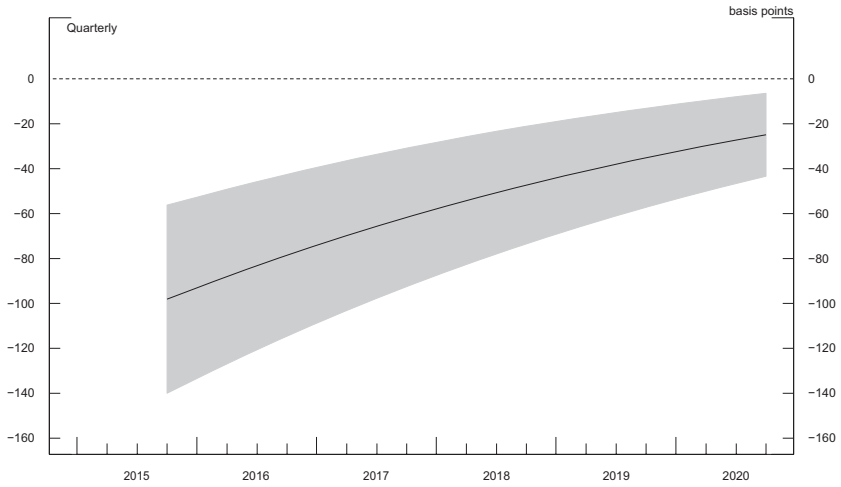
To summarize, the yield on the ten-year Treasury has fallen about 150 basis points since the start of the LSAP1 program. Although there have been many factors that have affected yields from 2008:Q4 to 2015:Q4, we would potentially attribute slightly less than two-thirds of the drop to the asset programs by the Federal Reserve.

4.5 Confidence Bands around the Estimates

Our TPE estimate depends critically on the assumed path of how the Federal Reserve's unconventional monetary policy is expected to unwind and, hence, how the net supply of assets return back to private investors. It also depends importantly on the model we use and the parameter estimates. To explore one aspect of the uncertainty around our estimate, figure 6 presents the 90 percent confidence interval around the point estimate for the cumulative effect of all the programs, which captures the sampling uncertainty for a given model and given balance sheet paths.[28] As can be seen in the figure, the confidence interval suggests that the TPE effect could have been as large as 140 basis points or as small as 56 basis points. These confidence bands are in line with the literature on asset purchases,

[28]We use a delta method on the term premium effect (TPE) equation (10) together with estimated standard errors of model parameters to calculate the standard errors of the TPE estimates. The 90 percent confidence interval of the TPE estimates is then calculated assuming that the model parameters and thus TPE estimates are normally distributed.

Figure 6. Effect of Balance Sheet Operations on the Ten-Year Treasury Term Premium



Source: Li and Wei (2013) and Ihrig et al. (2015).
Note: Shaded area indicates a 90 percent confidence interval for the cumulative effect of all programs beginning in 2015:Q4.

suggesting that our estimates are potentially in line with a range of other methodologies.

5. Conclusion

This paper provides a novel application of a term structure model that includes supply effects to evaluate the effect of the Federal Reserve's recent unconventional monetary policy on interest rates both at inception and over time. Overall, our results suggest that a large portion of the decline in interest rates from April 2009 to October 2014 may be attributed to the Federal Reserve's asset programs. And, as of this writing, there remains notable downward pressure on Treasury yields from unconventional policies taken several years ago. We highlight the importance of expectations of the Federal Reserve's balance sheet and of interest rates on the impact of the asset programs, as well as the necessity of careful application of an implied Federal Reserve portfolio strategy to calculating these effects.

In general, the results in this paper support the view that the central bank can effectively use asset programs to influence market interest rates, even when the target federal funds rate is at the zero lower bound. Going forward, this framework can be easily applied to study the effects of purchase programs by other central banks, in addition to, with some modifications, the effect of higher- or lower-than-expected debt issuance by the Treasury.

Appendix

This section reviews a few of the key inputs into the balance sheet construction.

Assets and Liabilities

In order to form a complete balance sheet through time, we need a projection of each element of the balance sheet.

Assets

Treasury Securities. SOMA Treasury holdings are assumed to evolve through a combination of outright purchases and outright sales in the secondary market, reinvestment at auction, and maturities.

- Outright purchases for the $300 billion LSAP1 program were according to maturities shown in table 7.

Table 7. LSAP1 Distribution (percent), 2009

Nominal Securities							TIPS
1½–2½ Years	2½–4 Years	4–5½ Years	5½–7 Years	7–10 Years	10–17 Years	17–30 Years	1½–30 Years
21	17	19	21	9	8	5	

- Outright purchases for the $600 billion LSAP2 program were according to the maturities shown in table 8.

Table 8. LSAP2 Distribution (percent), 2010

Nominal Securities							TIPS
1½–2½ Years	2½–4 Years	4–5½ Years	5½–7 Years	7–10 Years	10–17 Years	17–30 Years	1½–30 Years
5	20	20	23	23	2	4	3

- Reinvestment purchases for the first agency MBS program were according to the maturities shown in table 9.

Table 9. MBS Reinvestments into Treasuries Program Distribution (percent), 2010

Nominal Securities							TIPS
1½–2½ Years	2½–4 Years	4–5½ Years	5½–7 Years	7–10 Years	10–17 Years	17–30 Years	1½–30 Years
21	17	19	21	9	8	5	

- Outright purchases for the $400 billion maturity extension program (MEP) and its $267 billion continuation are simulated according to the maturity buckets and targets as announced by the Federal Reserve Bank of New York, shown in table 10.

Table 10. Maturity Extension Program Purchase Distribution (percent)

Nominal Coupon Securities				TIPS
6–8 Years	8–10 Years	10–20 Years	20–30 Years	3
32	32	4	29	

  - Securities assumed to be available for purchase reflect those outstanding on the Monthly Statement of the Public Debt as of November 30, 2011 as well as forecasts for future issuance. Holdings of any particular CUSIP are limited to

70 percent of the CUSIP outstanding, consistent with the Desk's current practice.
  - MEP sales and redemptions were in Treasury securities with remaining maturities of under three years. For the initial MEP, roughly three-quarters of System Open Market Account (SOMA) holdings of Treasury securities in this maturity range were sold; for the continuation, nearly all in this maturity range were redeemed or sold.
- Outright purchases for the LSAP3 program were according to the maturities shown in table 11.

Table 11. LSAP3 Distribution (percent), 2013

Nominal Securities							TIPS
1½–2½ Years	2½–4 Years	4–5½ Years	5½–7 Years	7–10 Years	10–17 Years	17–30 Years	1½–30 Years
0	0	13	12	15	30	30	

- The total par value of Treasury securities outstanding reflects the Congressional Budget Office's (CBO) projections for total debt held by the public that was in place at the time of the program.
  - The average maturity of Treasury debt extends from its current value of sixty months to seventy months, consistent with statements made by the Treasury Borrowing Advisory Committee in November 2011.[29]
  - The proceeds from maturing securities are reinvested at auction at rates consistent with the Blue Chip forecast for interest rates. Auction sizes are determined by the amount of total debt necessary to match CBO projections and follow the actual Treasury auction distribution in November 2011. This distribution is then altered as necessary to extend the average maturity of Treasury debt. The CBO's debt projections along with the maturity distribution of Treasury securities auctioned in November 2011 are summarized in tables 12 and 13.

[29] Refer to http://www.treasury.gov/press-center/press-releases/Pages/tg1349.aspx.

Table 12. CBO's Debt Projections

Year	CBO Debt Held by the Public ($ Billions)
2010	9,018.94
2011	10,164.11
2012	11,152.93
2013	11,773.39
2014	12,148.09
2015	12,462.72
2016	12,839.81
2017	13,169.09
2018	13,473.33
2019	13,820.23
2020	14,180.64
2021	14,541.09

Source: CBO's "Budget and Economic Outlook: An Update," August 24, 2011.

Table 13. Maturity Distributions of Treasury Securities Auctioned in November 2011

Maturity	November 2011 Issuance by Maturity ($ Billions)	Initial Shares of Issuance
1 Month	140	0.25
3 Month	116	0.21
6 Month	108	0.19
1 Year	25	0.04
2 Year	35	0.06
3 Year	32	0.06
5 Year	35	0.06
7 Year	29	0.05
10 Year	24	0.04
30 Year	16	0.03

Source: Wrightson auction calendar.

Agency Securities. The agency securities portfolio is assumed to evolve due to a combination of purchases, sales, and prepayments.

- Consistent with the FOMC's statement after the September 2011 FOMC meeting, principal payments from SOMA agency MBS and debt are reinvested in agency MBS. We use a current coupon model to estimate the coupon on newly purchased MBS securities based on the consensus long-run Blue Chip forecast for the ten-year Treasury rate.
- Prepayments on settled agency MBS holdings are generated by applying the realized prepayment rate on the SOMA holdings of MBS for historical values, then smoothed into a standard prepayment rate for projected values. This prepayment rate is calculated using a Richard and Roll (1989) prepayment model, which assumes prepayments are a function of the ratio of the coupon rate on the agency MBS securities and the prevailing level of the mortgage rate. The higher this ratio, the faster the prepayment speed.
- Prepayments on anticipated future purchases of agency MBS follow the Richard and Roll (1989) model for the life of the security.
- Under scenarios with securities sales, sales of agency securities begin six months after the first increase in the federal funds rate and last for four years. This timing is consistent with that laid out in the June 2011 FOMC minutes; however, the exact timing is merely illustrative and chosen so as to be easily implementable in our projections.
- Under these assumptions, and given the maturity schedule for agency debt securities, the volume of sales necessary to reduce holdings of these securities to zero over the four-year period only requires a six-month period of minimal sales near the end of those four years.

Premiums and Discounts. A premium (discount) is the amount paid above (below) the par value of a security. We use straight-line amortization of these premiums and discounts over the expected life of current SOMA holdings. We derive new premiums and discounts from outright Treasury purchases by using the difference between

the assumed coupon of the security being purchased and the corresponding market interest rate, as given by the yield-curve estimates shown in table 14.[30] We assume that agency MBS are purchased at a price 2 percent above par value, and therefore book some premiums on these asset purchases.

Liabilities

Reserve Balances. Reserve balances are the residual of assets less other liabilities less capital in the balance sheet projection. In general, increases in the level of Federal Reserve assets add reserve balances. By contrast, increases in the levels of liability items, such as Federal Reserve notes in circulation or other liabilities, or increases in the level of Reserve Bank capital, drain reserve balances.

A minimum level of $25 billion is set for reserve balances, roughly equal to the level of reserve balances before the start of the financial crisis. To maintain reserve balances at this level, first Treasury bills are purchased. Purchases of bills continue until these securities comprise one-third of the Federal Reserve's total Treasury security holdings—about the average level prior to the crisis. Once this level is reached, the Federal Reserve buys notes and bonds in addition to bills to maintain an approximate composition of the portfolio of one-third bills and two-thirds coupon securities.

Currency. Federal Reserve notes in circulation are assumed to grow at the same rate as nominal GDP. We use the consensus Blue Chip forecasts for real GDP growth and the price level to form the forecast for nominal GDP growth. Because this is an annual forecast, we use the annual growth rate as the annualized quarterly growth rate for the second and third quarters of each year, and then interpolate growth rates for the first and fourth quarters of the year.

[30]There is a slight inconsistency in our methodology: the yield curve used to price securities purchases is different from the yield curve used to determine the term premium effect of these purchases. No matter what, there would be some inconsistency between the two, unless we solved for a fixed point for the yield change (changes in the term premium affect the level of premiums, which then affects the size of the Federal Reserve's balance sheet, which then affects the level of the term premium). In addition, we only have Blue Chip projected rates to construct a forward-looking yield curve. To solve this problem, we use a simple yield curve based on historical relationships between the federal funds rate, the ten-year rate, and various tenors of the yield curve.

Table 14. Parameters for the Yield-Curve Estimates

Tenor	**1**	**2**	**3**	**4**	**5**	**10**	**15**	**20**	**30**
Constant	−0.0143	−0.0183	−0.0178	−0.0155	−0.0124	0.0018	0.0084	0.0096	0.0050
Fed. Funds	0.7264	0.5363	0.3923	0.2822	0.1958	−0.0394	−0.1206	−0.1487	−0.1682
10-yr T Coupon	0.4907	0.7460	0.8773	0.9455	0.9803	1.0000	0.9953	1.0134	1.0830

Other Liabilities. The Federal Reserve conducts reverse repurchases (RRPs) with foreign official and international accounts, and other counterparties. The volume of RRPs that is conducted with foreign official and international accounts is assumed to stay constant at its most recent historical monthly level, depending on the projection period. The portion that is conducted with others is assumed to stay at zero over the projection period.

The Treasury General Account (TGA) cash balance is projected to stay constant at $84 billion, which is the average level of the TGA since the LSAP programs began through 2016:Q1.

We maintain the (Supervisory Formula Approach, SFA) balance at its current level of zero throughout the forecast, consistent with the Treasury Borrowing Advisory Committee's recommendation not to resume the program at this time.[31]

Capital

Federal Reserve capital grows 15 percent per year, in line with the average rate of growth preceding the financial crisis.

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[31] Refer to "Minutes of the Meeting of the Treasury Borrowing Advisory Committee, the Securities Industry and Financial Markets Association, November 1, 2011," available for download at http://www.treasury.gov/press-center/press-releases/Pages/tg1349.aspx.

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