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Discussion Paper No. 2018-E-5

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JAPAN

IMES Discussion Paper Series 2018-E-5
June 2018

A Survey-based Shadow Rate and Unconventional Monetary Policy Effects

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Abstract

Many studies estimate a shadow interest rate, which can be negative when the short-term rate is at the effective lower bound, and use it as the monetary policy indicator. This study proposes a novel method to estimate the shadow rate using survey forecasts of macroeconomic variables and allowing the shadow rate to be negative even when the short-term rate is positive. The estimated U.S. shadow rate remained negative in 2015-17, when the Federal Reserve continued to hike its policy rate but kept its holdings of assets at sizable levels. The shadow spread, which is defined as the shadow rate minus the short-term rate, is negatively correlated with the Federal Reserve's holdings of assets, particularly mortgage-backed securities. The impact of the unconventional monetary policy on inflation was 0.5 percentage points at its peak.

Keywords: Monetary Policy; Effective Lower Bound; Zero Lower Bound; Shadow Rate; Survey Forecasts

JEL classification: E52

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This paper was previously circulated under the title "A Macroeconomic Survey-implied Shadow Rate and Unconventional Monetary Policy Effects." We are grateful for helpful discussions with and comments from Kosuke Aoki, Toni Braun, Eric Engen, Andrea Ferrero, Jeffrey Fuhrer, Joseph Gagnon, Georgios Georgiadis, Simon Gilchrist, Refet Gürkaynak, Don Kim, Jinill Kim, Junko Koeda, Andrew Levin, Francisco Ruge-Murcia, Yuji Sakurai, Toshitaka Sekine, Shigenori Shiratsuka, Hiroatsu Tanaka, Kozo Ueda, Dora Xia, Egon Zakrajsek, and Francesco Zanetti. We are particularly thankful to Taisuke Nakata for his very careful reading and constructive suggestions. We also wish to thank participants in seminars at the International Monetary Fund, Waseda University, and the Bank of Japan, as well as those at the 18th Annual Macro Conference in Osaka, the CIGS Conference on Macroeconomic Theory and Policy 2017, and the Sumer Workshop on Economic Theory 2017. We appreciate the efforts of Leo Krippner, Cynthia Wu, and Dora Xia in making their updated estimates of the shadow rate available to the public. Views expressed in this paper are those of the authors and do not necessarily reflect the official views of the Bank of Japan.

1. Introduction

Before the recent financial crisis, monetary policy in most advanced countries was primarily conducted by adjusting a target for the short-term policy interest rate. Many academic studies used the short-term interest rate as a summary of monetary policy when examining the effects of policy on output and prices. For example, empirical studies often used vector autoregressions (VARs) with a short-term interest rate. However, once short-term policy rates effectively hit the zero lower bound (ZLB), central banks started to rely on unconventional monetary policy (UMP), such as asset purchases and forward guidance, instead of conventional short rate adjustments. Consequently, the short-term interest rate alone is no longer an adequate indicator of the state of monetary policy. This poses a challenge when examining the macroeconomic effects of monetary policy.

To overcome this challenge, many studies estimate a shadow interest rate, particularly by employing term structure models, and use this as the monetary policy indicator (Ichiue and Ueno (2006, 2007, 2013, 2015), Krippner (2014), and Wu and Xia (2016)). The shadow rate is essentially equal to the short-term interest rate when the short rate is positive, but it can be negative when the short rate is at the effective lower bound (ELB). This property allows the shadow rate to be a consistent gauge of the monetary policy stance in both pre-ELB and ELB periods. Once an estimate of the shadow rate is obtained, we can employ various empirical methods to examine the effects of monetary policy on economic outcomes. Such empirical methods include VARs, a popular framework for analyzing monetary policy before the short rate hit the ELB.

This study develops a novel estimate of the shadow rate and uses it to examine the effect of UMP on economic activity. A key feature of our shadow rate estimate is that it incorporates survey forecasts of macroeconomic variables. Macroeconomic studies often use VARs to forecast future growth or inflation conditional on currently observable variables. In contrast, this study estimates the unobservable current shadow rate backward from observable survey forecasts. Intuitively, if a more accommodative monetary policy results in higher economic growth and inflation with a lag, as is often found in the VAR literature, then better survey forecasts imply a lower shadow rate, all else being equal.

We apply this method to U.S. data to estimate the shadow rate path. Specifically, we use forecasts from the Blue Chip Economic indicators (BCEI) and apply the Kalman filter to a VAR with a shadow rate, which is equal to the short rate in the pre-ELB period but is unobservable thereafter. The shadow rate in the UMP regime is estimated so that the macroeconomic forecasts from the VAR roughly match the counterparts from the Blue Chip survey. Once we obtain the estimate of the shadow rate path, we use it to conduct a structural VAR analysis and evaluate how exogenous variations in the shadow rate affect macroeconomic outcomes.

Our estimate of the shadow rate has several advantages over the estimates in existing studies, as discussed below in the literature review section. Most important, in contrast to the shadow rate estimated from term structure models, our shadow rate can deviate from the short-term interest rate even when the short rate is positive. This property is important since, in the U.S., the Federal Reserve started to hike the policy rate while keeping its holdings of assets at sizable levels in 2015; the monetary policy stance may be more accommodative than suggested by the short rate, to the extent that the balance sheet policy loosens monetary conditions.[1]

Our estimate of the U.S. shadow rate was on a declining trend after the short rate effectively hit the ZLB in 2008. Until 2014, our shadow rate largely followed Wu and Xia's (2016) estimate. However, while their estimate soared toward zero in 2015, our estimate remained more or less flat in 2015 and still negative at the end of 2017, when the target range of the policy rate was 1.25-1.50 percent. The shadow spread, which is defined as the shadow rate minus the short rate, stayed around -2.5 percent in 2015-17. The shadow spread is highly and negatively correlated with the Federal Reserve's asset holdings under the Large-scale Asset Purchase (LSAP) program, particularly its holdings of mortgage-backed securities (MBSs); a 1 percentage-point increase in the ratio of the holdings of MBSs to GDP was associated with a more than 0.2 percentage-point decline in the shadow spread, according to our baseline regression. However, we do not find any significant relationship between the shadow spread and the term spread, which casts doubt on the usefulness of longer-term interest rates in obtaining information about UMP.

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[1] The Federal Reserve's statement published on December 16, 2015 says: "The Committee is maintaining its existing policy of reinvesting principal payments from its holdings of agency debt and agency mortgage-backed securities in agency mortgage-backed securities and of rolling over maturing Treasury securities at auction, and it anticipates doing so until normalization of the level of the federal funds rate is well under way. This policy, by keeping the Committee's holdings of longer-term securities at sizable levels, should help maintain accommodative financial conditions."

We identify the effect of the Federal Reserve's UMP on economic activity by using the VAR that is used to estimate the shadow rate. We find that the Federal Reserve's UMP had a positive impact on the economy; the impacts on the year-on-year GDP growth rate and inflation rate were 0.4 and 0.5 percentage points, respectively, at their peaks. According to our counterfactual simulation, however, we show that the Federal Reserve's policy stance was less accommodative than justified by the economic collapse in 2009, although it was more accommodative thereafter. One possible reason is that the Federal Reserve's aggressive UMP had only limited impact on macroeconomic variables during the economic collapse, which may have impaired the transmission mechanisms of monetary policy to a large extent.

The rest of this paper is organized as follows. Section 2 reviews the literature. Section 3 describes our method and data. Section 4 shows the estimated shadow rate and examines its properties, including its relationship with the Federal Reserve's balance sheet. Section 5 evaluates the Federal Reserve's UMP, particularly its macroeconomic effects, based on counterfactual simulations. Section 6 concludes the paper.

2. Literature Review

There are three existing approaches to estimating the shadow rate in the literature. The first and most common approach uses a term structure model. Typically, in such studies as Ichiue and Ueno (2006, 2007, 2013, 2015), Krippner (2014), and Wu and Xia (2016), nonlinear filtering techniques are applied to the shadow rate term structure models originally proposed by Black (1995). The second approach can be called the correlation-based approach, since it estimates the shadow rate based on the correlation between the short-term interest rate and other financial and monetary variables in the pre-ELB period. Kamada and Sugo (2006) estimate Japan's shadow rate using a regression of the short-term interest rate on lending rates and a survey-based lending attitude index. Lombardi and Zhu (2014) estimate a dynamic factor model with monetary and financial variables, such as long-term interest rates, lending rates, and central bank balance sheet growth, and interpret the first factor as the monetary policy indicator or the shadow rate, since it is highly correlated with the federal funds rate in the pre-ELB period. The third approach uses a dynamic stochastic general equilibrium (DSGE) model. Kitamura (2010) estimates the shadow rate in Japan by applying the particle filter to a small New Keynesian model in which the shadow rate, not the short-term interest rate, influences the economy when the short rate is at the ELB. This paper's approach, which we call the survey-based approach, is different from these existing approaches.

The term structure model approach has at least three problems. One of these problems has become evident from recent events, casting doubt on the key assumption that the shadow rate is equal to the short rate when the short rate is positive. For instance, in the U.S., the Federal Reserve started to hike the policy rate from the ELB on December 16, 2015 and its target range reached 1.25-1.50 percent at the end of 2017. But it also kept holding assets at sizable levels. As a result, even if the short rate is positive, it may not be comparable with the short rate in the pre-UMP regime; the monetary policy stance may be more accommodative than suggested by the short rate to the extent that the balance sheet policy loosens monetary conditions. This suggests that the assumption of the shadow rate being equal to the short rate when the short rate is positive may be irrelevant when using the shadow rate as the monetary policy indicator. In contrast to the term structure model approach, this paper allows the shadow rate to deviate from the short rate even when the short rate is positive if UMP is conducted.

The second problem of the term structure model approach arises from the nonlinearity of the model. Since the shadow rate and the observable variables (i.e., longer-term interest rates) have a nonlinear relationship in shadow rate term structure models, nonlinear filtering is needed. Previous studies often use approximations to cope with the heavy computational burden that arises from this nonlinearity.[2] This nonlinearity is not only a matter of computational burden; it typically results in an implicit assumption of an arbitrary nonlinear relationship between macroeconomic variables and longer-term interest rates. Generally, in shadow rate term structure models, longer-term interest rates are positively associated with the shadow rate, but relative changes in the shadow rate are larger as longer-term interest rates are lower or closer to their effective lower bound. On the other hand, Wu and Xia (2016), for example, add their estimate of the shadow rate to a VAR, which assumes a linear relationship between the estimated shadow rate and macroeconomic variables. Putting these together, Wu and Xia (2016) implicitly assume that one unit of change in a

[2] To reduce the computational burden of the nonlinear Kalman filter, Ichiue and Ueno (2013) and Wu and Xia (2016) propose the use of first- and second-order approximations, respectively. Priebsch (2013) examines the properties of these approximations.

macroeconomic variable is associated with a smaller change in longer-term interest rates as longer-term interest rates are lower. This assumption may result in an overestimation of the effects of UMP, since longer-term interest rates are relatively low when UMP is conducted.[3] This paper's approach is free from these issues arising from nonlinearity since the method uses the linear Kalman filter and does not assume any linear or nonlinear relationship between macroeconomic variables and longer-term interest rates.

The third problem of the term structure model approach is its dependence on yield curve data. Although a decline in longer-term interest rates may be an important transmission channel through which UMP influences the economy, other channels can also play a role. For instance, UMP may improve the confidence of households and businesses regardless of whether or not longer-term interest rates decline.[4] The existence of such a channel casts doubt on the common practice of interpreting a lower longer-term yield as evidence for the effectiveness of UMP, since UMP may put upward pressure on longer-term interest rates through an improvement in people's expectations of economic growth and inflation, as discussed by Gertler and Karadi (2013). Moreover, longer-term interest rates may provide misleading information about the macroeconomic effects of UMP at times of market stress. The central bank's asset purchases may have a large effect on longer-term interest rates when market stress amplifies the importance of market segmentation, as discussed by Krishnamurthy and Vissing-Jorgenson (2011) and Gürkaynak and Wright (2012). In contrast, however, a lower longer-term interest rate may have a weaker effect on macroeconomic variables in part because market stress may impair businesses' access to financial markets. Therefore, if the shadow rate is estimated using yield curve data and is added to a VAR, as in Wu and Xia (2015), the macroeconomic effects of UMP may be overestimated at times of market stress. Our survey-based approach may well capture the total macroeconomic effects of UMP, including those dependent upon confidence, since we do not use longer-term interest rates but instead use actual values and survey forecasts of macroeconomic variables to estimate the shadow rate.

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[3] Ichiue and Ueno (2006) also implicitly assume a nonlinear relationship between long-term interest rates and the inflation rate.

[4] In this regard, Nakajima, Shiratsuka, and Teranishi's (2010) result suggests that the Bank of Japan's policy commitment under the zero interest rate policy and the quantitative easing policy stimulated the household-sector expectations for livelihood.

Although the correlation-based approach is free from these three problems associated with the term structure model, it is faced with a problem similar to the third one; it may fall short of adequately capturing the macroeconomic effects of UMP, for instance, because effects dependent upon the confidence of households and businesses may not be fully reflected in monetary and financial variables. The correlation-based approach may bring yet another problem. For example, since central bank balance sheets were very stable and had little correlation with the policy rate in the pre-ELB period, any shadow rate estimation that depends on the correlation in the pre-ELB period may not be able to adequately capture the balance sheet policy. Our survey-based approach is free from these problems since it does not depend on correlations across monetary and financial variables in the pre-ELB period.

The DSGE model approach by Kitamura (2010) is not confronted with the third problem of the term structure model approach since it estimates the shadow rate based on macroeconomic variables. He also does not assume a nonlinear relationship between macroeconomic variables and longer-term interest rates, although the particle filter he uses carries a heavy computational burden. Kitamura's approach does however face the first problem, since he assumes that the shadow rate is equal to the policy rate when the policy rate is positive. Moreover, an approach that depends on macroeconomic models, which are based on many theoretical assumptions, is more likely to suffer from potential misspecifications than our model-free approach.

This paper is related not only to the literature on shadow rate estimation but also to several other strands of studies. Survey forecasts or other indicators of private expectations are often used in the monetary policy literature for different purposes. Engen *et al.* (2015) may be most relevant to our paper; they extract expectations of future monetary policy by matching the forecasts from the Federal Reserve's large-scale semi-structural model (FRB/US) with Blue Chip forecasts, with the aim of examining the macroeconomic effects of forward guidance and lower term premiums. Aoki and Ueno (2012) show that even if a DSGE model is nonlinear due to the ELB, it can be estimated without non-linear solution techniques if data of expected short rates are available; they apply this method to Japan's data, using forward interest rates as the measure of expected short rates. In contrast to these studies, however, our method is essentially model-free and produces a convenient summary of the monetary policy stance (i.e., a shadow rate) in the UMP regime. Kim and Pruitt (2015) are also related to our study in the sense that they use Blue Chip forecasts to overcome the problem arising from the ELB, although they focus only on the survey respondents' perceptions about the monetary policy rule.

Several studies, such as Baumeister and Benati (2013), Chung *et al.* (2012), Fuhrer and Olivei (2011), and Engen *et al.* (2015), examine the macroeconomic effects of the Federal Reserve's UMP. While these studies generally focus on the effects through longer-term interest rates, this study does not assume specific transmission channels.[5] Despite the differences in methods and data, in terms of the magnitude of the UMP effects, this study is broadly in line with those studies; more specifically, the estimated magnitude in this study is in the lower range of the magnitudes in previous studies, as will be shown in Section 5. Chen *et al.* (2012), Engen *et al.* (2015), Kiley (2014), and Wu and Xia (2016) discuss the reasons behind the large estimates of UMP effects reported by earlier studies, such as Baumeister and Benati (2013), Chung *et al.* (2012), and Fuhrer and Olivei (2011). For instance, Engen *et al.* (2015) attribute Chung *et al.*'s (2012) large estimate in part to the assumption that the short-term interest rate is expected to be held fixed until 2014. This assumption actually contradicted several survey forecasts; a policy rate hike in the near future was expected at least until late 2011.[6] As shown by Gertler and Karadi (2013) and Chen *et al.* (2012) based on New Keynesian models, the effects of asset purchases would be smaller if the commitment to keep the short-term interest rate at the ELB were weaker, since asset purchases would increase the expected short rates to a larger extent through improved expectations of the future economy. Another reason is discussed by Chen *et al.* (2012) and Kiley (2014), who conclude that short-term interest rates have more powerful macroeconomic effects than

[5] Typically, previous studies examine the macroeconomic effects of UMP by using a macroeconomic model or a VAR and observing the response of macroeconomic variables to a shock to the long-term interest rate; the size of the shock is often estimated from event studies. Macroeconomic models, however, may be misspecified, particularly when there is little consensus about the transmission mechanisms of UMP. This is in fact the case, as best characterized by a famous quote from the former Federal Reserve chair, Ben Bernanke: "the problem with QE [quantitative easing] is it works in practice, but it doesn't work in theory." Event studies also come under criticism, for example, for the difficulty of identifying event dates. In addition, Hanson *et al.* (2017) argue that slow-moving capital could result in an overreaction of market prices to monetary policy announcements and an overestimation of monetary policy shocks. In these circumstances, shadow rate estimation can be a useful addition to monetary policy studies. Debortoli *et al.*'s (2018) result is consistent with the hypothesis of perfect substitutability between conventional and unconventional monetary policies, which rationalizes the use of a shadow rate as the monetary policy indicator.

[6] Nakata (2017) computes the expected time until the policy rate hike, using various survey forecasts, and shows that for the first two years of the lower bound episode, the federal funds rate was expected to stay at the lower bound only for a few additional quarters.

longer-term interest rates and attribute the large effects estimated by earlier studies to the failure to take this difference into account.

3. Method and Data

This section first explains the basic idea of our method, using an illustrative example. We then discuss the data, the state space model, and the estimation strategy.

3.1. Illustrative Example

To illustrate our method, in this subsection, we use a two-variable, reduced-form VAR(1):

$$\begin{bmatrix} z_t \\ s_t \end{bmatrix} = \begin{bmatrix} a_{11} & a_{12} \\ a_{21} & a_{22} \end{bmatrix} \begin{bmatrix} z_{t-1} \\ a_{t-1} \end{bmatrix} + \begin{bmatrix} \varepsilon_t^z \\ \varepsilon_t^s \end{bmatrix} \tag{1}$$

Here z_t and s_t are an economic activity measure and the shadow rate, respectively, at period t. The constant terms are omitted just for simplicity. The parameters, a's, are assumed to be known. The residuals, ε_t^z and ε_t^s have zero means and can be correlated.

Suppose that both z_t and s_t are observable. Then, the 1-period-ahead unbiased forecast of z_t can be calculated as:

$$z_{t+1|t} = a_{11} \cdot z_t + a_{12} \cdot s_t \tag{2}$$

Now, let's consider a case in which the shadow rate s_t is unobservable, but the forecast $z_{t+1|t}$ is observable from a survey. In this case, we can calculate s_t backward using (2) as:

$$s_t = \frac{z_{t+1|t} - a_{11} \cdot z_t}{a_{12}} \tag{3}$$

As illustrated in this equation, we can estimate exactly the unobservable current shadow rate from observable current and expected macroeconomic variables. We call the shadow rate estimated from macroeconomic forecasts in this manner the "survey-based shadow rate."

This example suggests three important properties of the survey-based shadow rate. First, the shadow rate is determined by current and expected macroeconomic variables but is not directly related to the short rate. Thus, the shadow rate can deviate from the short rate even when the short rate is positive. At the same time, the shadow rate can be equal to or greater than the short rate even when the short rate is at the ELB or when UMP is conducted; this suggests that our method does not rule out the possibility that UMP is ineffective or actually has a depressing effect on the economy, for instance, because it impairs the functioning of financial markets. Second, the shadow rate is guaranteed to have a linear relationship with current and expected macroeconomic variables. In other words, our method aims at estimating the shadow rate that is linearly associated with macroeconomic variables. Thanks to this property, our method is free from the aforementioned issues arising from arbitrary nonlinearity that are associated with the term structure model approach; although our shadow rate and macroeconomic variables have a linear relationship, any linear or nonlinear relationship between macroeconomic variables and longer-term interest rates is not assumed in our method. Third, the shadow rate does not depend on the correlation between the residuals. This means that the method does not need to identify the structural shocks, including the monetary policy shock, to estimate the shadow rate.

Note that our estimation of the shadow rate can be reliably conducted even if VAR forecasts and survey forecasts are not accurate enough in ex-post assessment. For instance, since a large economic shock is particularly difficult to forecast, the ex-post performances of both forecasts made just before such a shock are likely to be poor. But if we can consider these two forecasts to be poor to a similar extent, we can reasonably estimate the shadow rate. Note also that, although the illustrative example assumes that VAR forecasts are exactly equal to survey forecasts, our full analysis allows the VAR forecasts to deviate from the survey forecasts, as will be shown later, to mitigate the potential estimation bias due to the difference in the nature of these forecasts.

Although identification of structural shocks is not needed to estimate the shadow rate, it does help to interpret the relationship between macroeconomic forecasts and the shadow rate. Suppose, as is standard in the literature, that a monetary policy shock cannot contemporaneously affect macroeconomic variables. In equation (1), this timing assumption means that the reduced-form residual of economic activity, ε_t^z, is not correlated with the monetary policy shock. Then, a_{12} must be negative so that a monetary tightening shock, which increases ε_t^s but does not change ε_t^z, impairs economic activity with a lag, as often found in the literature. Accordingly, equation (3) suggests that the shadow rate s_t is negatively correlated with the forecast $z_{t+1|t}$, the current economic activity z_t being equal. This negative association can be interpreted as follows: since monetary accommodation is expected to improve economic activity with a lag, better expected economic activity implies more accommodative monetary policy or a lower shadow rate. The shadow rate and macroeconomic forecasts are negatively associated also in our full analysis, as will be shown later.

3.2. Data

We use quarterly actual data and survey forecasts from 1983 to 2017.[7] The actual data for output and prices are the log of real GDP and the log of the implicit GDP deflator, respectively. For a measure of the short-term interest rate, we use the 3-month Treasury bill (T-bill) rate at the end of the quarter.[8] These variables are often used in the VAR literature, including Christiano *et al.* (1999). We use the T-bill rate only in the pre-ELB period or until 2008Q3. These data are shown in Figure 1. In Section 4.5, we compute the shadow rate using 1-year and 2-year Treasury rates, instead of the T-bill rate, as a robustness check.

The survey forecasts are from the BCEI. We use the forecasts made in 1983Q4 and thereafter since we use actual data from 1983Q1 and thus the forecasts from our VAR with four lags are available only from 1983Q4. Every month, survey respondents are asked about their forecasts of quarter-on-quarter percent changes in real GDP and the GDP deflator for each quarter until the end of the following year. Since this paper uses log differences of GDP

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7 We use data from 1983 since there is wide agreement that the monetary policy regime switched in late 1982, the conventional end date of the Federal Reserve's non-borrowed reserves targeting (see Bernanke and Mihov (1998)).

8 The VAR literature often uses the 3-month T-bill rate or the federal funds rate as the short-term interest rate. When quarterly averages are used, these interest rates are highly correlated and thus the results hardly differ, whichever rate is chosen. On the other hand, when end-of-quarter rates are used, the results differ to some extent because money market rates, such as the federal funds rate, are extremely volatile at each quarter end. We use the T-bill rate at the end of quarter, so that the quarter-end volatility problem is not serious while we can justify the recursive identification assumption employed in Section 5 (the Federal Reserve can respond to contemporaneous realizations of structural shocks, but GDP and the GDP deflator cannot respond to the monetary policy shock within the period).

and the deflator as measures of growth and inflation, respectively, the consensus forecasts are transformed to log differences. We then take averages of the monthly forecasts to construct quarterly forecast data. The maximum forecasting horizon varies by quarter of the year; the forecasts are available up to 7 quarters ahead in the first quarter of the year while only up to 4 quarters ahead in the fourth quarter.[9] Figure 2 shows the calculated forecasts for selected forecasting horizons.

3.3. State Space Model and Estimation

In our empirical analysis, we use a three-variable VAR with four lags:

$$\mathbf{x}_t = \mathbf{c} + \mathbf{A}_1\mathbf{x}_{t-1} + \mathbf{A}_2\mathbf{x}_{t-2} + \mathbf{A}_3\mathbf{x}_{t-3} + \mathbf{A}_4\mathbf{x}_{t-4} + \boldsymbol{\varepsilon}_t \tag{4}$$

where $\mathbf{x}'_t = (y_t, p_t, s_t)$, y_t is the log of real GDP, p_t is the log of the GDP deflator, s_t is the shadow rate, and $\boldsymbol{\varepsilon}_t$~i.i.d $N(\mathbf{0}, \boldsymbol{\Omega})$. This VAR is standard in the literature, except that we use an unobservable shadow rate, instead of the observable short-term interest rate, although the shadow rate is assumed to be equal to the short rate in the pre-ELB period, as will be discussed.

Some recent studies add a financial or monetary variable other than the short-term interest rate to the VAR. Baumeister and Benati (2013), for instance, include a term spread in their four-variable VAR. This inclusion is motivated by their interest in macroeconomic effects from a decline in term spreads, given that the central bank started to suppress longer-term yields to stimulate the economy. Gertler and Karadi (2015) include a credit spread in their four-variable VAR because monetary policy may have effects through credit conditions. The size of asset purchases or the central bank balance sheet is also often used to examine

[9] We assume that the forecasts are made 1 month before the reported month. For instance, the forecasts in 2012Q4 are calculated by taking averages over the forecasts published in November and December 2012 and January 2013. This is because, for example, the BCEI published on January 10, 2013 was based on the survey conducted in January 2 and 3, when most information for January was not available to the respondents. Although the forecasting horizon is extended by 1 year in the report published in January, we use the extended forecasts only from the February report to prevent longer-term forecasts in the fourth quarter from being calculated based solely on the January report.

UMP effects.[10] In contrast to these studies, we do not include a financial or monetary variable other than the shadow rate in the VAR since it would make the shadow rate estimation depend on the pre-ELB correlation between the short-term interest rate and the financial or monetary variable; it would lead to a significant bias in the shadow rate estimate if the correlation differs between the pre-ELB and ELB periods. For example, as discussed earlier, since the size of the Federal Reserve's balance sheet was stable and hardly correlated with the policy rate, a shadow rate estimation that depends on the pre-ELB correlation may not be promising. Note that even if any financial or monetary variable other than the shadow rate is not included in the VAR, our method can capture the UMP effects through such variables; when a lower longer-term interest rate, a lower credit spread, or larger asset purchases lead to better expectations of economic conditions, the shadow rate estimate is likely to be lower.

Equation (4) can be rewritten into a companion form:

$$\boldsymbol{\xi}_{t+1} = \mathbf{d} + \mathbf{F}\boldsymbol{\xi}_t + \boldsymbol{\nu}_{t+1} \tag{5}$$

where

$$\boldsymbol{\xi}_t = \begin{bmatrix} \mathbf{x}_t \\ \mathbf{x}_{t-1} \\ \mathbf{x}_{t-2} \\ \mathbf{x}_{t-3} \end{bmatrix},\ \mathbf{d} = \begin{bmatrix} \mathbf{c} \\ \mathbf{0} \\ \mathbf{0} \\ \mathbf{0} \end{bmatrix},\ \mathbf{F} = \begin{bmatrix} \mathbf{A}_1 & \mathbf{A}_2 & \mathbf{A}_3 & \mathbf{A}_4 \\ \mathbf{I} & \mathbf{0} & \mathbf{0} & \mathbf{0} \\ \mathbf{0} & \mathbf{I} & \mathbf{0} & \mathbf{0} \\ \mathbf{0} & \mathbf{0} & \mathbf{I} & \mathbf{0} \end{bmatrix}, \text{ and } \boldsymbol{\nu}_t \sim N\left(\begin{bmatrix} \mathbf{0} \\ \mathbf{0} \\ \mathbf{0} \\ \mathbf{0} \end{bmatrix}, \begin{bmatrix} \boldsymbol{\Omega} & \mathbf{0} & \mathbf{0} & \mathbf{0} \\ \mathbf{0} & \mathbf{0} & \mathbf{0} & \mathbf{0} \\ \mathbf{0} & \mathbf{0} & \mathbf{0} & \mathbf{0} \\ \mathbf{0} & \mathbf{0} & \mathbf{0} & \mathbf{0} \end{bmatrix} \right).$$

Equation (5) represents the state equations of our state space model.

The observation equations are categorized into two types. The first says that the observed T-bill rate is equal to the shadow rate in the pre-ELB period or until 2008Q3:

$$i_t^o = \mathbf{e}_3'\boldsymbol{\xi}_t \tag{6}$$

[10] For instance, Weale and Wieladek (2016) include the ratio of the cumulative size of asset purchase announcements to GDP in their VAR. This is because the preferred habitat theory, pioneered by Tobin (1965, 1969) and Modigliani and Sutch (1966) and further developed by Vayanos and Vila (2009), predicts that a larger stock of long-term assets held by the central bank leads to persistently lower long-term interest rates, and that the impact on long-term yields is immediate in the timing of announcements of asset purchases.

where i_t^o is the T-bill rate and the superscript indicates that this variable is observable. $\mathbf{e}_\mathrm{j}$ is defined as the j-th column of the 12×12 identity matrix. Then, $\mathbf{e}_3'\boldsymbol{\xi}_t$ is the third element of $\boldsymbol{\xi}_t$ or the shadow rate at t. Although this restriction fits our purpose to estimate a monetary policy indicator that can be comparable with the short rate in the pre-ELB period, one might be interested in the shadow rate estimated without this restriction. Thus, while our baseline estimation imposes this restriction, the next section also shows the result without the restriction.

The second type of observation equation says that an observed survey forecast is equal to the corresponding VAR forecast plus an error. From equation (5), the h-quarter - ahead VAR forecast of $\boldsymbol{\xi}_t$ can be calculated as:

$$\boldsymbol{\xi}_{t+h|t} = (\mathbf{I} + \mathbf{F} + \cdots + \mathbf{F}^{h-1})\mathbf{d} + \mathbf{F}^h\boldsymbol{\xi}_t \tag{7}$$

Then, the observation equation regarding the h-quarter-ahead forecast of the quarter-on-quarter GDP growth rate is represented as:

$$\Delta y_{t+h|t}^o = (\mathbf{e}_1 - \mathbf{e}_4)'\boldsymbol{\xi}_{t+h|t} + w_{y,t,h} \tag{8}$$

where $\Delta y_{t+h|t}^o$ is the survey forecast of GDP growth, and $w_{y,t,h}$ is the observation error by which the survey forecast can deviate from the VAR counterpart. Here, $\boldsymbol{\xi}_{t+h|t}$ is multiplied by $(\mathbf{e}_1 - \mathbf{e}_4)'$ since the first and fourth elements of $\boldsymbol{\xi}_{t+h|t}$ are the VAR forecasts of the h and $h-1$-quarter-ahead log GDP, respectively, and the difference between them represents the expected growth rate. Similarly, the observation equation of the GDP deflator is represented as:

$$\Delta p_{t+h|t}^o = (\mathbf{e}_2 - \mathbf{e}_5)'\boldsymbol{\xi}_{t+h|t} + w_{p,t,h} \tag{9}$$

where $\Delta p_{t+h|t}^o$ is the survey forecast of the h-quarter-ahead quarter-on-quarter inflation rate, and $w_{p,t,h}$ is the observation error.

The observation equations can be summarized by:

$$\mathbf{o}_t = \mathbf{a} + \mathbf{H}'\boldsymbol{\xi}_t + \mathbf{w}_t \tag{10}$$

where

$$\mathbf{o}_t = \begin{bmatrix} i_t^o \\ \Delta y_{t+1|t}^o \\ \vdots \\ \Delta y_{t+7|t}^o \\ \Delta p_{t+1|t}^o \\ \vdots \\ \Delta p_{t+7|t}^o \end{bmatrix},\ \mathbf{a} = \begin{bmatrix} 0 \\ (\mathbf{e}_1 - \mathbf{e}_4)'\mathbf{d} \\ \vdots \\ (\mathbf{e}_1 - \mathbf{e}_4)'(\mathbf{I} + \cdots + \mathbf{F}^6)\mathbf{d} \\ (\mathbf{e}_2 - \mathbf{e}_5)'\mathbf{d} \\ \vdots \\ (\mathbf{e}_2 - \mathbf{e}_5)'(\mathbf{I} + \cdots + \mathbf{F}^6)\mathbf{d} \end{bmatrix},\ \mathbf{H}' = \begin{bmatrix} \mathbf{e}_3 \\ (\mathbf{e}_1 - \mathbf{e}_4)'\mathbf{F} \\ \vdots \\ (\mathbf{e}_1 - \mathbf{e}_4)'\mathbf{F}^7 \\ (\mathbf{e}_2 - \mathbf{e}_5)'\mathbf{F} \\ \vdots \\ (\mathbf{e}_2 - \mathbf{e}_5)'\mathbf{F}^7 \end{bmatrix},\ \text{and}\ \mathbf{w}_t = \begin{bmatrix} 0 \\ w_{y,t,1} \\ \vdots \\ w_{y,t,7} \\ w_{p,t,1} \\ \vdots \\ w_{p,t,7} \end{bmatrix}.$$

The error term $\mathbf{w}_t$ is uncorrelated with that of the state equation $\mathbf{v}_t$. We assume that $\mathbf{w}_t \sim N(\mathbf{0}, \mathbf{R})$ with a diagonal matrix $\mathbf{R}$.[11]

We estimate the model using a two-step approach. In the first step, the VAR, which is represented in equation (4), is estimated using data in the pre-ELB period, that is until 2008Q3. We use data of the T-bill rate for the shadow rate since these are assumed to be identical in the pre-ELB period, as represented by equation (6). In the second step, given the VAR parameters (i.e., $\mathbf{c}$, $\mathbf{A}$'s, and $\boldsymbol{\Omega}$), the shadow rate path and the variances of the observation errors (i.e., the diagonal elements of $\mathbf{R}$) are estimated, by applying the Kalman filter to the state space model represented in (5) and (10). A diffuse prior is used to initialize the shadow rate.[12]

4. The Shadow Rate and Its Properties

This section shows the estimated shadow rate and examines if it is an adequate measure of monetary policy stance. To this end, we investigate its properties from many aspects, in particular its relation to the Federal Reserve's balance sheet.

[11] We assume that $\mathbf{R}$ is diagonal since we confirmed that the iterative procedure of the estimation does not converge without this assumption, apparently due to the large number of parameters.

[12] We confirmed that one-step estimation, in which the VAR parameters, the shadow rate path, and the variances of the observation errors are estimated simultaneously, is hard to converge, apparently because of the large number of parameters.

4.1. The Baseline Shadow Rate

Panel 1 of Figure 3 shows that the estimated shadow rate turned negative shortly after the short-term interest rate hit the ELB in 2008Q4. Panel 2 compares the shadow rate with the updated estimates of Krippner (2014) and Wu and Xia (2016), focusing on the period from 2008Q4. Our shadow rate was similar to Wu and Xia's (2016) until 2014, despite the differences in methods and data. However, Wu and Xia's (2016) shadow rate increased sharply thereafter and reached almost zero at the latest data point, the end of November 2015. Similarly, Krippner's (2014) shadow rate reached around zero at the end of 2015, although it is substantially different from Wu and Xia's (2016) until 2014.[13] These sharp increases in 2015 obtained from term structure models seem to reflect the Federal Reserve's policy rate hike in December 2015. That is, since the shadow rate term structure models employed by these studies assume that the shadow rate is essentially equal to the short-term interest rate when the short rate is positive, their shadow rate had to increase toward zero as the policy rate hike from the ELB approached. On the other hand, our shadow rate remained more or less flat in 2015 and still negative at the end of 2017, when the target range of the policy rate was 1.25-1.50 percent.

4.2. Sensitivities to Survey Forecast Data

The illustrative example in Section 3.1 suggests that the shadow rate is negatively associated with survey forecasts of economic activity, current economic activity being equal. We here examine whether this negative relationship is actually confirmed in our full analysis. To this end, we estimate the shadow rate after increasing the survey forecasts of growth or inflation that are made in 2008Q4 and thereafter over all forecasting horizons.

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[13] One possible reason for the difference between Krippner's (2014) and Wu and Xia's (2016) estimates is that Krippner uses two latent factors while Wu and Xia use three. See Christensen and Rudebusch (2015), who document that shadow rate estimation from term structure models is sensitive to the number of latent factors. Christensen and Rudebusch's argument reminds us that the shadow rate estimated from term structure models is just a linear combination of latent factors, which can best explain movements in the yield curve, with one property that the shadow rate is equal to the short rate when the short rate is positive. Any reason other than this property does not support the use of the shadow rate as the monetary policy indicator; moreover, as discussed in Section 2, this property is even detrimental when the central bank can raise the policy rate while it conducts UMP.

Panel 1 of Figure 4 shows the shadow rates when the survey forecasts of the annualized quarter-on-quarter percent change of GDP are higher, together with the baseline shadow rate. The panel confirms the negative relationship between the shadow rate and the GDP growth forecasts; the shadow rate is lower by 0.16 and 0.74 percentage points on average in the UMP period when the growth forecasts are higher by 0.1 and 0.5 percentage points, respectively. Panel 2 confirms the negative relationship between the shadow rate and the inflation forecasts; the shadow rate is lower by 0.16 and 0.77 percentage points on average when the inflation forecasts are higher by 0.1 and 0.5 percentage points, respectively.

4.3. The Shadow Rate without the Pre-ELB Restriction

To consider whether our shadow rate is an adequate measure of monetary policy, we here estimate the shadow rate without the restriction that the shadow rate is equal to the T-bill rate until 2008Q3. Specifically, the shadow rate is estimated, excluding the first equation of (10) and given all the parameters as estimated in the baseline analysis.

Figure 5 shows that the estimated shadow rate was largely associated with the T-bill rate in the pre-ELB period. This suggests that the BCEI forecasts contained useful information about monetary policy in the pre-ELB period. Although the shadow rate was too low in the early part of the sample, this is not crucial since the Kalman filter with a diffusion prior is inaccurate in the early observation period. Another noticeable difference between the shadow rate and the short rate was seen for a few years from mid 2004, which suggests that monetary conditions were more accommodative than suggested by the short rate during this time. This coincided with the so-called Greenspan conundrum, in which U.S. long-term interest rates did not increase and thus monetary conditions were kept accommodative despite the Federal Reserve's consecutive policy rate hikes. Bernanke (2005, 2007) attributes the conundrum to the global saving glut; that is, a huge amount of U.S. bond purchases from public investors in emerging-market and oil-producing countries lowered the U.S. long-term yields.[14] In sum, Figure 5 suggests that although the estimated shadow rate largely captures monetary policy, it can also reflect other factors that influence monetary conditions.[15, 16]

4.4. To What Extent Does Our Shadow Rate Reflect the Federal Reserve's Balance Sheet Policy?

Now we return to the baseline estimate of the shadow rate and examine how well the shadow rate reflects the Federal Reserve's balance sheet policy. To this end, we use the shadow spread (i.e., the shadow rate minus the short-term rate) as a measure of UMP; we subtract the short rate from the shadow rate to adjust the effects of conventional monetary policy. Figure 6 compares the shadow spread, with the Federal Reserve's asset holdings relative to GDP.[17] Not surprisingly, the shadow spread is essentially equal to the shadow rate before the Federal Reserve started to hike its policy rate in 2015. The shadow spread stayed around -2.5 percent thereafter.

Panel 1 of Figure 6 divides the assets into two categories. The first one (LSAP assets) consists of Treasuries, agency MBSs, and agency bonds; most of these debt securities are long-term and held by the Federal Reserve under the LSAPs program, aiming at stimulating the economy. The other category (non-LSAP assets) reflects loans from the Federal Reserve

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[14] Bertaut *et al.* (2012) show that the roughly \$1 trillion acquisitions of U.S. Treasuries, MBSs, and other agency bonds by the global saving glut countries during the 2003–2007 period lowered the U.S. Treasury 10-year yield by 1.1 percentage points. According to Chung *et al.* (2012), regressing quarterly changes in the 10-year Treasury yield on those in the federal funds rate for the period 1987–2007 yields a coefficient of about 0.25, implying that a 1 percentage-point reduction in the short-term interest rate is typically associated with around a 0.25 percentage-point decline in the long-term yield. Combining these results, the impact of the global saving glut corresponded approximately to a 4 to 5 percentage-point reduction in the short rate, which can explain the difference between the shadow rate and the short rate during this period.

[15] Figure 5 also shows that the estimated shadow rate is very similar to that of the baseline analysis in the UMP regime, which supports the robustness of the baseline result.

[16] The shadow rate estimated from the term structure model approach can also reflect non-monetary policy factors; for instance, when long-term interest rates are suppressed lower by the global saving glut, the term structure models are likely to produce a lower shadow rate.

[17] The Federal Reserve's asset holdings are reported weekly. This paper uses the latest data for each quarter.

through a variety of facilities that were adopted to support short-term funding of depository institutions, foreign central banks, and commercial paper issuers.[18] The panel shows that the shadow spread had a strong and negative relationship with the LSAP assets, which suggests that the shadow spread was driven mainly by the Federal Reserve's asset purchases. In particular, the rapid expansions of LSAP asset holdings up until early 2010 and from late 2012 to 2014, which correspond to the so-called QE1 and QE3, respectively, were clearly associated with the decline in the shadow spread. The exception is the 1-year period from early 2011, when the shadow spread increased slightly while the Federal Reserve conducted QE2 and the Maturity Extension Program (MEP).[19]

Panel 2 of Figure 6 further disaggregates the LSAP assets into Treasuries and MBSs; we omit agency bonds because of their small size. According to the panel, the decline in the shadow spread appears to be associated more with the holdings of MBSs than those of Treasuries. For instance, until early 2010, when the shadow spread fell rapidly, MBS holdings increased by 6 to 7 percent of GDP, but Treasury holdings increased by around only 2 percent of GDP. This observation is consistent with Panel 1, which shows that the programs purchasing only long-term Treasuries (QE2 and the MEP) were not clearly associated with a decline in the shadow rate while the programs purchasing MBSs (QE1 and QE3) were. This result is also in line with the event study by Krishnamurthy and Vissing-Jorgenson (2011); they find that the MBS purchases in QE1 were crucial to lower MBS yields and corporate yields, which are relevant determinants of housing and business fixed investment, respectively.[20]

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[18] See Hamilton and Wu (2012) for a summary of the facilities.

[19] QE2 was conducted from November 2010 to June 2011. The MEP, in which the Federal Reserve sold or redeemed short-term Treasury securities and used the proceeds to buy longer-term Treasury securities, was announced in September 2011 and continued through the end of 2012.

[20] Krishnamurthy and Vissing-Jorgenson (2011) predict that the portfolio effect should be smaller during QE3 than during QE1 since market conditions were more stressed when QE1 was conducted. On the other hand, our result does not suggest that the Federal Reserve's asset purchases had a weaker effect during QE3 than during QE1. One possible reason behind this result is that the effect of a lower long-term interest rate on macroeconomic variables was stronger during QE3 since market stress was weaker and thus businesses' and households' access to financial markets was less impaired.

To confirm the relationship between the shadow spread and LSAP asset holdings, we run several regressions.[21] We first regress the shadow spread on the LSAP and non-LSAP assets-to-GDP ratios, using data from 2008Q4. The regression uses Newey and West (1987) standard errors to cope with serial correlation in the residuals. Column (1) in Table 1 shows that LSAP assets are negatively associated with the shadow spread at the 1 percent significance level, while the coefficient on non-LSAP assets is not significantly different from zero.

We also run similar regressions after dividing the Federal Reserve's asset holdings into Treasuries, MBSs, and other assets (i.e., agency bonds plus non-LSAP assets). The result in columns (2) of Table 1 confirms that MBSs have a stronger relationship with the shadow spread than Treasuries and other assets do; although both coefficients on Treasuries and MBSs are negative and significant, the absolute value of MBSs is more than twice that of Treasuries.

The quantitative impact of the balance sheet policy can be seen from the size of the coefficients. For example, the coefficient on LSAP assets in column (1) of Table 1 suggests that when the Federal Reserve increases its holdings of LSAP assets by 1 percent of GDP, it can lower the shadow rate by 0.15 percentage points.[22] During the QE1 program, the Federal Reserve increased its LSAP asset holdings by more than 10 percent of GDP, which corresponds to a 1.5 percentage-point decline in the shadow rate. The coefficient on MBSs is larger than that on LSAP assets; a 1- percent of GDP increase in the MBS holdings leads to a more than 0.2 percentage-point decline in the shadow rate.

Although we prefer the parsimony baseline regressions, in particular the second one, which enables us to examine the difference between Treasury and MBS purchases, these

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[21] To address a concern about the endogeneity of GDP, the denominator of the dependent variable, we confirmed that our main results are robust to using GDP in 2008Q3 to divide the subcategories of the Federal Reserve's balance sheet in 2008Q4 and thereafter.

[22] Gagnon *et al.*'s (2011) time-series analysis suggests that a 1 percent of GDP increase in the Federal Reserve's longer-term debt holdings decreases the 10-year government bond yield by 0.069 percentage points. According to Chung *et al.*'s (2012) result based on past correlation between the short- and long-term yields, Gagnon *et al.*'s (2011) estimate roughly corresponds to a 0.25-0.30 percentage point decline in the short-term interest rate. The fact that this back-of-envelope calculation result is larger than our estimate of 0.15 percentage points suggests that the macroeconomic effect of a lower long-term interest rate is smaller than that of a lower short rate, as argued by Chen *et al.* (2012), Kiley (2014) and Stein (2012).

regressions might be spurious since the shadow spread trended down while the Fed's asset holdings relative to GDP trended up, as shown in Figure 6. To check the robustness, we add a time trend to the baseline regressions since it is safer to ignore low-frequency relationships when testing whether two variables of interest are correlated in a statistically significant manner. Columns (3) and (4) of Table 1 show that our main findings are preserved. The coefficients on LSAP assets and MBSs are still significantly negative, at least at the 5 percent level, although that on Treasuries is no longer significant. The coefficient on MBSs is larger in absolute value than those on LSAP assets and Treasuries. However, the absolute values of the coefficients are smaller than reported in columns (1) and (2); they are likely to be underestimated since the low-frequency correlation is removed by adding the time trend.

As we discussed in Section 4.3, non-monetary policy factors, such as fiscal policy or the global saving glut, can lead to fluctuations in the shadow rate. Thus, to further check the robustness, we run regressions controlling for the ratios of government surplus and foreign official investment to GDP as well as a time trend. As shown in columns (5) and (6) of Table 1, the coefficients on LSAP assets and MBSs are still significantly negative. On the other hand, both columns report that the coefficients on government surplus and foreign official investment are insignificant, which suggests that our estimate of the shadow rate was not driven by non-monetary policy factors in the UMP period.

4.5. Relationship between the Shadow Rate and Longer-term Yields

To further consider the properties of our estimated shadow rate, this subsection examines the relationship between the shadow rate and longer-term yields.

Although short-term interest rates are the generally preferred monetary policy indicator in the literature, at least before they effectively hit the ZLB, some studies focus on monetary policy effects through longer-term interest rates, such as the 1- and 2-year yields, for two reasons. The first reason is that financial market expectations of future monetary policy, which are reflected in longer-term interest rates, may play a more important role than actual policy rate changes, as argued by Gürkaynak, *et al.* (2005), who conduct an event study about the effects of changes in futures rates with 1 year or less to expiration on asset prices. The second reason is that longer-term interest rates were not significantly constrained by the

ELB in the early part of the UMP period; Swanson and Williams (2014) find that the 1- and 2-year Treasury yields were unconstrained through 2010, suggesting that forward guidance policy was about as effective as usual during this period, although they show that these yields became more constrained from 2011. The results obtained by Gürkaynak, *et al.* (2005) and Swanson and Williams (2014) enable Gertler and Karadi (2015) to justify their use of the 1-year rate as the monetary policy indicator in the VAR, although they use observations until June 2012, when the 1-year rate was already constrained according to Swanson and Williams (2014). With a similar spirit, Hanson and Stein (2015) use the 2-year yield for their event study with observations until February 2012.

Figure 7 compares the shadow spread as well as 1-, 2-, 5-, and 10-year term spreads.[23] We examine these spreads, instead of the shadow rate and longer-term yields, to focus on the effects of UMP by adjusting those of conventional monetary policy. The relationship between the shadow spread and the term spreads is weak and often negative. For instance, Panel 1 of the figure shows that, until early 2010, the 2-year spread stayed around 1 percent while QE1 was implemented and the shadow spread fell. Moreover, a negative correlation was observed in 2013-14; the 2-year spread moved up, reflecting increasing market expectations of a policy rate hike in the near future, but the shadow spread decreased as the Federal Reserve expanded its balance sheet under the QE3 program. These observations suggest that although the 2-year rate has some information about expected future short rates, it reflects asset purchases to a limited extent at best.

Another possible reason for the weak relationship between the shadow spread and the term spreads is that it arises from the so-called forward guidance puzzle, in which the macroeconomic effects of forward guidance are weaker than predicted by conventional New Keynesian models, possibly because households and firms cannot understand the central bank communications as market participants, as discussed in Del Negro, Giannoni, and Patterson (2015), Carlstrom, Fuerst, and Paustian (2015), Kiley (2014), McKay, Nakamura, and Steinsson (2016), and Nakata, Schmidt, and Yoo (2017). Since our shadow rate is estimated from current and forecasted macroeconomic variables, with the aim of capturing the macroeconomic effects of UMP, the shadow rate is not necessarily estimated lower when

[23] This paper uses zero-coupon rates estimated by Gürkaynak *et al.* (2007) as the longer-term yields.

longer-term interest rates are lower, unless a lower longer-term interest rate has a positive impact on the economy.

A third possible reason for the weak relationship between the shadow spread and the term spreads is that more monetary accommodation, which is represented by a lower shadow rate, could put upward pressure on longer-term interest rates through improved expectations of future output growth and inflation, as discussed by Gertler and Karadi (2013).

The relationships observed in Figure 7 are confirmed by regressions of the shadow spread on a term spread. To control for the effect of balance sheet policy on the shadow rate, we add a term spread to our most favored baseline regression whose results are reported in column (2) in Table 1. Table 2 shows that the coefficient on the term spread is insignificant for all four regressions. In contrast, all four regressions show that the coefficients on the Fed's holdings of Treasuries and MBSs are robust to adding a term spread; both coefficients are significant at the 1 percent level and the absolute value of the coefficient on MBSs is in the range from 0.20-0.25.

In sum, the shadow spread has a weak relationship with the term spreads for three possible reason: longer-term yields may not capture asset purchases well; the macroeconomic effects of forward guidance are weaker than predicted by conventional New Keynesian models; and more monetary accommodation could put upward pressure on longer-term interest rates through improved expectations of future output growth and inflation. The discussion here casts doubt on the usefulness of longer-term yields as the monetary policy indicator in the UMP regime.

So far, we have analyzed the usefulness of longer-term yields as a monetary policy indicator in the UMP regime based on the relationship with our baseline estimate of the shadow. To consider any potential estimation bias in the shadow rate that might arise from disregarding information contained in the longer-term yields, we here estimate the shadow rate using a longer-term interest rate, instead of the T-bill rate. Specifically, we use the 1- or 2-year yields, since the literature argues that such a longer-term interest rate may be a better monetary policy indicator than the short-term interest rate, even in the pre-ELB period. The left and right panels of Figure 8 show the shadow rate estimates based on the 1-year and 2-year rates, respectively. According to the figure, the estimated shadow rate is qualitatively similar to the baseline result although the shadow rate estimated from the longer-term yield was slightly higher than the baseline shadow rate both in the pre-ELB and UMP periods to a similar extent. This result supports the robustness of the baseline estimation. These panels also show that the longer-term yield moved only a little and was generally higher than the shadow rate until 2015. This result confirms that the 1- and 2-year yields cannot capture a large part of the UMP, apparently because these yields reflect the effect of asset purchases to a limited extent at best.

5. Evaluating Unconventional Monetary Policy

Using the estimated shadow rate, this section evaluates the Federal Reserve's UMP, in particular its effects on the year-on-year GDP growth rate and inflation rate.

So far, we have not identified the monetary policy shock since this is not needed to estimate the shadow rate, as discussed in Section 3. However, it is essential to identify the shock in order to evaluate monetary policy effects. We use the standard recursive identification with the shadow rate being ordered last to identify the exogenous variation in the Federal Reserve's UMP.

Figure 9 shows the impulse response functions from a one-standard-deviation monetary policy tightening shock. Panel 1 shows that the shadow rate increases immediately after the shock, while GDP and the GDP deflator decrease with a lag. These impulse responses are in line with those found in the literature, including Christiano *et al.* (1999). Panel 2 shows the impulse responses of the 1-quarter log changes in GDP and the deflator. The panel shows that GDP growth and inflation start to decline around 4 quarters after a monetary tightening shock. This suggests that the monetary policy shock is more likely to be estimated positive when 4- or more-quarters-ahead survey forecasts of growth and inflation are weaker, all else being equal. There are some fluctuations in the impulse responses, particularly for GDP growth. This suggests that the VAR forecasts also tend to fluctuate with the forecast horizon, as often found in the literature. This however is not a serious issue for the shadow rate estimation since we allow the VAR forecasts to deviate from the survey forecasts.

Following Wu and Xia (2016), we compare the baseline scenario, using the estimated shadow rate, with two counterfactual scenarios to assess the Federal Reserve's

UMP. In contrast with Wu and Xia (2016), who estimate the shadow rate only from the yield curve data and then include the estimated shadow rate as well as macroeconomic variables in a VAR, we use the VAR from which the shadow rate is estimated, so that the shadow rate is guaranteed to have a linear relationship with the other VAR variables (i.e., the logs of GDP and the GDP deflator).

Figure 10 shows the shadow rates in the three scenarios. In the first counterfactual scenario, which we call the "no monetary policy shock scenario," the monetary policy shock is set to be zero from 2008Q4. This scenario can be interpreted as the case in which the Federal Reserve continued to follow its monetary policy rule; the shadow rate responded to GDP and inflation as the short-term interest rate did in the pre-ELB period. In the second counterfactual scenario, which we call the "no UMP scenario," we change the monetary policy shock so that the shadow rate was equal to the T-bill rate. This scenario can be interpreted as the case in which the Federal Reserve did not adopt any policy except for lowering the short-term interest rate to near zero, although people expected the Federal Reserve to adopt UMP to deal with the economic decline.

The left panels of Figure 11 show the year-on-year GDP growth rate and inflation rate in the three scenarios. The right panels show the deviations of the baseline from the two counterfactual scenarios. The deviation from the no monetary policy shock scenario indicates the effect of the deviation from the monetary policy rule on GDP growth and inflation. The deviation from the no UMP scenario measures the effect of UMP.

In the no monetary shock scenario, the shadow rate decreased more rapidly than in the baseline scenario from late 2008 to 2009. This more rapid decline suggests that although the collapses in GDP growth and inflation justified more aggressive monetary accommodation, positive monetary policy shocks mitigated the decline of the shadow rate in the baseline scenario. Despite the large difference in the shadow rate between these two scenarios, however, GDP growth and inflation showed a clear difference only from 2010, since monetary policy shocks take time to influence GDP growth and inflation, as suggested by the impulse response functions in Figure 9. The counterfactual scenario shows that, after the decline, the shadow rate increased sharply from a low of -2.8 percent in 2009Q4 to nearly 2 percent in mid-2012, reflecting the recoveries in GDP growth and inflation. The shadow rate in this scenario was consistently higher than in the baseline from mid-2010. This difference can be explained by two factors. First, thanks to the more aggressive monetary accommodation from late 2008 to 2009, GDP growth and inflation were higher in 2010-11 in the counterfactual scenario. Second, negative monetary policy shocks lowered the shadow rate in the baseline scenario. In sum, this simulation suggests that the Federal Reserve's policy stance was not accommodative enough to cope with the economic collapse from late 2008 to 2009, but its policy stance was more accommodative thereafter. This result does not necessarily mean that the Federal Reserve was not aggressive from late 2008 to 2009. Rather, the Federal Reserve's aggressive UMP may have had only limited impact on macroeconomic variables during the economic collapse, which may have impaired the transmission mechanisms of monetary policy to a large extent.

In the no UMP scenario, where the shadow rate was equal to the T-bill rate, both GDP growth and inflation were weaker than in the baseline case from mid-2010. This result suggests that the UMP had a positive impact on the U.S. economy. The peak effect on GDP growth was 0.4 percentage points while that on inflation was 0.5 percentage points; they occurred in 2015Q3 and 2017Q1, respectively. The estimated effect on inflation is largely in line with those obtained in previous studies; specifically, the estimated magnitude in this study is in the lower range of the magnitudes in previous studies and is close to that in Engen *et al.* (2015), who also use the Blue Chip survey and find that the UMP had essentially no effect through 2010, while the impact on inflation peaks at 0.5 percentage points in mid-2016.[24]

6. Conclusion

This study provided a novel estimate of the shadow rate using macroeconomic forecasts, and used it to evaluate the Federal Reserve's UMP. Our estimate has a number of advantages over existing estimates: our estimate of the shadow rate can differ from the short rate even when the short rate is not constrained at the ELB; our estimate does not impose arbitrary linear or nonlinear relationship between macroeconomic variables and longer-term interest rates; and our estimate can capture the stance of monetary policy that cannot be fully captured by longer-term yields or other monetary and financial variables.

[24] Since many papers do not report the effect on GDP growth, we focus on the comparison of the effect on inflation.

Our estimate of the U.S. shadow rate was highly and negatively correlated with the Federal Reserve's asset holdings under the LSAP program, in particular its holdings of MBSs; a 1 percent of GDP increase in the MBS holdings was associated with a more than 0.2 percentage-point decline in the shadow rate. The shadow rate was negative even after the Federal Reserve started to raise the short rate in December 2015; this suggests that the balance sheet policy made monetary conditions more accommodative than suggested by the short rate.

Through a structural VAR analysis, we found that the Federal Reserve's UMP had a positive impact on GDP growth and inflation; the impacts of the UMP on the year-on-year growth rate and inflation rate peaked at 0.4 and 0.5 percentage points, respectively. According to our counterfactual simulation, however, we showed that the Federal Reserve's policy stance was less accommodative than justified by the economic collapse from late 2008 to 2009, although it was more accommodative thereafter. One possible reason behind this result is that the Federal Reserve's aggressive UMP had only limited impact on macroeconomic variables during the economic collapse, which may have impaired the transmission mechanisms of monetary policy to a large extent.

There are several possible directions for future work. One direction is to apply our method to other countries; the method is applicable to any country in which macroeconomic forecasts are available and a VAR describes the economy well. Another direction is to take advantage of economic theory. Although this paper's VAR approach has the advantage of keeping the analysis essentially model-free, the restrictions imposed by economic theory are expected to help estimate the shadow rate. Integrating economic theory into our shadow rate estimation procedure may be particularly useful for countries where the availability of survey forecasts is relatively modest. Furthermore, our approach of informing the shadow rate estimation with survey forecasts can be adapted to the estimation of other unobservable variables, such as the natural rate of interest. For example, Holston, Laubach, and Williams (2017) estimate the natural rate of interest, while they do not take the ELB into account, on the assumption that the monetary policy authority can influence the economy only through adjustments in the short-term interest rate. Use of survey forecasts could eliminate potential estimation bias that arises from disregarding the effects of various types of UMP.

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Table 1. Regressions of the Shadow Spread on the Federal Reserve's Asset Holdings

	(1)	(2)	(3)	(4)	(5)	(6)
LSAPs	-0.145 **		-0.086 **		-0.066 *	
	(0.016)		(0.019)		(0.026)	
Non-LSAPs	-0.051		-0.013		0.110	
	(0.032)		(0.033)		(0.070)	
Treasury		-0.088 **		-0.032		-0.007
		(0.022)		(0.025)		(0.035)
MBS		-0.227 **		-0.177 **		-0.145 **
		(0.049)		(0.038)		(0.035)
Other		-0.056		-0.032		0.031
		(0.035)		(0.028)		(0.051)
Gov. surplus					-0.097	-0.049
					(0.067)	(0.043)
Foreign offical inv.					0.111	0.022
					(0.055)	(0.043)
Trend			-0.027 **	-0.026 **	-0.005	-0.022
			(0.007)	(0.008)	(0.016)	(0.014)
Adjusted R-squared	0.884	0.913	0.913	0.940	0.928	0.939
Durbin-Watson statistics	0.644	0.784	0.812	1.090	1.453	1.362

Note: This table reports the estimated coefficients of regressions of the shadow spread (i.e., the shadow rate minus the 3-month T-bill rate) on subcategories of the Federal Reserve's asset holdings relative to GDP. All regressions include a constant term, although the estimate is not reported. Columns (3)-(6) include a trend, which increases by 1 every quarter. Columns (5) and (6) control for the ratios of government surplus and foreign official investment to GDP. Data of foreign official investment are obtained from Bertaut *et. al.*'s (2014) dataset and are available up to 2016Q4. The observation period is 2008Q4-2017Q4 for Columns (1)-(4) and 2008Q4-2016Q4 for Columns (5) and (6). Newey and West (1987) standard errors are reported in brackets. * denotes significance at 5%; ** at 1%.

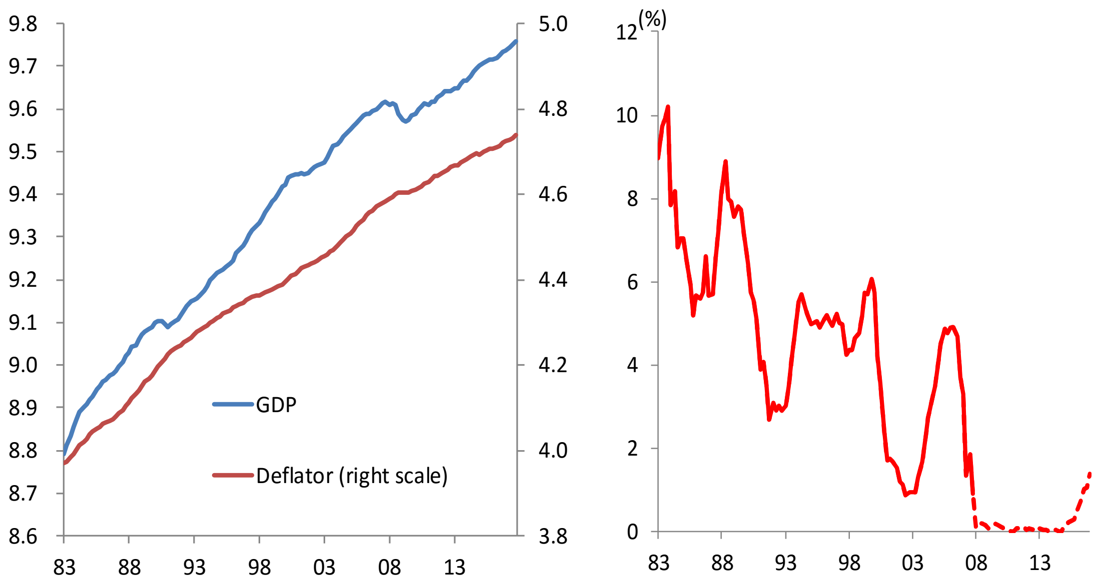
Table 2. Regressions of the Shadow Spread on a Term Spread

Maturity (years)	1	2	5	10
Treasury	-0.091 **	-0.086 **	-0.073 **	-0.068 **
	(0.021)	(0.023)	(0.026)	(0.025)
MBS	-0.214 **	-0.231 **	-0.252 **	-0.241 **
	(0.046)	(0.047)	(0.051)	(0.049)
Other	-0.045	-0.059	-0.069 *	-0.060
	(0.034)	(0.032)	(0.032)	(0.033)
Term spread	-0.335	0.047	0.118	0.094
	(0.235)	(0.121)	(0.079)	(0.051)
Adjusted R-squared	0.913	0.910	0.915	0.917
Durbin-Watson statistics	0.824	0.785	0.836	0.862

Note: This table reports the estimated coefficients of regressions of the shadow spread (i.e., the shadow rate minus the 3-month T-bill rate) on subcategories of the Federal Reserve's asset holdings relative to GDP and a term spread (i.e., a zero-coupon yield minus the 3-month T-bill rate). The maturity is 1, 2, 5, or 10 years. All regressions include a constant term, although the estimate is not reported. The observation period is 2008Q4-2017Q4. Newey and West (1987) standard errors are reported in brackets. * denotes significance at 5%; ** at 1%.

Figure 1. Actual Data

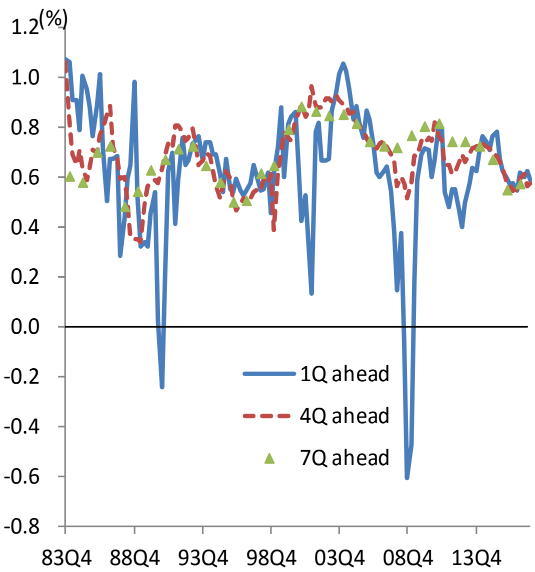
(1) GDP and Deflator (2) TB rate



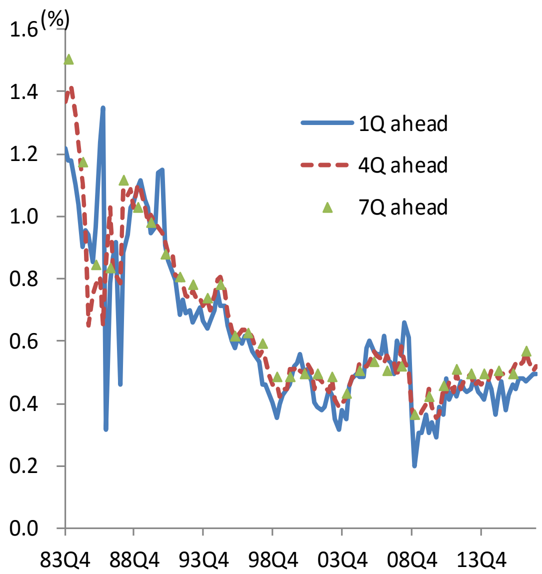
Note: Panel 1 shows the logs of GDP and the GDP deflator. Panel 2 shows the 3-month Treasury bill rate, with a broken line from 2008Q4.

Figure 2. Survey Forecasts for Selected Horizons

(1) GDP growth



(2) Inflation

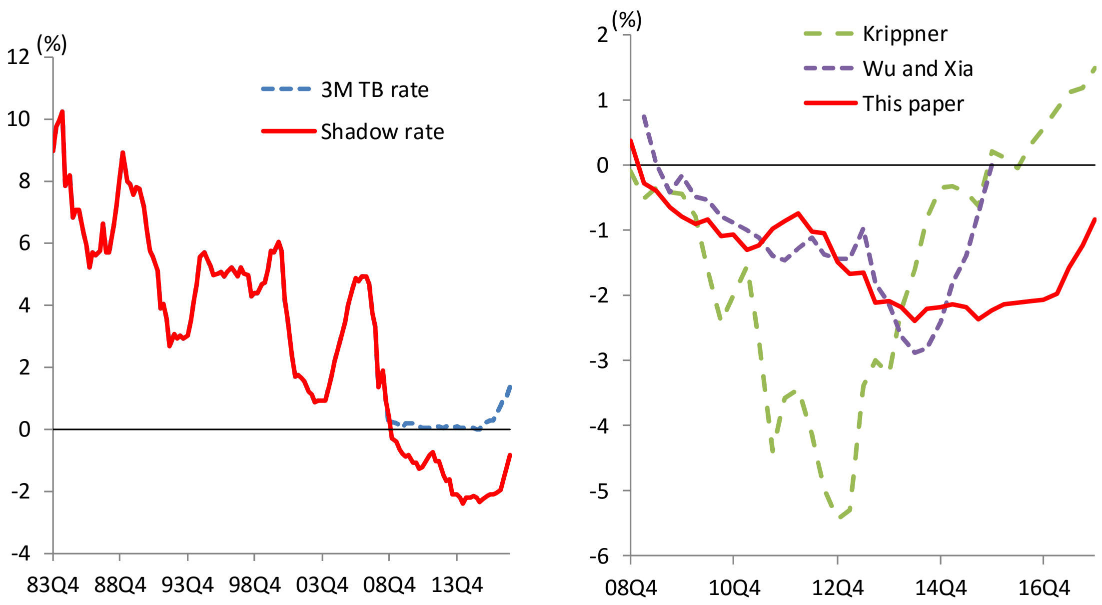


Note: Panel 1 shows the 1-, 4-, and 7-quarter-ahead forecasts of the log differences of GDP. Panel 2 shows those of the GDP deflator.

Figure 3. The Shadow Rate

(1) Long time-series

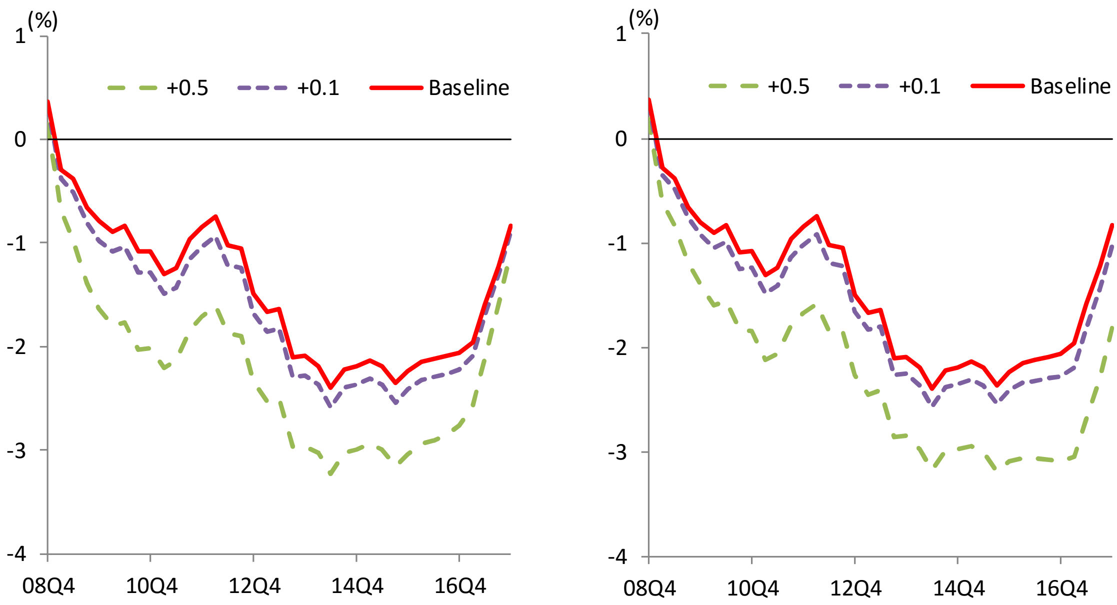
(2) Comparison with other estimates



Note: Panel 1 shows the estimated shadow rate and the 3-month T-bill rate. Panel 2 shows the shadow rate with the updated estimates of Wu and Xia (2016) and Krippner (2014). The shadow rates and the T-bill rate are those at the end of each quarter with one exception; Wu and Xia's estimate in 2015Q4 is that at the end of November, 2015 since they do not update the estimate after the December 2015 policy rate hike from the zero lower bound.

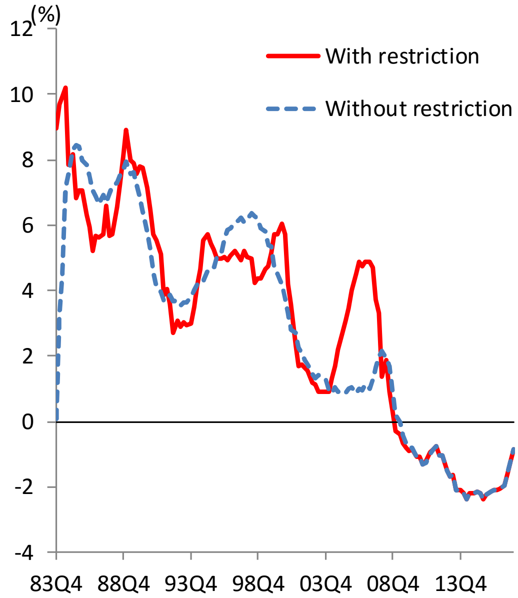
Figure 4. Sensitivities to Survey Forecasts

(1) To growth forecasts (2) To inflation forecasts



Note: This figure shows the shadow rates estimated after increasing the survey forecasts of growth or inflation that were made in 2008Q4 and thereafter over all forecasting horizons in parallel, together with the baseline shadow rate. Panel 1 shows the shadow rates when the survey forecasts of the annualized quarter-on-quarter percent change of GDP are higher by 0.1 and 0.5 percentage points. Panel 2 shows the shadow rates when the survey forecasts of the annualized quarter-on-quarter percent change of the GDP deflator are higher by 0.1 and 0.5 percentage points.

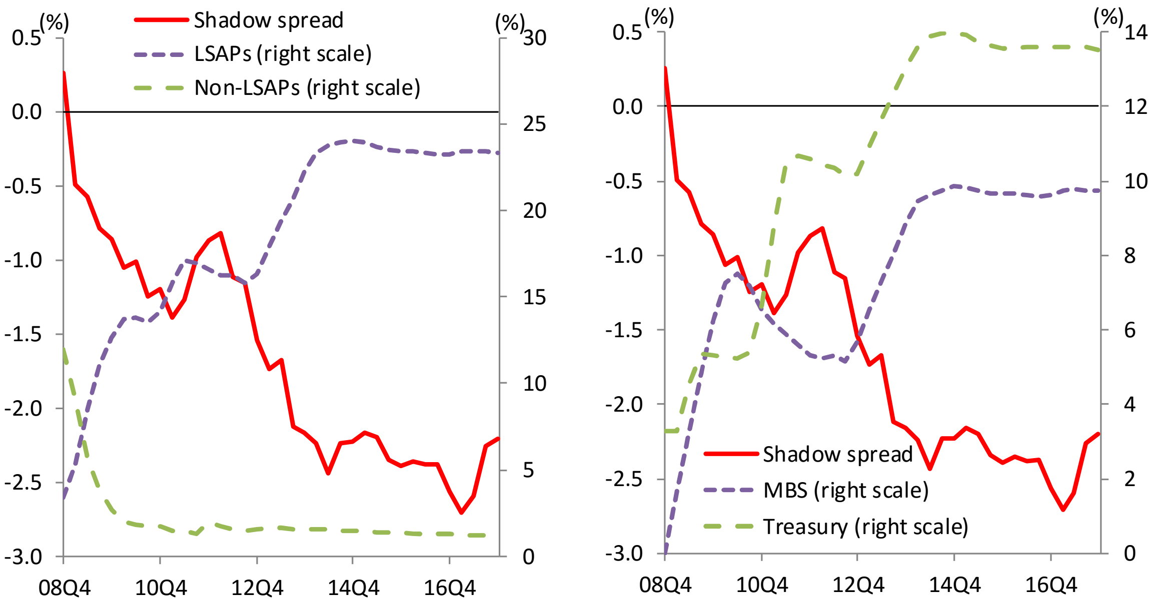
Figure 5. The Shadow Rate Estimated without the Restriction in the pre-ELB Period



Note: “With restriction” is the baseline result of the shadow rate, which is estimated with the restriction that the shadow rate is equal to the 3-month T-bill rate until 2008Q3. “Without restriction” is the shadow rate estimated without the restriction, given all the parameters as estimated in the baseline analysis.

Figure 6. The Shadow Spread and the Federal Reserve's Asset Holdings

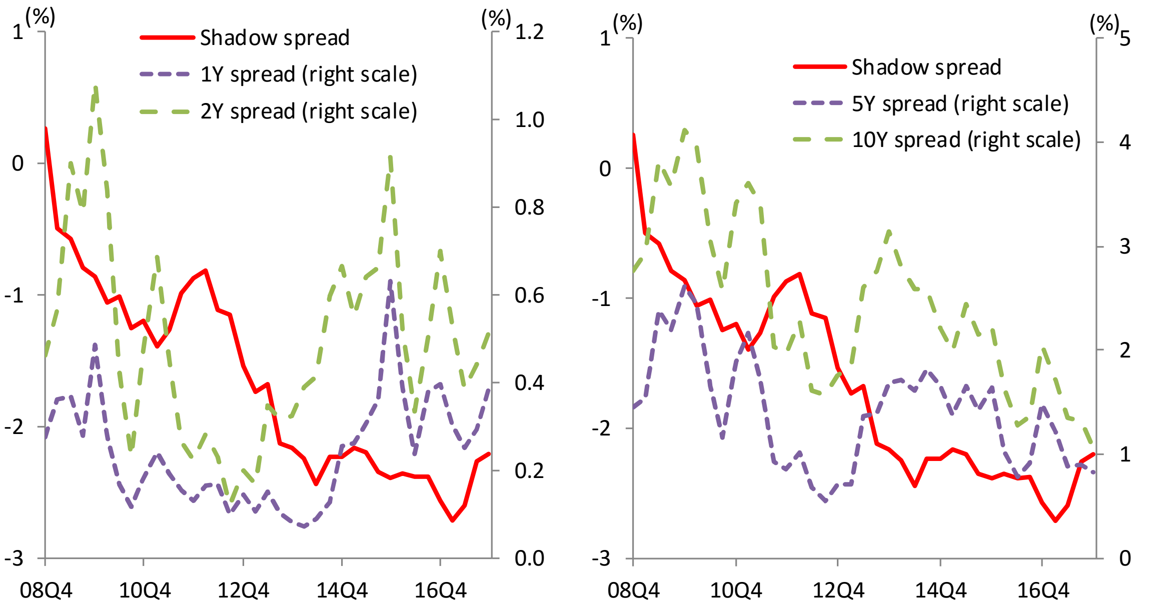
(1) LSAPs and non-LSAPs (2) Treasuries and MBSs



Note: This figure compares the shadow spread (i.e., the estimated shadow rate minus the 3-month T-bill rate), with subcategories of the Federal Reserve's balance sheet. "LSAPs" consist of the Federal Reserve's holdings of Treasuries, agency mortgage backed securities, and agency bonds, while "non-LSAPs" are calculated by subtracting "LSAPs" from the total assets held. All balance sheet data are the ratios to GDP.

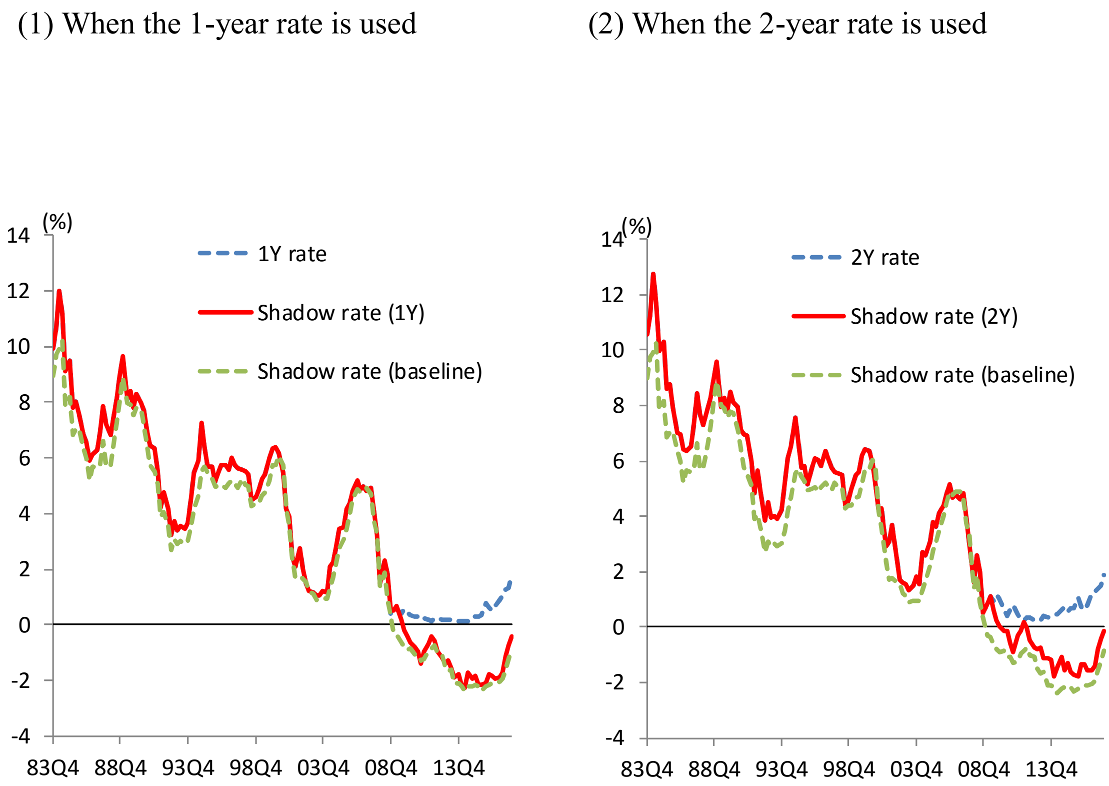
Figure 7. The Shadow Spread and Term Spreads

(1) 1- and 2-year spreads (2) 5- and 10-year spreads



Note: The figure compares the shadow spread (i.e., the estimated shadow rate minus the 3-month T-bill rate) with the 1-, 2-, 5-, and 10-year term spreads (i.e., the zero-coupon yield minus the 3-month T-bill rate).

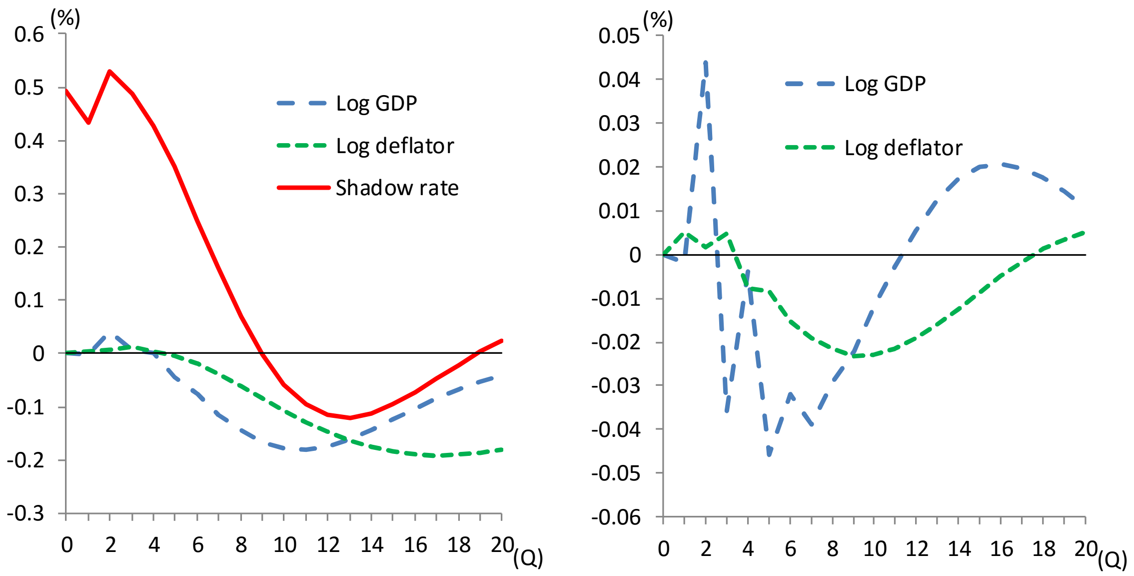
Figure 8. Longer-term Shadow Rates



Note: This figure shows a longer-term yield as well as the shadow rate estimated using the longer-term yield, instead of the 3-month T-bill rate, together with the baseline shadow rate. Panels 1 and 2 show the cases in which the 1- and 2-year rates are used, respectively.

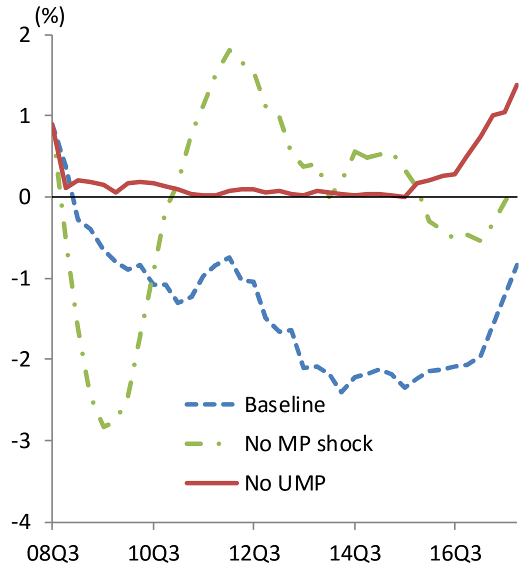
Figure 9. Impulse Response Functions from a Monetary Tightening Shock

(1) Level (2) First difference



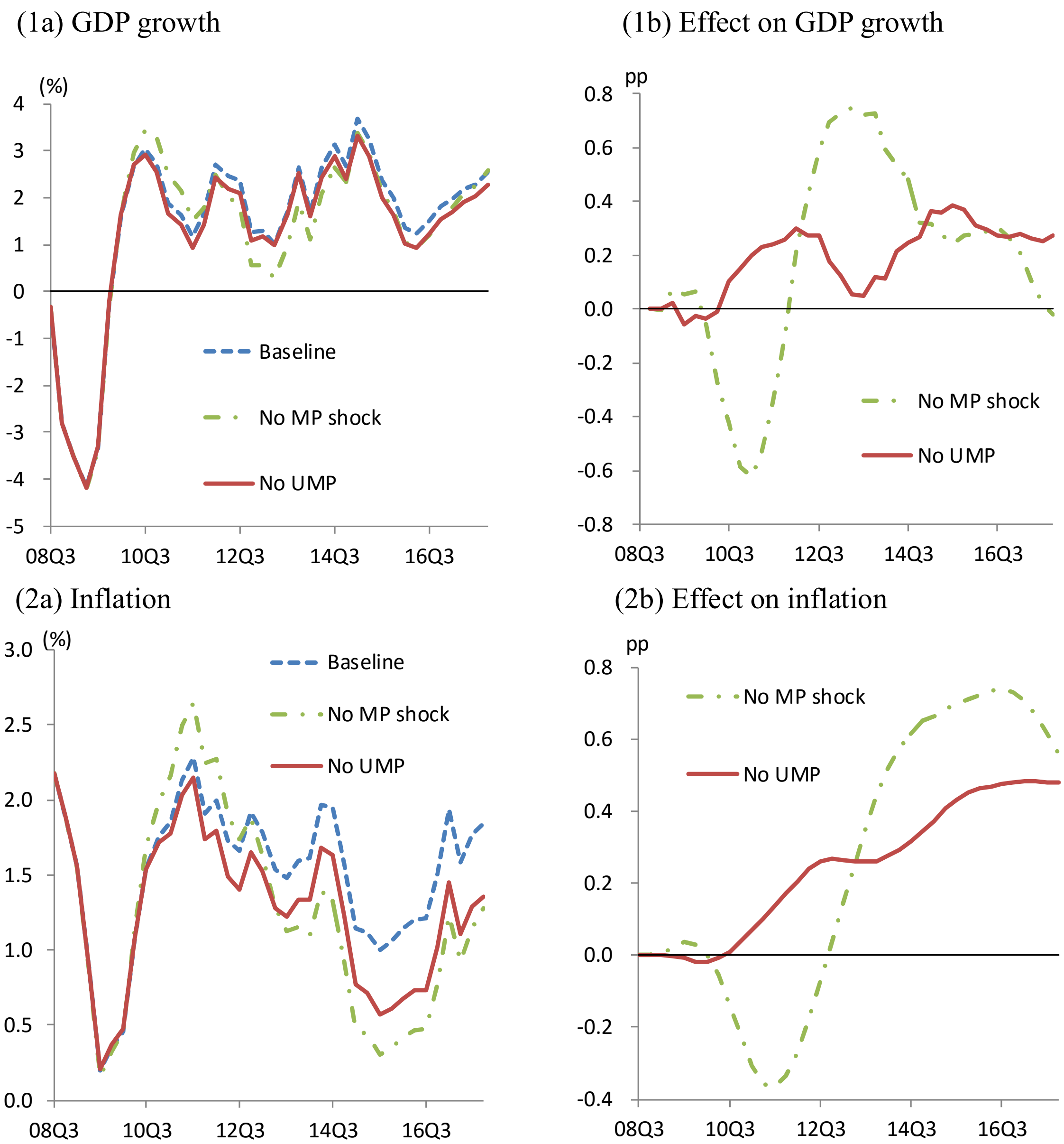
Note: The figure shows impulse response functions from a one-standard-deviation monetary policy tightening shock.

Figure 10. Counterfactual Simulations of the Shadow Rate



Note: “Baseline” uses the estimated shadow rate. “No MP shock” is a counterfactual shadow rate when the monetary policy shock has been zero since 2008Q4. In the “No UMP” scenario, the shadow rate has been equal to the 3-month T-bill rate.

Figure 11. Counterfactual Simulations of GDP Growth and Inflation



Note: Panels 1a and 2a show the four-quarter log differences of GDP and the GDP deflator, respectively, for three scenarios. "Baseline" uses the estimated shadow rate. In the "No MP shock" scenario, the monetary policy shock has been zero since 2008Q4. In the "No UMP" scenario, the shadow rate has been equal to the 3-month T-bill rate. Panels 1b and 2b correspond to Panels 1a and 2a, respectively, and show "Baseline" minus the counterfactual scenario.