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Scarcity Effects of Quantitative Easing on Market Liquidity: Evidence from the Japanese Government Bond Market

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Scarcity Effects of Quantitative Easing on Market Liquidity: Evidence from the Japanese Government Bond Market

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Abstract

Quantitative easing could improve market liquidity through many channels such as relaxing bank funding constraints, increasing risk appetite, and facilitating trades. However, it can also reduce market liquidity when the increase in the central bank's holdings of certain securities leads to a scarcity of those securities and hence higher search costs in the market. Using security-level data from the Japanese government bond (JGB) market, this paper finds evidence of the scarcity (flow) effects of the Bank of Japan (BOJ)'s JGB purchases on market liquidity. Moreover, we also find evidence that such scarcity effects could dominate other effects when the share of the BOJ's holdings exceeds certain thresholds, suggesting that the flow effects may also depend on the stock.

JEL Classification Numbers: C23, C26, C54, E52, E58, G10, G14

Keywords: Quantitative easing, quantitative and qualitative monetary easing, market liquidity, Japanese government bond, scarcity effects

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I. INTRODUCTION

1. Have the large-scale asset purchases by major central banks—commonly knowns as quantitative easing (QE)—had any effect on the liquidity conditions of the assets that are purchased? After the global financial crisis (GFC), central banks in major advanced economies embarked on QE programs to provide further monetary easing beyond the zero lower bound and reduce long-term interest rates. As a result, their balance sheets, particularly holdings of domestic government bonds, have expanded rapidly to unprecedented levels (Figure 1). If such rapid balance sheet expansions have impaired market functioning and reduced market liquidity in the intervened asset markets, transaction and hedging costs of the private sector may increase, undermining—at least partially—some of the intended impact of the policies on the broader economy (Schlepper and others, 2017).[2] Although liquidity conditions in asset markets have been closely monitored, central banks could potentially benefit from analyzing the effects of QE on market liquidity by fine-tuning the QE operations to limit negative effects when further pursuing their monetary policy objectives (Iwatsubo and Taishi, 2016). From a financial stability perspective, liquidity in government bond markets is becoming more of an issue as interest rate spikes tend to happen more frequently under unconventional monetary policies (Sakiyama and Yamada, 2016). Moreover, a lower market liquidity could potentially amplify the volatility of asset prices when the central banks start shrinking their balance sheets due to a larger price impact. In this context, it would be important for policy makers to understand in which situations QE could improve market liquidity and in which situations it tends to reduce it.

2. In theory, QE can affect market liquidity of the purchased assets. It has long been argued that traditional monetary policy affects market liquidity—the ability to rapidly buy or sell a sizable volume of securities at a low cost and with a limited price impact (e.g., Fleming and Remolona, 1999; Lagos and Zhang, 2016; Lee and others, 2016). In particular, traditional monetary policy expansions can improve market liquidity by reducing the costs of market making and trading, or by increasing the risk appetite of market makers. QE could also affect market liquidity in a similar way. As summarized by IMF (2015), such effects could take place through three main channels:[3]

- *Bank funding channel*: QE can increase bank reserves and therefore funding liquidity. The relaxed funding constraints make it easier for banks to finance their inventories and thereby support market liquidity (Brunnermeier and Pederson, 2009);

[2] Appendix I provides a detailed discussion of the concept and measurement of market liquidity. It is worth mentioning that this implication, however, by no means suggests that QE is ineffective. In fact, many studies such as Krishnamurthy and Vissing-Jorgensen (2011) have documented that QE policies significantly lowered nominal interest rates.

[3] Regulatory changes may have also affected market making and market liquidity. For example, IMF (2015) found that reduced market making seems to have had a detrimental impact on the level of market liquidity, but this decline is likely driven by a variety of factors including regulatory changes.

- *Risk appetite channel*: QE can raise the risk appetite of market makers (Bekaert and others, 2013; Jiménez and others, 2014), and hence increase their willingness to hold inventories and facilitate trades;

- *Market functioning channel*, through which two opposite effects may take place: i) the appearance of the central bank as a solvent, committed, and uninformed buyer in the market can directly reduce search frictions that prevent investors from finding counterparties for trades, and hence support market-making activities and reduce liquidity risk premium (Lagos and others, 2011). This effect only takes place throughout the duration of the QE program or if investors believe that the central bank would intervene again in the market should the prices of the purchased securities drop too much (IMF, 2015; Christensen and Gillan, 2015). We will refer to this mechanism as the trade facilitating channel in the rest of the paper. ii) As the central bank's holdings of certain securities grow, further outright purchases may increase the scarcity of these securities, leading to higher search costs and lower market liquidity—the so-called "*scarcity effects*" (IMF, 2015; Schlepper and others, 2017; and Pelizzon and others, 2017).[4]

3. **Earlier empirical studies do not seem to provide a clear direction for the effects of QE on market liquidity.** Kandrac and Schlusche (2013) found no significant liquidity effects associated with the Treasury purchases by the Federal Reserve. Similarly, focusing the "flow effects" of the Federal Reserve's Treasury purchases, Kandrac and Schlusche (2013) found no evidence of flow effects on the liquidity in the Treasury market.[5] However, Kandrac (2013) found evidence of negative flow effects of the Federal Reserve's outright purchases of mortgage-backed securities (MBS) on the market functioning in the MBS market, although the magnitude of such effects appears to be modest. Moreover, IMF (2015) found that the MBS purchases had different effects on the liquidity in the MBS market at different stages of the QE. More specifically, it found that QE improved liquidity in the MBS market during the first reinvestment program (October 2011–November 2012), had no effect throughout the duration of QE3 (December 2012–October 2014), and even reduced market liquidity after November 2014 when the negative scarcity effects associated with the large-scale central bank purchases dominated any positive effect.

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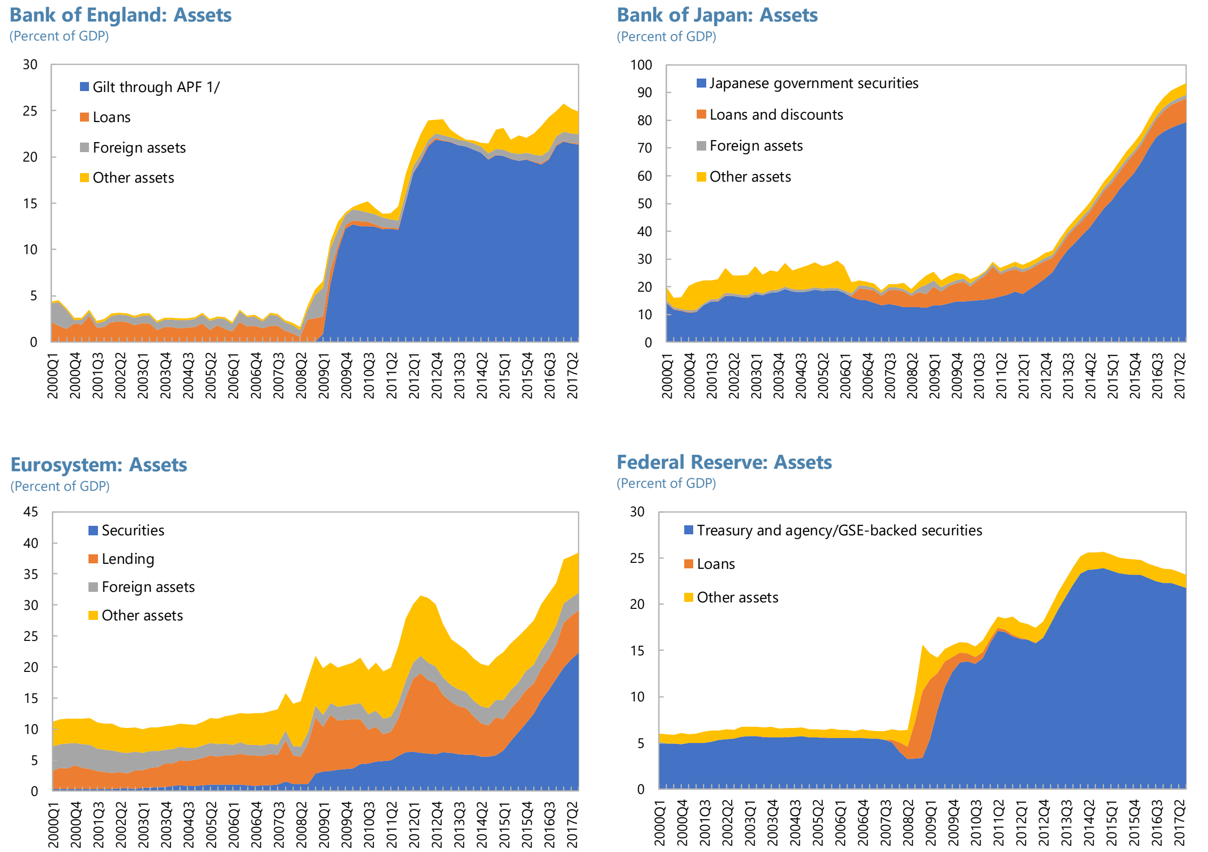
[4] The term "scarcity effects" has also been used in literature to refer to the effects of QE policies on bond yields or prices, which are the main policy target and intended transmission channel to the real economy. In fact, there have been many theoretical and empirical studies on the scarcity effects of QE on bond yields, including Schlepper and others (2017), and Pelizzon and others (2017). In particular, Fukunaga and others (2015) found that the BOJ's QQE policy had significant effects on long-term interest rates.

[5] As defined by D'Amico and King (2013), "flow effects" refer to the instantaneous response of bond prices or market liquidity to a central bank's ongoing purchase operations, and "stock effects" refer to the impact that QE policies had on bond prices or market liquidity by permanently reducing the total amount of bonds available for purchase by the public.

Figure 1. Balance-Sheet Breakdown of Major Central Banks



Sources: Haver Analytics; and IMF staff calculations.
1/ APF: Asset Purchase Facility.

4. More recent literature found both positive and negative effects of QE programs on the market liquidity of the purchased assets, depending the purchasing policy and asset market. A consensus has not yet been reached on this issue. De Pooter and others (2016) found that the Securities Market Program (SMP) adopted by the European Central Bank (ECB) between May 2010 and September 2012—large-scale asset purchases of sovereign debt from member nations—reduced the liquidity premia of the purchased sovereign bonds, supporting their market liquidity. Iwatsubo and Taishi (2016) found that the changes in the BOJ's purchasing policy since the start of the quantitative and qualitative monetary easing (QQE) in April 2013 had a positive impact on the liquidity in the Japanese government bond (JGB) market by facilitating investors' expectations of purchase schedule and reducing market uncertainty. Similarly, Christensen and Gillan (2017) also found that QE in the United States improved the liquidity in the Treasury inflation-protected securities (TIPS) market by temporarily increasing the bargaining power of sellers in the market. However, Sakiyama and Yamada (2016) found evidence that market liquidity in certain sectors has been adversely affected by QQE, and in particular, that the depth of the market has declined. In addition, using intraday transaction-level data, Schlepper and others (2017) found that the Public Sector Purchase Program (PSPP) launched by the ECB/Eurosystem since March 2015, had a negative impact on the liquidity in the German government bond market which is both statistically and economically significant, highlighting the importance of scarcity effects in government bond markets. A most recent study on the JGB markets by Pelizzon and others (2017) found that the liquidity in the JGB markets shows an improvement through a so-called “spotlight effect” but also experience a deterioration through the scarcity effect.[6]

5. The JGB market seems to provide a good opportunity to explore the scarcity effects as the holdings of government bonds by the Bank of Japan (as a share of total amount outstanding) have exceeded the other major central banks. To stimulate economic growth and end deflation, the Bank of Japan (BOJ) launched in April 2013 the quantitative and qualitative monetary easing (QQE) program with unprecedented large-scale asset purchases, most of which were concentrated in JGBs, to expand monetary base and lower long-term interest rates. Until September 2016, purchases were targeted at ¥80 trillion of JGBs per year, equivalent to almost one-sixth of domestic GDP. The large magnitude and protracted duration of QQE have resulted in a dramatic increase in the JGBs held by the BOJ. Although the BOJ reduced the amount of JGB purchases to about ¥40-50 trillion (annualized) as a result of the introduction of yield curve control (YCC) in September 2016, its JGB holdings continued to rise to over 40 percent of total amount outstanding by June 2017, far exceeding the shares of domestic government debt securities held by other major central banks that have also implemented QE measures such as the Bank of England (25 percent), European Central bank (22 percent), and Federal Reserve (17 percent) (Figure 2).[7]

6. This paper provides evidence for the scarcity (flow) effects of QQE on the liquidity in the JGB markets. We argue that the scarcity effects depend on the stage of QE, and more specifically, the central bank’s holdings of the purchased securities. Using security-level data of the JGB markets, we find that the BOJ’s outright purchases have a significantly negative impact on market liquidity, suggesting the existence of scarcity effects as the other effects are mostly positive. However, this finding should only be described as a potential side effect of QQE and should by no means be interpreted as indicating that QQE is ineffective. In fact, JGB yields have declined significantly after the introduction of QQE—suggesting that QQE has been overall effective in pushing down interest rates—despite the concern that

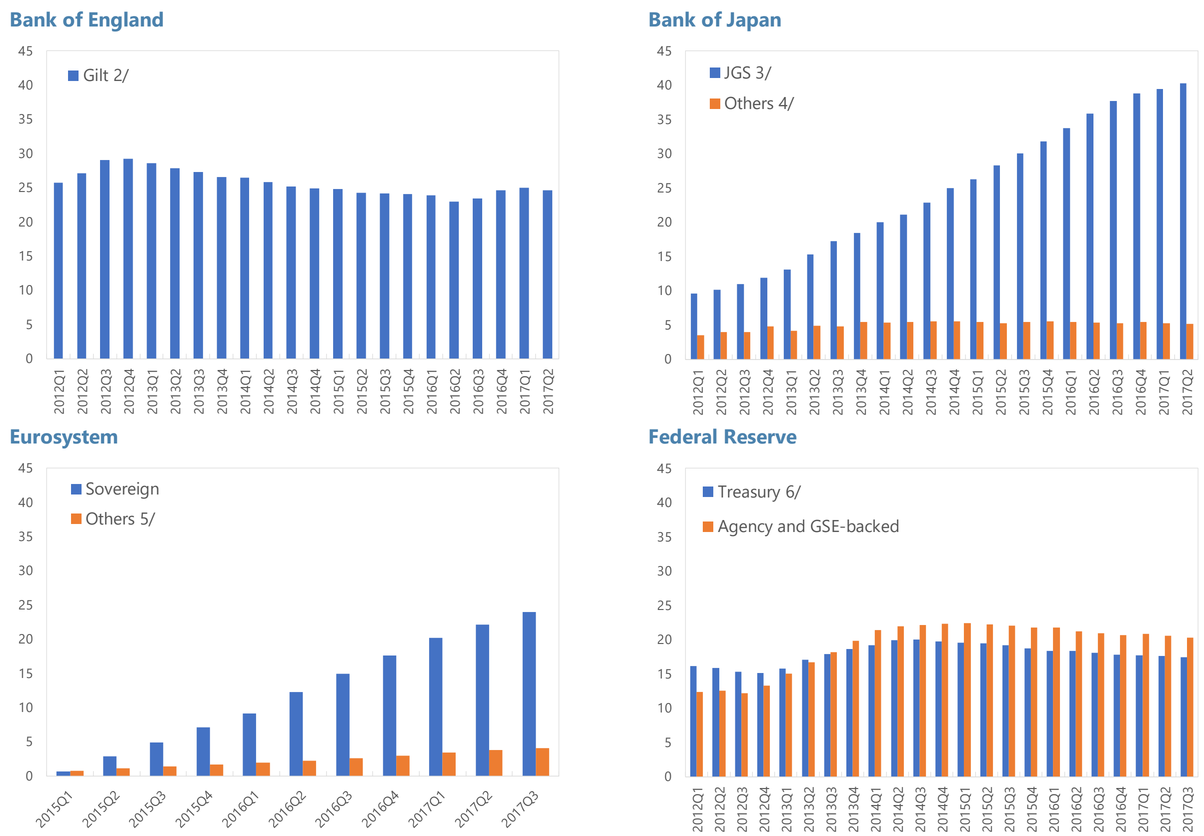
[6] The spotlight effect is created in a situation in which a significant demand-supply imbalance is expected to take place through events such as the inclusion of certain bonds that have not been actively traded in the QE program, thus creating rare trading opportunities for these bonds. This effect is included in the trade facilitating channel in this paper.

[7] The BOJ’s holdings of Japanese government debt securities mainly comprise of JGBs and Treasury Discount Bills, both of which have exceeded 40 percent of their respective total amount outstanding. After the policy change of September 2016, the BOJ had more flexibility to manage the quantity of its purchases in line with its interest rate objectives. This new framework allowed BOJ to reduce its JGB purchases from about ¥80 trillion per year in 2016 to about ¥40-50 trillion per year since the beginning of 2017 in order to keep the benchmark 10-year JGB yield around its target of zero percent.

lower liquidity in the JGB market may lead to higher liquidity risk premia. Moreover, we find some evidence that QQE improves the JGB market liquidity when the BOJ's holdings are relatively small—such positive effects could come from the bank funding channel, the risk appetite channel, or the trade facilitating channel—but reduce it when the BOJ's holdings (as a share of total amount outstanding) exceed certain thresholds. This finding implies that the *flow* effects (on market liquidity) also depend on the *stock* of the BOJ's holdings.

Figure 2. Holdings of Domestic Debt Securities by Major Central Banks 1/

(Percent of amount outstanding)



Sources: Haver Analytics; and IMF staff calculations.

[1] Only the types of debt securities that were purchased under the QE policy in each jurisdiction were considered, except for the Bank of England where only the holdings of domestic government debt securities (Gilts) are plotted as the purchases of high-quality debt issued by private companies are much smaller.

[2] Calculated by dividing the Bank of England's holdings of Gilts by the net total amount outstanding of Gilts (excluding government holdings).

[3] JGS: Japanese government securities, including both JGBs and Treasury Discount Bills.

[4] Including domestic debt securities issued by financial institutions and non-financial corporations.

[5] Including covered bonds and corporate bonds issued by euro area residents, calculated by dividing the Eurosystem's holdings of covered bonds and corporate bonds by the total amount outstanding of debt securities issued by euro area MFIs, non-monetary financial corporations, and non-financial corporations.

[6] Calculated by dividing the Federal Reserve's holdings of Treasury securities by the total amount outstanding of marketable Treasury securities.

7. The rest of the paper is organized as follows. Section II provides the key stylized facts of JGB markets, raises the main questions of interest, and formulates a statistically testable hypothesis to address the questions. Section III describes the measure of JGB market liquidity used in this paper, provides some key observations of the measure, and proposes another hypothesis based on the observations. Sections IV and V present the econometric models to statistically test the hypotheses and the main results. Section VI offers some concluding remarks.

II. KEY STYLIZED FACTS OF JGB MARKETS

8. Deep and liquid JGB markets have contributed to a stable and low yield curve, providing stable and cheap funding for the Japanese government. This is important for the government financing given that Japan has the highest public debt in the world relative to the size of economy. According to the updated dataset of Arslanalp and Tsuda (2014), Japan's government debt reached almost 200 percent of GDP by June 2017, of which over 90 percent are JGBs or short-term Treasury Discount Bills (TDBs).[8] Although nearly 90 percent of such debt has been held by residents, sustained declines in JGB market liquidity could still make yield spikes more frequent and amplify the volatility of yields when negative shocks occur (Sakiyama and Yamada, 2016). For example, similar to the "flash crash" in the U.S. Treasury market on October 15, 2014 and in the German bund market in April 2015, the JGB market also experienced a yield spike after the introduction of QQE in April 2013—the first time since the fire sale in 2003 known as the "VaR (Value at Risk) shock". More recently in March 2016, a circuit breaker in the JGB futures market was triggered after a sudden plunge in JGB yields.

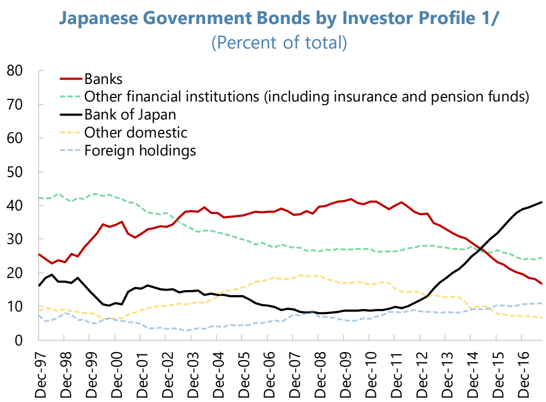
9. JGBs also play a vital role in facilitating funding markets for financial institutions in Japan. As a result of QQE, the investor base of JGBs has changed substantially as the holdings by the BOJ increased while those by banks and other domestic sectors declined (Figure 3). However, JGBs—together with TDBs—are still a vital component of the balance sheets of all financial institutions in Japan, much more so than in international peers (Figure 3). In particular, they account for more than 10 percent of total bank assets and nearly 40 percent of the assets of insurance companies and pension funds. Moreover, the efficiency of funding markets depends heavily on the easy availability of JGBs to facilitate transactions. JGBs accounted for 85 percent of all yen-denominated bond issuance and 99 percent of total trading in yen-denominated bonds during April 2016–March 2017 (Ministry of Finance, Japan, 2017). They are also used as the collateral in almost all repurchase agreements (repos) and in the secured call money market, and are the main instrument used by broker-dealers and other market participants to hedge positions.

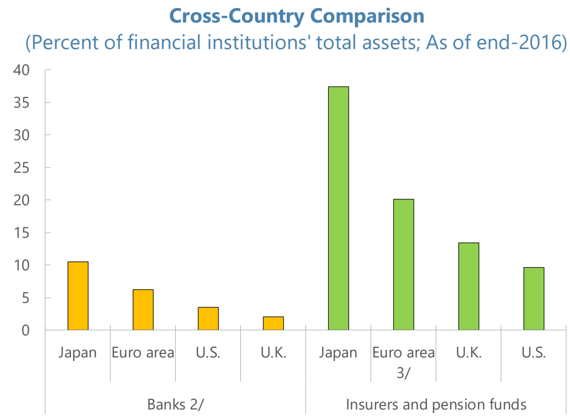
10. As a result, disruptions in JGB markets can spread rapidly across the financial system and reduce the efficiency of all the major funding markets. The

[8] The original maturities of TDBs are typically less than one year.

interconnectedness also involves foreign investors in Japan, who often invest in JGBs or TDBs, or use them as hedging instruments. By December 2016, foreign investors held ¥113 trillion of JGBs and TDBs, accounting for nearly 11 percent of total amount outstanding. Since JGBs are the key instrument in Japan's major funding markets (notably call and repo markets) and the key linkage among all financial institutions and investors, a high level of market liquidity—the ability to rapidly buy or sell a sizable volume of securities at a low cost and with a limited price impact—is important to ensure an efficient transfer of funding throughout the financial system.

Figure 3. Holdings of Domestic Government Debt Securities





Sources: Bank of England; Bank of Japan; Haver Analytics; ADB AsiaBondsOnline database; and IMF staff calculations.
[1] Includes JGBs and TDBs.
[2] Monetary financial institutions (MFIs) excluding the Eurosystem for euro area, MFIs excluding domestic central bank for the U.K., depository corporations (excluding domestic central bank) for Japan, and private depository institutions for the U.S.
[3] On an aggregated but unconsolidated basis.

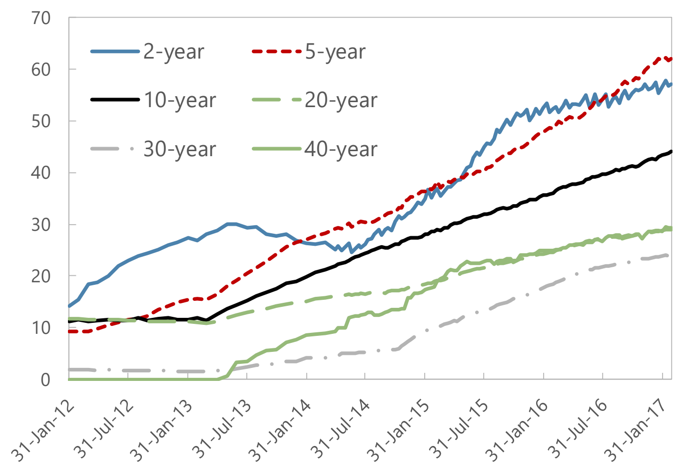
11. **Despite having substantially increased the monetary base and provided the needed monetary easing to the economy, the rapid expansion of the BOJ's balance sheet appears to be associated with signs of potential scarcity in the JGB markets.** JGB trading in most maturities seems to have been negatively impacted by BOJ purchases, as investors have become increasingly reluctant to sell bonds out of their remaining portfolios. As the JGBs held by the BOJ increased rapidly and substantially across all maturities until the introduction of YCC (Figure 4), signs of scarcity of JGBs in the market seem to have emerged (Figure 5):

- The BOJ has been conducting the Securities Lending Facility (SLF) through repos since 2004 to provide the markets with a temporary and secondary source of Japanese government securities. The use of SLF by financial institutions remained minimal until 2016, when its size started to increase rapidly to over ¥6 trillion per month by early 2017—despite the adoption of YCC in September 2016 (Figure 5).

- Both the number and amount of fails in JGB transactions have trended upward and become more volatile since 2013 (Figure 5). According to some market participants, the increased fails in JGB transactions could be partly attributed to the higher foreign participation in the JGB markets but may also reflect the scarcity of JGBs in the market.

- The spread between the general collateral (GC) and special collateral (SC) repo rates (i.e., GC-SC spread) increased sharply from end-2016 to early 2017. Such a spread indicates the lending fee added on to each issue of the security that is specified in the SC repo, and hence can be affected by the issue's supply and demand (i.e., the issuance volume and the size of market participants' short positions).[9] A larger spread indicates a higher lending fee of JGBs in the SC repo market, typically implying some degree of scarcity in the market. The elevated spread between end-2016 and early 2017 also coincides with the period when the use of SLF peaked (Figure 5).

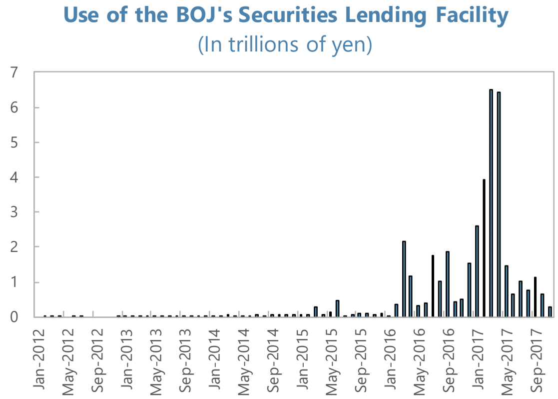
Figure 4. JGBs Held by the BOJ: By Original Maturity
(In percent of total amount outstanding 1/)

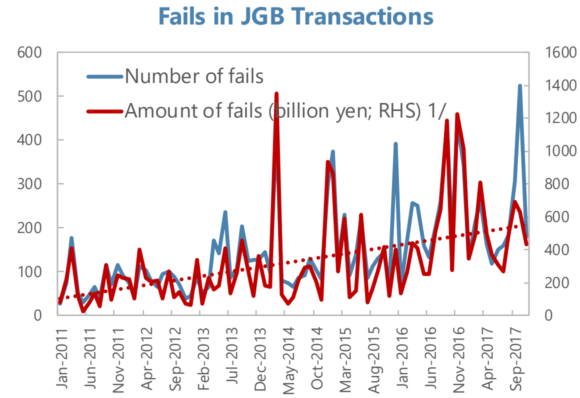


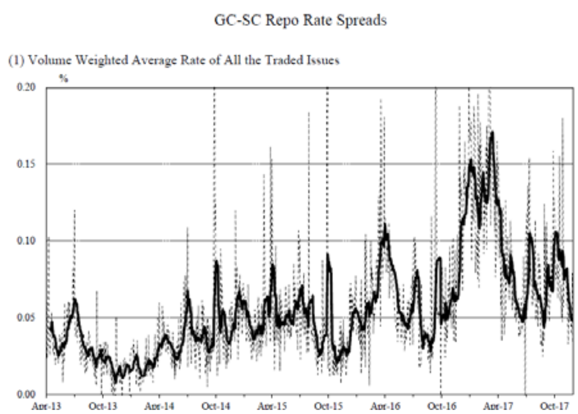
Sources: Bank of Japan; Ministry of Finance, Japan; and IMF staff calculations.
1/ Total amount outstanding is calculated from the issuance data using the method described in Section IV.

[9] SC repo is a repo transaction in which a particular security is specified as the only acceptable collateral. Market participants of JGBs, such as dealers, frequently take a short position to engage in market-making and arbitrage transactions, and the specific issues needed to cover the short position are often borrowed from the SC repo market (Kurosaki and others, 2015). The SC repo rate is typically a negative value and indicates the costs for borrowing a particular issue of a security (mostly JGBs). The scarcer the issue becomes, the larger the negative repo rate becomes. If the negative value of the SC repo rate widens, there is a possibility of market participants having difficulties taking a short position, which affects the transactions in the JGB market.

Figure 5. Signs of Potential Scarcity in the JGB Markets







Source: Bank of Japan.

[1] The amount of fails is calculated in face value.

[2] This chart is taken from the BOJ's Liquidity Indicators in the JGB Markets (December 2017). GC and SC repo stand for general collateral and special collateral repo markets, respectively. The latest data is end-November 2017. The bold black line indicates 10-day backward moving average.

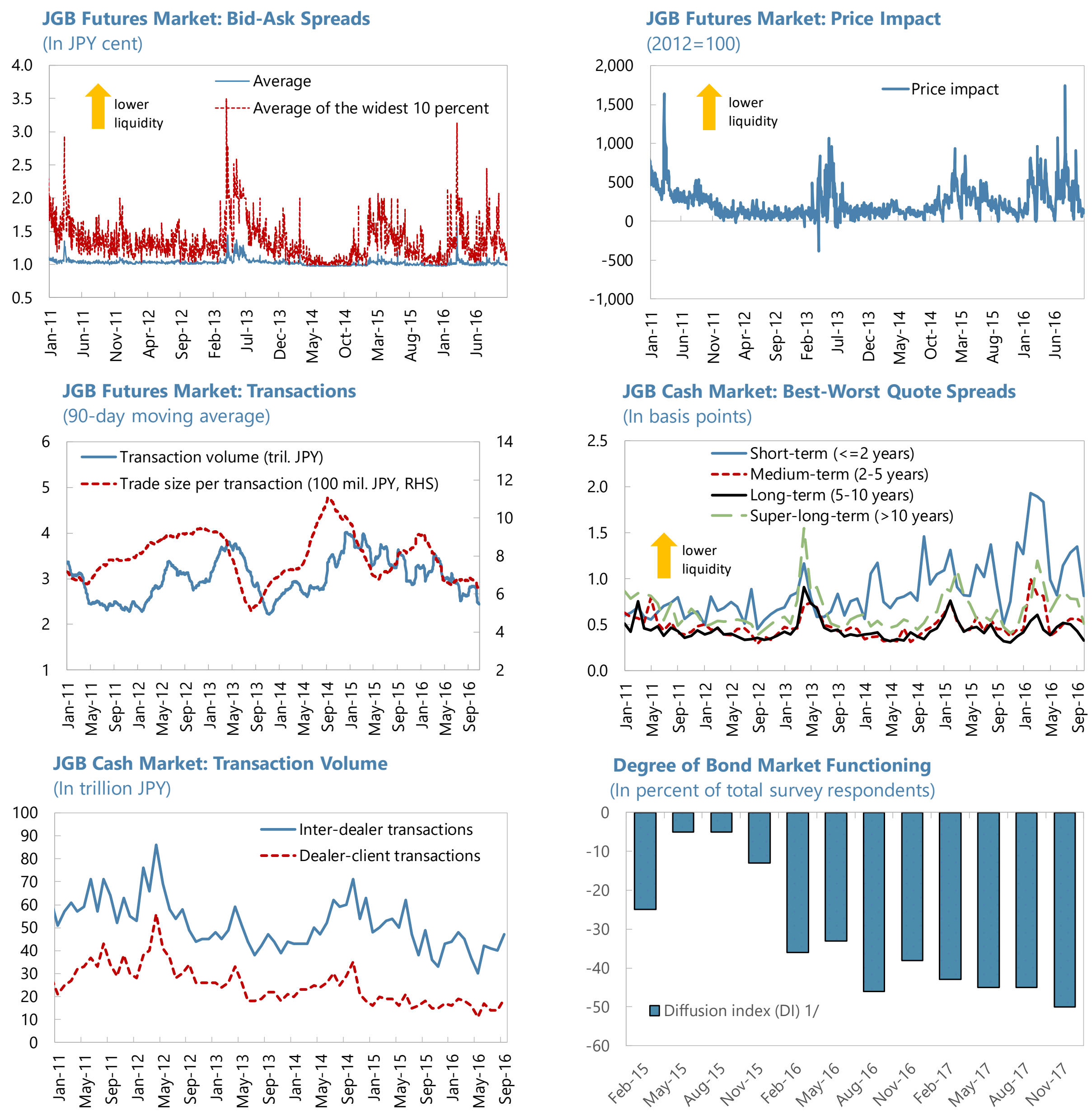
12. Amid these signs of potential scarcity, some transaction-based indicators documented a relative decline in the liquidity in JGB markets after the implementation of QQE. Although traditional liquidity indicators of the JGB markets including bid-ask spreads and the daily price range to transaction volume ratio suggest that JGB market liquidity has not declined, some of the nuanced liquidity indicators constructed by the BOJ based on transaction data show that the liquidity in both JGB futures and cash markets seems to have declined relatively since the introduction of QQE. On the one hand, when looking at the indicators for the JGB futures market, the bid-ask spreads and the price impact of individual trades calculated from transaction data are somewhat higher, and transactions have been on a downward trend in recent years (Figure 6). On the other hand, the best-worst quote spreads of JGBs with short- or super-long-term residual maturities (in dealer-to-client market) show a widening trend, and transaction volume in the cash market has also declined (Figure 6). Moreover, the results from the Bond Market Survey conducted by the BOJ since 2015 also show that market participants have felt continued deterioration in bond market functioning, particularly since 2016 (Figure 6). While this may be a temporary phenomenon following the rapid decline in the long-term yield observed after the expansion of QQE (QQE2) in October 2014 as well as the negative interest rate policy (NIRP) introduced in January 2016, it may also reflect other factors such as the scarcity of JGBs in the market as a result of the BOJ's massive purchases, structural changes in the markets, and regulatory changes. Moreover, many market participants attributed the decline in JGB market liquidity, at least partly, to the scarcity of JGBs in the market. In other words, the scarcity effects might have dominated the positive effects from the three main channels (i.e., bank funding, risk appetite, and trade facilitating channels) in JGB markets.

13. Against this backdrop, this paper tries to shed light on the following main questions using empirical methods: What is the impact of the BOJ's outright purchases on the liquidity in the JGB markets? Has there been any evidence of the scarcity effects?

14. A hypothesis can be proposed to address these questions statistically. Since the bank funding, risk appetite, and trade facilitating channels should produce positive effects of QQE on JGB market liquidity, an estimated negative impact of the BOJ's purchases on market liquidity would imply the existence of scarcity effects. Based on this observation, we can propose the following hypothesis to statistically address the questions above:

> ***Hypothesis* 1:** The BOJ's outright purchases have significantly negative (flow) effects on JGB market liquidity.

Figure 6. Indicators for JGB Market Liquidity



Source: Bank of Japan.

[1] Collected from the BOJ's Bond Market Survey published since March 2015. A total of 46 respondents were received in the latest survey in November 2017. There are three options to the survey question on bond market functioning, i.e., high, not very high, and low. The diffusion index (DI) is calculated as the percent of the respondents that answered high minus the percent of the respondents that answered low. Therefore, a negative DI indicates that more respondents felt a low market functioning compared to those that felt a high market functioning.

III. THE MEASURE OF MARKET LIQUIDITY

15. This paper uses the estimated bid-ask spreads developed by Corwin and Schultz (2012) as the measure of JGB market liquidity.[10] The methodology was developed by Corwin and Schultz (2012) based on the observation that daily high (low) prices are almost always buyer-initiated (seller-initiated) trades. Hence, the ratio of high price over low price (the high–low ratio) reflects both the variance of the security and its bid-ask spread. Although the former component increases proportionately with the length of the trading interval, the latter does not—allowing us to derive a spread estimator as a function of high–low ratios over one-day and two-day intervals. Specifically, the sum of the price ranges over two consecutive single days reflect two days' volatility and twice the spread, while the price range over a two-day period reflects two days' volatility and one single spread. Therefore, the difference between the sum of the high-low ratios from two consecutive single days and the high-low ratio from the respective two-day period reflects a single bid-ask spread. The estimator was initially developed for the stock market, but it can also be used for other markets with frequent trading activities, such as the JGB markets. Compared with the quoted bid-ask spreads, this estimator uses actual transaction prices rather than quoted prices which may come from "fake" quotes.[11] Corwin and Schultz (2012) also showed that it generally outperforms other low-frequency estimators.

16. The Corwin-Schultz bid-ask spreads are estimated for each JGB issue at the bond level as well as at the maturity level for "on-the-run" JGBs.[12] We first estimate the Corwin-Schultz bid-ask spreads using the daily high and low price data for each JGB issue—including all the JGBs outstanding with original maturities of 2, 5, 10, 20, 30, and 40 years—and for each day between January 31, 2012 and February 28, 2017. [13] The measure is not estimated before 2012 due to limitations on the other data used in the empirical analysis (see Section IV). We then average the daily bond-level bid-ask spreads to obtain monthly measures, and present the summary statistics in Appendix Table 2. There appears to be a gradual increase in the measure after the implantation of QQE in April 2013 but before the introduction of YCC in September 2016 (Figure 7). Moreover, the measure seems to exhibit

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[10] In fact, the Corwin-Schultz bid-ask spreads are a measure of market illiquidity, i.e., an increase in the measure implies a decline in market liquidity.

[11] It is worth noticing that the Corwin-Schultz bid-ask spreads are for the JGB cash market, while the actual bid-ask spreads presented in Figure 6 are for the JGB futures market. Moreover, the transaction-based liquidity indicators shown in Figure 6 including the actual bid-ask spreads for the JGB futures market are only available at the aggregate level and not at the bond or maturity level.

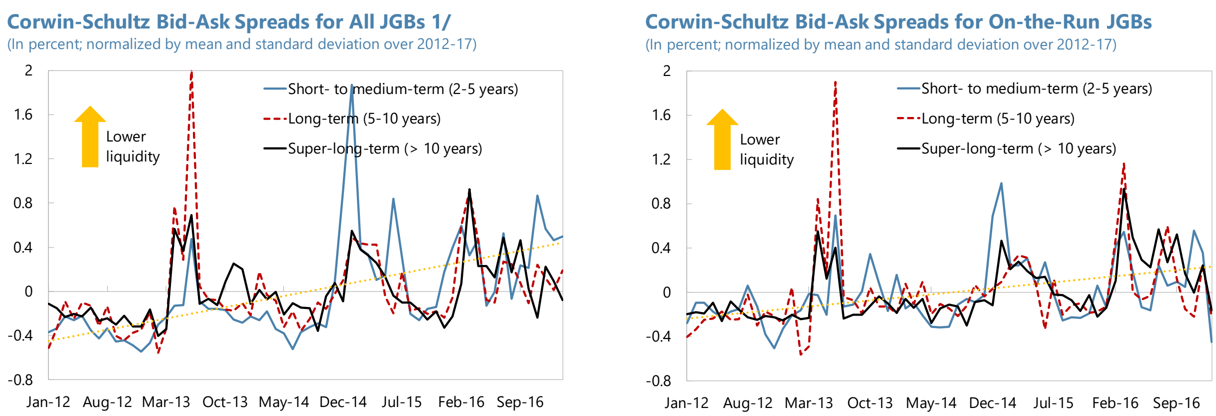
[12] Appendix I provides the detailed calculations of the bid-ask spread estimator for each JGB issue.

[13] This paper only considers the fixed rate coupon-bearing JGBs issued by the Ministry of Finance of Japan whose original maturities are among 2, 5, 10, 20, 30 and 40 years, as the remaining JGBs issued are either different types of bonds or not typically traded in the market. For example, there are also inflation-indexed JGBs with an original maturity of 10 years and floating rate coupon-bearing JGBs with an original maturity of 15 years. Moreover, the Ministry of Finance also issues JGBs for retail investors which have original maturities of 3, 5, or 10 years. But they are typically held to maturity by retail investors and not traded in the market.

(continued…)

similar dynamics as some other transaction-based liquidity indicators in the JGB cash market such as the best-worst quote spreads shown in Figure 6, which also indicate a gradual decline in the liquidity of JGBs with short- or super-long-term residual maturities after the implementation of QQE and before the adoption of YCC. Finally, we also estimate the daily bid-ask spreads for "on-the-run" JGBs that are defined as the most recently issued JGBs for each original maturity due to the liquidity differentials between on- and off-the-run issues (Pasquariello and Vega, 2009). The data are available between December 29, 2006 and January 20, 2017, and cover all the on-the-run issues with original maturities of 2, 5, 10, 20, 30, and 40 years. As expected, the measure for on-the-run issues exhibits a similar pattern as the measure for all JGBs and seems to have also increased gradually after the implementation of QQE and before the introduction of YCC (Figure 7).[14]

Figure 7. The Corwin-Schultz Measure of JGB Market Liquidity



Sources: Bloomberg, L.P.; and IMF staff calculations.
[1] Corwin-Schultz bid-ask spreads first averaged across all the JGBs with the same original maturity and then normalized by mean and standard deviation over 2012–17.

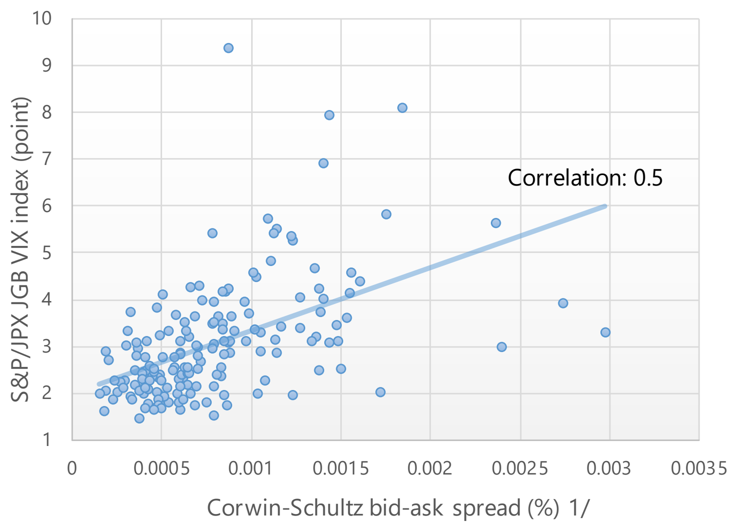
17. A deterioration in the measure of JGB market liquidity tends to be associated with a higher volatility in the JGB markets. There is a positive correlation between the S&P/JPX JGB VIX index—a measure of the implied volatility of JGBs—and the Corwin-Schultz measure of JGB market liquidity since the GFC (Figure 8). Since the Corwin-Schultz measure is in fact a measure of market illiquidity, this suggests that a deterioration in market liquidity is likely accompanied by an increase in market volatility.[15] Despite some variations across maturities, the average correlation between the two is about 0.5 during 2008–17. The correlation is particularly strong (0.7) for the 10-year JGBs, suggesting the importance of the market liquidity of 10-year JGBs for market volatility. A significant increase in the market

[14] Appendix I, Figures 1-2 show in details the monthly measures of all JGBs and only on-the-run JGBs, respectively, broken down by original maturity.

[15] Although the Corwin-Schultz measure aims to control for the volatility component of prices, it does not imply that the measure is orthogonal to the price volatility.

volatility could potentially threaten the stable and cheap funding for the Japanese government and aggravate the existing public debt problem.

Figure 8. Implied Volatility and Market Liquidity of JGBs
(2008−17)



Sources: Bloomberg, L.P.; Japan Exchange Group; and IMF staff calculations.
[1] Average Corwin-Schultz bid-ask spreads across all maturities.

18. There appears to be a positive or U-shaped relationship between the Corwin-Schultz measure of JGB market liquidity and the share of the BOJ's holdings for some maturities. At the maturity level, the Corwin-Schultz measure seems to be somewhat correlated with the share of JGBs held by the BOJ for most maturities. We average the Corwin-Schultz measure of the JGB issues with the same original maturities (2, 5, 10, 20, 30, or 40 years), and plot them against the share of JGBs held by the BOJ for each original maturity (Figure 9). Despite an unclear correlation between the two variables for the 20-year JGBs, the correlation seems to be, broadly speaking, positive for 2, 5, 30, and 40-year JGBs, and U-shaped for the 10-year JGBs—the yield of which is the benchmark for long-term interest rates and the target of the YCC framework.

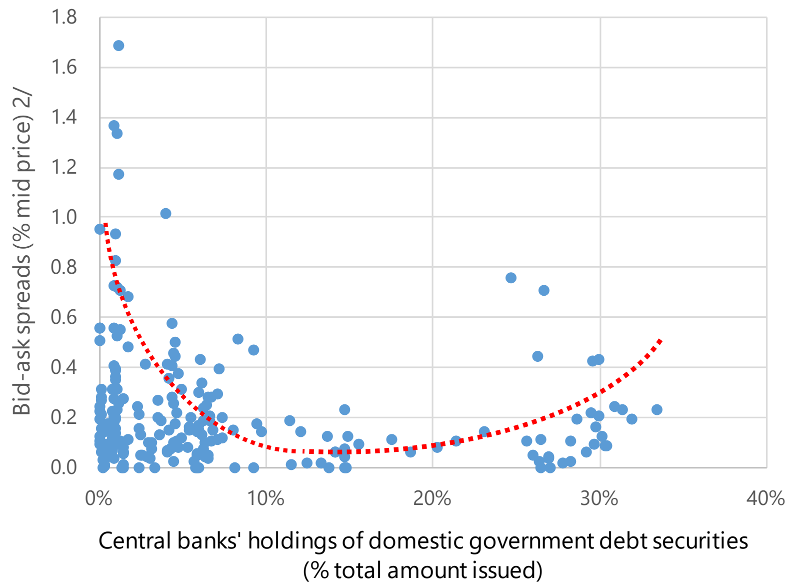
19. In fact, a U-shaped relationship also appears to exist in a cross-country context between the market liquidity of domestic government debt securities and the share of these securities held by domestic central bank. For simplicity and the purpose of illustration, we use the quoted bid-ask spreads as a measure of market (il)liquidity for domestic sovereign bonds and plot them against the holdings of these bonds by domestic central bank as a share of total amount outstanding (Figure 10). The figure also seems to suggest a U-shaped relationship between the two variables, implying that market liquidity tends to decline when the share of domestic sovereign bonds held by the central bank increases once it exceeds a certain threshold. This finding could shed light on the first question raised in Section II and seems to be in line with the theoretical predictions mentioned earlier: QE could affect market liquidity through the bank funding and risk appetite channels which mostly lead to positive effects when the share of domestic central bank's holdings is still small; however, once such a share exceeds a certain threshold and causes a shortage of the securities in the market, then the scarcity effects start to kick in, offsetting those positive effects. This mechanism is also consistent with the empirical finding from the MBS market in the United States that the effects of QE on market liquidity was first positive but turned negative later after QE3 as the scarcity associated with the large-scale purchases by the Fed increased (IMF, 2015).

Figure 9. Market Liquidity and BOJ's Holdings of JGBs: By Original Maturity
(Averages across all bonds with the same original maturity; 2012–17)

Sources: Bank of Japan; Ministry of Finance, Japan; Bloomberg, L.P.; and IMF staff calculations.
[1] The bid-ask spreads are first estimated following Corwin and Schultz (2012) and then averaged across all the JGB issues with the same original maturity.

Figure 10. Market Liquidity and Central Banks' Holdings of Domestic Sovereign Debt Securities

(2013–15 quarterly average; advanced economies 1/)



Sources: Arslanalp and Tsuda (2012); Bloomberg, L.P.; and IMF staff calculations.
1/ Advanced economies in the sample include Australia, Austria, Belgium, Canada, Denmark, Finland, France, Germany, Ireland, Italy, Japan, Netherlands, New Zealand, Portugal, Slovenia, Spain, Sweden, Switzerland, the United Kingdom, and the United States.
2/ Quoted bid-ask spreads are used for simplicity.

20. Based on these observations, we can propose another hypothesis:

> ***Hypothesis* 2:** The flow effects of the BOJ's outright purchases on JGB market liquidity become negative when the share of the BOJ's holdings exceeds a certain threshold.

Apparently, this hypothesis is a sufficient condition for the existence of scarcity effects, i.e., Hypothesis 1. Moreover, it also implies that the *flow* effects—as defined in D'Amico and King (2013)—of QQE on JGB market liquidity also depend on the level of *stock*.

IV. Empirical Strategy and Data

A. Panel Regressions

21. Panel data models are used to statistically test Hypotheses 1 and 2. Since the channels of banking funding and risk appetite should have only positive effects on market liquidity, a significantly negative estimate of the effects of the BOJ's purchases on JGB market liquidity would suggest the existence of scarcity effects. In particular, we run fixed-effect panel regressions, both at the maturity level (using on-the-run JGBs) and at the bond level, to estimate the effects of the BOJ's outright purchases of JGBs on the Corwin-Schultz measure of JGB market liquidity.

22. Two possible panel regression models can be used to statistically test Hypotheses 1 and 2. The first possibility is that the effects of QQE on JGB market liquidity is a decreasing function of the measure of JGB scarcity in the market—proxied by the share of JGBs held by the BOJ.[16] As a result, the effects on market liquidity will become negative at some point when the scarcity of JGBs increases. The function is assumed to be linear for simplicity in the panel regression framework. This suggests the following fixed-effects regression model with an interaction term between the purchases of JGBs by the BOJ and the share of JGBs held by the BOJ:

$$L_{i,t} = \beta_0 + \delta_i + \beta_1 Purch_{i,t} + \beta_2\left(Purch_{i,t} \cdot S_{i,t-1}\right) + \beta_3 S_{i,t-1} + \beta_4 SLF_{i,t} + \beta_5 X_t + \varepsilon_{i,t} \quad (1)$$

In specification (1), $L_{i,t}$ is the Corwin-Schultz measure of JGB market (il)liquidity for bond *i* in the bond-level regressions or for maturity *i* in the maturity-level regressions, normalized by its mean and standard deviation over time.[17] $Purch_{i,t}$ denotes the BOJ's outright purchases of bond (maturity) *i*, standardized by the total amount outstanding of that bond (maturity).[18] $S_{i,t-1}$ is the lagged value of the share of the BOJ's holdings of bond (maturity) *i*—a proxy for the measure of the scarcity of JGBs in the market.[19] $SLF_{i,t}$ represents the size of the BOJ's SLF operations for bond (maturity) *i* to control for any potential effects of the SLF on market liquidity, and is also standardized by the total amount outstanding of that bond (maturity). Since the SLF is likely to be offered when market liquidity is low, it could be subject to the endogeneity bias. Hence, to mitigate the potential endogeneity, we use the two-stage least squares to estimate model (1) where the SLF variable is instrumented by its lagged value, $SLF_{i,t-1}$.

23. X_t in specification (1) includes all the control variables that do not vary across bonds or maturities. The first control variable is the logarithm of the Nikkei Stock Average Volatility Index—an index indicating the expectation of market volatility in one month from now. Similar to the CBOE volatility index (VIX), the Nikkei Stock Average Volatility Index

[16] See the next section for the justification of proxying the scarcity of JGBs in the market by the share of the JGBs held by the BOJ.

[17] The regression model (1) implicitly assumes that the BOJ's purchases have the same effects (if any) on the market liquidity measure for different maturities. However, the measure for certain maturities (e.g., super long term) is typically higher than that for some other maturities due to the liquidity differentials across maturities. By subtracting its mean and dividing by its standard deviation, the new dependent variable has the same mean of 0 and standard deviation of 1 across maturities, thus alleviating the magnitude issue.

[18] The variable $Purch_{i,t}$ is in fact the daily purchase intensity, which will be discussed in the data section. Moreover, the BOJ's purchases are less likely to be endogenous as the amount of monthly purchases is preannounced.

[19] We also estimate equation (1) by adding $S_{i,t-1}$ as a separate explanatory variable to control for the "stock effect" for robustness check (see the subsection on robustness in Section V).

(continued…)

(VI) has been widely used to measure investors' risk aversion in Japan. Moreover, the S&P/JPX JGB VIX Index, which measures the implied volatility of JGBs calculated from options on JGB futures, is also used as an alternative measure of risk aversion in Japan, but does not change the main results qualitatively. The second type of control variables include a number of dummies to control for the announcement effects of QQE in April 2013, QQE2 in October 2014, NIRP in January 2016, and YCC in September 2016. For example, the dummy of QQE equals 1 from the announcement day of QQE to three months after that, and equals 0 elsewhere. Moreover, a dummy is included to control for the level effects of the U.S. election in November 2016, which triggered some volatility in the JGB markets.[20] Finally, for maturity-level regressions, another dummy is included to control for the level effects of GFC during 2008–09.[21]

24. Model (1) implies that the effects of the BOJ's outright purchases on JGB market liquidity can be expressed as a linear function:

$$\frac{\partial(L_{i,t})}{\partial(Purch_{i,t})} = \beta_1 + \beta_2 S_{i,t-1},$$

Since the Corwin-Schultz measure $L_{i,t}$ is an illiquidity measure, a scenario where $\beta_1 + \beta_2 S_{i,t-1} > 0$ would suggest a negative impact of the BOJ's purchases on JGB market liquidity and hence support Hypothesis 1. This scenario could result from three possible cases of model (1): i) $\beta_1 > 0$ and $\beta_2 = 0$, ii) $\beta_1 = 0$ and $\beta_2 > 0$, and iii) $\beta_1 > 0$ and $\beta_2 > 0$. In other words, if the estimates of β_1 and β_2 fall into any of the three cases, then there is evidence of scarcity effects at the given significance level. Moreover, Hypothesis 2 can be statistically tested in model (1) by testing $\beta_2 > 0$, which, if not rejected, also suggests that the flow effects depend on the level of stock.

25. An alternative model is a fixed-effects *threshold* panel regression model with the measure of JGB scarcity as the threshold variable. Another possibility consistent with Hypothesis (1) is that the effects of the BOJ's purchases on market liquidity are—instead of a linear function of the measure of JGB scarcity—a constant, the value of which depends on whether the scarcity of JGBs exceeds a certain threshold. This suggests a fixed-effects threshold panel regression model with the share of JGBs held by the BOJ as the threshold variable:[22]

[20] The regression results are broadly robust to the assumed length of effective window of the dummies (3 months). Changing the window to 1 month or 5 months does not alter our main results qualitatively.

[21] The sample period of bond-level regressions starts from January 31, 2012, and hence does not cover the GFC.

[22] S* is the threshold to be estimated, and there could be more than one threshold identified by the regressions. See Hansen (1999) for the theoretical background of the threshold non-dynamic panel regressions. We also estimate equation (1) by adding $S_{i,t-1}$ as a separate explanatory variable to control for the "stock effect" for robustness check (see the subsection on robustness in Section V).

$$\begin{cases} L_{i,t} = \alpha_0 + \delta_i + \alpha_1 Purch_{i,t} + \alpha_3 S_{i,t-1} + \alpha_4 SLF_{i,t-1} + \alpha_5 X_t + \varepsilon_{i,t}, & \text{if } S_{i,t-1} \leq S^* \\ L_{i,t} = \alpha_0 + \delta_i + \alpha_2 Purch_{i,t} + \alpha_3 S_{i,t-1} + \alpha_4 SLF_{i,t-1} + \alpha_5 X_t + \varepsilon_{i,t}, & \text{if } S_{i,t-1} > S^* \end{cases} \quad (2)$$

In model (2), the lagged value of SLF, $SLF_{i,t-1}$, is used to mitigate the endogeneity issue of contemporaneous SLF discussed before. The effects of the BOJ's outright purchases on JGB market liquidity can be written as:

$$\begin{cases} \frac{\partial(L_{i,t})}{\partial(Purch_{i,t})} = \alpha_1, & \text{if } S_{i,t-1} < S^* \\ \frac{\partial(L_{i,t})}{\partial(Purch_{i,t})} = \alpha_2, & \text{if } S_{i,t-1} \geq S^* \end{cases}$$

Unlike in model (1), both Hypotheses 1 and 2 can be statistically tested in this threshold panel regression model (2) by testing $\alpha_2 > 0$. In other words, as long as the BOJ's purchases reduce JGB market liquidity when the share of its holdings exceeds the threshold S^*, Hypothesis 2 would hold and the scarcity effects would have existed.[23] Model (2) is estimated by the threshold regression method developed by Hansen (1999) for non-dynamic panels with fixed effects. Apparently, model (2) also implies that the flow effects depend on the level of stock.

26. Models (1) and (2) are estimated at both bond and maturity levels to obtain robust results. The bond-level data consist of all the bond-level JGBs with the original maturity of 2, 5, 10, 20, 30, or 40 years, spanning from January 31, 2012 to February 28, 2017.[24] The maturity-level data consist of only on-the-run JGBs with the same original maturities but with a longer sample period, spanning from December 29, 2006 to January 20, 2017. Since on-the-run JGBs "age" and become "off the run" issues which are typically less liquid over time, we use the on-the-run issue for each date point. In other words, the specific on-the-run issues could be different for different date points. The estimates from maturity-level regressions may provide some insights for the market liquidity of on-the-run JGBs although they might be less precise than those from the bond-level regressions due to the limited cross-section variations (only six original maturities). In this context, the maturity-level regressions may also be less subject to the endogeneity concern in the bond-level regressions that the JGBs purchased by the BOJ are more likely to be off-the-run issues and hence less liquid—because dealers may want to sell their less liquid issues to the BOJ first.

27. Since the observations are likely to be subject to cross-section correlations and autocorrelations in model (1), the Driscoll-Kraay and two-way cluster robust standard errors are also computed in addition to the White robust standard errors. We first

[23] The main difference between the two models is that model (1) implies a faster deterioration in market liquidity as the BOJ's purchases continue once the share of the BOJ's holdings passes the threshold.

[24] Bond-level data are not available prior to 2012 because the amount outstanding of each bond cannot be calculated as the buybacks of the Ministry of Finance from the BOJ or private sector are not available.

estimate the White robust standard errors for the fixed-effects panel regression model (1) as a comparison basis. However, since bonds with the same maturity or even different maturities could be substitutes for each other and liquidity could spill over from one asset class to another, the market liquidity of different bonds are likely to be correlated (IMF, 2015). As a result, the observations could be subject to both cross-section and over-time correlations. To deal with the potential bias from these correlations, we compute the Driscoll-Kraay standard error, which was developed by Driscoll and Kraay (1998) and is robust to heteroskedasticity, autocorrelation, and cross-section dependence. Since the bonds with the same maturity could potentially have the strongest cross-section and over-time correlations, we also use the two-way cluster robust standard error with clustering by maturity and time to estimate model (1).

28. Models (1) and (2) are also estimated for a subsample with 2-10 year JGBs. Considering the importance of 2-10 year JGBs for banks and the real economy, we also estimate the two models using 2-10 year JGBs—in addition to using all the JGBs in the full sample—to examine whether the effects of the BOJ's purchases on JGB market liquidity, if any, may be different for this particular segment of maturities. Moreover, the yields of 2-10 year JGBs are also the main target of the BOJ's YCC framework.

B. Data

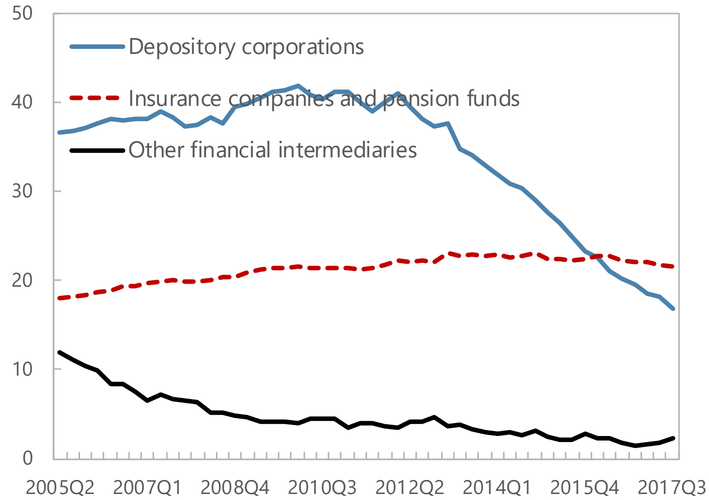
29. One key variable in the empirical analysis is a measure of the scarcity of JGBs in the market at the bond level. Ideally, we would like to have a measure of the excess demand for each JGB as a measure of scarcity. However, such excess demand is not observable. Since the JGB holdings by the long-term investors are not typically traded, a second-best measure is the amount of each JGB left for trading in the market after taking out the holdings by the BOJ and long-term institutional investors (such as life insurers and pension funds). However, it is difficult to construct such a measure due to the lack of bond-level holdings data of the long-term investors.

30. Instead, we use the share of each JGB issue held by the BOJ to approximate the degree of scarcity. The share of domestic government debt securities held by the long-term investors—most of which are long-term JGBs—is relatively stable compared to the shares held by depository corporations or other financial intermediaries (Figure 11). This suggests that the share of each JGB issue held by the BOJ may serve as a good proxy to measure the bond-level scarcity of JGBs in the market. This measure is directly linked with QQE, and a higher value of the measure corresponds to a higher degree of scarcity.

31. The share of each JGB issue held by the BOJ is calculated by dividing the BOJ's holdings of each issue by the amount outstanding of that issue. JGBs held by the BOJ are published by the BOJ at the bond level on a 10-day basis since April 30, 2014 and on a monthly basis between January 2012 and March 2014.[25] These holdings are evaluated at the face value. Therefore, the BOJ's purchases can be simply calculated as the amount that was purchased by the BOJ over the period between two holding dates.[26] However, the number of days between two holding dates are not constant—depending on when the BOJ publishes such data, and the average distance is about 10 days. Therefore, we calculate the daily purchase intensity, i.e., the purchases between the two holding dates divided by the number of days between them. We also normalize the purchase intensity of each issue by the total amount outstanding of that issue to control for—to some extent—the effects (if any) of new issuances.

Figure 11. Holdings of Domestic Government Debt Securities: By Type of Financial Institutions

(In percent of total amount issued)



Sources: Bank of Japan; and IMF staff calculations.

32. The amount outstanding of each JGB issue is computed based on the issuance data from the Japanese Ministry of Finance (MOF) on a face-value basis. The issuances via both regular auctions and the liquidity-enhancing auctions are taken into account. With the issuance dates and maturity dates, we can calculate the amount outstanding of each JGB issue at every date point. In addition, the MOF has bought back certain JGB issues from the BOJ during our sample period, and the amount of these buybacks are deducted from the

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[25] Since April 30, 2014, the JGBs held by the BOJ are published every 10 days on average. Staff of the BOJ kindly collected and provided such data of the BOJ's holdings to the authors for this research in the context of the IMF's 2017 FSAP for Japan.

[26] The holding dates are defined as the dates when the BOJ's share of holdings is available or published. By calculating the BOJ's purchases in this way, we implicitly use net purchases that exclude matured bonds—rather than gross purchases—in the empirical analysis.

(continued…)

amount outstanding of each corresponding JGB issue.[27] Since the bond-level amount outstanding is only available after 2012 due to the availability of data on buybacks, we compute the maturity-level amount outstanding using data from Bloomberg, L.P. which can extend our maturity-level dataset back to December 29, 2006.

33. The amount of SLF operations by the BOJ is also used to control the effect of the lending program on JGB market liquidity. One of the purposes of SLF is to alleviate the pressure on JGB market liquidity when market liquidity is low—by offering the market with JGBs in a temporary manner (mainly through repo transactions) to reduce the scarcity of JGBs in the market. Due to the endogeneity problem mentioned before, we use the lagged value of SLF as an instrumental variable in the panel regressions with robust standard errors or two-way cluster robust standard errors. However, the lagged value of SLF is used directly in the regressions with the Driscoll-Kraay standard errors as instrumental variables are currently not allowed in the Driscoll-Kraay estimation.

V. Results

A. Maturity-Level Fixed-Effects Panel Regressions

34. Result from the maturity-level regressions tend to suggest a negative impact of the BOJ's outright purchases on the market liquidity of 2-10 year JGBs. The main results are presented in Appendix III, Table 1 and seem to be broadly consistent with Hypothesis (1). In particular, columns 2-4 show the results using the full sample with the White robust, Driscoll-Kraay, and two-way cluster robust standard errors, respectively. Although the estimates of β_2 in model (1) across all the three columns are statistically insignificant, the signs of these estimates are all positive—in line with our expectation. However, columns 5-7 show that the estimates of β_2 for the subsample of 2-10 year JGBs (medium- to long-term JGBs) are likely to be significantly positive. This finding supports Hypothesis 2 and hence provides evidence for the scarcity effects (i.e., Hypothesis 1), although the magnitudes tend to be larger than those when the full sample is used.

35. Moreover, the maturity-level results for 2-10 year JGBs seem to be consistent with the theoretical prediction of a U-shaped relationship between JGB market liquidity and the share of the BOJ's holdings. Columns 5-7 in Appendix III, Table 1 also show that the estimates of β_1 in model (1) are significantly negative when the subsample of 2-10 year JGBs is used. This result, together with the significantly positive estimate of β_2 for the subsample, suggests that the BOJ's outright purchases tightened the Corwin-Schultz bid-ask spreads when the share of the BOJ's holdings was small, but widened them when the holdings exceeded some threshold—implying a U-shaped relationship between JGB market (il)liquidity and the share of the BOJ's holdings. However, since the number of cross-section maturities is very limited for the maturity-level panel regressions, the estimates could be less

[27] Staff of the MOF kindly provided the authors with the data of the amount of issuances for each JGB issue and the MOF's buybacks from the BOJ since 2012 in the context of the IMF's 2017 FSAP for Japan.

precise than those from the bond-level panel regressions. Therefore, we only discuss the magnitudes of the scarcity effects for bond-level panel regressions in the next sub-section.

36. **The maturity-level results also suggest significant deteriorations in JGB market liquidity across all maturities during the GFC and after the announcement of the NIRP in January 2016.** These findings have also been documented by previous studies. For example, IMF (2015) found that most asset markets in advanced economies such as the corporate bond market in the U.S. and sovereign bond markets in Europe experienced declines in market liquidity during the GFC period. In addition, BOJ (2017) computed the liquidity indicators in the JGB markets constructed from transaction data, most of which showed a deterioration in JGB market liquidity following the BOJ's announcement of the NIRP (Figure 6). Moreover, the U.S. election in November 2016 also seems to be associated with some declines in market liquidity for both the full sample and the subsample, with a larger impact for the latter.

B. Bond-Level Fixed-Effects Panel Regressions

37. **Results from the bond-level fixed-effects panel regressions lend support to both Hypotheses 1 and 2.** The main results from bond-level regressions are presented in Appendix III, Tables 2. Columns 2-4 show the results using the full sample with the three different standard errors, respectively. The results point to a significantly negative flow effect of the BOJ's purchases on JGB market liquidity, as the estimate of β_2 is significantly positive across all the three different standard errors—different from those in the maturity-level regressions with all JGBs. In addition, scarcity effects are also found for the 2-10 year JGBs as the estimate of β_2 for the subsample is also significantly positive as shown in columns 5-7. Moreover, the U-shaped relationship between market liquidity and the BOJ's share of holdings is also found in the bond-level regressions, as the estimates of β_1 are mostly significantly negative when either the full sample or the subsample is used. Finally, the results suggest that the market liquidity—in both the full sample and the subsample of 2-10 year JGBs—declined significantly after each of the three key monetary policy announcements by the BOJ, i.e., QQE, QQE2, and NIRP. Finally, there is some evidence that the announcement of YCC improved market liquidity while the U.S. election in November 2016 reduced market liquidity, although neither of which is statistically significant.

38. **Although the magnitude of the impact of an individual BOJ purchase on JGB market liquidity is quite modest, the cumulative effect may not be negligible.** In particular, a one-percentage-point increase in the purchase intensity could raise the Corwin-Schultz bid-ask spread by about 0.3 standard deviations based on the estimates of the regression with the full sample and the two-way cluster robust standard error, given that the average share of the BOJ's holdings is about 40 percent. Although this one-time impact seems small, the cumulative effect may not be negligible. For example, when QQE was expanded in October 2014, the BOJ's purchase increased by about 0.3 percent of total amount outstanding for an average JGB issue over a 10-day period. If such an increase continues for three months from now when the share of the BOJ's holdings is about 40

percent, then the cumulative effect on the Corwin-Schultz bid-ask spread is about 1.2 standard deviations by the end of the three months. This deterioration in the level of market liquidity could potentially increase the likelihood of “flash-crash”-type scenarios.

C. Fixed-Effects Threshold Panel Regressions

39. The fixed-effects threshold panel regressions using maturity-level data produce similar results as those from the non-threshold maturity-level regressions, albeit with less statistical significance. The results of threshold panel regressions are presented in Appendix III, Table 3. Columns 2, 4, and 6 show the results using the full sample and the two subsamples of maturity-level data, respectively. The signs of the estimated coefficients all imply a U-shaped relationship between market liquidity and the central bank’s purchases with a positive turning point, i.e., $\beta_1 < 0$ and $\beta_2 > 0$—although some of the estimates are not statistically significant. Moreover, the results also suggest that JGB market liquidity likely declined during the GFC, after the announcement of NIRP, and after the U.S. election in November 2016—the first two of which are also found in the non-threshold maturity-level regressions.

40. Results from the fixed-effects threshold regressions tend to support a V-shaped relationship between market liquidity and the BOJ’s holdings, albeit with less statistical significance. The maturity-level results are presented in columns 2 and 4 in Appendix III, Table 3, and those from bond-level regressions are presented in the other columns. The estimates of α_1 are all statistically significant when either the full sample or the subsample is used, in line with our prediction. Although the estimates of α_2 in the maturity-level regressions are not statistically significant, the estimate in the bond-level regression with the full sample is significantly positive, lending support to both Hypotheses 1 and 2.

41. The magnitude of the effects of the BOJ’s purchases on JGB market liquidity is broadly comparable with that in the bond-level non-threshold panel regressions. In particular, a one-percentage-point increase in the daily purchase intensity could increase the Corwin-Schultz bid-ask spread by about 0.4 standard deviations based on the estimates of the regression with the full sample. Therefore, in the example discussed above where the purchases of an average JGB issue increase by 0.3 percent of total amount outstanding every 10 days for three months from now when the share of the BOJ’s holdings is about 40 percent, then the Corwin-Schultz bid-ask spread will increase by about one standard deviation by the end of the three months.

42. The bond-level threshold regressions also suggest that JGB market liquidity deteriorated after the announcements of QQE, QQE2, and NIRP, but improved after the announcement of YCC. In particular, the first three announcements all had a significantly adverse impact on market liquidity, with the largest impact coming from QQE. In contrast, the announcement of YCC seems to have improved JGB market liquidity to some extent—in line with the recent developments in the BOJ’s liquidity indicators after the adoption of YCC (BOJ, 2017)—although such an improvement is statistically insignificant for 2-10 year JGBs.

D. The Role of SLF

43. **There are signs that the SLF by the BOJ may have helped dampen the scarcity effects of the BOJ's purchases on JGB market liquidity to some extent**. The bond-level fixed-effects panel model (1) does not find a significant impact of the SLF on JGB market liquidity (Appendix III, Table 2). However, this result could be biased due to the fact that the counterfactuals without the SLF cannot be directly observed, despite the use of lagged SLF as an instrumental variable. To better explore the effectiveness of the SLF, we estimate the same bond-level fixed-effects panel regression model (1) separately with the sample when the SLF did not take place and with the rest of the sample when the SLF took place. The results with the full sample are presented in columns 2–4 in Appendix III, Tables 4 and 5, respectively. We find that the estimates of the coefficient of the interaction term, β_2, is mostly significantly positive when the SLF was not conducted, but statistically insignificant when the SLF was conducted in all three regressions. This suggests that the SLF, when conducted, seems to have helped reduce the adverse effects of the purchases on market liquidity. The finding also broadly holds for the subsample of 2-10 year JGBs as presented in columns 5-7 in Appendix III, Tables 4 and 5.

E. Robustness

44. **The baseline results are robust when time fixed effects are used in lieu of the macro-level variables.** It is worth highlighting that some other macro-level factors may have also affected market liquidity during the sample period. For example, regulatory changes could also affect market liquidity through its impact on market-making activities, as argued by IMF (2015). Moreover, the broad-based shift away from trading in cash markets and into futures markets in the wake of QE has also likely exasperated the lack of liquidity in cash markets. Therefore, to control for these macro-level changes over time, we replace the macro-level announcement dummies and Nikkei VI by time fixed effects in the baseline model (1). Table 1 presents the main results with time fixed effects for the full sample in both maturity- and bond-level regressions (columns 3 and 5). For comparison purpose, we also include the baseline results with two-way cluster robust standard errors in Table 1 (columns 2 and 4). The estimates of β_1 and β_2 from both the maturity- and bond-level regressions are all statistically significant with expected signs, lending support to Hypotheses 1 and 2.

45. **However, the findings of this paper should be interpreted with caution for a few reasons.** First, market liquidity has many dimensions such as cost, quantity, and time (IMF, 2015), or tightness, depth, and resiliency (Kurosaki and others, 2015). Although the Corwin-Schultz measure of market liquidity is constructed using transaction prices, it only captures the cost or tightness dimension of market liquidity but not the others. Second, some of the results, particularly the effects of policy announcements, vary across the choice of model and sample. Third, the effects of the SLF may still be subject to endogeneity concerns despite the

use of lagged values as an instrument. Last but not least, the findings should only be interpreted as a potential side effect of QQE and should not be interpreted as indicating that QQE is ineffective. In fact, JGB yields have declined significantly after the introduction of QQE—suggesting that QQE has been overall effective in pushing down interest rates—despite the concern that lower liquidity in the JGB market may lead to higher liquidity risk premia.

Table 1. Key Results of Fixed-Effects (FE) Panel Regressions 1/

Dependent variable	Corwin-Schultz measure (standardized by mean and standard deviation)			
	Maturity-Level		Bond-Level	
Estimation method	FE with two-way clustering by maturity and time	FE with both maturity and time fixed effects	FE with two-way clustering by maturity and time	FE with both bond and time fixed effects
$Pur_{i,t}^{BoJ}$ 2/	-0.58 (1.63)	-2.54*** (0.93)	-0.28 (0.22)	-0.25*** (0.07)
$Pur_{i,t}^{BoJ} \cdot S_{i,t-1}^{BoJ}$ 3/	1.48 (3.40)	5.74*** (2.22)	0.83** (0.35)	0.45** (0.20)
$S_{i,t-1}^{BoJ}$	-0.55 (0.47)	-1.03 (1.12)	-1.62** (0.66)	-1.21*** (0.20)
$SLF_{i,t}$ 4/	222.68*** (74.49)	18.05 (147.03)	-0.005 (0.01)	0.002 (0.003)
$log(VIX_t^{Nikkei})$	0.12 (0.21)	—	0.11 (0.20)	—
$Dum(GFC)$	0.87*** (0.19)	—	—	—
$Dum(QQE)$	0.14 (0.28)	—	0.84*** (0.33)	—
$Dum(QQE2)$	0.03 (0.28)	—	0.21** (0.09)	—
$Dum(NIRP)$	0.91*** (0.29)	—	0.66*** (0.20)	—
$Dum(YCC)$	0.23 (0.17)	—	-0.15 (0.13)	—
$Dum(US)$	0.87** (0.36)	—	0.19 (0.18)	—
$Constant$	—	-0.12 (0.19)	—	0.69*** (0.08)
# obs.	1,086	1,110	38,893	38,895
# groups	6	6	456	458
Maturity/bond FEs	Yes	Yes	Yes	Yes
Time FEs	No	Yes	No	Yes
Clustering by	Maturity and time	—	Maturity and time	—
Overall-R^2	0.13	0.55	0.08	0.29

1/ The sample periods for the maturity- and bond-level FE panel regressions are December 29, 2006–January 20, 2017 and January 31, 2012–February 28, 2017, respectively.
2/ $Pur_{i,t}^{BoJ}$ denotes the daily average of BoJ's outright purchases of bond *i* (normalized by the total amount outstanding of that bond).
3/ $S_{i,t-1}^{BoJ}$ denotes the lagged value of BoJ's holdings of bond *i* as a share of the total amount outstanding of that bond.
4/ $SLF_{i,t}$ denotes the daily average of SLF for bond *i* (normalized by the total amount outstanding of that bond), and is instrumented by its lagged value in the FE with robust s.e. and FE with two-way cluster-robust s.e.
Note: *, **, and *** denote statistical significance at the 10 percent, 5 percent, and 1 percent levels, respectively.

VI. CONCLUDING REMARKS

46. Using bond-level data of the JGB market, this paper finds strong evidence of the scarcity (flow) effects of QE on market liquidity. In particular, using the estimated bid-ask spread developed by Corwin and Schultz (2012) as the measure of liquidity in the JGB cash market, we build both regular fixed-effects panel regression and fixed-effects threshold panel regression models to estimate the effects of QQE on the level of JGB market liquidity. Each of the two models is estimated using both maturity-level (on-the-run JGBs) and bond-level data. The results suggest that the BOJ's outright purchases had significantly adverse (flow) effects on the liquidity in the JGB market. This finding also holds for the subsample of 2-10 year JGBs. Moreover, it is also robust to the use of different types of standard errors and the use of time fixed effects in both maturity- and bond-level regressions (i.e., for both on-the-run and overall JGBs). However, we should reiterate the caveat highlighted above that the finding should only be interpreted as a potential side effect of QQE and should by no means be interpreted as suggesting that QQE is ineffective.

47. This paper also finds some evidence that the scarcity (flow) effects depend on the share of the BOJ's holdings (stock). The bond-level regressions find that QQE first improved the JGB market liquidity when the BOJ's holdings are relatively small—such positive effects could come from the bank funding channel, the risk appetite channel, or the trade facilitating channel—but reduced market liquidity when the share of the BOJ's holdings exceeded certain thresholds. This result suggests that the flow effects may also depend on the stock of the BOJ's holdings. Moreover, results of the bond-level panel regressions suggest that the liquidity in JGB markets seems to have declined after the announcements of QQE, QQE2, and NIRP, but have improved somewhat after the implementation of YCC—albeit with less statistical significance.[28]

48. Moreover, this paper sheds some light on the effectiveness of the BOJ's SLF program. By estimating the bond-level panel regression model separately for the sample when the SLF was conducted and the rest of the sample when the SLF was not conducted, we find that the BOJ's purchases had a significantly negative impact on JGB market liquidity when the SLF was not conducted, but mostly an insignificant impact when the SLF was

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[28] This result should be interpreted with caution and only as the announcement effect on the cost dimension of market liquidity. In particular, although the BOJ's purchases of JGBs have dropped significantly since introduction of YCC in September 2016, concerns remain around the lower price volatility and depth of market liquidity according to market participants. While the Corwin-Schultz bid-ask spread used in this paper has narrowed due to the lower price volatility since the introduction of YCC, some other measures of market liquidity, particularly the depth dimension of market liquidity, showed no signs of improvement. For example, the turnover ratio in the JGB market remains low and the lending fee in the repo market remains high even after the YCC. Moreover, according to some market participants, the liquidity has deteriorated after the YCC due to decreasing investment opportunities and trading volume caused by the lower price volatility. In this regard, a full evaluation of the effects of YCC on market liquidity, particularly the depth dimension of market liquidity, is warranted for future research.

conducted. This finding suggests that the SLF may have helped dampen the scarcity effects of QQE to some extent.

49. These findings could have important policy implications. First, central banks that have implemented QE programs should continue to monitor closely the developments in the liquidity of the securities that have been purchased by the central banks, and the signals of potential scarcity for these securities (e.g., an increased use of SLF by private financial institutions or higher fails in repo transactions). Second, central banks should also closely monitor its holdings of each security as a share of the total (or tradable) amount outstanding, and adjust its purchases accordingly to avoid creating substantial scarcity of certain securities in the market. This is particularly important for monetary operations when QE policies have started to or are about to normalize. Last but not least, in times of stress, central banks could continue to provide securities lending facilities to the market to temporarily alleviate the pressure on market liquidity.

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APPENDIX I. MARKET LIQUIDITY: CONCEPT AND MEASUREMENT

Market liquidity is the ability to rapidly buy or sell a sizable volume of securities at a low cost and with a limited price impact (IMF, 2015). The level of market liquidity is important to the efficient transfer of funds from savers to borrowers and hence to the functioning of financial markets. The concept of market liquidity is different from those of funding liquidity (the ease with which market participants can obtain funding) and monetary liquidity (or central bank liquidity which typically refers to monetary aggregates). However, these three different concepts of liquidity are interconnected. The ability for market makers to provide market liquidity depends on their availability of funding (Brunnermeier and Pederson, 2009). Conversely, market liquidity tends to enhance funding liquidity because traders' funding, i.e., their capital and margin requirements, depends on the ease with which assets can be sold (Foucault and others, 2013). Moreover, a higher level of monetary liquidity from monetary policy easing relaxes funding conditions for banks, which in turn can facilitate market-making activities. However, the relationship among these three concepts of liquidity is not one-to-one and could be nonlinear in certain circumstances (IMF, 2015).

The level of market liquidity has many dimensions and cannot be captured by a single measure. IMF (2015) classifies the measures of market liquidity into three dimensions, i.e., cost, quantity, and time. Some other literature (e.g., Kurosaki and others, 2015) characterizes market liquidity by three other dimensions from a different angel, i.e., tightness, depth, and resiliency. However, regardless of which classification one uses, every measure has its advantages and disadvantages, and cannot capture all the dimensions of market liquidity. Some measures, such as the Corwin-Schultz bid-ask spreads (the measure used in this paper), effective spreads (actual or estimated), and imputed "round-trip costs", only capture the cost and tightness dimensions. Some other measures, such as quote depth, dealer depth, and the volume of limit orders at the best-ask price, capture the quantity and depth dimensions. Others such as the Amihud (2002)'s price impact measure capture the cost and resiliency dimensions.[29]

[29] Some commonly used measures can be misleading. For the cost dimension, quoted bid-ask spreads that are not based on actual transactions may not reflect the actual costs of trades. For the quantity dimension, market turnover is a widely available quantity measure whose high values during market turmoil are often used to indicate high liquidity even though transactions have a large price impact at such times (i.e., market liquidity is low).

APPENDIX II. CALCULATION OF THE CORWIN-SCHULTZ BID-ASK SPREADS

A. Methodology

We estimate the bid-ask spreads using the methodology developed by Corwin and Schultz (2012), where the spreads (*S*) are estimated using two-day high and low prices of Japanese government bonds and bills as a nonlinear function, where:

$$S = \frac{2(e^{\alpha} - 1)}{1 + e^{\alpha}}$$

α is defined as $\frac{\sqrt{2\beta} - \sqrt{\beta}}{3 - 2\sqrt{2}} - \sqrt{\frac{\gamma}{3 - 2\sqrt{2}}}$,
β is defined as $\ln(H_t/L_t)^2 + \ln(H_{t+1}/L_{t+1})^2$,
γ is defined as $\left[ln\left(\frac{H_{t,t+1}}{L_{t,t+1}}\right)\right]^2$,
H is the daily high price of the security,
L is the daily low price of the security, and
t stands for time (in days).

In line with Corwin and Schultz (2012), we assign a zero value to estimated high-low spreads that are less than zero (i.e. negative values); negative values could particularly occur in the presence of large price fluctuations where the 2-day variance in the prices may exceed the single-day variance. Subsequently, monthly spreads are calculated by averaging all two-day trading periods within a calendar month.

B. Data

Daily high (H) and low (L) price data are btained from Bloomberg Finance L.P. for Japanese government bonds (JGBs) at all available maturity levels. The underlying securities are selected and obtained using Bloomberg Finance L.P.'s fixed income search (SRCH) function. Our sample selection criteria include both currently active and inactive JGB securities at all maturities and excludes the securities that have already been funged into another security to avoid double counting of bonds (see Appendix II, Table 1 for data coverage).

Appendix II. Table 1. Data Coverage—Number of JGB and JTDB Securities by Issuance Year and Tenor

Tenor	Issuance year			
	1983-89	1990-99	2000-09	2010-17
0	0	0	60	467
1	0	0	17	128
2	0	73	120	87
4	0	34	6	0
5	0	0	96	48
6	0	33	3	0
10	50	111	93	43
15	4	0	41	0
20	13	36	76	49
30	0	1	30	25
40	0	0	2	8
Total	67	288	544	855

Sources: Bloomberg Finance L.P.; and IMF staff.

C. Estimated Corwin-Schultz Bid-Ask Spreads

Upon obtaining daily data of high and low prices for the securities in the sample, we estimate bid-ask spreads using the Corwin-Schultz methodology at bond-level. We then average the estimated bid-ask spreads of each bond within a calendar month to obtain the bid-ask spreads at monthly frequency (see Appendix II, Table 2 for the summary statistics by tenor and Appendix II, Figure 1 for the average bid-ask spread estimates for JGBs by tenor). Additionally, we also estimate the bid-ask spreads for on-the-run bonds that are defined as the most recently issued JGB securities at each tenor (estimated bid-ask spreads for the on-the-run JGBs by tenor are shown in Appendix II, Figure 2).[30]

Appendix II. Table 2. Summary Statistics by Tenor—Bond-level High-Low Spreads based on Corwin and Schultz (2012)

(In percent)

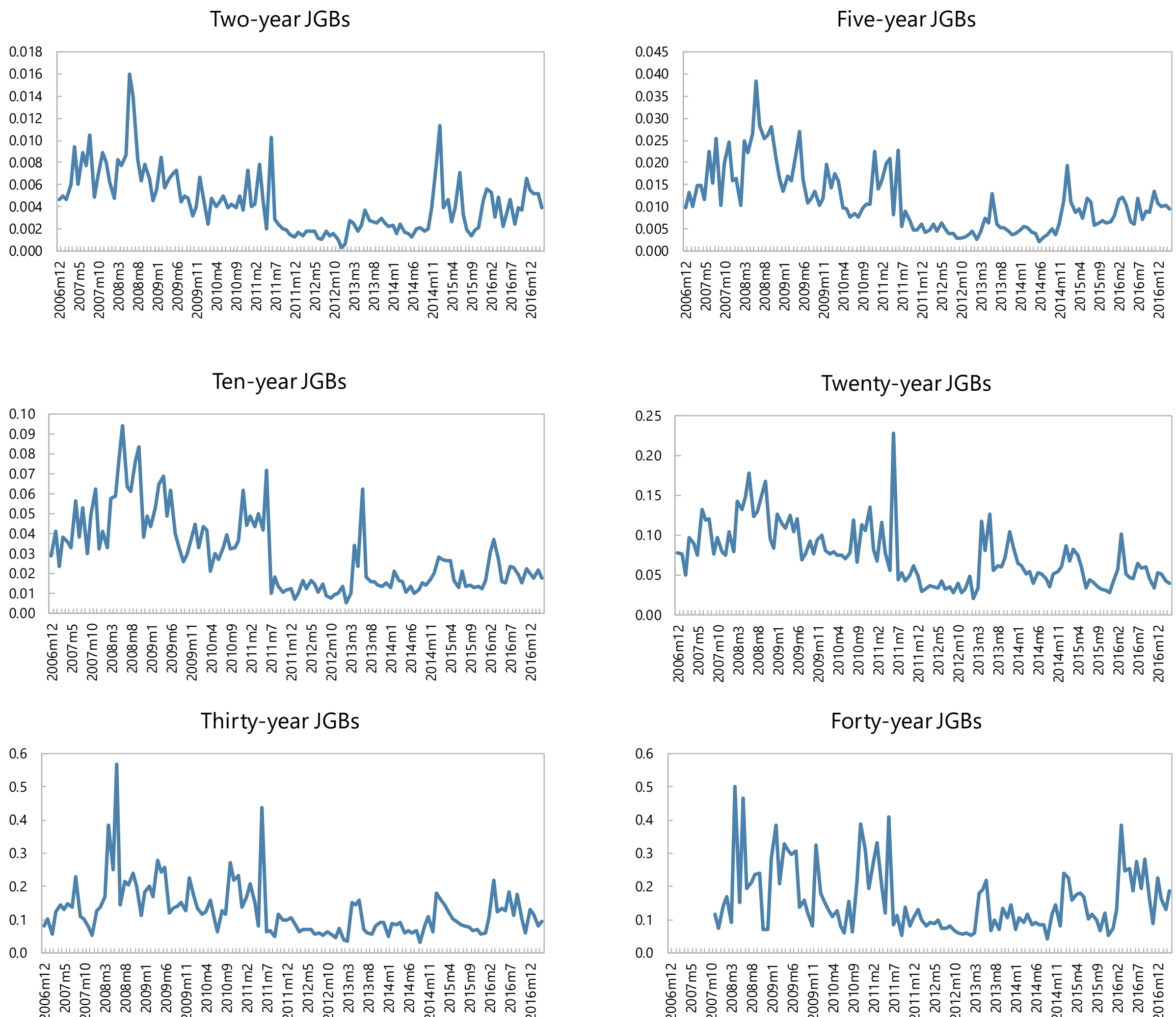
Tenor	Mean	Median	High	Low	Standard Deviation
			2010		
0	0.000	0.000	0.000	0.000	0.000
1	0.000	0.000	0.001	0.000	0.000
2	0.004	0.005	0.011	0.000	0.003
5	0.013	0.011	0.048	0.000	0.012
10	0.037	0.028	0.113	0.000	0.032
20	0.092	0.106	0.201	0.000	0.048
30	0.156	0.154	0.221	0.132	0.021
40	0.170	0.167	0.187	0.157	0.016
			2016		
0	0.001	0.000	0.011	0.000	0.002
1	0.002	0.001	0.009	0.000	0.003
2	0.005	0.004	0.015	0.000	0.004
5	0.009	0.011	0.022	0.000	0.007
10	0.022	0.022	0.050	0.000	0.015
20	0.055	0.054	0.144	0.000	0.031
30	0.131	0.119	0.203	0.073	0.037
40	0.209	0.212	0.230	0.195	0.011
			2017		
0	0.001	0.001	0.006	0.000	0.001
1	0.004	0.003	0.011	0.000	0.004
2	0.005	0.005	0.011	0.000	0.003
5	0.010	0.012	0.023	0.000	0.006
10	0.019	0.021	0.055	0.000	0.011
20	0.045	0.041	0.094	0.000	0.025
30	0.099	0.091	0.153	0.050	0.025
40	0.144	0.154	0.178	0.000	0.051

Sources: Bloomberg Finance L.P.; and IMF staff estimates.

[30] Due to data limitations, our sample starts only in December 2006. Although the measure for on-the-run JGBs are higher than that for all JGBs for some maturities, it does not mean that on-the-run JGBs are less liquid. In fact, this is mainly due to the replacement of missing values by zero as recommended by Corwin and Schultz (2012). Without such replacement, the measure for on-the-run JGBs would be lower than that for all JGBs.

Appendix II. Figure 1. Average Corwin-Schultz Bid-Ask Spreads

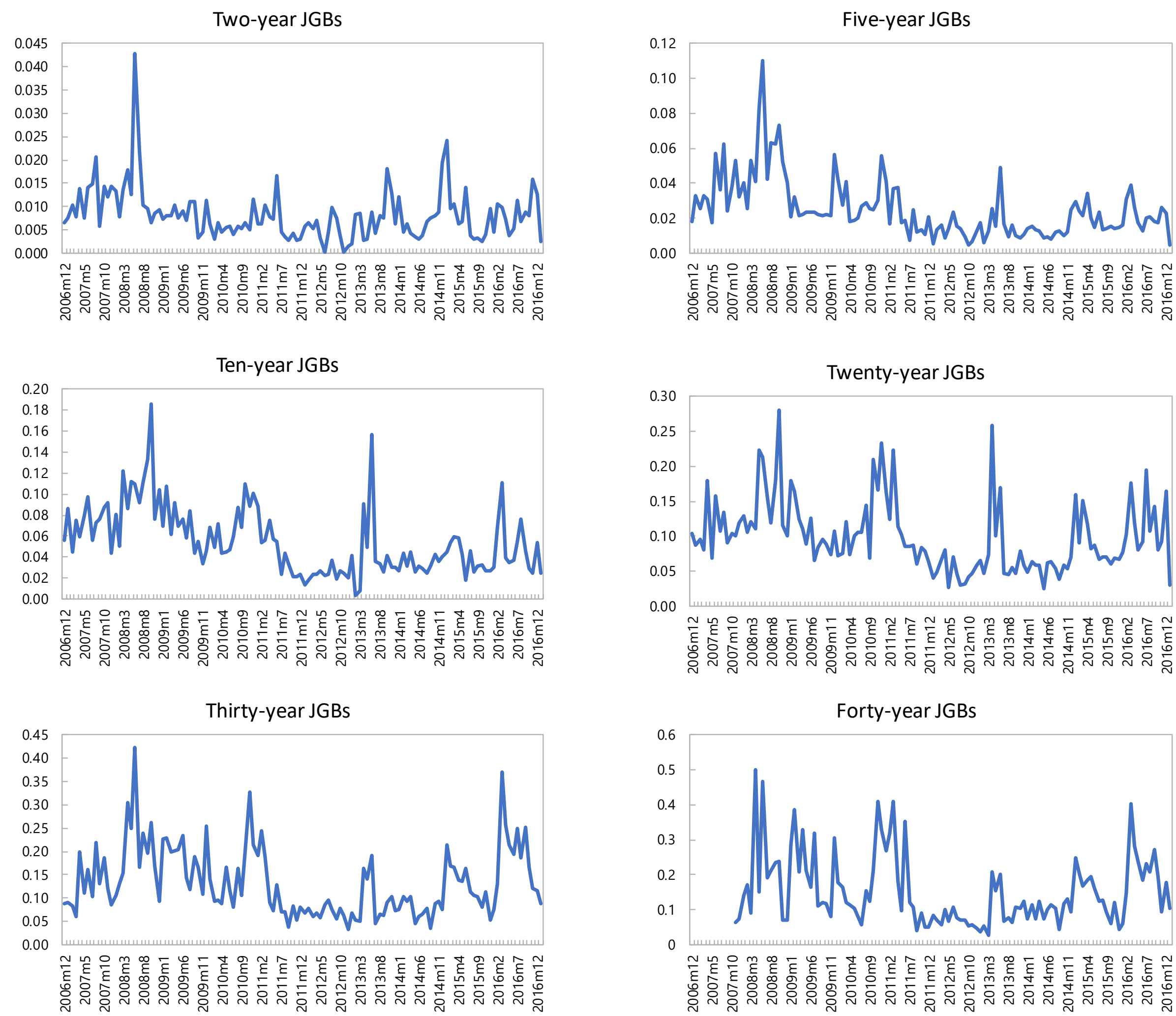
(In percent)



Sources: Bloomberg Finance L.P.; and IMF staff estimates.

Appendix II. Figure 2. Corwin-Schultz Bid-Ask Spreads for On-the-Run JGBs

(In percent)



Sources: Bloomberg Finance L.P.; and IMF staff estimates.

APPENDIX III. RESULTS OF PANEL REGRESSIONS

Appendix III. Table 1. Results of Maturity-Level Fixed-Effects Panel Regressions 1/

Dependent variable	Corwin-Schultz measure (standardized by mean and standard deviation)					
	All JGBs			2-10 year JGBs		
Estimation method	FE with robust s.e.	FE with Driscoll-Kraay s.e.	FE with two-way clustering	FE with robust s.e.	FE with Driscoll-Kraay s.e.	FE with two-way clustering
$Pur_{i,t}^{BoJ}$ 2/	-0.58	-0.85	-0.58	-3.07**	-3.49	-3.07**
	(1.56)	(2.30)	(1.63)	(1.24)	(2.59)	(1.30)
$Pur_{i,t}^{BoJ} \cdot S_{i,t-1}^{BoJ}$ 3/	1.48	2.22	1.48	6.42*	7.56	6.42*
	(3.07)	(5.00)	(3.40)	(3.48)	(5.62)	(3.48)
$S_{i,t-1}^{BoJ}$	-0.55	-0.36	-0.55	-1.11**	-0.84	-1.11**
	(0.44)	(0.67)	(0.47)	(0.52)	(0.63)	(0.46)
$SLF_{i,t}$ 4/	222.68***	86.99**	222.68***	346.52	93.39	346.52
	(71.12)	(35.08)	(74.49)	(362.70)	(58.18)	(308.59)
$log(VIX_t^{Nikkei})$	0.12	0.12	0.12	0.05	0.05	0.05
	(0.15)	(0.20)	(0.21)	(0.20)	(0.22)	(0.19)
$Dum(GFC)$	0.87***	0.87***	0.87***	0.94***	0.96**	0.94***
	(0.09)	(0.34)	(0.19)	(0.10)	(0.47)	(0.20)
$Dum(QQE)$	0.14	0.14	0.14	0.23	0.22	0.23
	(0.10)	(0.24)	(0.28)	(0.22)	(0.21)	(0.27)
$Dum(QQE2)$	0.03	0.02	0.03	0.48	0.44**	0.48
	(0.33)	(0.12)	(0.28)	(0.51)	(0.20)	(0.41)
$Dum(NIRP)$	0.91***	0.96***	0.91***	1.11***	1.13***	1.11***
	(0.18)	(0.21)	(0.29)	(0.24)	(0.23)	(0.19)
$Dum(YCC)$	0.23	0.21	0.23	0.20	0.20	0.20
	(0.21)	(0.13)	(0.17)	(0.36)	(0.25)	(0.30)
$Dum(US)$	0.87***	0.88***	0.87**	1.06***	1.16***	1.06***
	(0.24)	(0.19)	(0.36)	(0.39)	(0.19)	(0.36)
$Constant$	-0.52	-0.51	—	-0.14	-0.19	—
	(0.46)	(0.68)		(0.55)	(0.72)	
# obs.	1,086	1,086	1,086	549	549	549
# groups	6	6	6	3	3	3
Clustering by	—	—	Maturity and time	—	—	Maturity and time
Overall-R^2	0.13	0.15	0.13	0.20	0.20	0.20

1/ The sample period is December 29, 2006–January 20, 2017. Eight lags of the dependent variable and the lagged value of $SLF_{i,t}$ are used in the FE regressions with Driscoll-Kraay standard error.
2/ $Pur_{i,t}^{BoJ}$ denotes the daily average of BoJ's outright purchases for maturity *i* (normalized by the total amount outstanding of that maturity).
3/ $S_{i,t-1}^{BoJ}$ denotes the lagged value of BoJ's holdings of maturity *i* as a share of total amount outstanding of that maturity.
4/ $SLF_{i,t}$ denotes the daily average of SLF for maturity *i* (normalized by the total amount outstanding of that maturity), and is instrumented by its lagged value in the FE with robust s.e. and FE with two-way cluster-robust s.e. Moreover, $SLF_{i,t}$ was dropped in FE with two-way cluster-robust s.e. for 20-40 year JGBs as its instrument has little variation over time.
Note: *, **, and *** denote statistical significance at the 10-, 5-, and 1-percent levels, respectively.

Appendix III. Table 2. Results of Bond-Level Fixed-Effects Panel Regressions 1/

Dependent variable	Corwin-Schultz measure (standardized by mean and standard deviation)					
	All JGBs			2-10 year JGBs		
Estimation method	FE with robust s.e.	FE with Driscoll-Kraay s.e.	FE with two-way clustering	FE with robust s.e.	FE with Driscoll-Kraay s.e.	FE with two-way clustering
$Pur_{i,t}^{BoJ}$ 2/	-0.28***	-0.25*	-0.28	-0.58***	-0.58***	-0.58***
	(0.08)	(0.15)	(0.22)	(0.10)	(0.20)	(0.16)
$Pur_{i,t}^{BoJ} \cdot S_{i,t-1}^{BoJ}$ 3/	0.83***	0.67**	0.83**	1.22***	1.23***	1.22***
	(0.26)	(0.29)	(0.35)	(0.26)	(0.29)	(0.23)
$S_{i,t-1}^{BoJ}$	-1.62***	-1.62***	-1.62**	-2.53***	-2.53***	-2.53***
	(0.18)	(0.48)	(0.66)	(0.20)	(0.61)	(0.36)
$SLF_{i,t}$ 4/	-0.005	0.001	-0.005	0.0004	-0.0001	0.0004
	(0.01)	(0.001)	(0.01)	(0.002)	(0.001)	(0.002)
$log(VIX_t^{Nikkei})$	0.11***	0.11	0.11	0.17***	0.17	0.17
	(0.03)	(0.22)	(0.20)	(0.04)	(0.27)	(0.14)
$Dum(QQE)$	0.84***	0.83***	0.84***	0.83***	0.83***	0.83***
	(0.05)	(0.28)	(0.33)	(0.08)	(0.28)	(0.32)
$Dum(QQE2)$	0.21***	0.21**	0.21**	0.33***	0.33**	0.33**
	(0.03)	(0.10)	(0.09)	(0.04)	(0.15)	(0.17)
$Dum(NIRP)$	0.66***	0.66***	0.66***	0.44***	0.44***	0.44***
	(0.04)	(0.17)	(0.20)	(0.06)	(0.14)	(0.17)
$Dum(YCC)$	-0.15***	-0.15	-0.15	-0.08**	-0.08	-0.08
	(0.02)	(0.10)	(0.13)	(0.04)	(0.18)	(0.20)
$Dum(US)$	0.19***	0.19*	0.19	0.35***	0.35	0.35
	(0.03)	(0.11)	(0.18)	(0.05)	(0.22)	(0.26)
$Constant$	-0.05	-0.05	—	0.15	0.15	—
	(0.11)	(0.70)		(0.12)	(0.87)	
# obs.	38,895	38,895	38,893	16,273	16,273	16,271
# groups	458	458	456	256	256	254
Clustering by	—	—	Maturity and time	—	—	Maturity and time
Overall-R^2	0.04	0.08	0.08	0.04	0.12	0.12

1/ The sample period is January 31, 2012–February 28, 2017. Eight lags of the dependent variable and the lagged value of $SLF_{i,t}$ are used in the FE regressions with Driscoll-Kraay standard error.
2/ $Pur_{i,t}^{BoJ}$ denotes the daily average of BoJ's outright purchases of bond *i* (normalized by the total amount outstanding of that bond).
3/ $S_{i,t-1}^{BoJ}$ denotes the lagged value of BoJ's holdings of bond *i* as a share of the total amount outstanding of that bond.
4/ $SLF_{i,t}$ denotes the daily average of SLF for bond *i* (normalized by the total amount outstanding of that bond), and is instrumented by its lagged value in the FE with robust s.e. and FE with two-way cluster-robust s.e.
Note: *, **, and *** denote statistical significance at the 10%, 5%, and 1% levels, respectively.

Appendix III. Table 3. Results of Bond-Level Fixed-Effects Threshold Panel Regressions 1/

Dependent variable	Corwin-Schultz measure (standardized by mean and standard deviation)			
Estimation method	Fixed-Effects Threshold Panel Regression			
	All JGBs		2-10 year JGBs	
	Maturity-Level	Bond-Level	Maturity-Level	Bond-Level
$Pur_{i,t}^{BoJ} \cdot 1(S_{i,t-1}^{BoJ} \leq S^{*})$ 2/ 3/	-19.08***	-1.53***	-10.89***	-4.54***
	(5.49)	(0.55)	(2.50)	(1.34)
$Pur_{i,t}^{BoJ} \cdot 1(S_{i,t-1}^{BoJ} > S^{*})$	0.36	0.35***	0.36	0.42
	(0.58)	(0.13)	(0.59)	(0.31)
$S_{i,t-1}^{BoJ}$	0.10	-0.70***	-1.04***	-2.50***
	(0.29)	(0.13)	(0.31)	(0.20)
$SLF_{i,t-1}$ 4/	80.22**	0.002	90.41	0.01
	(36.98)	(0.01)	(70.61)	(0.01)
$log(VIX_{t}^{Nikkei})$	0.15	-0.01	0.04	0.19***
	(0.13)	(0.04)	(0.17)	(0.07)
$Dum(GFC)$	0.98***	—	0.87***	—
	(0.11)		(0.15)	
$Dum(QQE)$	0.30*	1.21***	0.33	1.84***
	(0.16)	(0.03)	(0.22)	(0.07)
$Dum(QQE2)$	0.04	0.28***	0.42*	0.35***
	(0.16)	(0.03)	(0.22)	(0.06)
$Dum(NIRP)$	0.93***	0.79***	1.11***	0.46***
	(0.17)	(0.03)	(0.23)	(0.07)
$Dum(YCC)$	0.19	-0.23***	0.20	-0.08
	(0.17)	(0.03)	(0.23)	(0.06)
$Dum(US)$	0.85***	0.05	1.15***	0.26***
	(0.18)	(0.03)	(0.25)	(0.07)
$Constant$	-0.76*	0.07	-0.05	-0.21
	(0.42)	(0.11)	(0.54)	(0.22)
Estimated *threshold* (S^{*})	0.05	0.05	0.25	0.05
# obs.	1026	22,446	549	4644
# groups	6	174	3	36
Overall-R^2	0.18	0.09	0.23	0.20

1/ The sample periods for the maturity- and bond-level FE panel regressions are December 29, 2006–January 20, 2017 and January 31, 2012–February 28, 2017, respectively.
2/ $Pur_{i,t}^{BoJ}$ denotes the daily average of BoJ's outright purchases of maturity *i* (normalized by the total amount outstanding of that maturity).
3/ $1(\cdot)$ denotes the indicator function, which equals 1 if the argument is true and 0 otherwise. $S_{i,t-1}^{BoJ}$ denotes the lagged value of BoJ's holdings of maturity *i* as a share of the total amount outstanding of that maturity.
4/ The lagged value of $SLF_{i,t}$ is used to mitigate the endogeneity issue.
Note: *, **, and *** denote statistical significance at the 10 percent, 5 percent, and 1 percent levels, respectively.

Appendix III. Table 4. Results of Bond-Level Fixed-Effects Panel Regressions: Without SLF 1/

Dependent variable	Corwin-Schultz measure (standardized by mean and standard deviation)					
	All JGBs			2-10 year JGBs		
Estimation method	FE with robust s.e.	FE with Driscoll-Kraay s.e.	FE with two-way clustering	FE with robust s.e.	FE with Driscoll-Kraay s.e.	FE with two-way clustering
$Pur_{i,t}^{BoJ}$ 2/	-0.26*** (0.09)	-0.26* (0.15)	-0.26 (0.21)	-0.56*** (0.10)	-0.56*** (0.20)	-0.56*** (0.13)
$Pur_{i,t}^{BoJ} \cdot S_{i,t-1}^{BoJ}$ 3/	0.61** (0.28)	0.61** (0.29)	0.61 (0.42)	1.14*** (0.30)	1.14*** (0.30)	1.14*** (0.28)
$S_{i,t-1}^{BoJ}$	-1.61*** (0.18)	-1.61*** (0.49)	-1.61** (0.66)	-2.52*** (0.20)	-2.52*** (0.62)	-2.52*** (0.36)
$log(VIX_t^{Nikkei})$	0.12*** (0.03)	0.12 (0.22)	0.12 (0.20)	0.19*** (0.04)	0.19 (0.27)	0.19 (0.14)
$Dum(QQE)$	0.83*** (0.05)	0.83*** (0.28)	0.83*** (0.32)	0.81*** (0.08)	0.81*** (0.28)	0.81*** (0.31)
$Dum(QQE2)$	0.22*** (0.03)	0.22** (0.10)	0.22** (0.09)	0.33*** (0.04)	0.33** (0.15)	0.33** (0.17)
$Dum(NIRP)$	0.65*** (0.04)	0.65*** (0.17)	0.65*** (0.20)	0.41*** (0.06)	0.41*** (0.15)	0.41** (0.16)
$Dum(YCC)$	-0.14*** (0.02)	-0.14 (0.10)	-0.14 (0.13)	-0.06 (0.04)	-0.06 (0.18)	-0.06 (0.20)
$Dum(US)$	0.20*** (0.03)	0.20* (0.11)	0.20 (0.18)	0.41*** (0.05)	0.41* (0.23)	0.41 (0.27)
$Constant$	-0.07 (0.11)	-0.07 (0.71)	—	0.09 (0.12)	0.09 (0.88)	—
# obs.	37,921	37,921	37,919	15,633	15,633	15,631
# groups	457	457	455	255	255	253
Clustering by	—	—	Maturity and time	—	—	Maturity and time
Overall-R^2	0.04	0.07	0.07	0.04	0.12	0.12

1/ The sample includes the dates and bonds that did not have SLF operations during January 31, 2012–February 28, 2017. Eight lags of the dependent variable and the lagged value of $SLF_{i,t}$ are used in the FE regressions with Driscoll-Kraay standard error.
2/ $Pur_{i,t}^{BoJ}$ denotes the daily average of BoJ's outright purchases of bond *i* (normalized by the total amount outstanding of that bond).
3/ $S_{i,t-1}^{BoJ}$ denotes the lagged value of BoJ's holdings of bond *i* as a share of the total amount outstanding of that bond.
Note: *, **, and *** denote statistical significance at the 10 percent, 5 percent and 1 percent levels, respectively.

Appendix III. Table 5. Results of Bond-Level Fixed-Effects Panel Regressions: With SLF 1/

Dependent variable	Corwin-Schultz measure (standardized by mean and standard deviation)					
	All JGBs			2-10 year JGBs		
Estimation method	FE with robust s.e.	FE with Driscoll-Kraay s.e.	FE with two-way clustering	FE with robust s.e.	FE with Driscoll-Kraay s.e.	FE with two-way clustering
$Pur_{i,t}^{BoJ}$ 2/	-0.32	-0.35	-0.32	-1.37	-1.23***	-1.37**
	(0.39)	(0.27)	(0.43)	(0.88)	(0.35)	(0.63)
$Pur_{i,t}^{BoJ} \cdot S_{i,t-1}^{BoJ}$ 3/	0.71	1.03	0.71	3.38	2.14***	3.38
	(1.31)	(0.65)	(1.02)	(3.09)	(0.44)	(2.83)
$S_{i,t-1}^{BoJ}$	-2.10***	-2.02***	-2.10***	-2.66***	-2.90***	-2.66***
	(0.67)	(0.70)	(0.80)	(0.76)	(0.85)	(0.67)
$SLF_{i,t}$ 4/	0.002	0.001	0.002	-0.01	-0.003	-0.01
	(0.01)	(0.004)	(0.01)	(0.01)	(0.002)	(0.01)
$log(VIX_t^{Nikkei})$	0.03	0.02	0.03	-0.13	-0.12	-0.13
	(0.20)	(0.20)	(0.27)	(0.24)	(0.27)	(0.27)
$Dum(QQE)$	1.62**	1.62**	1.62**	1.65**	1.65**	1.65***
	(0.70)	(0.70)	(0.73)	(0.81)	(0.64)	(0.16)
$Dum(QQE2)$	-0.11	-0.11	-0.11	-0.02	0.02	-0.02
	(0.25)	(0.19)	(0.27)	(0.22)	(0.20)	(0.18)
$Dum(NIRP)$	0.91***	0.92***	0.91***	1.01***	0.97***	1.01***
	(0.18)	(0.14)	(0.18)	(0.21)	(0.14)	(0.16)
$Dum(YCC)$	-0.24**	-0.24***	-0.24*	-0.28***	-0.29***	-0.28**
	(0.10)	(0.08)	(0.14)	(0.10)	(0.09)	(0.12)
$Dum(US)$	-0.06	-0.05	-0.06	-0.02	-0.03	-0.02
	(0.10)	(0.12)	(0.17)	(0.11)	(0.15)	(0.16)
$Constant$	0.60	0.60	—	1.49*	1.56	—
	(0.71)	(0.67)		(0.86)	(1.05)	
# obs.	974	974	920	640	640	618
# groups	246	246	192	136	136	114
Clustering by	—	—	Maturity and time	—	—	Maturity and time
Overall-R^2	0.06	0.14	0.14	0.05	0.19	0.15

1/ The sample includes the dates and bonds that had SLF operations during January 31, 2012–February 28, 2017. Eight lags of the dependent variable and the lagged value of $SLF_{i,t}$ are used in the FE regressions with Driscoll-Kraay standard error.
2/ $Pur_{i,t}^{BoJ}$ denotes the daily average of BoJ's outright purchases of bond *i* (normalized by the total amount outstanding of that bond).
3/ $S_{i,t-1}^{BoJ}$ denotes the lagged value of BoJ's holdings of bond *i* as a share of the total amount outstanding of that bond.
4/ $SLF_{i,t}$ denotes the daily average of SLF for bond *i* (normalized by the total amount outstanding of that bond), and is instrumented by its lagged value in the FE with robust s.e. and FE with two-way cluster-robust s.e.
Note: *, **, and *** denote statistical significance at the 10 percent, 5 percent and 1 percent levels, respectively.