Scarcity and Spotlight Effects on Liquidity and Yield: Quantitative Easing in Japan

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Abstract

We investigate the determinants of the term structures of market liquidity and bond yield of the Japanese Government Bond (JGB) market in the context of the quantitative easing (QE) programs implemented by the Bank of Japan (BoJ) in recent years. We distinguish between two opposing effects of QE on the liquidity of JGBs, the "scarcity effect," which is *gradually* manifested as a negative impact on liquidity, due to the shrinkage in the available supply of bonds; and the "spotlight effect," which induces an *immediate* improvement in the liquidity of targeted bonds, reflecting BOJ's massive demand. Between 2011 and 2016, we find that JGBs exhibited an improvement in liquidity through the spotlight effect, but also experienced a deterioration in liquidity through the scarcity effect. As for bond yields, both the spotlight and scarcity effects worked in the *same* direction (i.e., they both raised (reduced) bond prices (yields), as expected). However, despite the illiquidity caused by the scarcity induced by the purchases, this yield decline is amplified rather than being muted, despite the elevated illiquidity premium.

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1 Introduction

Since the global financial crisis in 2008, the major central banks of the world have engaged in unconventional monetary policy in the form of quantitative easing (QE) programs to stimulate their economies. These policies have been particularly evident in Japan, where the Bank of Japan (BoJ) has been implementing a substantial Large Scale Asset Purchase (LSAP) program by purchasing several assets, including Japanese government bonds (JGBs), shares of real estate investment trusts (REITs), and even equity exchange-traded funds (ETFs), with the objective of stimulating the economy through a reduction in interest rates and, more broadly, the cost of capital in the economy. The BoJ's holding of JGBs reached 437 trillion yen in June 2017 – which corresponds to about 81% of Japan's nominal gross domestic product – while its average holding ratio of sovereign debt, across JGBs, jumped from 10% to 40.3% during this period, unprecedented in the annals of central bank history.[1] Predictably, these programs had an ameliorative effect on bond yields in the JGB market, as has been widely noted.[2] However, they have also had an impact on market liquidity (i.e., the ability of market participants to buy and sell reasonable amounts of bonds with minimal price impact) that has not been fully explored, thus far, and even the available evidence is less than consistent.[3]

The preferred habitat theory proposed by Modigliani and Sutch (1966), Vayanos and Vila (2009), Greenwood and Vayanos (2014), and D'Amico and King (2013), among many others, identifies two main channels through which central banks purchase affects bond yield: The flow (or spotlight) effect and the stock (or scarcity) effects. The scarcity effect is due to the long term effect of the reduction of the bond supply that generates a local supply effect, and the theory predicts that the QE programs would push down yields

[1]The amount outstanding in the JGB market was 1,087 trillion yen, compared to that in US Treasury market, which was about 2,300 trillion yen (23trillion US dollars) in 2017. Throughout this paper, the yen-dollar exchange rate is taken to be 100 yen to the dollar, although there was some fluctuations around this level over time. According to the Japan Securities Dealers Association, the JGB trading volume was 9.1 trillion yen to 19.8 trillion yen per day during our sample period, while the US Treasury trading volume was about 55 trillion yen to 60 trillion yen (around 550 billion US dollars) per day according to the Securities Industry and Financial Markets Association.

[2]The accumulated evidence suggests that the programs had significant short-term effects on targeted and other bond yields in the United States (as documented by Krishnamurthy and Vissing-Jorgensen, 2011; Gagnon, Raskin, Remache and Sack, 2011; Swanson, 2017), in the United Kingdom (Kapetanios, Mumtaz, Stevens and Theodoridis, 2012; Joyce, McLaren and Young, 2012a; McLaren, Banerjee and Latto, 2014; Meaning and Warren, 2015), the Euro area (Altavilla, Carboni and Motto, 2015; Altavilla, Canova and Ciccarelli, 2016; Andrade, Breckenfelder, De Fiore, Karadi and Tristani, 2016; Blattner and Joyce, 2016; Eser and Schwaab, 2016) and in Sweden (De Rezende, 2017; De Rezende and Ristiniemi, 2018).

[3]Some papers point to increased liquidity (e.g., Christensen and Gillan, 2013; De Pooter, Martin and Pruitt, 2015), while others document declining liquidity, or increased scarcity (e.g., Kandrac, 2013; Coroneo, 2015; Schlepper, Riordan, Hofer and Schrimpf, 2017). Schlepper et al. (2017), among others, is an exception, who provide concrete evidence of the scarcity impact on market liquidity.

with a persistent increase in price. In contrast, the flow effect is more short term, and is related to the amount purchased in the market on a given day. It is closely related to portfolio rebalancing activity due to the outcomes of the purchases, and the resultant impairment in liquidity and market functioning that lead to sluggish price discovery (as discussed in D'Amico and King (2013)).[4]

These two channels also affect market liquidity differentially. The flow effect, represented by the amount purchased in a certain day, should stimulate trading. In fact, since cash is not a perfect substitute for bonds by investors, they are likely to seek to reinvest some of the proceeds of their sales in other instruments. In addition, as noted by some market participants, the presence of a "back-stop buyer" makes dealers more willing to hold larger bond inventories, which facilitates market-making and, therefore, improves liquidity. On the other hand, the scarcity effect induced due to the stock of bonds held by the BoJ, leads to a reduction in the quantity of bonds held by private investors. This, in turn, could make it more difficult for dealers to source specific bonds in the secondary market; hence, they face a larger risk of holding a short position due to the reduction in the float of bonds that become increasingly scarce and more difficult to borrow in the repo market.[5] Moreover, asset purchases by a price-insensitive central bank might distort price signals, reducing the willingness of market participants to trade. Therefore, the effect of QE on market liquidity has two opposing effects that have different immediate impacts and persistence. A related aspect that is largely ignored in the literature is the "spotlight effect," which induces an immediate increase in the price and a reduction of the yield as well as an improvement in liquidity, arising from the attention focused on individual bonds selected by an aggressive purchaser (the central bank). In fact, each purchase operation provides trading opportunities and makes it easier for bond holders to sell their holdings of bonds to dealers. The demand from the BoJ increases competition among dealers which, in turn, leads to a tightening of the bid–ask spread. However, the spotlight effect could have also the opposite effect. The inclusion of a bond in the target list might induce traders to buy the bond in order to hold it eventually for the next auction or because they would avoid the potential scarcity later on when BoJ would actually buy it. Therefore, the inclusion of a bond on the list may be accompanied by a reversal in the liquidity improvement immediately after the event, due to a sort of "hoarding" of the bond. In contrast, for the impact of QE on the yields, both greater

[4]D'Amico and King (2013) also predict that the reduction in the yield through a duration effect occurs because the removal of longer-duration bonds from the market; the central bank's purchases shorten the aggregate duration of the remaining bonds and, hence, reduces the term premiums on the remaining longer-dated securities.

[5]A similar argument has been developed in a theoretical model by Ferdinandusse et al. (2018), to justify an increase in the cost of market-making (Kandrac, 2014).

attention or hoarding would both generate an increase of the price and a reduction of the yield, unambiguously.

These three effects have different time dimensions. Stock-based scarcity is more of a long run effect, while the flow-based impact that arises from the purchase and the spotlight effect related to the inclusion of a certain bond on the list of the target bonds are more short term in nature. Given that the first two effects have opposing impacts on liquidity and the third one (the spotlight effect) has uncertain effects on market liquidity, it is natural to conjecture that this would result in a sort of U-shaped relationship of liquidity with QE policies: with a significant improvement due to the flow and eventually the spotlight effect on liquidity, initially, and then an eventual reduction, due to the scarcity effect. In any case, the net effect of these three channels is not obvious from a theoretical perspective, and only a detailed empirical analysis can help us disentangle the effects from the three channels and shed light on this issue.

Another aspect that should not be ignored is that, theoretically, higher illiquidity should be compensated by a higher liquidity premium (Amihud and Mendelson (1986, 1991)). While the spotlight effect garners attention to particular bonds, their illiquidity is also elevated through the scarcity created by the purchases. This diminution in liquidity should, therefore, adversely affect the bond yield as a consequence. This is the point that papers in the literature, such as D'Amico and King (2013), have largely ignored. According to the Amihud and Mendelson (1986) argument, the positive effect of large-scale bond purchases by the central bank should be, at least partially, nullified by the negative effect arising through the decline in liquidity resulting from a reduction in the "free float" of these bonds (i.e., the bonds available for trading in the market). The consideration of the three effects we highlighted above and the indirect effect that liquidity might have on the bond yield in the long run may imply that the net effect of these channels is theoretically ambiguous and is likely to depend on the structure of the market and the design of the asset purchase program. Further, these effects have a term structure dimension both for yield and liquidity. Thus, the QE intervention of the BoJ created both a scarcity effect and a spotlight effect, which have opposing impacts on the entire term structure of bond yields and liquidity; which of the three effects dominates is an open question that can only be addressed empirically, on both a bond-by-bond basis and a period-by-period basis, which is our central objective in this paper.

The BoJ was the first major central bank to move toward introducing QE, way back in 2001. This was accentuated after the global financial crisis in 2008, when the BoJ, along with other major global central banks, employed aggressive measures to stimulate the economy.[6] The BoJ's Comprehensive Monetary Easing (CE) program was first implemented in 2010 but was expanded in the scale of purchases several times since then: The total size of the program was 35 trillion yen at the initiation of the program and it gradually increased thereafter, reaching 101 trillion yen by the end of 2012. The Quantitative and Qualitative Easing (QQE) program started in April 2013, and received a further impetus under BoJ Governor Haruhiko Kuroda. The bond purchase program was approximately doubled to 50 trillion yen (about 500 billion US dollars) per year, and further increased to 80 trillion yen (about 800 billion US dollars) per year since October 2014. The first and second halves of the QQE period differ in terms of the amounts of purchases involved, as well as the maturities targeted, which provides a natural experiment to determine how the supply and the maturity structure affect the liquidity across bonds and across maturities.

These QE programs were implemented by a reverse auction mechanism similar to that used by the Fed in its QE auctions and the Bank of England (see Joyce and Tong (2012), Song and Zhu (2016)). For each purchase operation, the BoJ announced the total amount and the maturity buckets of the JGBs to be purchased. Following the auction, the results were disclosed only to dealers who submitted successful offers. This information is then disclosed by the BoJ ten days to one month later. The amount purchased in each auction thus represents the flow, i.e., the amount purchased in the market on a given day The spotlight effect created by the LSAP arises because the BoJ repeatedly announced the target list of the bonds it would purchase 90 minutes before the auction. Such an action created unique trading opportunities for bonds on the target list for dealers and other investors. Hence, the inclusion of a bond, especially an off-the-run bond, in the BoJ's target list drew keen attention from bond dealers and investors, resulting in potentially positive effects for bond prices and liquidity. On the other side, as we argued before, it might generate instead an hoarding effect. Thus, the spotlight effect has an immediate impact on the price and liquidity of individual government bonds, and is conceptually different from the broad signaling effect of the QE announcement, because it is caused not only by general policy intervention but also by the interaction between the central bank's actions and dealer reactions in each purchase operation.

With regard to the scarcity effect, we consider the BoJ's relative holding ratio of a bond as a proxy for the deteriorating effect on liquidity throughout subsequent periods. It is important to stress that, most of the other central banks have been at much lower levels of their sovereign bond holdings. The BoJ is, by far, the highest at 40.3% by June 2017, with no sign of a reduction in the near future. Further, there is substantial

[6] Figure 1 shows the time line for the implementation of the BoJ's QE programs.

variation in the holdings across bonds, with one bond in our sample for which the central bank's holding ratio was as high as 78.9% of the outstanding amount. Given the cross-sectional and time-series variation in central bank holdings, we have a fairly wide range of observations and are able to observe at least part of the full U-shape in the relationship of liquidity as a function of holdings. The BoJ purchased a wide array of bonds and increased its ownership ratio so that the resultant scarcity increased the illiquidity of the bonds: the more of a bond the BoJ holds, the larger the bond's illiquidity as measured by the bid–ask spread.

We begin by conducting a univariate analysis across variables that compares the change in liquidity across the different interventions, and then performing an econometric analysis, similar to Friewald et al. (2012).[7] First, we conduct an analysis of market liquidity by performing a cross-sectional analysis with time-fixed effects on the daily bid–ask spreads (used as a proxy for liquidity) to identify the spotlight and scarcity effects. Second, we investigate the impact of the BoJ's purchases on bond yields, using the same approach.[8]

We find that, initially, the BoJ intervention improved liquidity in the CE period and, therefore, the spotlight effect prevailed. However, in the subsequent interventions (the QQE period), the scarcity effect dominated and liquidity reduced significantly. The cross-sectional panel regression aims to investigate the roles of the spotlight and scarcity effects across the different periods and across the different bonds. In order to capture the spotlight effect on liquidity, we consider the actual purchases in the *previous* purchase operation. We find, indeed, that a spotlight effect on liquidity is associated with the actual purchases in the most recent LSAP operation. We find that the coefficients of the holding ratio are significant and positive across specifications, indicating that larger BoJ holdings increased the bid–ask spread, thus worsening liquidity. In summary, we confirm that the spotlight effect from the LSAP improved bond liquidity by narrowing the bid–ask spread, but scarcity measured by the BoJ's holding ratio lead to a deterioration in liquidity in the latter QQE programs, thus leading to two opposing effects of the BoJ intervention on market liquidity resulting in a U-shaped pattern of the liquidity over time.

Next, we look at the impact on bond yield resulting from the QE operations and investigate its relation to the spotlight and scarcity effects discussed earlier. The spotlight effect arises from the strong demand for the broad range of JGBs. The yields (prices) of bonds on the target list, as expected, fall (rise). In the cross-sectional analysis of yields,

[7] Friewald et al. (2012) use Fama–MacBeth cross-sectional regressions, but we apply a time-fixed-effects model for our cross-sectional analysis.

[8] Additionally, we conduct similar analyses with weekly data, presented in the Appendix, as a robustness check, to confirm that the errors in the daily data do not swamp the underlying economic influences.

a dummy variable for the targeted bond is associated with lower yields, and a variable that captures scarcity also pushes yield down (and prices up). According to Amihud and Mendelson (1991), the degree of illiquidity should be a discounting factor for the bond price. Our results suggest, however, that the level of the yield is more influenced by demand factors induced by the LSAP than the illiquidity created by the purchases, and hence the net effect is that yields go down. This suggests that the central bank's objective for the LSAP (i.e., the reduction of interest rate levels) is achieved even though it is accompanied by the concomitant increase in the illiquidity of the bonds created by the purchases.

We further explore the change in liquidity by dividing our sample into three distinct bond-life stages. This bond-life stage concept – essentially related to whether a bond is on-the-run, off-the-run, and older ones – is an essential element for understanding the differential effects on liquidity and yield caused by the LSAPs. We show that the effect of the LSAP on liquidity is heterogeneous among the different bond categories, with the oldest bonds showing an improvement in liquidity, and the youngest a deterioration instead. Overall, our results suggest that the aggressive QE conducted by the central bank gradually decreased the attractiveness of investment in JGBs for institutional investors such as pension funds and mutual funds, in terms of both bond yields and market liquidity: not only did the QE lead to lower yields, it also raised the illiquidity of government bond transactions.

Our paper makes several contributions. First, it is the earliest, to our knowledge, to explicitly address the spotlight effect created by the LSAP. Second, it is one of the few to investigate how the scarcity of net available bonds affects bond market illiquidity.[9] Third, we explore the effects of the LSAPs on a bond-by-bond basis, categorized by the three bond-life stages we identify. This bond-life stage concept is an essential element for understanding the differential effects on liquidity and yield caused by the LSAPs.

The remainder of this paper is organized as follows. Section 2 reviews the literature. Section 3 presents a short history of the BoJ's LSAP programs. Section 4 describes the hypotheses we test and Section 5 presents our data and descriptive statistics. Sections 6 and 7 report the main results of our empirical estimations on market liquidity and bond yield, respectively. Section 8 concludes the paper.

[9]As is intuitively reasonable, the greater the scarcity, the larger the bid–ask spread, which is the *opposite* of the findings of earlier studies, such as that of Iwatsubo and Taishi (2017). In their study, the BoJ's LSAPs actually *improve* liquidity because the authors do not include periods in which the scarcity e ぱね l ffect exceeds the spotlight effect, and their estimation does not clearly distinguish between the scarcity and the spotlight effects.

2 Literature

The theoretical literature on the effect of QE interventions on the term structure of interest rates, led by Vayanos and Vila (2009) and D'Amico et al. (2012), refers largely to three channels through which such policies can affect longer-term interest rates. The first channel, dubbed the local supply channel, arises due to scarcity: the central bank's purchase of assets with a specific maturity reduces the availability of such bonds and leads to higher prices of securities with similar maturities. The second channel is through duration risk, as the central bank's purchase of long-term securities reduces the average duration of the remaining bonds available for the portfolios of investors – shrinking the available supply of long-term bonds – and thus lowers the term premium, the level of long-term bond yields relative to short-term yields. The third channel is attributable to the signaling or the expectations channel, through which the central bank alerts the market of its future purchases. Vayanos and Vila (2009) model the supply shock affecting the bond yields through the actions of risk-averse arbitrageurs: when a central bank purchases bonds with specific maturities, it creates a supply shock for the market, and the bond yield changes as a result of arbitrageurs' carry trade.

The local scarcity channel implies that a change in the supply of bonds in a specific sector or of a certain maturity can differentially affect the yields of those bonds, and bonds with similar, but not identical, characteristics. Empirical studies based on the Vayanos and Vila's (2009) framework have been carried out by Greenwood and Vayanos (2010), D'Amico et al. (2012), and D'Amico and King (2013), for example. Greenwood and Vayanos (2014) empirically examine how the supply and maturity structure of government debt affect bond yields and expected returns. To evaluate the effect of purchases by the Fed, Cahill et al. (2013) measure the impact on the Treasury yields of five Federal Open Market Committee announcements of the Treasury purchase program. They focus on both the duration risk premium and the local supply effects on the bond yield on the day of the program announcement and the next day, and conduct a comparative study of the five programs using intraday CUSIP-level data. Song and Zhu (2016) also use intraday CUSIP-level data to measure the Fed's "cost" for each auction. They define the cost as the price difference between the auction offer price and the secondary market traded price, and identify three factors, such as bond cheapness, value uncertainty, and scarcity, that affect the Fed's total cost. The liquidity premium is attributed to the yield difference between equivalent securities with different levels of liquidity. In a similar vein, Amihud and Mendelson (1991) find a significant yield differential between Treasury notes and Treasury bills with the same residual time to maturity. This evidence indicates that the liquidity differences affect bond pricing. By the time Treasury notes approach maturity, they have already been locked away in investors' portfolios and a large part of each issue is not readily available in the market. This "lock-in proportion" is, in fact, typically excluded from the free float of bonds. Krishnamurthy (2002) studies the price difference between on-the-run and the most recent off-the-run 30-year bonds and the results that arise from the demand for liquid assets, using a similar argument.

From an empirical point of view, a paper that is more closely related to ours in terms of the scarcity effect on bond yields is that of Blattner and Joyce (2016), who examine how shocks to the net supply of government bonds affect the term structure of interest rates and the macroeconomy. They use a free-float measure to quantify the net debt supply and report that the European Central Bank (ECB)'s government bond purchases reduced the 10-year bond yield by 30 basis points (bps) in 2015. They measure the scarcity created by foreign official institutions that the institutions constitute a third of the total outstanding German central government debt. Our paper differs from theirs because we address the scarcity created by the central bank itself, with a holding ratio as high as 78.9% of the outstanding debt. Our time-series as well as cross-sectional estimations allow us to identify the impact of the relation between scarcity and yield changes, across bonds in different life-stages, and across time over the various LSAP programs.

Another closely related paper on the scarcity issue is that of Joyce and Tong (2012), who investigate the impact of the Bank of England's QE program during 2009–2010 on the UK government bond (Gilt) yield. Using high-frequency securities-level data, they examine the yield change around the program announcement date, and that around each reverse auction, to capture the effect through the local supply channel and duration risk channel, showing that the bank's QE purchases had a significant and persistent impact on yields. D'Amico et al. (2013) quantify the scarcity value of Treasury collateral by estimating the impact of security-specific demand and supply factors on the repo market. They find that the amount purchased through the Fed's operations has a negative and significant impact for on- and off-the-run securities.

However, none of these empirical papers in the literature investigates the scarcity effect on liquidity. The sole exception is the theoretical paper by Ferdinandusse et al. (2018). In their model, a lower share of preferred habitat holdings is associated with more elastic demand, so that liquidity improves initially, but then falls even more with a high share of preferred habitat holdings, due to the scarcity generated by the central bank purchases. This model captures one dimension of the impact of CB interventions on liquidity, the differential impact on liquidity between the "flow effect" that improves liquidity and the "stock effect" that generates scarcity, and therefore, reduces liquidity. However, this model does not deal with the other aspect of the central bank intervention, the spotlight effect, which is part of our analysis.

The spotlight effect has been extensively analyzed in the stock market literature by Harris and Gurel (1986), Shleifer (1986), Beneish and Gardner (1995), and Beneish and Whaley (1996), as the result of exogenous events that cause a significant demand–supply imbalance, principally associated with changes in the composition of the Dow Jones Industrial Average and the Standard & Poor's (S&P) 500 index.[10] Many studies that followed examine the price pressure and the imperfect substitution hypothesis by means of the stock price and volume effects. The event associated with the announcement of the index composition stimulates trading activity so that spreads decrease with trading volumes, as in Stoll (1978), Copeland and Galai (1983), and McInish and Wood (1992). Beneish and Gardner (1995) find that firms are less widely followed after delisting from the Dow Jones Industrial Average. Beneish and Whaley (1996) find that the timing of the index-change announcements altered the way that stock prices react when the S&P began its practice of preannouncing changes five days beforehand.[11]The central bank's LSAP has a feature in common with the studies on the stock index change events. It creates a trading opportunity, since the LSAP program indicates the central bank's commitment to purchase *specified* assets. However, there are unique aspects as well. In the case of an S&P 500 event, the replacement of constituents happens unexpectedly. Replacement is necessary when a constituent shrinks in market value, or when a company is newly listed or delisted due to a merger or acquisition, and so forth. The demand for a new entry is easily calculated based on the outstanding amount of index-linked assets, and the timing of index fund purchases is well known to be the day before the change. This situation allows dealers and speculators to create a position prior to index fund action, and price pressure begins before the actual demand from index funds. In the case of an LSAP conducted by the BoJ, the schedule of LSAP operations is not disclosed (i.e., the targeted securities and the auction schedule are not announced in advance). The central bank announces a bundle of bonds that it is interested in purchasing, but there are always many alternatives on the target list, so that market participants need to do some guesswork to narrow down which bond the central bank is ultimately likely to buy. Nevertheless, the inclusion of a bond in the target list, i.e. the spotlight effect, might have an opposite effect on the liquidity of the bond. If a trader would like to participate to the action it would hoard this bond so that to have it available for the auction or exactly because it would like to hold it in the future and knows that it would be scarce after the auction. This behavior might reduce the liquidity of this bond rather than increase the liquidity of it. This effect has been documented first by Pelizzon, Riedel, Simon and

[10]There is a plethora of studies, too numerous to mention here, examining this impact in other markets around the world.

[11]Several more recent studies update these studies and also study other market microstructure effects.

Subrahmanyam (2019) in the analysis of the inclusion of European corporate bond in the eligibility list of bonds that could be used as collateral for borrowing money from ECB.

The liquidity term structure shows the relation between the time to maturity and liquidity. In assessing liquidity, one may focus on particular maturities or on the distinction between on- and off-the-run bonds. Goyenko et al. (2011) analyze the term structure of bond market liquidity and its relation to expected bond returns. They find that the difference in liquidity between long- and short-term bonds measured by bid–ask spreads increases during recessions. A similar analysis is provided by Schuster and Uhrig-Homburg (2012). However, the impact of central bank interventions on the term structure of bond market liquidity has not been investigated thus far. Further, the distinction between the scarcity and spotlight effects on the term structure of liquidity, as opposed to the term structure of interest rates, is novel in our paper.

Our paper is also related to the growing literature on BoJ's unconventional monetary policy, and in particular, it is related to: Lam (2011), Ueda (2013), Rogers et al. (2014), Fukunaga et al. (2015), and Iwatsubo and Taishi (2017). Lam (2011) uses an event study approach to investigate the impact of the BoJ's monetary easing measures on the Japanese financial market. This author finds that the easing measures from December 2008 to August 2011 had a statistically significant impact on lowering bond yields. Ueda (2013) focuses on political pressure on the BoJ and the differences in behavior between foreign and domestic investors. Fukunaga et al. (2015) examine the effects of changes in bond holder composition and the remaining maturity of bonds on the term structure of interest rates. They are interested in the change in the term premium of JGBs and consider that preferred habitat investors include not only the BoJ but also long-term investors, such as pension funds and insurance companies. Iwatsubo and Taishi (2017) investigate the effect of the BoJ's purchasing policy changes on market liquidity. They find that an increase in purchasing frequency, a decrease in the purchase amount per operation, and uniform purchase amounts improved market liquidity when QQE was introduced in 2013. These results predate the period of our analysis, because they do not look at QQE2, when the scarcity effects were accentuated. To our knowledge, no paper covers the recent aggressive LSAPs conducted by the BoJ, which radically differ from the interventions of other central banks in terms of both size and scope, particularly given that the effects change fundamentally when the central bank's holdings substantially exceed normal levels.

3 Research Issues and Hypotheses

In this paper, we aim to investigate the impact of QE on market liquidity and yield from both a time-series and a cross-sectional perspective. We first answer the general question of whether, on average, QE improves or reduces market liquidity. As already mentioned, QE has three effects on the liquidity of sovereign bonds, such as JGBs: the scarcity effect, which results from the reduction in liquidity due to shrinkage in the available bonds in the market, and the flow effect, which causes, from a macro perspective, an immediate improvement in liquidity during QE implementation, due to greater attention to the JGB market in general, and the spotlight effect generated by the targeted bonds in particular. This prediction is also in line with Ferdinandusse et al. (2018), who predict that the QE's exogenous shock affects the model's steady state and creates transition dynamics in the process. Therefore, their model provides a theoretical justification for the existence of a long-run scarcity effect (i.e., their stock effects) as well as a short-run spotlight effect (i.e., their flow effect) as a consequence of central bank purchases.

Hypothesis 1 *Since, at the initial level, the flow-based and the spotlight effect are stronger than the stock-based scarcity effect, QE, on average, induces an improvement in liquidity. However, in the long run, the scarcity effect prevails and liquidity declines. This would result in a sort of U-shaped relationship with liquidity.*

In addition to the macro perspective, we aim to investigate, at the micro level, the impact of the spotlight and scarcity effects. From a micro perspective, there should also be a cross-sectional effect, given that the BoJ buys different bonds over time; therefore, there is a spotlight effect drawing attention to individual bonds selected by the central bank. The inclusion of an individual JGB in the list of candidates for LSAP elicits keen attention from bond dealers and other market participants; thus, the spotlight effect has an *immediate* impact on bond liquidity. On the other hand, the scarcity effect is only *gradually* manifested as a negative impact on liquidity. Since the LSAP program involves the repeated purchase of significant amounts of individual securities, it is important to disentangle these two effects at the micro level.

We investigate the spotlight effect and the flow-based by looking at the fact that both the inclusion of a bond in the target list and the record of purchase by the BoJ induce market participants' greater awareness of a trading opportunity in that bond. Intuitively, the spotlight effect is expected to improve bond liquidity. Since the list of target bonds that the BoJ announces for each auction represents a group of bonds eligible for the BoJ operation and includes more than 90% of the bonds in the targeted maturity bucket, but only one-third of those on the target list are eventually purchased, we expect the

BoJ's *actual* purchases to have a larger effect on liquidity than mere inclusion in the list does. Based on this argument, we derive the following prediction of the spotlight effect on liquidity. We aim to stress that the inclusion in the target list might induce hoarding as well and therefore reduce bond liquidity. In the following hypothesis we consider the positive effect on the liquidity stronger than the hoarding effect and therefore we test for an improvement of the liquidity. Anyway, which of the two effects would prevails is an empirical question.

Hypothesis 2 *Liquidity is higher on reverse auction days because the spotlight effects and the flow-based, captured by the inclusion of a particular bond in the target list and its subsequent purchase, decrease the bid–ask spread.*

We next consider the effect of the BoJ purchases on liquidity through the scarcity (local supply) channel. Following the preferred habitat concept of Modigliani and Sutch (1966), which assumes that the scarcity effect is mainly due to the preferred habitat investors, one could conjecture that these investors demand only those bonds that are consistent with their preferred maturity. This argument is also considered in Ferdinandusse et al. (2018) in modeling the role played by preferred habitat investors in their theoretical analysis of the effect of QE on liquidity and bond pricing. It can be motivated as a consequence of bond market microstructure, given that the stock-based scarcity effect is mainly due to market-making risk: the reduction of the float of the bond that it purchased increases the probability that dealers will be unable to close their short positions by searching for the supply of a particular bond that preferred habitat investors might demand. Therefore, market makers raise their ask price to avoid the creation of such a "forced-short" position. Based on this argument, we derive the following prediction for the effect of LSAPs on liquidity through the scarcity channel.

Hypothesis 3 *The stock-based scarcity of bonds caused by a series of QE purchases increases their illiquidity due to the reduction in the float of bonds with that particular maturity.*

Next, we introduce the notion of three bond-life stages that distinguish between fresh, old, and shadow bonds. Fresh bonds are newly issued bonds that will typically be on-the-run. Old bonds are those that were issued more than one year ago and, as such, are likely to be off-the-run. Shadow bonds are also aged bonds whose remaining maturity corresponds to the maturity of other recently issued, shorter-term, original-maturity fresh bonds. Under normal market conditions, the liquidity of fresh bonds is likely to be the highest, followed by that of old bonds, with the liquidity of shadow bonds being the lowest. The spotlight effect has the least impact on fresh bonds, since they are likely to be on-the-run, and the market normally focuses on these bonds for trading anyway, so the additional effect of the QE purchases is likely to be minimal. For old bonds, that spotlight effect increases the opportunity to trade, and thus improves their liquidity. Compared to old bonds, shadow bonds should also experience a similar impact due to the spotlight effect, but creating a trading opportunity is more difficult, since they are likely to be locked away in long-term portfolios, even though they are roughly similar to the shorter-maturity new bonds; thus, the spotlight effect on liquidity is different depending on the bond-life stage: whether the bond is fresh, old, or shadow.

Hypothesis 4 (a) *The flow-based spotlight effect on the liquidity of old bonds is greater than that on fresh bonds.* (b) *The spotlight effect on the liquidity of shadow bonds is marginal, given their high illiquidity to begin with.*

Next, we aim to investigate, at the micro level, the impact of the spotlight and scarcity effects on the bond yield. From a time-series perspective, LSAP operations should lead to a decline in the bond yield, due to massive demand from the BoJ. From a cross-sectional perspective, two channels can be identified for the impact of the purchases on the level of the bond yield. On the one hand, the sizable demand from the BoJ raises the price and reduces the yield of any bond that is either on the target list or that has actually been recently purchased. On the other hand, according to the argument of Amihud and Mendelson (1991), the degree of illiquidity should be a discounting factor for the bond price. This argument has been stressed in Ferdinandusse et al. (2018) and De Pooter et al. (2015). In particular, De Pooter et al. (2015), in their calibration of the Amihud and Mendelson (1991) model, find that an official purchase of one percent of sovereign debt outstanding decreases the liquidity premium by 23 bps on impact. Most of this effect is temporary, and so official purchases tend to overshoot on market impact, and liquidity premia rise immediately after a purchase. This means that, in the cross-section of the bond yields, increasing scarcity should raise the bond yield in the long run. It is an empirical question as to which channel has a larger impact.

Hypothesis 5 *Bond yields are lower on reverse auction days because of the flow-based spotlight effects, captured by the inclusion in the target list or the purchase of a particular bond, which both raise bond prices and reduce bond yields. However, in the long run, the bond yield reduction is mitigated by greater bond illiquidity, also attributable to the stock-based scarcity effect.*

As for the liquidity investigation, we introduce three bond-life stages that distinguish among fresh, old, and shadow bonds in terms of yield. Similar arguments are applicable to the effect of central bank purchase on bond yields. The spotlight effect reflects the increased demand for bonds, but the effect is countered by scarcity. Scarcity contributes to higher bond prices and lower yields because of the effect of the purchase on the supply–demand imbalance, but this is partially offset by greater illiquidity.

Hypothesis 6 (a) *The flow-based spotlight effect on the yield of old bonds is greater than that on the yield of fresh bonds.* (b) *The spotlight effect on the yield of shadow bonds is mitigated by their generally high illiquidity.*

4 LSAPs in Japan

4.1 Summary of Recent Purchase Programs

Since 2009, the BoJ has announced four major monetary programs. The first of these was the CE program. Under the CE program, on October 28, 2010, a new asset purchase program of 35 trillion yen was announced, with the objective of decreasing longer-term interest rates. As part of the CE program, the BoJ conducted reverse auctions of financial assets up to 5 trillion yen per month, including about 1.5 trillion yen in JGBs, and gradually increased the program's total purchase amount over time.

The next major milestone was the nomination of Haruhiko Kuroda as the Governor of the BoJ on February 28, 2013. This announcement stimulated market speculation about the potential expansion of monetary easing. On April 4, 2013, the BoJ announced the introduction of QQE, whereby it increased its purchases of JGBs to an annual amount of about 50 trillion yen. It also increased its reverse auctions of longer-dated JGBs and announced its intention to extend the average remaining maturity of its JGB purchases to seven years, up from three years. On October 31, 2014, the BoJ announced the expansion of the QQE such that the purchase amount would increase at an annual pace of about 80 trillion yen, approximately 30 trillion yen more than the previous amount, thus aiming to decrease interest rates across the entire yield curve. The BoJ announced that it was shifting its purchases further toward longer-term bonds to extend the average remaining maturity of purchases to between about 7 and 10 years. On January 29, 2016, the BoJ introduced QQE with a negative interest rate. In this announcement, the BoJ revealed its policy of targeting a negative interest rate and continuing to purchase JGBs in amounts increasing by about 80 trillion yen annually. The average remaining maturity of the BoJ's JGB purchases thus rose to 12 years. Figure 1 shows the time line of the BoJ's monetary policies.

[Figure 1 about here.]

As explained above, the BoJ accelerated its LSAPs several times after 2009.[12] However, for reasons of data availability and the uncertainty Kuroda introduced to the program, we examine the QE effects by separating our sample into five subperiods, as follows:

CEbase	June 1, 2011, to January 31, 2012,	8 months
CE0	February 1, 2012, to February 27, 2013,	13 months
QQEX	February 28, 2013, to May 31,2013,	3 months
QQE1	June 1, 2013, to October 30, 2014,	17 months
QQE2	October 31, 2014, to January 28, 2016,	15 months

We designate June 1, 2011, to January 31, 2012, as the "calm" period, because (1) the size of the BoJ's intervention was small and stable, and (2) its holding ratio remained around 13% of outstanding JGBs. During CE0, the BoJ gradually increased the JGB purchase amount. We next have the QQEX period between the CE0 and QQE1 periods (February 28, 2013, through May 31, 2013), when Kuroda was appointed as the new Governor and market participants were uncertain about how the new monetary policy would be implemented. Figure 2 shows the historical yields of JGBs, with remaining maturities of 1, 5, 10, and 30 years over time.

[Figure 2 about here.]

As shown in Figure 2, a large fluctuation in yields is observed on the QQE announcement day, April 4, 2013. However, we are more concerned with the two months surrounding the QQE announcement. After February 2013, the yield began to decline rapidly, which coincided with the timing of Kuroda's nomination as Governor of the BoJ. Upon Kuroda's nomination, market participants may have expected the BoJ's rapid expansion of intervention in the JGB market. Even so, a strong reaction through a sharp decline in bond yields was observed after the announcement. The volatility of JGB prices was also high in this period. Our empirical analyses in the following sections, therefore, treats this period as a special period (QQEX).

Figure 3 shows the amounts (in trillions of yen) of nominal JGBs purchased monthly by the BoJ.

[Figure 3 about here.]

[12] According to the BoJ's LSAP program history, we can define three broadly defined periods, listed as follows:

CE	October 28, 2010, to April 3, 2013,	29 months
QQE1	April 4, 2013, to October 30, 2014,	19 months
QQE2	October 31, 2014, to January 28, 2016,	15 months

As shown in Figure 3, the BoJ gradually increased its holdings of JGBs after February 2012, but then accelerated its pace of bond purchases after the QQE announcement in April 2013. Most of the purchases in the first QQE period (QQE1) consisted of securities with maturities of between 1 and 10 years. After the expansion of the QQE, in the second QQE period (QQE2), the monthly purchase amounts increased, particularly for bonds with maturities of more than 10 years.

In Table 1, panels (a) and (b) display the number of purchase operations, and the monthly purchase amounts for the five periods, respectively. The BoJ conducted 8.57, 10.92, and 14.07 purchase operations per month in CEbase, CE0, and QQEX, respectively. The BoJ increased its number of purchase operations mainly for bonds of between 1 and 10 years' maturity. In the latter two periods, the operations for bonds with maturities of 1 to 10 years occurred 18 times per month, on average, and those for bonds with maturities longer than 10 years occurred 6.3 and 10.03 times per month in QQE1 and QQE2, respectively. The targeted maturity range of the BoJ's asset purchase programs shifted toward long-term bonds. As shown in Table 1(b), within the maturity range of 1 to 10 years, the monthly amount of purchases increased for bonds between 3 and 10 years. The purchased amount for bonds with maturities of more than 10 years substantially increased in QQE2. A more detailed analysis of the patterns of the BoJ's auctions and purchases is summarized in Table 12 in the Appendix.

[Table 1 about here.]

The purchase amount in each period dramatically increased after the introduction of QQE (QQE1 and QQE2). A breakdown by remaining maturity reveals that both the auction frequency and the total amount decreased for shorter-term bonds, which indicates that the BoJ had been trying to proceed with huge amounts of purchases, while minimizing the influence of each purchase on the market.

4.2 Reverse Auctions

We now describe the timeline of the BoJ's reverse auctions. On the day the BoJ executes an operation, it proceeds with an auction through its financial network system (BOJ-NET) according to the following schedule:

Time	Auction
10:10	Announcement of the today's operation
11:40	Bid submission cutoff
Around 12:00	Notification of results
Two days later	Settlement

On the auction day, the BoJ announces a purchase operation to the auction participants at 10:10 a.m. and discloses the following information through the BOJ-NET, its website: (1) the total amount of the operation, (2) the particular issues targeted, (3) the purchase date, and (4) the bid submission cutoff date and time. These announcements convey to the participants not only the list of targeted issues, but also any issues dropped from the target list. After the BoJ executes an auction, it provides the results to the submitters around 12:00 p.m.

5 Data and Descriptive Statistics

5.1 Liquidity Measures and Yield

Our data consist of daily observations from the universe of nominal coupon JGBs from February 1, 2009, to January 28, 2016.[13] The original maturities of the bonds in our sample are 2, 5, 10, 20, 30, and 40 years, respectively. The daily price and best quote data at the end of each trading day are obtained from Bloomberg.[14] We use the last price, the bid price, and the ask price since June 1, 2011, to investigate the LSAP's effect on yields and liquidity.[15] The characteristics of each security, such as the issue date, the redemption date, and outstanding amounts, are publicly available on the MOF's website. The amounts held by the BoJ, periodically announced on the BoJ's website, are downloaded from there. The information announced for each reverse auction is collected from Reuters News and Nikkei Telecom. Information about newly issued bonds is from the MOF and the Japan Securities Dealers Association website. We also obtained the yields on a constant maturity basis, used to estimate our yield curve, from the MOF.

We first define the bond yield as follows. $Y_{n,t}$, the yield to maturity of government bond n at time t, is defined as:

$$Y_{n,t} = \frac{coupon_n + \frac{100-P(n,t)}{\tau_n}}{P(n,t)} \times 100 \quad (\%), \tag{1}$$

where $coupon_n$ is the coupon rate (%) of security n, $\tau_{n,t}$ is the remaining maturity of

[13]Inflation-linked bonds are excluded from our sample.

[14]We exclude data points for days when the Japanese market is not open from our sample. We also exclude bonds with fewer than 90 days to redemption from our analysis, because the prices are too noisy, and sometimes the yield to maturity increases as the redemption date approaches, due to the increasing impact of the noise.

[15]We inspected the data before May 31, 2011, which we found to be qualitatively different from the data after June 1, 2011, because Bloomberg started incorporating quotes posted to the Bloomberg Electric Trading Platform into their database, only toward the end of May 2011. Hence, we decided to use only the data after June 1, 2011.

security n at time t, and $P_{n,t}$ is the price of security n at time t.[16] The change in yield from time t to time $t + \Delta t$ is

$$\Delta Y_{n,t,\Delta t} = Y_{n,t+\Delta t} - Y_{n,t}. \tag{2}$$

Table 2 presents the descriptive statistics for the bond yields. As shown in Figure 2 and Table 2, the yields of short-, mid- and long-term JGBs declined by 5.4 bps, 19.5 bps, and 36.7 bps, respectively, between CEbase and QQEX, and by 9.2 bps, 21.4 bps, and 37.8 bps, respectively, between QQEX and QQE2.

[Table 2 about here.]

We next define our market liquidity measure: the bid–ask spread. We are aware that there are other measures of liquidity, but we have chosen the the bid–ask spread, first because of its obvious simplicity in indicating how market makers (dealers) perceive liquidity conditions, and second, because of the constraints of data availability.[17] The percentage of the bid–ask spread of security n at time t is defined as:

$$sprd_{n,t} = \frac{ask - bid}{midprice} \times 100, \tag{3}$$

where *midprice* is the average of the ask and bid prices. The change in the bid–ask spread from time t to time $t + \Delta t$ is

$$\Delta sprd_{n,t,\Delta t} = sprd_{n,t+\Delta t} - sprd_{n,t}. \tag{4}$$

Figure 4 shows the liquidity term structure of JGBs, based on the bid–ask spread for all JGBs considered for six randomly selected days, at about one-year intervals, and Table 3 presents the descriptive statistics of these spreads. As the figure shows, the bid–ask spreads present a time-to-maturity structure with a significantly positive slope. However, the bid–ask spread does not increase linearly with time to maturity, but with a certain concavity. The figure also shows significant dispersion varying with time – in the bid–ask spreads for bonds with the same time to maturity. The dispersion is wider for bonds with less than 10 years remaining to maturity than those with longer maturities. On January 31, 2014, which is about 10 months after the implementation of QQE1, clustering of liquidity occurs across the entire liquidity term structure. Many bonds with remaining

[16] We use the daily last price data for $P_{n,t}$ in the empirical analysis.

[17] The quotes reported by Bloomberg, which we use in our analysis, are not firm quotes, but are the best publicly available data. Unfortunately, more detailed tick-by-tick data are not publicly available for JGBs.

time of less than 10 years show a bid–ask spread of 20 to 40 bps, while the corresponding most-liquid on-the-run segments show a bid–ask spread of 5 to 10 bps. Bonds with a remaining maturity of 20 years increase their bid–ask spread to 25 to 45 bps, while on-the-run bonds with maturities of 20, 30, and 40 years show bid–ask spreads of 20, 25, and 30 bps, respectively. Our analysis below aims to examine this variation by capturing both changes through time and the drivers of the cross-sectional dispersion due to the QE interventions.

[Figure 4 about here.]

[Table 3 about here.]

5.2 Spotlight Variables

As described in Section 4.2, the BoJ announces an offer amount in the morning of each day of operation and reports the results of the auction around noon. The BoJ notifies the auction participants about whether the offer was successful. The details of the auction results are communicated only to the successful bidders.

We now construct the spotlight effect variable based on the reverse auction announcements for the targeted securities. To examine the effect of being targeted for a purchase operation, we define the following variable,

$target_{n,t}$: Target dummy, which equals 1 when security n is targeted for the auction

We next construct a measure for the disclosure of the amount purchased by the BoJ. As mentioned, the BoJ does not disclose the details of the auction results until it discloses its holding amounts in a periodic disclosure.[18] But since the auction participants know whether their offer is successful or not on the same day, this information spreads quickly among them. The periodicity of the release of information about BoJ's holdings is typically longer than the period between two consecutive auctions. Our preliminary analysis of these data, which is not presented in this paper, suggests that the BoJ is likely to purchase a bond that it bought in the previous operation, since there is a higher

[18]The BoJ periodically discloses its JGB holding amounts. Before May 2014, the announcement frequency was once a month and, since then, it has increased to thrice a month.

probability of consecutive purchase as reported in Table 12 in the Appendix. To examine this effect on market liquidity and bond yield, we define the following variable:

$purchased_{n,t}$: Amount purchased in the previous auction of targeted security n as a percentage of its amount outstanding. $purchased_{n,t}$ has a value when a bond is included in the target list. (5)

Since our variable $purchased_{n,t}$ is not the amount purchased in the auction of that day but the amount in the previous auction, we can avoid the problem of endogeneity between the bond yield and the amount purchased, as pointed out by D'Amico and King (2013) and many other papers.

5.3 Scarcity Variables

We next define the variables used in our investigation of the impact of the scarcity of a bond on bond market liquidity and yield. The BoJ's LSAPs have a significant impact on the bond supply, as indicated by Figure 5, which plots the holding ratio of government bonds, defined as the total amount of the BoJ's holdings divided by the total amount of outstanding JGBs.[19]

[Figure 5 about here.]

As shown in Figure 5, the BoJ's holding ratio was around 10% until mid-2012, but then sharply increased and reached around 37% in February 2016.

We construct our scarcity variables for individual securities, defined as follows. The BoJ's relative holdings of security n at time t as a percentage of outstanding securities is

$$h_{n,t} = \frac{H_{n,t}/O_{n,t}}{\sum_n H_{n,t}/\sum_n O_{n,t}}, \tag{6}$$

where $O_{n,t}$ is the outstanding amount of security n and $H_{n,t}$ is the amount of security n held by the BoJ at time t. According to Greenwood and Vayanos (2014), the local scarcity channel implies that a change in the supply of bonds in a specific sector, or of a certain maturity, can differentially affect those bonds and bonds with similar, but not identical, characteristics. We follow this reasoning for our investigation on the effect of scarcity on yield, but not for liquidity. Market makers are concerned about the float of a particular bond and the potential failure of the delivery, but not necessarily its substitutes, since

[19] We did not include the amount issued by the auction in this calculation.

their demand is bond-specific. We also use the logarithm of the outstanding amount of security n, $lnO_{n,t}$ as a control variable.

5.4 Three Bond-Life Stages in Liquidity

We further explore the liquidity effects at the bond level by introducing three bond-life stages according to the literature on bond liquidity. First, the liquidity difference between on- and off-the-run bonds is well known by practitioners as well as academics (e.g., Boudoukh and Whitelaw (1993), Fleming (2003), and several others). Second, the liquidity differences between short- and long-term bonds is upward sloping (as documented by Goyenko et al. (2011)). This result reflects increasing duration risk as the bond maturity is extended. Third, as Amihud and Mendelson (1991) indicate, the time to maturity of two bonds does not tell the full story about the liquidity differences. The original maturity carries certain ownership characteristics that affect the level of liquidity when the time to maturity of one long-term bond gets shorter and matches that of a newly issued shorter-term bond (as also documented by Krishnamurthy (2002)).

We therefore specify three distinct bond-life stages corresponding to the bond liquidity levels mentioned above: fresh, old, and shadow bonds. Fresh bonds are those within one year of issuance, and are typically on-the-run. These bonds have sufficient availability for dealers to make markets. In contrast to fresh bonds, shadow bonds have a time to maturity that is in the range of other original maturity, newly issued bonds. For example, original 10-year bonds with a remaining time to maturity of 4.5 years have more newly issued, substitutable bonds with an original maturity of five years. Therefore, these bonds are no longer the first choice for someone who wishes to trade four- to five-year maturity bonds. Old bonds (Krishnamurthy (2002)) become illiquid due to the shrinkage of free float as a result of being "locked-away" in the portfolios of long-term investors. These three groups capture the unique features of the bond liquidity at a broad level.

To capture these effects, we introduce dummy variables that correspond to three distinct bond-life stage groups: fresh, old, and shadow bonds. We define $fresh_{n,t}$ as a dummy variable that equals 1 if the bond was issued within 1 year before the trade date. The dummy variable, $shadow_{n,t}$, equals 1 after the remaining time of a 5-, 10-, 20-, 30-, or 40-year bond reaches less than 2, 5, 10, 20, or 30 years, respectively. We further define $old_{n,t}$ as a dummy variable that equals one, when the bond has been issued more than one year prior to the trade data, but before it reaches the shadow range of its bond-life stage.

[Figure 6 about here.]

Figure 6 shows the BoJ's purchased amounts split among fresh, old, and shadow bonds. In the CEbase period, the BoJ purchased almost the same amounts of fresh, old, and shadow bonds, but it increasingly purchased fresh bonds after the QQEX period, with the ratio of fresh bond holdings reaching about 70% in QQE2.

[Table 4 about here.]

Table 4 shows the BoJ's holding ratio of fresh, old, and shadow bonds for each remaining maturity. The key characteristic is the ratio of the fresh bonds, which reached 53.3 %, 33.5 %, 44.4 %, and 24.6 % in QQE2.

[Table 5 about here.]

Table 5 shows the correlation between candidates for the explanatory variables used for our analysis. The correlation between *target* and *purchased* is between 0.1902 and 0.2427. This indicates that only a small portion of the targeted bonds are actually purchased by the BoJ. *purchased* is not correlated with the coupon rate; the logarithmic outstanding amount, lnO; or the remaining time to maturity, τ. These low correlations confirm the conjecture that the BoJ purchased a broad range of bonds. Among the variables, the highest correlation is the one between coupon rate and the outstanding amount, which is -0.6221 and -0.6935. We exclude the coupon rate from the regression analysis because of multicollinearity concerns.

6 Empirical Analysis of Liquidity

In this section, we conduct our empirical analysis of the impact of QE on the JGB market using the bid–ask spread as a proxy for liquidity. We investigate the following four hypotheses.

Hypothesis 1 *Since, at the initial level, the flow-based spotlight effect is stronger than the stock-based scarcity effect, QE, on average, induces an improvement in liquidity. However, in the long run, the scarcity effect prevails and liquidity declines. This would result in a sort of U-shaped relationship with liquidity.*

Hypothesis 2 *Liquidity is higher on reverse auction days because the flow based bond spotlight effects, captured by the inclusion of a particular bond in the target list or its subsequent purchase, decrease the bid–ask spread.*

Hypothesis 3 *The stock-based scarcity of bonds caused by a series of QE purchases increases their illiquidity due to the reduction in the float of bonds with that particular maturity.*

Hypothesis 4 (a) *The flow-based spotlight effect on the liquidity of old bonds is greater than that on fresh bonds.* (b) *The spotlight effect on the liquidity of shadow bonds is marginal, given their high illiquidity to begin with.*

We first test for overall liquidity improvement in the JGB market, in the context of the QE interventions, by comparing average liquidity levels between periods. In Section 6.2, we investigate these hypotheses based on cross-sectional regressions. In Section 6.3, we explore this impact on market liquidity in further detail by introducing the three bond-life stages.

6.1 Overall Impact on Market Liquidity during the QQE Periods

The descriptive statistics in Table 3 and the differences between the term structures of liquidity in each period in Figure 4 indicate that the bid–ask spread got narrower before the announcement of the QQE by Governor Kuroda, and then got slightly wider during QQE1 and QQE2. We confirm that the change in the bid–ask spread is statistically significant by comparing the average spread period by period.

[Table 6 about here.]

Table 6 presents the results of the Welch two-sample t-test. Comparisons with the CE-base period confirm the general improvement in market liquidity across bonds during the QQE1 and QQQ2 periods. However, there are several important exceptions showing that the differences between the two QE interventions in terms of their liquidity impacts vary differentially across maturities and through time. Still, these results highlight the short-term and long-term effects of the intervention, representing the spotlight and scarcity effects, respectively. More specifically, the 1-to-3-year bucket in the QQEX period, as well as the 3-to-10-year bucket in the CE0 and QQE1 periods, highlight a reduction in liquidity (i.e., the bid–ask spreads increased). The bid–ask spreads in the QQE are also significantly narrower than those in CE0 for all remaining maturities.[20]

[20] According to Table 1(b), the BoJ's monthly purchase amounts increased in these periods. For example, the purchase amount of bonds with between 3 and 10 years to maturity during QQE1 and QQE2 increased to 4.1 and 4.9 trillion yen, respectively from 3.4 trillion yen in QQEX. Similarly, the purchases of bonds with 1 to 3 years to maturity in CE0 jumped to 2.1 trillion yen from 0.9 trillion yen in CEbase. In addition, stronger demand for short-term JGBs from foreign investors amplified these purchases and pushed the illiquidity of this bucket in QQE1 and QQE2.

On the other hand, the results of comparisons between the QQE1 and QQEX periods, and between the QQE2 and QQE1 periods, show the deterioration in market liquidity (except for the bonds with a maturity of longer than 10 years in the QQE1 period and those between 3 and 10 years in the QQE2 period). This is again in line with the long-run impact captured by a significant increase in the scarcity effect (i.e., the stock effect) for the same amount of purchases (i.e., the flow effect), and a potentially lower spotlight effect. The largest reduction in the bid–ask spread occurred for bonds with a maturity longer than 10 years throughout the four periods. The reduction in the bid–ask spreads for bonds with a maturity longer than 10 years in CE0 is estimated to be −7.184 bps, and those in the QQEX, QQE1, and QQE2 periods are −11.114, −11.482, and −10.323 bps, respectively. These results are consistent with the conjecture that the BoJ shifted its purchases toward longer-maturity bonds in the QQE periods.

In summary, improvements in liquidity are observed in the two former periods and deteriorations are observed in the two latter periods. The results support Hypothesis 1, and are consistent with Ferdinandusse et al. (2018), whose theoretical model predicts that asset purchases initially improve liquidity but, as the bonds becomes scarcer, the liquidity eventually declines. In the comparison thus far, however, we do not control for larger macroeconomic factors, such as the Eurozone financial crisis, which may have had a diminishing influence on the liquidity of long-term bonds over time. In the following subsection, we perform cross-sectional regressions controlling for these effects.

6.2 Cross-Sectional Differences in Bid–Ask Spreads

In this subsection, we investigate how spotlight and scarcity effects affect the level of liquidity across the sample of JGBs. We ask whether spotlight effects such as the target list inclusion or the actual bond purchases had a positive impact on liquidity, and whether the overall level of liquidity affects individual bonds' degree of scarcity. To this end, we perform a cross-sectional analysis of the bid–ask spread in terms of levels instead of changes. We examine whether the variables measuring the spotlight or scarcity effect can explain the cross-sectional differences in bid–ask spreads.

The following regressions are performed:

$$sprd_{n,t} \;=\; \alpha + \sum_i \beta_i Spotlight^i_{n,t} + \sum_j \gamma_j Scarcity^j_{n,t} + \sum_k \theta_l Control^k_{n,t} + \epsilon_{n,t}, \quad (7)$$

where $\{Spotlight^i_{n,t}\}$ includes variables for examining the spotlight effect, such as a dummy for being targeted $target_{n,t}$; and the amount purchased in the previous auction, $purchased_{n,t}$.[21] The term $\{Scarcity^j_{n,t}\}$ includes the BoJ's relative holding ratio, $h_{n,t}$. The term $\{Control^k_{n,t}\}$ includes the logarithm of the amount outstanding, $lnO_{n,t}$; and the remaining time to maturity, τ, and its square, which characterize the duration risk associated with the bid–ask spread. The variable $\epsilon_{n,t}$ represents the error term. We run this regression with daily time dummies.

In the second step, we check if there is an impact of the unexpected purchases. We define the unexpected purchase as the difference between the amount of actual purchase and the amount purchased in the previous auction of targeted security scaled by its amount outstanding;

$$unexpected = purchase_{n,t} - purchased_{n,t},$$

where $purchase_{n,t}$ is the purchase amounts of targeted security n in the day t auction as a percentage of its amount outstanding and $purchase_{n,t}$ is defined in Eq. (5). We then look into the additional effects with the unexpected purchase variable. More formally we consider the residual of the regression Eq. (7); $\hat{\epsilon}_{n,t}$ and perform the following regression:

$$\hat{\epsilon}_{n,t} = \alpha + \beta unexpected_{n,t} + \eta_{n,t}, \tag{8}$$

where the variable $\eta_{n,t}$ represents the error term.

[Table 7 about here.]

Panel A of Table 7 presents the results for the cross-sectional regression of the bid–ask spread for the five periods in our sample. The dependent variable is the end-of-day spread in bps, and the regression equation is presented in Eq. (7). We calculate the significance of the coefficients from two-way cluster-robust standard errors (Cameron et al. (2011)). The adjusted R-squared values of the cross-sectional regression of the bid–ask spread are very high, from 0.650 to 0.907. Among the variables related to the spotlight effect, those for bonds in the target list and purchased in a previous operation have significantly negative coefficients in CE0 (−0.1467), QQEX (−0.0500), QQE1 (−0.1068), and QQE2 (−0.0436), but the coefficient was insignificant in CEbase, during which period the BoJ purchased relatively small amounts, and mostly short-maturity bonds. This result is consistent with Hypothesis 2 (that the spotlight effect improves the liquidity of a bond). The target dummy variable has a significantly positive coefficient in CE0 (0.7748), QQEX (1.0438), and QQE1 (0.9227), however. As mentioned earlier, during QQE1 and QQE2, the BoJ specified targets for nearly all the bonds in the bucket, so that bonds targeted

[21] We do not use the purchased amount of the day but use the amount in the previous auction to avoid the problem of endogeneity. See Section 5.

earlier, but not purchased in a previous operation, showed wider bid–ask spreads at the end of the operation day.

A variable related to the scarcity effect is the relative holding ratio of a bond, $h_{n,t}$. $h_{n,t}$, which exhibits significant explanatory power throughout the different periods. The higher the holding ratio, the larger the bid–ask spread, as expected, which is consistent with Hypothesis 3. An increased BoJ holding reduces the float of the bonds in the market, so that market makers post wider bid–ask spreads due to the increased difficulty of covering their short position or refilling their inventory. The relative scarcity explains the cross-sectional differences of the bid–ask spread, while the market-wide scarcity worsens the liquidity in the entire JGB market. Among the control variables, the remaining time-squared has significantly negative coefficients, which indicate larger liquidity improvements for longer maturity bonds, except during CEbase and QQE2. Here again, the shift of the BoJ purchases toward longer-maturity bonds reduced the bid–ask spread more for longer maturities, but the effect diminished in QQE2, and the remaining time-squared in QQE2 no longer has a significant negative coefficient. The negative coefficient of the amount outstanding in QQE2 suggests that the BoJ focused on purchasing bonds with large outstanding amounts.

Panel B of Table 7 presents the regression results of the unexpected purchases for the residuals of the first-step regression. The coefficients of the unexpected purchase and intercepts in five periods are statistically insignificant at five percent level. This confirms that the spotlight effects are associated with the BoJ's expected purchase based on the results of the previous operation.

6.3 Liquidity in the Three Bond-Life Stages

In this subsection, we differentiate between bonds in three different bond-life stages, namely as fresh, old, and shadow bonds. These three bond-life stages correspond to particular phases in the life of bonds, which become important when we investigate the relations between liquidity and the spotlight and scarcity effects, under the central bank's aggressive asset purchase programs. We now investigate whether these bond-life stages are connected with the spotlight and scarcity effects. We add the cross terms of the old and shadow bond dummies, together with the spotlight and scarcity variables to examine the structural breaks in the three different bond-life stages:

$$
\begin{aligned}
sprd_{n,t} &= \alpha + \sum_i \beta_i Spotlight^i_{n,t} + \sum_j \gamma_j Scarcity^j_{n,t} \\
&\quad + \sum_i \sum_l \kappa_{i,l} Stage^l_{n,t} \times Spotlight^i_{n,t} + \sum_j \sum_m \lambda_{j,m} Stage^m_{n,t} \times Scarcity^j_{n,t} \\
&\quad + \sum_k \theta_k Control^k_{n,t} + \epsilon_{n,t}, \qquad (9)
\end{aligned}
$$

where the term $\{Stage^l_{n,t} \times Spotlight^i_{n,t}\}$ includes a dummy indicating whether the bond has been issued more than one year ago but is not in the shadow area, $old_{n,t}$; a dummy indicating whether the bond reached the shadow area, $shadow_{n,t}$; and the cross term of the two life stage dummy variables with the two spotlight variables, with the term $\{Stage^m_{n,t} \times Scarcity^j_{n,t}\}$ including the old bond dummy, the shadow bond dummy, and their cross terms with the scarcity effect variable $h_{n,t}$. The terms $\{Spotlight^i_{n,t}\}$, $\{Scarcity^j_{n,t}\}$, and $\{Control^k_{n,t}\}$ include the same variables as Eq. (7) and $\epsilon_{n,t}$ represents the error term. We run Eq. (9) with daily time dummies.

[Table 8 about here.]

Table 8 presents the results of the cross-sectional regression for the bid–ask spread with the bond-life stage dummies and their cross terms with the spotlight and scarcity variables. The time-to-maturity variables in CEbase and CE0 have positive coefficients that are larger than those after QQEX. This means that the term structure of liquidity (the spread differences across maturities), which was upward sloping before the QQE implementation, flattened as a result of QQEs' expanded asset purchase operations, focused on the longterm bonds.

The liquidity of an individual fresh bond improved when it was purchased in the previous operation, except during CE0 and QQE1, when the BoJ changed the total size of its operations. Inclusion of the target without purchases in the previous operation had a positive impact on the bid–ask spread in the first three periods; however, this effect disappeared in the latter two periods. With respect to the scarcity effect, the higher holding ratio is associated with the wider bid–ask spread up to QQE1, but it turned insignificant in QQE2. The BoJ had to buy more and more fresh bonds in QQE2, because the supply of older bonds kept shrinking. The holding ratio of fresh bonds rose to 35.1% in QQE2 from 7.2% in QQEX and 20.4% in QQE1, and thus the concentrated trading activity mitigated the illiquidity effect on the fresh bonds.

Regarding old bonds, their associated dummies in QQE1 and QQE2 indicate the improvement of liquidity for the whole subgroup. However, old bonds with a higher holding ratio suffer a relative illiquidity effect. The holding ratio for the old bonds also rose to 23.5% from 14.7%. However, the level of the holding ratio for the old bonds is lower than that of the fresh bonds simply because a large proportion of the old bonds is locked away in institutional investors' portfolios, and is not available for purchase by the central bank. The spotlight effect for old bonds is associated with the target flag throughout the five periods, although the statistical significance weakens after QQEX. The coefficients of the target are significantly negative; while the BoJ selects a smaller number of bonds for its target list (on average, 103.0 in CEbase and 98.6 in CE0), they then become insignificant after the widening coverage of the target list (124.0 in QQEX, 135.4 in QQE1, and 140.7 in QQE2), as shown in Table 1 (c). The coefficients for the purchase in the previous operation for the old bonds are mixed in terms of both signs and statistical significance, because the probability of repeated purchase of the old bonds varies from 6.3% to 78.6% per different maturities.

As for shadow bonds, the coefficents of their dummies during QQE1 and QQE2 periods turn negative, which implies an improvement of liquidity for the subgroup. The shadow bonds purchased in the previous operation show better liquidity, except during CEbase. The BoJ's higher holding ratio is associated with a deterioration of liquidity in QQE1 and QQE2.

In summary, under the aggressive QQE (QQE1 and QQE2), the spotlight effect had only marginally affected the liquidity of the fresh bond, which is normally liquid. The liquidity of the old and shadow bonds improved through the spotlight effect of the BoJ purchases. The channel for the spotlight effect is more often through the actual purchase record, but sometimes the inclusion of a target list contributes to liquidity improvement. Regarding scarcity, in the case of fresh bonds, a higher holding ratio is associated with a wider bid–ask spread until QQE1; however, the BoJ increased its purchase of fresh bonds in QQE2, so the spotlight and scarcity effects probably canceled each other out. Instead, the scarcity for aged bonds, both shadow and old, is associated with a narrower bid–ask spread initially, and then a wider bid–ask spread in the QQE1 and QQE2 periods, indicating that, in the long run, the scarcity effect prevailed even more for these bonds. These results confirm Hypothesis 4, since they show that the spotlight effect on the liquidity of old bonds is greater than that on the liquidity of fresh bonds, and the spotlight effect on the liquidity of shadow bonds is mitigated by their high illiquidity.

7 Empirical Analysis of the LSAP Effect on Yield

In this section, we investigate the following hypotheses.

Hypothesis 5 *Bond yields are lower on reverse auction days because of the flow-based bond spotlight effects, captured by the inclusion in the target list or the purchase of a particular bond, which both raise bond prices and reduce bond yields. However, in the long run, the bond yield reduction is mitigated by greater bond illiquidity, also attributable to the stock-based scarcity effect.*

Hypothesis 6 (a) *The flow-based spotlight effect on the yield of old bonds is greater than that on the yield of fresh bonds.* (b) *The spotlight effect on the yield of shadow bonds is mitigated by their generally high illiquidity.*

7.1 Overall Impact of the QQE Periods on Yield

We confirm the reduction in the yield statistically by comparing the average yield period by period.

[Table 9 about here.]

Table 9 shows the results of a Welch two-sample t-test. Although the declines in the yield from the previous periods are all significantly different from zero, the impact of QE varies across maturities and through time. The comparisons of the CEbase with the CE0 period show the decline in yields for all remaining maturities: the changes for bonds of less than 1 year, 1 to 3 years, 3 to 10 years, and longer than 10 years are -2.54, -4.79, -15.07, and -15.00 bps, respectively. From CEbase to QQE2, the yield for the four buckets declined by 12.46, 14.60, 40.89, and 74.14 bps, respectively. Among them, the decline for the longer-than-10-years bucket is the largest. The changes between QQE1 and QQEX are relatively small: the longer-than-10-year bucket yield declines by 33.53 bps between QQE1 and QQE2 because the BoJ shifted its purchases toward longer-maturity bonds in QQE2. In summary, the declines in yields for short- and middle-term bonds are relatively small, since their level of yields was already low, and those for long-term bonds are somewhat larger, except between QQEX and QQE1.

7.2 Cross-Sectional Differences in Yields

In this subsection, we investigate how spotlight and scarcity effects affect the levels of yields across JGBs. We ask whether spotlight effects, such as an inclusion of a bond in the target list or the purchase record in the previous purchase operation, lower the yield of the bonds because of increased demand. In the case of scarcity, we expect two opposing effects. First, the scarcity of the particular bond amplifies the market impact caused by the BoJ purchase. Second, there is the theoretical prediction of Amihud and

Mendelson (1991) that investors demand higher yields (lower prices) for illiquid bonds as a compensation for their illiquidity. Therefore, we perform a cross-sectional analysis of the yields to examine whether the variables measuring the spotlight or scarcity effect can explain the cross-sectional differences in bond yields. The following regressions are performed to assess these effects:

$$Y_{n,t} = \alpha + \sum_i \beta_i Spotlight^i_{n,t} + \sum_j \gamma_j Scarcity^j_{n,t} + \sum_k \theta_k Control^k_{n,t} + \epsilon_{n,t}, \quad (10)$$

where $\{Spotlight^i_{n,t}\}$ includes variables for examining the spotlight effect, such as dummy for being targeted, $target_{n,t}$; and the amount purchased in the previous auction, *purchased*. The term $\{Scarcity^j_{n,t}\}$ includes the BoJ's relative holding ratio, $h_{n,t}$. and the term $\{Control^k_{n,t}\}$ includes the logarithm of the amount outstanding, $lnO_{n,t}$; the remaining time to maturity, τ, and its square. The variable $\epsilon_{n,t}$ represents the error term. We run the regression of this model with daily time dummies.

We then check if there is an impact of the unexpected purchases on bond yield. Using the residual of the regression Eq. (10), we perform the following regression:

$$\hat{\epsilon}_{n,t} = \alpha + \beta unexpected_{n,t} + \eta_{n,t}, \quad (11)$$

where the variable $\eta_{n,t}$ represents the error term.

[Table 10 about here.]

Panel A of Table 10 presents the regression results of the cross-sectional model with time-fixed effects for the bond yields. The dependent variable is the end-of-day yield in bps and the regression equation is presented in Eq. (10). The adjusted R-squared values of the cross-sectional yield are very high, from 0.956 to 0.982. Among the variables related to the spotlight effect, the target dummy has significantly negative coefficients throughout the periods. This finding is consistent with Hypothesis 5. It is interesting to note that the spotlight effect on liquidity is captured by *purchased*, but that on yield, it is mainly captured by *target*. In terms of yield changes, the BoJ's purchase operation moves the yield of entire bucket (substitution effects), but in the case of bid–ask spread, the liquidity of an individual bond is influenced by the trading activity of the bond itself. However, our finding that bonds purchased in a previous operation tend to have significantly positive coefficients, except in QQE1, is puzzling.

Concerning the scarcity effect, the relative holding ratio of a bond has no effect on its yield before QQEX, but it turns out to have a negative impact in QQE1 and QQE2. The higher the holding ratio, the lower the bond yield, which indicates that the illiquidity increases the market impact rather than mitigating the spotlight effect on bond yields. This is incompatible with Hypothesis 5, which is based on the theoretical prediction from Amihud and Mendelson (1986, 1991) that higher illiquidity should be compensated by a higher liquidity premium. This effect drives the rational behavior of long-horizon investors, but not necessarily that of the BoJ, since the purpose of the LSAPs is solely to drive down bond yields. Hence, the clearly dominant demand from the BoJ may attenuate the theoretical relation between illiquidity and bond yields. However, the spotlight effect is the dominant pricing factor for otherwise illiquid bonds.

The coefficients of the time-to-maturity variable is 13.21 in CEbase and declines to 6.16 in QQE2. In earlier periods, the BoJ asset purchase operation depresses the yield of the long-term bonds more than that of short-term bonds. These effects on the yields of the long-term bonds weaken despite the fact the BoJ purchases shifted more toward long-term bonds in the latter periods.

Panel B of Table 10 presents the regression results of the unexpected purchases for the residuals of the first-step regression. The coefficients of the unexpected purchase in five periods expect the one for QQE2 are statistically insignificant at five percent level. Intercepts in all five periods are insignificant. These results confirm that the spotlight effects are not associated with the expected and unexpected BoJ's purchases. For the yields, the inclusion of the target captured spotlight effects instead of the purchase because the deviation of yields among the bonds belong to the same bucket (target list) are wiped out by arbitrage activity.

7.3 Yield in the Three Bond-Life Stages

We now incorporate the distinction between the three bond-life stages into the effect on the bond yield, which might mask the relations we investigate. We regress the same regressors of Eq. (9) for the bond yield model.

[Table 11 about here.]

To examine more precisely the relation behind the results of Table 10, we add the cross terms of the old and shadow bond dummies with the spotlight and scarcity variables. Table 11 presents the results of the cross-sectional regression for the yield with the bond-life stage dummies and their cross terms with the spotlight and scarcity variables. The target variables for fresh bonds have significantly negative coefficients through all the periods except CEbase and QQE2. The variable for bond purchases also has a negative coefficient, but it is statistically significant only in QQE1. The illiquidity premium for the fresh bonds captured by the coefficient of the holding ratio was positive until QQEX, but it turned negative after QQE1. In QQE2, the scarcity enlarged the market impact of the fresh bonds significantly. However, the scarcity effects on the fresh bonds are contrary to our expectation.

The yield changes of the old and shadow bonds are different from those of the fresh bonds in general. The dummy variable for inclusion in the target list exhibits a larger yield decline, indicative of the spotlight effect, except for QQEX, when the anticipation and announcement of the aggressive QQE program under the then-new Governor Kuroda generated an unusual reaction from investors. The scarcity of both the old and shadow bonds is associated with a large market impact throughout the various periods, as in the case of the fresh bonds. The holding ratio variable has a significant negative coefficient only for fresh bonds in QQE2, with those of old and shadow bonds being negative but insignificant. Interestingly, the fact that the increasing bond scarcity pushed bond prices up together with the spotlight effect is limited to fresh bonds. The explanation is that the BoJ's strategy to shift to buying new bonds as much as possible induced this phenomenon. Overall, the results of the analysis with the control variables remain similar to those in Table 10.

8 Concluding Remarks

The LSAPs of the major central banks around the world created scarcity in the assets they targeted, while generating a spotlight effect for those assets. This is particularly true in Japan, where the BoJ, its central bank, bought and continues to buy large amounts of a range of assets, including JGBs, shares of REITs, and ETFs as part of its various LSAP programs over the years. Due to these massive purchase programs, especially during a period of about three years (April 2013 to January 2016), the BoJ's average holding ratio of JGBs jumped from 10% to 37% of the total outstanding amount of these bonds in our sample, perhaps the largest holding ratio any central bank has ever reached. This scarcity can be, therefore, viewed as a supply shock, which has been addressed by many financial economists, market analysts, and central banks in their studies of bond yields. We analyze both the scarcity and spotlight effects in the context of the various QE programs in the past several years. In contrast to the prior literature, we investigate how such a supply shock created by the LSAPs affected *both* yields and liquidity in the JGB market and how the spotlight effect focuses attention on bonds that were hitherto not actively traded, thus creating rare trading opportunities for eligible bonds in the QE program. Our analysis adds substantial color at the bond level and across programs to the effect of these QE programs on the term structure of bond yields and liquidity by explicitly investigating both effects on liquidity and bond yields.

Our results suggest that, in the absence of concrete information prior to the BoJ's purchases, dealers and investors pay heed to which bonds and how much of each bond the BoJ bought in the prior operation. We confirm the reduction of bond yields and show that the scarcity and spotlight effects both contribute to it. We then investigate, at the micro level, the impact of the spotlight and scarcity effects on the bond yield; from a time-series perspective, we find that an LSAP operation leads the decline in the bond yield due to the huge demand from the BoJ.

We confirm a spotlight effect on the bid–ask spread that is associated with the record of purchases but not with the inclusion of bonds in the target list. We also document that the other important effect we investigate, the scarcity effect, gradually penetrates the illiquidity of bonds. The greater the scarcity, the more difficult the market making for the particular bonds becomes, ultimately manifesting itself in worsening illiquidity. This timing difference of spotlight and scarcity effects is observed at the macro level in the period-by-period comparative analysis of the average bid–ask spread. Scarcity measured by the bond itself, as well as its substitutable bonds, shows a strong relation with illiquidity.

In addition to liquidity effects, from a cross-sectional perspective, between the two channels identified for the level of the yield, the increase in scarcity causes the liquidity to deteriorate and the prices to decline, but this effect is swamped by the spotlight effect. In terms of the three life stages – fresh, old, and shadow – the liquidity of fresh bonds improves when a bond is purchased in the previous operation while the holding ratio of the BoJ is rapidly increasing. It is important to note that illiquidity caused by scarcity amplifies the yield decline rather than adding to the illiquidity premium.

The important takeaway from our analysis is that an aggressive QE program could eventually worsen market liquidity and amplify the market impact in the sovereign bond market, while it improves liquidity at the inception. In principle, higher liquidity could mitigate the price impact, but this was not the case for the BoJ's LSAPs; increased illiquidity ought to be penalized by higher yields, but we find evidence to the contrary. Both these phenomena reflect the strong demand from the purchase program conducted by the BoJ. The lesson from this experience is that the impact of QE programs may fulfil the objective of depressing bond yields, but may also come with unintended consequences by decreasing liquidity.

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A The pattern of the BoJ's purchases

In this section, we provide the detailed analysis of the pattern of the BoJ's purchase operations. As described in Section 4.2, the BoJ announces the issues targeted for each purchase operation. It also announces the issues dropped for the operation.

[Table 12 about here.]

Table 12 shows the number of targeted and dropped bonds per operation, and the proportion of purchased bonds in the targeted bucket, as well as ratio of repeated purchase of the bond purchased in the BoJ's previous operation for each life stage. Although the number of target bonds for the fresh bonds does not change much throughout periods (16 to 18 bonds), those for the old and shadow bonds do: 38.4 to 70.8 and 45.2 to 55.7, respectively. The purchase ratio of the fresh bonds increased from 25.7% in CEbase to 56.0% in QQE1 and 45.5% in QQE2. Once a fresh bond is purchased in the previous operation, the probability that the bond is purchased consecutively is very high (69.3 to 80.1) after CE0. However, the probability of consecutive purchase for the bonds belonging to the old and shadow stages got much lower (29.4 to 45.2) in QQE1 and QQE2. This suggests that the BoJ is forced to buy fresh bonds because of a lack of supply of old and shadow bonds.

B Weekly analysis

B.1 Analyses of the bid–ask spread and yield by weekly data

We repeat the analyses using weekly data, since bond data may suffer from infrequent observations. However, weekly data are expected to be less affected by the gaps in the data as well as outliers. Therefore, we run the cross-sectional regression similar to Eqs. (7) and (10).

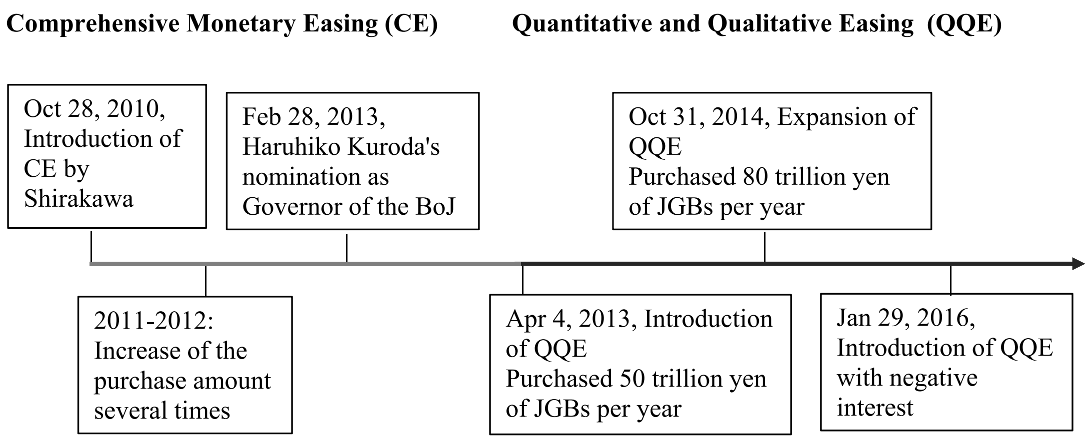
Table 13 shows the results of the cross-sectional analysis of bond liquidity, in which *purchased* has a significantly negative coefficient in CE0, QQEX, and QQE1. These results are broadly similar to those from the daily cross-sectional analysis presented in Table 7, except in QQE2. The purchasing action in QQE2 is particularly more concentrated in fresh bonds, in order to continue the operation as intended by the BoJ, with the result that an improvement of liquidity did not occur. The relative holding ratio, however, has positive coefficients for all periods, as in Table 7. It is confirmed in weekly analysis that scarcity worsens the liquidity.

Table 14 shows the cross-sectional analysis on the bond yield that the spotlight effect on yield is captured by the target and scarcity variables, which both push yields down in the same direction as the spotlight effect as in Table 10.

[Table 13 about here.]

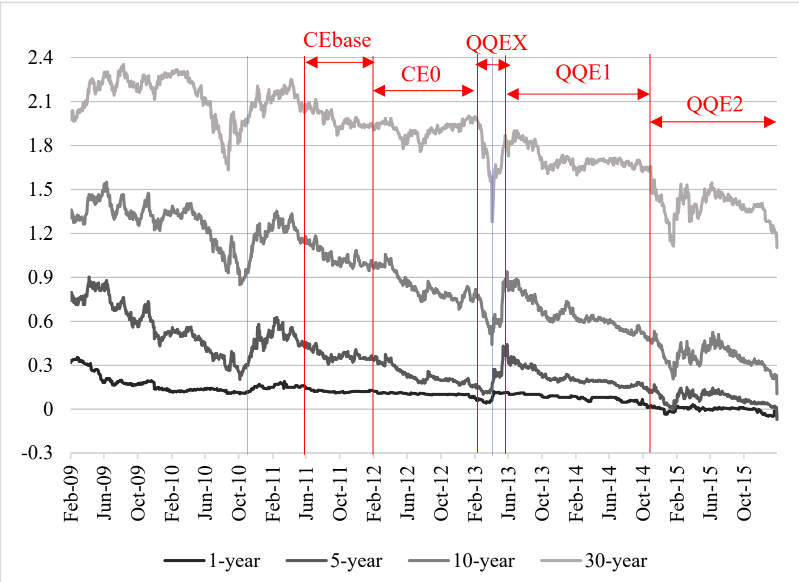
[Table 14 about here.]

Figure 1: Time line of the Bank of Japan (BoJ)'s monetary policies



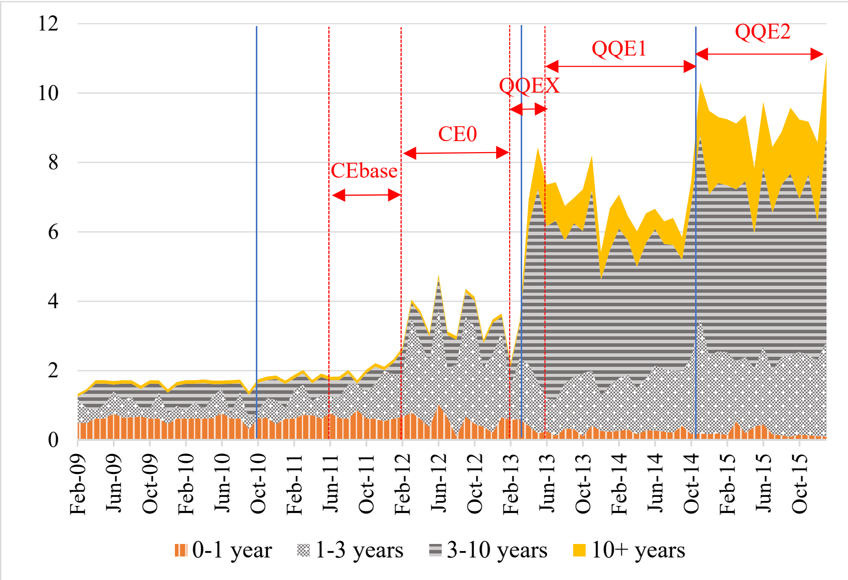
Note: This figure outlines the time line of recent monetary policies implemented by the BoJ. The information announced for each QQE program is collected on the BoJ's website.

Figure 2: Historical yield of JGBs



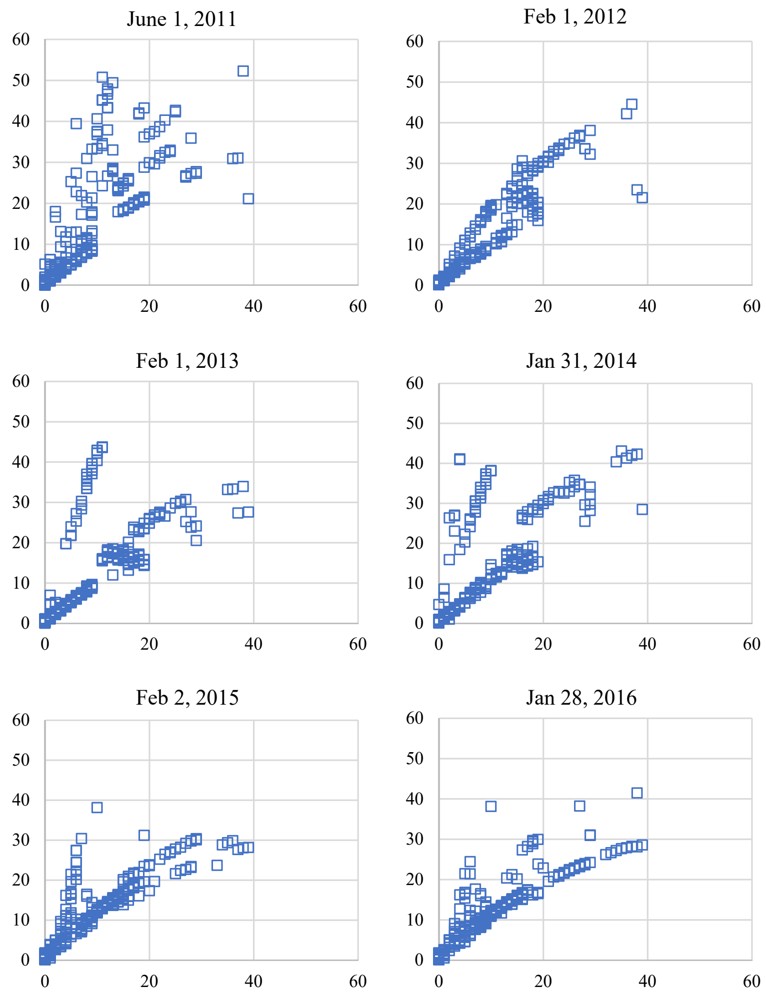
Note: The time-series evolution of the JGB yield with remaining maturities of 1, 5, 10, and 30 years, in order of color darkness. The daily yield data are obtained from the Japanese Ministry of Finance (MOF) website and covers the period from February 1, 2009, to January 28, 2016. The QE period from June 2011 is divided into five subperiods: The CEbase from June 1, 2011, to January 31, 2012, the CE0 from February 1, 2012, to February 27, 2013, the QQEX from February 28, 2013, to May 31, 2013, the QQE1 from June 1, 2013, to October 30, 2014, and the QQE2 from October 31, 2014, to January 28, 2016.

Figure 3: The BoJ's monthly purchase amounts of nominal JGBs (in trillions of yen)



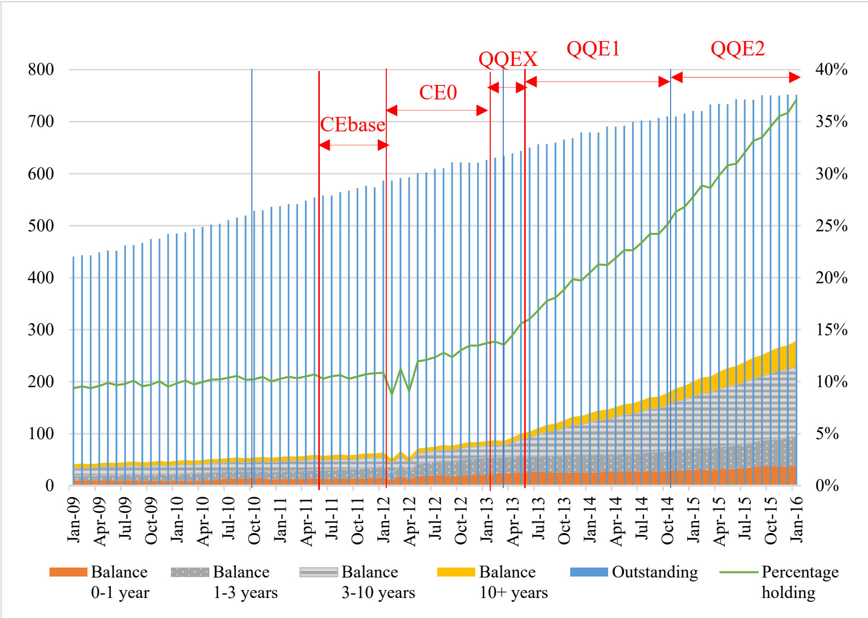
Note: The orange, dotted-gray, gray-striped, and yellow areas indicate the BoJ's monthly purchase amounts of bonds with a remaining maturity of less than 1 year, between 1 and 3 years, between 3 and 10 years, and more than 10 years, respectively. We calculate these by the increments of the amounts held by the BoJ. Recall that our data consist of the amounts of all nominal JGBs held by the BoJ from February 2009 to January 2016. The characteristics of each security, such as the issue date, the redemption date, and outstanding amounts, are publicly available on the MOF's website. The amounts held by the BoJ, periodically announced on the BoJ's website, are downloaded from there. Information about newly issued bonds is from the MOF and the Japan Securities Dealers Association website.

Figure 4: Liquidity term structure of the bid–ask spread



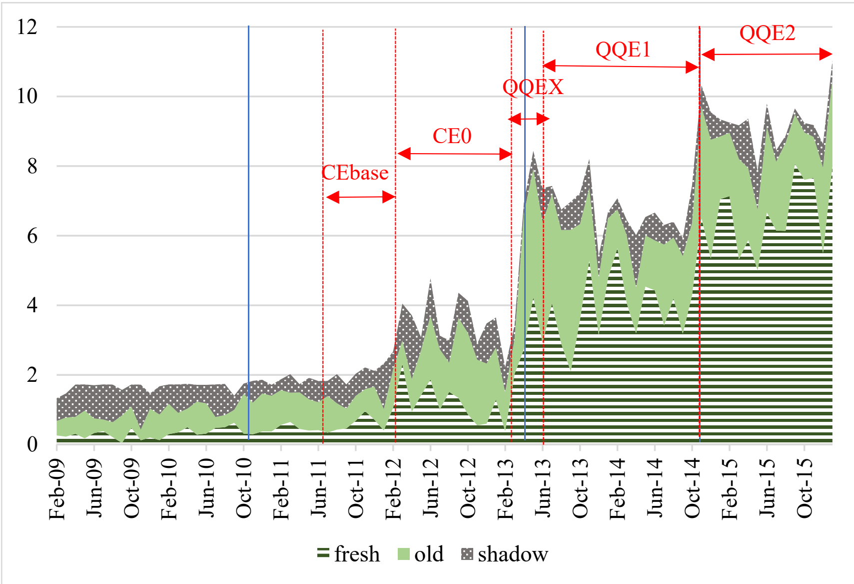
Note: This figure shows the distribution of the bid–ask spread (in bps) for individual JGBs for six randomly selected days at about one-year intervals in our sample period (May 2011 through January 2016). We exclude bonds with fewer than 90 days to redemption. The bid–ask spread is defined as $(askprice - bidprice)/midprice$ at the end of the days from Bloomberg. The daily price and best quote data at the end of each trading day are obtained from Bloomberg for the period from June 1, 2011, to January 28, 2016. The characteristics of each security, such as the issue date, the redemption date, and outstanding amounts, are publicly available on the MOF's website. Information about newly issued bonds is from the MOF and the Japan Securities Dealers Association website.

Figure 5: Outstanding amounts and the BoJ's holdings of nominal JGBs (in trillions of yen)



Note: The blue bars are the monthly outstanding amounts of nominal JGBs. The orange, dotted, striped, and yellow areas indicate the BoJ's holdings of nominal bonds with maturities of less than 1 year, 1 to 3 years, 3 to 10 years, and more than 10 years, respectively. The green line is the BoJ's holding ratio. Our data consist of all nominal JGBs outstanding from February 2009 to January 2016. The characteristics of each security, such as the issue date, the redemption date, and outstanding amounts, are publicly available on the MOF's website of the issuer. The amounts held by the BoJ, periodically announced on the BoJ's website, are downloaded from there. The information announced for each reverse auction is collected from Reuters News and Nikkei Telecom. Information about newly issued bonds is from the MOF and the Japan Securities Dealers Association website.

Figure 6: The BoJ's monthly purchase amounts of fresh, old, and shadow bonds (in trillions of yen)



Note: The green-and-white-striped area indicates the BoJ's monthly purchase amounts of fresh bonds, the pale-green area indicates those of old bonds, and the gray dotted area indicates those of shadow bonds. Our definition of fresh bonds consists of those whose age is less than one year. Shadow bonds are those with a residual time to maturity that corresponds to that of others with shorter original maturity in the market. Old bonds consist of those between fresh and shadow bonds. We calculate these areas by the increments of the amounts held by the BoJ. Our data consist of the amounts of all nominal JGBs held by the BoJ from February 2009 to January 2016. The data sets are obtained from the BoJ website. The characteristics of each security, such as the issue date, the redemption date, and outstanding amounts, are publicly available on the MOF's website. Information about newly issued bonds is from the MOF and the Japan Securities Dealers Association websites.

Table 1. Summary of the BoJ's LSAPs

(a) The average numbers of the BoJ's purchase operations for each target range in a month

	0–1 y	1–10 y		10+ y	Total
CEbase	1.99	5.59		0.99	8.57
CE0	2.01	7.90		1.01	10.92
QQEX	1.96	9.49		2.62	14.07
	0–1 y	1–3 y	3–10 y	10+ y	Total
QQE1	2.00	6.01	12.01	6.30	26.32
QQE2	2.01	6.02	12.04	10.03	30.10

(b) The BoJ's monthly purchase amounts (in billions of yen) for each maturity range

	0–1 y	1–3 y	3–10 y	10+ y	Total
CEbase	654.2	909.8	332.5	99.7	1996.3
CE0	553.7	2112.0	726.5	101.0	3493.1
QQEX	391.7	1643.0	3434.5	688.1	6157.2
QQE1	256.9	1512.7	4095.7	891.6	6756.9
QQE2	211.2	2289.9	4882.4	1937.9	9321.4

Note: Panels (a) and (b) show the number of the BoJ's operations and monthly purchase amounts, respectively. In panel (a), the target ranges for the auctions are segmented into three distinct buckets, such as less than 1 year, 1 to 10 years, and more than 10 years for the CEbase, CE0, and QQEX periods, and after QQE1, they are announced as four periods such as less than 1 year, 1 to 3 years, 3 to 10 years, and more than 10 years for the first and second QQE periods, respectively. The period is divided into five subperiods: The CEbase from June 1, 2011, to January 31, 2012, the CE0 from February 1, 2012, to February 27, 2013, the QQEX from February 28, 2013, to May 31, 2013, the QQE1 from June 1, 2013, to October 30, 2014, and the QQE2 from October 31, 2014, to January 28, 2016. The amounts held by the BoJ, periodically announced on the BoJ's website, are downloaded from there. The characteristics of each security, such as the issue date, the redemption date, and outstanding amounts, are publicly available on the MOF's website. Information about newly issued bonds is from the MOF and the Japan Securities Dealers Association website.

Table 2. Descriptive statistics of the bond yield

		0–1 year	1–3 years	3–10 years	10+ years	Entire sample
CEbase	Average	13.520	15.100	55.140	162.600	15.330
	Median	12.000	14.330	49.590	167.300	9.926
	Std. Dev.	4.683	2.796	25.807	27.101	67.958
	Observations	2924	8279	13221	17566	41990
CE0	Average	10.980	10.320	40.070	147.500	12.650
	Median	10.170	10.100	34.130	153.400	9.154
	Std. Dev.	3.513	2.147	24.491	31.318	65.293
	Observations	6140	11992	23024	29592	70748
QQEX	Average	9.163	9.744	35.640	125.900	10.050
	Median	9.749	11.200	32.800	130.800	8.940
	Std. Dev.	2.664	4.432	20.861	33.463	56.870
	Observations	1563	2671	5556	7184	16974
QQE1	Average	8.530	9.044	32.920	121.800	11.430
	Median	7.999	8.834	27.720	121.600	10.680
	Std. Dev.	4.926	2.561	18.833	35.636	55.995
	Observations	7123	15214	31557	40225	94119
QQE2	Average	1.062	0.501	14.240	88.160	10.830
	Median	0.608	0.500	10.650	84.200	9.590
	Std. Dev.	2.741	2.022	11.779	33.933	45.706
	Observations	6441	13861	28039	34151	82492

Note: This table shows the average, median, and standard deviation of the bond yield (in bps) for each remaining maturity. We exclude bonds with fewer than 90 days to redemption. The period is divided into five subperiods: The CEbase from June 1, 2011, to January 31, 2012, the CE0 from February 1, 2012, to February 27, 2013, the QQEX from February 28, 2013, to May 31, 2013, the QQE1 from June 1, 2013, to October 30, 2014, and the QQE2 from October 31, 2014, to January 28, 2016. The yield is computed by the end-of-day price from Bloomberg. The daily price and best quote data at the end of each trading day are obtained from Bloomberg for the period from June 1, 2011, to January 28, 2016. The characteristics of each security, such as the issue date, the redemption date, and outstanding amounts, are publicly available on the MOF's website. Information about newly issued bonds is from the MOF and the Japan Securities Dealers Association website.

Table 3. Descriptive statistics of the bid–ask spread

		0–1 year	1–3 years	3–10 years	10+ years	Entire sample
CEbase	Average	0.965	2.616	8.984	28.500	15.330
	Median	0.800	2.174	7.142	25.480	9.926
	Std. Dev.	0.604	1.624	6.232	10.009	13.644
	Observations	2924	8279	13221	17566	41990
CE0	Average	0.937	2.206	10.160	21.240	12.650
	Median	0.799	1.844	6.761	18.290	9.154
	Std. Dev.	0.538	1.549	9.560	8.291	11.055
	Observations	6140	11992	23024	29592	70748
QQEX	Average	0.662	2.100	7.120	17.310	10.050
	Median	0.600	1.852	6.618	15.110	8.940
	Std. Dev.	0.334	1.189	3.505	5.683	7.818
	Observations	1563	2671	5556	7184	16974
QQE1	Average	0.869	2.647	11.030	16.940	11.430
	Median	0.693	1.899	7.206	14.720	10.680
	Std. Dev.	0.959	2.963	9.775	6.044	9.115
	Observations	7123	15214	31557	40225	94119
QQE2	Average	0.945	2.706	8.284	18.070	10.830
	Median	0.800	2.488	7.670	16.260	9.590
	Std. Dev.	0.543	1.415	4.178	6.393	8.115
	Observations	6441	13861	28039	34151	82492

Note: This table shows the average, median, and standard deviation of the bid–ask spread (in bps) for each remaining maturity. We exclude bonds with fewer than 90 days to redemption. The period is divided into five subperiods: The CEbase from June 1, 2011, to January 31, 2012, the CE0 from February 1, 2012, to February 27, 2013, the QQEX from February 28, 2013, to May 31, 2013, the QQE1 from June 1, 2013, to October 30, 2014, and the QQE2 from October 31, 2014, to January 28, 2016. The bid–ask spread is defined as $(askprice - bidprice)/midprice$ at the end of the day from Bloomberg. The daily price and best quote data at the end of each trading day are obtained from Bloomberg for the period from June 1, 2011, to January 28, 2016. The characteristics of each security, such as the issue date, the redemption date, and outstanding amounts, are publicly available on the MOF's website. Information about newly issued bonds is from the MOF and the Japan Securities Dealers Association website.

Table 4. The BoJ's holding ratio of fresh, old, and shadow bonds (%)

		0–1 y	1–3 y	3–10 y	10+ y	Total
CEbase	*fresh*	23.2	6.1	0.3	0.2	2.2
	old	18.7	8.1	6.9	9.4	9.6
	shadow	29.9	24.1	22.7	5.8	23.1
CE0	*fresh*	32.2	21.0	0.5	0.3	6.9
	old	20.7	19.5	7.4	9.1	9.8
	shadow	31.7	22.9	23.5	5.5	23.5
QQEX	*fresh*	43.9	19.0	1.7	0.4	7.2
	old	35.8	32.7	8.9	8.3	11.3
	shadow	26.1	22.6	25.3	5.6	22.6
QQE1	*fresh*	20.7	20.2	25.9	12.0	20.4
	old	33.2	24.9	17.8	10.6	14.7
	shadow	27.3	25.2	29.2	9.2	25.4
QQE2	*fresh*	53.3	33.5	44.4	24.6	35.1
	old	47.2	39.8	33.4	15.6	23.5
	shadow	31.2	28.3	35.3	18.3	30.6

Note: This table shows the BoJ's holding ratio of fresh, old, and shadow bonds for each remaining maturity. The fresh bonds are those within one year of issuance and the shadow bonds have time to maturity that enters into the range of other original maturity bonds. The old bonds are those between fresh and shadow bonds. Our data consist of the amounts of all nominal JGBs held by the BoJ from February 2009 to January 2016. The data sets are obtained from the BoJ website. The characteristics of each security, such as the issue date, the redemption date, and outstanding amounts, are publicly available on the MOF's website. Information about newly issued bonds is from the MOF and the Japan Securities Dealers Association websites.

Table 5. Correlation matrix

CEbase	*target*	*purchased*	*h*	Coupon	*lnO*
purchased	0.2361				
h	−0.0103	0.0455			
Coupon	−0.1477	−0.0777	0.2955		
lnO	0.134	0.0449	−0.317	−0.6221	
τ	−0.1663	−0.0755	−0.4265	0.3117	−0.3052

CE0	*target*	*purchased*	*h*	Coupon	*lnO*
purchased	0.2427				
h	0.0168	0.0716			
Coupon	−0.1301	−0.0966	0.1505		
lnO	0.1208	0.0553	−0.2551	−0.6367	
τ	−0.1814	−0.0792	−0.4955	0.3567	−0.2932

QQEX	*target*	*purchased*	*h*	Coupon	*lnO*
purchased	0.1917				
h	−0.0098	0.0478			
Coupon	−0.0504	−0.1007	0.0486		
lnO	0.0548	0.053	−0.182	−0.6561	
τ	−0.0627	−0.0675	−0.5266	0.392	−0.2917

QQE1	*target*	*purchased*	*h*	Coupon	*lnO*
purchased	0.2368				
h	−0.0166	0.0729			
Coupon	−0.0132	−0.0972	−0.0501		
lnO	0.0165	0.0831	−0.0367	−0.6721	
τ	0.0067	−0.0313	−0.4877	0.3958	−0.2712

QQE2	*target*	*purchased*	*h*	Coupon	*lnO*
purchased	0.1902				
h	0.0117	0.0456			
Coupon	0.0028	−0.0931	−0.311		
lnO	0.0026	0.0578	0.1563	−0.6935	
τ	−0.0031	−0.0121	−0.4143	0.4292	−0.2462

Note: This table shows a correlation between candidates for explanatory variables: target dummy, *target*; the amount purchased in the previous auction, *purchased*; the relative holding ratio of the bond, *h*; coupon rate, and the logarithm of the amount outstanding, *lnO*. The characteristics of each security, such as the issue date, the redemption date, and outstanding amounts, are publicly available on the MOF's website. The amounts held by the BoJ, periodically announced on the BoJ's website, are downloaded from there. The information announced for each reverse auction is collected from Reuters News and Nikkei Telecom. Information about newly issued bonds is from the MOF and the Japan Securities Dealers Association website.

Table 6. Differences in the bid–ask spreads during the two sample periods

		CE0		QQEX		QQE1		QQE2	
0–1 y	CEbase	−0.028	**	−0.304	***	−0.096	***	−0.020	
1–3 y		−0.409	***	−0.516	***	0.033		0.090	***
3–10 y		1.177	***	−1.865	***	2.048	***	−0.702	***
10+ y		−7.184	***	−11.114	***	−11.482	***	−10.323	***
0–1 y	CE0			−0.276	***	−0.068	***	0.008	
1–3 y				−0.106	***	0.443	***	0.500	***
3–10 y				−3.042	***	0.871	***	−1.879	***
10+ y				−3.930	***	−4.298	***	−3.139	***
0–1 y	QQEX					0.208	***	0.284	***
1–3 y						0.549	***	0.606	***
3–10 y						3.913	***	1.163	***
10+ y						−0.368	***	0.792	***
0–1 y	QQE1							0.076	***
1–3 y								0.057	**
3–10 y								−2.750	***
10+ y								1.159	***

Note: This table shows the Welch two-sample t-test, whose alternative hypothesis is that the true difference in means is not equal to zero. Each sample consists of bonds with maturities longer than 90 days to redemption. The differences in the bid–ask spreads for the two sample periods and the statistical significance of the tests are shown in the table. The bid–ask spread is computed as (ask price − bid price)/mid-price at the end of the day from Bloomberg. Asterisks indicate statistical significance at the 10% (*), 5% (**), and 1% (***) levels. The period is divided into five subperiods: The CEbase from June 1, 2011, to January 31, 2012, the CE0 from February 1, 2012, to February 27, 2013, the QQEX from February 28, 2013, to May 31, 2013, the QQE1 from June 1, 2013, to October 30, 2014, and the QQE2 from October 31, 2014, to January 28, 2016. The daily price and best quote data at the end of each trading day are obtained from Bloomberg for the period from June 1, 2011, to January 28, 2016. The characteristics of each security, such as the issue date, the redemption date, and outstanding amounts, are publicly available on the MOF's website. Information about newly issued bonds is from the websites of the MOF and the Japan Securities Dealers Association.

Table 7. Cross-sectional regression of the bid–ask spread

PANEL A

		CEbase		CE0		QQEX		QQE1		QQE2	
Spotlight	*target*	0.2638		0.7748	**	1.0438	**	0.9227	***	0.1856	
		(0.75)		(1.98)		(2.55)		(3.08)		(1.35)	
	purchased	0.1498	**	−0.1467	***	−0.0500	*	−0.1068	***	−0.0436	***
		(2.09)		(−3.27)		(−1.80)		(−3.23)		(−2.61)	
Scarcity	h	0.5319	***	1.7438	***	0.3570	***	1.8603	***	0.3991	***
		(2.89)		(5.00)		(4.67)		(5.58)		(4.70)	
Control	lnO	−4.1527		−2.7496	***	−0.8972		−3.1722		−0.2264	***
		(−12.21)		(−6.67)		(−9.43)		(−9.29)		(−3.79)	
	τ	1.8821		1.6238		1.1128		0.9839		1.2092	
		(25.46)		(15.84)		(27.63)		(15.80)		(72.67)	
	τ^2	−0.0196		−0.0209	***	−0.0081	***	−0.0070	***	−0.0117	
		(−8.92)		(−6.99)		(−6.22)		(−3.99)		(−24.87)	
	Observations	41990		70748		16974		94119		82492	
	Adjusted R squared	0.824		0.674		0.907		0.650		0.840	

PANEL B

	CEbase	CE0		QQEX	QQE1	QQE2
Intercept	0.000068	0.000131		0.001597	0.000108	0.000056
	(0.000)	(0.001)		(0.017)	(0.001)	(0.002)
Unexpected purchase	−0.00647	−0.05463	*	−0.02406	0.00392	−0.01179
	(−0.109)	(−1.698)		(−1.529)	(0.257)	(−0.965)
Adjusted R squared	−0.00002	0.00008		0.00011	−0.00001	0.00000

Note: This table presents the results for the two-steps cross-sectional regression of the bid–ask spread for the five periods with time-fixed effects. The sample consists of nominal JGBs outstanding with remaining maturities of at least 90 days. In Panel A, the dependent variable is the bid–ask spread in bps and the regressors are target dummy, *target*; the amount purchased in the previous auction, *purchased*; the relative holding ratio of the bond, h; the logarithm of the amount outstanding, lnO; and the remaining time to maturity, τ, and its square. The regression equation is presented in Eq. (7). In this table, the daily time dummies are not shown. In Panel B, the dependent variable is the residuals calculated in Eq. (7) and the regressor is the unexpected purchase. The regression equation is presented in Eq. (8). The t-values are in parentheses and are calculated from double-cluster-robust standard errors. Asterisks indicate statistical significance at the 10% (*), 5% (**), and 1% (***) levels. The daily price and best quote data at the end of each trading day are obtained from Bloomberg for the period from June 1, 2011, to January 28, 2016. The characteristics of each security, such as the issue date, the redemption date, and outstanding amounts, are publicly available on the MOF's website. The amounts held by the BoJ, periodically announced on the BoJ's website, are downloaded from there. The information announced for each reverse auction is collected from Reuters News and Nikkei Telecom. Information about newly issued bonds is from the MOF and the Japan Securities Dealers Association website.

Table 8. The spotlight and scarcity effects of the three bond-life stages on the spread

		CEbase		CE0		QQEX		QQE1		QQE2	
Spotlight	*target*	1.6426	***	1.4223	***	1.1429	***	0.1705		0.2112	
		(3.40)		(3.32)		(3.17)		(0.85)		(1.21)	
	purchased	−0.3620	***	0.0133		−0.0304	**	0.0109		−0.0259	*
		(−4.89)		(0.46)		(−2.36)		(0.61)		(−1.74)	
Scarcity	*h*	3.1792	***	1.0244	***	0.3675	***	0.3145	*	−0.0113	
		(4.85)		(4.03)		(3.87)		(1.84)		(−0.13)	
Life stage	*old*	1.4878	***	−0.8252		0.3772		−1.5568	***	−0.4657	***
		(2.73)		(−1.37)		(1.51)		(−3.11)		(−2.98)	
Cross term	*target* × *old*	−2.0156	***	−1.0207	***	−0.1077		−0.0202		−0.0882	
with		(−4.83)		(−2.84)		(−0.27)		(−0.14)		(−0.51)	
old	*purchased* × *old*	0.4157	***	−0.2880	***	−0.0201		0.1335	***	−0.0363	
		(3.00)		(−3.09)		(−0.33)		(2.60)		(−0.55)	
	h × *old*	−1.7924	***	1.8745	***	−0.0373		0.7813	**	0.3026	***
		(−2.70)		(3.25)		(−0.35)		(2.28)		(2.77)	
Life stage	*shadow*	1.8829	***	2.3894	**	0.5655	**	−1.0126		−0.4333	**
		(2.88)		(2.50)		(2.10)		(−1.28)		(−2.51)	
Cross term	*target* × *shadow*	−1.3176	***	−0.9085	*	−0.1637		1.4229	***	−0.0211	
with		(−3.7)		(−1.7)		(−0.3)		(3.3)		(−0.1)	
shadow	*purchased* × *shadow*	0.4757	***	−0.3085	***	−0.0806		−0.4050	*	−0.0873	*
		(3.8)		(−2.7)		(−0.8)		(−1.8)		(−1.9)	
	h × *shadow*	-3.2269	***	−0.0965		−0.0039		3.0238	***	0.7962	***
		−4.89		(−0.24)		(−0.03)		(4.40)		(4.31)	
Control	*lnO*	−4.3408	***	−2.5198	***	−0.7853	***	−2.0774	***	−0.0479	
		(−12.55)		(−6.21)		(−8.02)		(−6.55)		(−0.93)	
	τ	1.7653	***	1.6274	***	1.1274	***	1.2303	***	1.2446	***
		(26.45)		(15.44)		(26.04)		(15.68)		(72.92)	
	τ^2	−0.0163	***	−0.0199	***	−0.0083	***	−0.0124	***	−0.0124	***
		(−8.77)		(−6.76)		(−6.17)		(−5.83)		(−25.98)	
	Observations	41990		70748		16974		94119		82492	
	Adjusted R squared	0.8313		0.6837		0.9071		0.6781		0.8407	

Note: This table presents the results for the cross-sectional regression of the bid–ask spread with two dummies of the bond-life stage and their cross terms with the spotlight and scarcity effects. The sample consists of nominal JGBs outstanding with remaining maturities of at least 90 days. The dependent variable is the bid–ask spread in bps and the regressors are two bond-life stage dummies, $old_{n,t}$ and $shadow_{n,t}$; and the cross terms of the dummies with the spotlight and scarcity variables. The regression equation is presented in Eq. (9). In this table, the daily time dummies are not shown. The t-values are in parentheses and are calculated from cluster-robust standard errors. Asterisks indicate statistical significance at the 10% (*), 5% (**), and 1% (***) levels. The daily price and best quote data at the end of each trading day are obtained from Bloomberg for the period from June 1, 2011, to January 28, 2016. The characteristics of each security, such as the issue date, the redemption date, and outstanding amounts, are publicly available on the MOF's website. The amounts held by the BoJ, periodically announced on the BoJ's website, are downloaded from there. The information announced for each reverse auction is collected from Reuters News and Nikkei Telecom. Information about newly issued bonds is from the MOF and the Japan Securities Dealers Association website.

Table 9. Differences in the bond yields for two sample periods

		CE0		QQEX		QQE1		QQE2	
0–1 y	CEbase	−2.54	***	−4.36	***	−4.99	***	−12.46	***
1–3 y		−4.79	***	−5.36	***	−6.05	***	−14.60	***
3–10 y		−15.07	***	−19.49	***	−22.21	***	−40.89	***
10+ y		−15.00	***	−36.59	***	−40.61	***	−74.14	***
0–1 y	CE0			−1.82	***	−2.45	***	−9.92	***
1–3 y				−0.57	***	−1.27	***	−9.82	***
3–10 y				−4.41	***	−7.14	***	−25.82	***
10+ y				−21.59	***	−25.61	***	−59.14	***
0–1 y	QQEX					−0.63	***	−8.10	***
1–3 y						−0.70	***	−9.25	***
3–10 y						−2.73	***	−21.40	***
10+ y						−4.02	***	−37.55	***
0–1 y	QQE1							−7.47	***
1–3 y								−8.55	***
3–10 y								−18.68	***
10+ y								−33.53	***

Note: This table shows the Welch two-sample t-test whose alternative hypothesis is that the true difference in means is not equal to zero. Each sample consists of bonds with longer than 90 days to redemption. The differences in the yields for the two sample periods and the significance of the tests are shown in the table. Asterisks indicate statistical significance at the 10% (*), 5% (**), and 1% (***) levels. The period is divided into five subperiods: The CEbase from June 1, 2011, to January 31, 2012, the CE0 from February 1, 2012, to February 27, 2013, the QQEX from February 28, 2013, to May 31, 2013, the QQE1 from June 1, 2013, to October 30, 2014, and the QQE2 from October 31, 2014, to January 28, 2016. The daily price and best quote data at the end of each trading day are obtained from Bloomberg for the period from June 1, 2011, to January 28, 2016. The characteristics of each security, such as the issue date, the redemption date, and outstanding amounts, are publicly available on the MOF's website. The amounts held by the BoJ, periodically announced on the BoJ's website, are downloaded from there. The information announced for each reverse auction is collected from Reuters News and Nikkei Telecom. Information about newly issued bonds is from the MOF and the Japan Securities Dealers Association website.

Table 10. Cross-sectional regression of the bond yield

PANEL A

		CEbase		CE0		QQEX		QQE1		QQE2	
Spotlight	*target*	−1.8128	*	−2.5104	**	−4.9577	***	−2.6341	***	−2.0725	***
		(−1.85)		(−2.47)		(−2.64)		(−4.66)		(−3.22)	
	purchased	1.3174	***	0.4457	***	0.3163	**	−0.0043		0.1891	*
		(4.00)		(3.62)		(1.98)		(−0.06)		(1.94)	
Scarcity	h	0.2022		0.0416		−0.8941		−3.3517	***	−3.6423	***
		(0.39)		(0.06)		(−1.36)		(−5.48)		(−4.32)	
Control	*lnO*	−2.4939	***	−3.5055	***	−2.8267	***	−2.6188	***	−0.4186	
		(−2.82)		(−3.78)		(−3.26)		(−3.97)		(−0.65)	
	τ	13.2195	***	11.5401	***	9.6507	***	9.1050	***	6.1685	***
		(68.65)		(44.55)		(30.13)		(40.39)		(27.38)	
	τ^2	−0.1926	***	−0.1442	***	−0.1154	***	−0.1003	***	−0.0362	***
		(−37.19)		(−18.36)		(−11.12)		(−12.75)		(−4.48)	
	Observations	41990		70748		16974		94119		82492	
	Adjusted R squared	0.982		0.969		0.956		0.966		0.956	

PANEL B

	CEbase	CE0	QQEX	QQE1	QQE2	
Intercept	0.00074	−0.00013	−0.01069	−0.00096	−0.00047	
	(0.001)	(0.000)	(−0.009)	(−0.002)	(−0.001)	
Unexpected purchase	−0.06966	0.05355	0.16100	−0.03476	0.09895	**
	(−0.560)	(0.821)	(1.042)	(−0.897)	(2.602)	
Adjusted R squared	−0.00002	0.00008	0.00011	−0.00001	0.00000	

Note: This table presents the results for the two-steps cross-sectional regression of the bond yields for the five periods with time-fixed effects. The sample consists of nominal JGBs outstanding with remaining maturities of at least 90 days. In Panel A, the dependent variable is the yield in bps and the regressors are target dummy, *target*; the amount purchased in the previous auction, *purchased*; the relative holding ratio of the bond, h; the logarithm of the amount outstanding, *lnO*; and the remaining time to maturity, τ, and its square. The regression equation is presented in Eq. (10). In this table, the daily time dummies are not shown. In Panel B, the dependent variable is the residuals of the first-step regression of bond yield and the regressor is the unexpected purchase. The t-values are in parentheses and are calculated from cluster-robust standard errors. Asterisks indicate statistical significance at the 10% (*), 5% (**), and 1% (***) levels. The daily price and best quote data at the end of each trading day are obtained from Bloomberg for the period from June 1, 2011, to January 28, 2016. The characteristics of each security, such as the issue date, the redemption date, and outstanding amounts, are publicly available on the MOF's website. The amounts held by the BoJ, periodically announced on the BoJ's website, are downloaded from there. The information announced for each reverse auction is collected from Reuters News and Nikkei Telecom. Information about newly issued bonds is from the MOF and the Japan Securities Dealers Association website.

Table 11. Spotlight and scarcity effects of the three bond-life stages on yield

		CEbase		CE0		QQEX		QQE1		QQE2	
Spotlight	*target*	−0.3216		−1.9668	**	−4.3306	**	−1.0120	*	−0.7117	
		(−0.36)		(−2.09)		(−2.38)		(−1.74)		(−1.30)	
	purchased	−0.2472		−0.0367		−0.0832		−0.2055	***	−0.0972	
		(−1.32)		(−0.48)		(−1.21)		(−2.90)		(−1.19)	
Scarcity	h	4.5776	***	3.2609	***	3.0609	***	−1.7884		−2.5366	**
		(2.96)		(4.29)		(3.55)		(−1.62)		(−2.09)	
Life stage	*old*	−0.6717		1.3444		−0.9364		−0.0576		−0.9076	
		(−0.47)		(0.81)		(−0.41)		(−0.03)		(−0.34)	
Cross term	*target* × *old*	−3.7994	***	−3.8755	***	−0.9677		−1.2153	***	−1.0295	**
with		(−3.49)		(−3.54)		(−0.70)		(−2.67)		(−2.50)	
old	*purchased* × *old*	1.7091	***	0.2542		−0.2005		0.0273		−0.1002	
		(2.81)		(1.35)		(−0.59)		(0.17)		(−0.51)	
	h × *old*	−3.0432	*	−3.8545	***	−3.5057	***	−1.9239		−1.0033	
		(−1.92)		(−4.38)		(−2.91)		(−1.37)		(−0.59)	
Life stage	*shadow*	−4.6328	**	−2.5638		3.3005		0.8787		1.0130	
		(−2.47)		(−1.04)		(1.29)		(0.39)		(0.42)	
Cross term	*target* × *shadow*	0.8559		1.7701		−1.1481		−2.6686	***	−2.0467	***
with		(1.0)		(1.6)		(−1.1)		(−5.7)		(−5.7)	
shadow	*purchased* × *shadow*	1.8376	***	0.5004	**	3.0433	***	0.2860		0.5695	*
		(3.8)		(2.1)		(3.0)		(1.6)		(1.7)	
	h × *shadow*	-4.4599	***	−3.3924	***	−4.9630	***	-2.0789		-2.2948	
		−2.77		(−2.96)		(−4.13)		(−1.31)		(−1.24)	
Control	*lnO*	−3.7752	***	−4.6327	***	−2.5329	***	−2.8738	***	−0.5768	
		(−3.99)		(−4.65)		(−2.66)		(−3.73)		(−0.79)	
	τ	12.8923	***	11.3671	***	9.8926	***	9.1183	***	6.2037	***
		(58.88)		(36.15)		(27.68)		(34.44)		(23.57)	
	τ^2	−0.1854	***	−0.1416	***	−0.1204	***	−0.1011	***	−0.0371	***
		(−33.81)		(−15.94)		(−11.02)		(−11.82)		(−4.29)	
	Observations	41990		70748		16974		94119		82492	
	Adjusted R squared	0.9831		0.9699		0.9574		0.9662		0.9566	

Note: This table presents the results for the cross-sectional regression of the bond yield with two dummies of the bond-life stage and their cross terms with the spotlight and scarcity effects. The sample consists of nominal JGBs outstanding with remaining maturities of at least 90 days. The dependent variable is the yield in bps. The regressors are two bond-life stage dummies, $old_{n,t}$ and $shadow_{n,t}$; and the cross term of the dummies with the spotlight and scarcity variables as in Eq. (9). In this table, the daily time dummies are not shown. The t-values are in parentheses and are calculated from cluster-robust standard errors. Asterisks indicate statistical significance at the 10% (*), 5% (**), and 1% (***) levels. The daily price and best quote data at the end of each trading day are obtained from Bloomberg for the period from June 1, 2011, to January 28, 2016. The characteristics of each security, such as the issue date, the redemption date, and outstanding amounts, are publicly available on the MOF's website. The amounts held by the BoJ, periodically announced on the BoJ's website, are downloaded from there. The information announced for each reverse auction is collected from Reuters News and Nikkei Telecom. Information about newly issued bonds is from the MOF and the Japan Securities Dealers Association website.

Table 12. Patterns of the BoJ's purchase operations for each life stage

		fresh	*old*	*shadow*	All
CEbase	# of targeted bonds	17.9	56.0	45.2	103.0
	# of dropped bonds	1.0	7.1	3.0	10.3
	Purchase rate	25.7	19.3	27.2	23.9
	Consecutive purchase	47.8	42.5	67.1	53.9
CE0	# of targeted bonds	16.7	38.4	47.0	98.6
	# of dropped bonds	1.6	7.3	3.9	12.1
	Purchase rate	44.5	23.9	43.7	36.8
	Consecutive purchase	80.1	50.7	70.7	64.2
QQEX	# of targeted bonds	18.7	58.5	46.7	124.0
	# of dropped bonds	1.7	5.4	2.9	8.2
	Purchase rate	47.6	24.7	26.3	28.7
	Consecutive purchase	79.5	68.0	75.4	72.4
QQE1	# of targeted bonds	18.1	70.8	46.5	135.4
	# of dropped bonds	1.5	5.9	3.5	7.5
	Purchase rate	56.0	35.9	27.5	35.7
	Consecutive purchase	69.3	45.2	45.5	49.8
QQE2	# of targeted bonds	16.5	68.6	55.7	140.7
	# of dropped bonds	1.0	4.0	1.2	4.7
	Purchase rate	45.5	22.1	15.0	22.0
	Consecutive purchase	73.1	35.4	29.4	42.6

Note: This table shows the number of targeted bonds per operation, the number of dropped bonds per operation, the proportion of purchased bonds in the targeted buckets for each life stage, and the rate of consecutive purchase. The fresh bonds are those within one year of issuance; the shadow bonds have time to maturity that enters into the range of other original maturity bonds. The old bonds are those between fresh and shadow bonds. The period is divided into five subperiods: The CEbase from June 1, 2011, to January 31, 2012, the CE0 from February 1, 2012, to February 27, 2013, the QQEX from February 28, 2013, to May 31, 2013, the QQE1 from June 1, 2013, to October 30, 2014, and the QQE2 from October 31, 2014, to January 28, 2016. The characteristics of each security, such as the issue date, the redemption date, and outstanding amounts, are publicly available on the MOF's website. The amounts held by the BoJ, periodically announced on the BoJ's website, are downloaded from there. The information announced for each reverse auction is collected from Reuters News and Nikkei Telecom. Information about newly issued bonds is from the MOF and the Japan Securities Dealers Association website.

Table 13. Cross-sectional regression of the weekly average bid–ask spread

		CEbase		CE0		QQEX		QQE1		QQE2	
Spotlight	*target*	0.0618		1.4189	**	1.0518		2.2423	***	0.2740	
		(0.16)		(2.24)		(1.37)		(4.31)		(1.64)	
	purchased	0.2612	***	−0.1255	*	−0.0076		−0.1058	***	0.0058	
		(4.92)		(−1.83)		(−0.39)		(−3.65)		(0.31)	
Scarcity	h	0.8481	***	1.8955	***	0.5122	***	1.4240	***	0.3423	***
		(3.43)		(4.64)		(5.13)		(4.65)		(3.13)	
Control	lnO	−4.6533	***	−3.4974	***	−1.0792	***	−3.6419	***	−0.3155	***
		(−10.40)		(−6.54)		(−8.81)		(−10.05)		(−2.83)	
	τ	1.9342	***	1.5861	***	1.1133	***	0.9316	***	1.2134	***
		(17.69)		(14.39)		(16.83)		(14.96)		(60.46)	
	τ^2	−0.0208	***	−0.0201	***	−0.0080	***	−0.0071	***	−0.0122	***
		(−5.81)		(−6.28)		(−5.44)		(−3.67)		(−23.54)	
Observations		7239		13899		3434		20567		17234	
Adjusted R squared		0.856		0.661		0.933		0.685		0.930	

Note: This table presents the results for the regression of the weekly bid–ask spread for the five periods. The sample consists of nominal JGBs outstanding with remaining maturities of at least 90 days. The dependent variable is the weekly average bid–ask spread in bps. The regression equation is similar to the daily model of Eq. (7). The regressors are the target dummy, *target*; the amount purchased in the previous auction, *purchased*; the relative holding ratio of the bond, h; the logarithm of the amount outstanding, lnO; and the remaining time to maturity, τ, and its square. We run the regression with weekly time dummies. In this table, the weekly time dummies are not shown. The t-values are in parentheses and are calculated from double-cluster-robust standard errors. Asterisks indicate statistical significance at the 10% (*), 5% (**), and 1% (***) levels. The price and best quote data at the end of each trading day are obtained from Bloomberg for the period from June 1, 2011, to January 28, 2016. The characteristics of each security, such as the issue date, the redemption date, and outstanding amounts, are publicly available on the MOF's website. The amounts held by the BoJ, periodically announced on the BoJ's website, are downloaded from there. Information about newly issued bonds is from the MOF and the Japan Securities Dealers Association website.

Table 14. Cross-sectional regression of the bond yield based on weekly data

		CEbase		CE0		QQEX		QQE1		QQE2	
Spotlight	*target*	−2.4156	**	−3.8985	***	−7.3984	***	−6.9898	***	−4.1926	***
		(−1.99)		(−2.87)		(−2.64)		(−5.91)		(−2.87)	
	purchased	0.3436		0.4528	***	0.2357		0.0439		0.1442	
		(1.31)		(3.10)		(0.77)		(0.56)		(1.44)	
Scarcity	h	−0.4591		−0.0199		−0.5446		−2.5562	***	−2.4964	***
		(−0.91)		(−0.03)		(−0.80)		(−4.21)		(−2.81)	
Control	*lnO*	−2.0898	***	−2.4476	***	−1.2268		0.0970		1.8317	**
		(−2.81)		(−2.70)		(−1.31)		(0.13)		(2.50)	
	τ	13.8988	***	11.7442	***	9.7958	***	9.2544	***	6.4291	***
		(43.96)		(39.21)		(22.06)		(34.14)		(26.98)	
	τ^2	−0.2155	***	−0.1542	***	−0.1226	***	−0.1051	***	−0.0450	***
		(−21.94)		(−19.13)		(−10.16)		(−11.74)		(−5.61)	
	Observations	6870		13199		3290		19733		16651	
	Adjusted R squared	0.986		0.975		0.959		0.966		0.961	

Note: This table presents the results for the cross-sectional regression of the weekly yield for the five periods. The sample consists of nominal JGBs outstanding with remaining maturities of at least 90 days. The dependent variable is the weekly average yield in bps. The regression equation is similar to the daily model of Eq. (10). The regressors are the target dummy, *target*; the amount purchased in the previous auction, *purchased*; the relative holding ratio of the bond, h; the logarithm of the amount outstanding, *lnO*; and the remaining time to maturity, τ, and its square. We run the regression with weekly time dummies. In this table, the weekly time dummies are not shown. The t-values are in parentheses and are calculated from double-cluster-robust standard errors. Asterisks indicate statistical significance at the 10% (*), 5% (**), and 1% (***) levels. The price and best quote data at the end of each trading day are obtained from Bloomberg for the period from June 1, 2011, to January 28, 2016. The characteristics of each security, such as the issue date, the redemption date, and outstanding amounts, are publicly available on the MOF's website. The amounts held by the BoJ, periodically announced on the BoJ's website, are downloaded from there. Information about newly issued bonds is from the MOF and the Japan Securities Dealers Association website.