Cover Risk

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Abstract

The common method of shorting an equity or fixed-income security is to borrow the security in the repurchase agreement (repo) market. Cover risk denotes the risk of short sellers being unable to find a counterparty, that is, failure to deliver. This risk increases when a central bank conducts a large-scale asset purchase (LSAP) program in the government bond market to reduce bond float. We build a search-theoretic model to explore the impact of LSAPs by introducing the interactions between short sellers, bondholders, and a central bank. We test the model prediction using data from a Japanese government bond electronic platform on specific intraday collateral repo transactions. We find cover risk rises as a central bank holds larger proportions of a bond. The rates are sensitive to the timing of order, with a delay of one hour estimated to raise the non-execution probability by 3.6%. Our results suggest that aggressive LSAPs weaken dealers' market-making capability.

Keywords: Short position; scarcity; large-scale asset purchase; search friction; repo
JEL classification: C54; E43; E52; E58; G12; G14

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1 Introduction

The common method of shorting an equity or fixed-income security is to borrow the security and sell it. This is the basic practice of dealers who make the over-the-counter market for government bonds. Securities can be borrowed through the repurchase agreement (repo) market or a lending facility operated by the central bank. When securities are hard to locate, brokers sometimes cannot fill the quantity of lendable shares requested. Occasionally, a significant amount of time can pass before the necessary securities can be located.

This study focuses on such market situations in which counterparties are becoming harder to find because the large fraction of qualified owners has been reduced because of the aggressive large-scale asset purchase (LSAP) conducted by the Bank of Japan (BoJ). Since the global financial crisis in 2008, the world's major central banks have engaged in unconventional monetary policies in the form of quantitative easing (QE) programs to stimulate their economies. These policies, however, have commonly reduced the availability of bonds from the secondary market, impairing bond market liquidity and activities.

With regard to central bank LSAPs, D'Amico et al. (2018) quantify the scarcity value of Treasury collateral. Corradin and Maddaloni (2017) highlight the importance of security-specific demand as determinants of specialness. Musto et al. (2017) show that local supply effects arising from the European Central Bank's purchasing program has had a similar impact on the frequency of failures to deliver.

Cover risk refers to the difficulty of locating a counterparty willing to trade a particular security, or a large quantity of a given security. According to Amihud et al. (2006), this is another source of illiquidity. A short seller must negotiate the price with her counterparty in a less than perfectly competitive environment, since alternative trading partners are not immediately available. This search friction is particularly relevant in over-the-counter markets in which there is no central marketplace.

A search-based theory has been developed for the over-the-counter securities lending market by Duffie et al. (2002), who construct a dynamic model for the determination of prices and lending fees. Their model implies that the lending fee effects are greater for a smaller float. Vayanos and Weill (2008) extend that work to multiple-asset model to clarify the premium of on-the-run bonds. In their calibration model, borrowers' longer search times are associated with greater specialness in the repo market due to the lower competition between lenders; however, the authors do not consider market scarcity.

We build a search-theoretic model based on the procedure of Vayanos and Weill (2008) and Ferdinandusse et al. (2018), specifically considering the scarcity effect on the repo market. Modeling the sovereign bond spot market in a search-theoretic framework based on the work of Duffie et al. (2005), Ferdinandusse et al. (2018) show that it becomes harder for buyers to find sellers as the stock of bonds becomes depleted on the secondary market by the QE program. We apply their procedure to explore the impact of LSAPs on the repo market. LSAPs increase the bond holding of the central bank and increase short sellers' repo demand, but they decrease the repo supply (amounts held by non–central bank investors). We introduce the interactions

between short sellers, lenders, and a central bank to the search-theoretic model and solve the utility flow functions for the repo borrowing fee through Nash bargaining. Our model predicts that the borrowing fee will increase and short sellers will need more time to find a counterparty, given the scarcity effect of LSAPs, and that each purchase operation will further increase the borrowing fee, due to the high demand for repo transactions. Our model differs from those of Duffie et al. (2002) and Vayanos and Weill (2008), in that theirs clarify the relation between prices in the cash market and lending fees, whereas we focus on the repo lending fees and the central bank's securities lending facility (SLF). The BoJ's SLF can be a last resort for short sellers to cover their position.

The government bond market in Japan provides an ideal setting for examining cover risk. In our sample period, from January 2013 to April 2018, the BoJ implemented LSAP programs by targeting Japanese government bonds (JGBs). The BoJ's holding of JGBs reached ¥416 trillion in March 2018, corresponding to about 85% of Japan's nominal gross domestic product, while its average holding ratio across JGBs jumped from 11.6% to 43.9%, unprecedented in the annals of central bank history. The BoJ holdings of some JGBs exceeds 85% of the outstanding debt, providing a natural experiment to determine how scarcity affects bond specialness and search frictions across bonds and maturities.

First, the scarcity effect is amplified in this period due to the large stock of bonds held by the BoJ and the resulting reduction in the quantity of bonds held by private investors. This makes it more difficult for dealers to locate specific bonds in the secondary market; hence, they face greater risk in holding a short position. Since dealers rely heavily on the repo market to locate specific bonds to cover short positions, analyzing repo market transactions is the best way to identify cover risk. This study aims to measure the difficulty of locating lendable securities. No study, as far as we know, has empirically investigated the relation between the amount of time necessary to locate specific securities and the borrowing fees sacrificed to cover a short position. We expect that, in the case of highly scarce bonds, it takes longer to find a counterparty and/or the costs of borrowing are higher.

In the search process, a trader submits a bid rate based on the bond's scarcity and assessment of the search difficulty. The trader might under- or overestimate search friction, so that the actual search time and cost depend on the initial order rate. Tick-by-tick information from the JBond Totan Securities (JBOND) repo platform allows us to compute the length of time and incremental costs of borrowing. We measure the interval between the initial submission time and the time of execution or cancellation. There are also cases in which an order for a bond is not filled until market closure. Additionally, we measure the difference between the initial bid rate and the filled (or final) rate. We expect greater scarcity to be associated with higher costs, and larger degrees of underestimation (overestimation) to be associated with longer (shorter) times to execution and greater (smaller) incremental borrowing costs. We expect longer times and higher rate concession to execution when the initial fee is lower than the consensus fee based on the empirical model.

Second, we investigate a specific effect on days when the BoJ conducts its bond purchase operations. On those days, JGB dealers submit their offers for bonds in the BoJ's target list

(eligible bonds). In case the BoJ purchases a bond they offered, they need to find the bond in the repo markets. We find that nearly 50% of purchased bonds have corresponding bid orders in the repo market operated by the JBOND electronic platform after the purchase operation on the same day.[1]

Third, a central bank, such as the BoJ, starts a facility to lend the bonds it holds to dealers upon their request. Since the central bank strengthens the functional role of lending securities through its inventory, the scarcity effect and cover risk should be mitigated. Toward to the end of our sample periods, the demand for the central bank's lending facility increases. An interesting question concerns the relation between the official lending rate of the BoJ and the rate determined in the repo market.

In our empirical studies, we examine the relation between specialness and scarcity measured by the BoJ holding ratio and find a positive association between them after the BoJ began aggressive QE programs. We have access to all orders submitted to the JBOND market during a day, 69.1% of which are filled, 30.7% of which are canceled, and 0.2% of which are unfilled in our entire sample periods. The rate of unfilled orders rises as the BoJ's holding ratio increases. Orders submitted late in the day, such as after 3 p.m., have a higher level of specialness and the rate of unfilled orders then rises to nearly 40%. We estimate the order execution probability, one of the key variables to measure cover risk, using a panel probit model conditional on bond scarcity, the order size, and the time remaining to market close. We show that cover risk rises when a bond is scarcer and the remaining time is shorter. The higher the BoJ holding ratio, the greater the specialness. The average specialness of filled bid orders entered between 3 p.m. and 4 p.m. in the most recent sample period (September 2016 to April 2018) is 9.3 bps, and that of unfilled orders is 30.8 bps. The specialness of unfilled orders is three times higher than filled orders, but still no counterparty can be found. We also estimate the determinants of the rate concession and the length of negotiation for filled, canceled, and unfilled orders. Our empirical results are consistent with the model's predictions. They show that bond borrowers raise initial specialness according to the scarcity level after the expansion of quantitative and qualitative easing (QQE). According to the estimated model, the final borrowing rates dropped by about 0.13–0.19 bps from the initial bid rate, and their negotiation times increased by up to 2.3 minutes as the BoJ holding rate rose by 10%.

Next, we conduct event studies on the BoJ's purchase operation and measure its impact on borrowing rates. The BoJ reports back to dealers the results of its operation (auction) around noon, so that, if a dealer posts an offer without a position, the dealer will need to locate the bond sold to the BoJ. We can thus study whether the BoJ's purchase increases the search friction. The panel regressions indicate that the larger the amounts the BoJ purchases, the greater the degree of specialness of the bid order a dealer places. The costs to cover a short position increase as the bonds are purchased in the BoJ operation.

We further test the impact of the SLF. In 2014, the BoJ improved the usability of its lending facility by adding a morning operation, making the facility available twice a day. The

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[1]A total of 18% of the bonds purchased by the BoJ had corresponding bid orders in the repo market before the BoJ started the LSAP, which rose to 49% at the end of our sample period.

lending amount per issue was also raised in 2015 and again in 2016. After February 2016, the BoJ set the lending rate at -0.5% (or -0.6%), which is lower than the usual rate available in the repo market. If the special collateral (SC) rate drops below the BoJ's lending rate, dealers will borrow bonds from the BoJ. We thus expect the BoJ's lending facility to have a ceiling effect on the SC repo rate. In the period after September 2016, we find a ceiling effect on the bid rate. This means dealers price the bid rate in the repo market according to the level of the lending rate set by the BoJ's SLF.

The remainder of this paper is organized as follows. Section 2 reviews the literature. Section 3 describes the repo market and the LSAP program conducted by the BoJ. Section 4 constructs a model based on search theory and presents the research hypotheses. Section 5 describes the empirical methodology and the results. Section 6 concludes the paper.

2   Literature

The seminal work of Duffie (1996) specifies a model describing the link between the repo and cash markets and shows that bonds trading on specialness should carry a price premium in the cash market. Jordan and Jordan (1997) empirically test most of Duffie's predictions and shed light on the role played by the liquidity of bonds (on-the-run issues) and the holders of a security, introducing the concept of the availability of a specific security. Both Duffie (1996) and Jordan and Jordan (1997) use sample data from the US repo market.

Duffie et al. (2002) have developed a search-based theory for the securities lending market, extended to multiple-asset model by Vayanos and Weill (2008). Duffie et al. (2002) study the over-the-counter market and construct a dynamic model for the determination of prices, lending fees, and short interest (the quantity of securities held short). Their model implies that lending fee effects are larger for a smaller float. The expected price decline associated with lending fees is then likely to be more pronounced in situations characterized by a high degree of belief heterogeneity and a small number of circulating shares. In the calibration model proposed by Vayanos and Weill (2008), borrowers' longer search times are associated with greater specialness in the repo market, due to the lower competition between lenders. The authors aim to clarify the premium of on-the-run bond, but do not consider market scarcity. Unlike their setting, we address the case in which the demand for repo transactions is high because of the purchase operations of the central bank and in which collateral bonds have become scarce in the market due to the LSAPs.

Duffie et al. (2005) build a dynamic asset-pricing model that captures search and bargaining features and analytically derive equilibrium allocations, prices negotiated between investors, as well as market makers' bid and ask prices. Duffie et al. (2007) show that illiquidity discounts are higher when counterparties are harder to find or the fraction of qualified owners is smaller. Ferdinandusse et al. (2018), whose paper is one of the closest to ours, model sovereign bond markets in a search-theoretic framework based on that of Duffie et al. (2005). They show that, as the stock of bonds becomes depleted on the secondary market by the QE program, it becomes harder for buyers to find a seller. The authors predict that the QE program

crowds out buyers besides the central bank and leads to lower bond liquidity. We apply their procedure to construct a model exploring the impact of LSAPs on the JGB repo market by introducing the interactions between short sellers, lenders, and a central bank.

There are many empirical works on the impacts of the QE programs on the repo market. Among them, D'Amico et al. (2018) quantify the scarcity value of Treasury collateral by estimating the impact of security-specific demand and supply factors on the repo rates of all outstanding US Treasury securities. This scarcity effect seems to pass through to Treasury cash market prices, providing additional evidence of the scarcity channel of QE. The US Federal Reserve System's reverse repo operations could help reduce scarcity premiums by alleviating potential shortages of high-quality collateral.

Corradin and Maddaloni (2017) highlight the importance of security-specific demand and introduce a novel measure of availability on the street by using the amount of a security that is available for trading, possibly linked to short-selling activity. The authors analyze the determinants of the quantiles of the distribution of specialness by means of quantile panel regressions, and they show that very special bonds are more sensitive to sizable changes in supply and demand. Kinugasa and Nagano (2017) examine the impact of the BoJ's QQE on repo specialness, using repo transaction data from May 2014 to March 2017. They show that the BoJ's holding ratio of JGBs increases repo specialness, and the BoJ's SLF mitigates bond scarcity.

Musto et al. (2017) show that a decline in the frequency of special trades is associated with an increase in the volume of failures. Local supply effects arising from the European Central Bank's Securities Markets Programme purchases also had a similar impact, but they were mitigated by the introduction of penalties for failure to deliver. Dunne et al. (2011) analyze how the crisis affected the bidding behavior of banks in refinancing operations in the euro area. Mancini et al. (2016) conduct a comprehensive study of the European repo market and show that the importance of the central counterparty-based segment in this market makes it more resilient during crises and even acts as a shock absorber.

Boissel et al. (2015) argue that central clearing counterparties provide some protection in periods of intermediate sovereign stress (2009–2010), but this protection became ineffective at the peak of the sovereign crisis (in 2011). Buraschi and Menini (2002) analyze more specifically the relation between the current term structure of special repos and future collateral values, using data on the German government repo market. Dufour and Skinner (2006) analyze the Italian BTP repo market. Arrata et al. (2018) show that most short-term interest rates in the euro area are below the European Central Bank deposit facility rate, the rate at which the central bank remunerates banks for excess reserves. Using proprietary data from a public sector purchase program's purchases and repo transactions for specific (special) securities, the authors assess the scarcity channel of the public sector purchase program and its impact on repo rates.

The SLF run by the central bank has a competitive and complementary relationship with the repo market. Fleming et al. (2010) assess the effectiveness of the term SLF of the central bank and find that it significantly narrowed repo spreads between Treasury collateral and less

liquid collateral. The authors find that the effects are driven by operations in which appreciably less liquid securities can be pledged as collateral and that such operations increase the repo rates for liquid non-Treasury collateral. We build a model considering the effects of SLFs on short sellers' behaviors.

3 Repo transactions and LSAPs in Japan

In this section, we first describe the role of repo transactions in the JGB market and summarize recent LSAP programs in Japan, which increased market scarcity. We next explain the BoJ's SLF, which has a competitive relationship with repo transaction.

3.1 Role of the repo market

A repo is a form of short-term (usually overnight) borrowing or lending in government securities. In a repo transaction, a lender turns over an asset to a borrower in exchange for cash. At maturity, the borrower returns the asset and the lender returns the cash, together with some previously agreed interest rate payment, called the repo rate. A repo transaction is categorized as either a general collateral (GC) repo or an SC repo. GC repo transactions cannot specify bonds to be traded mainly for the purpose of raising funds, and their rates are generally priced at a level close to the risk-free interest rate. On the other hand, SC repos are bond-specific transactions for the purpose of lending those bonds, and their rates are priced below the GC repo rates, according to bond availability.

The cash and repo markets are closely linked through short sales. The repo market is often used to create short-selling positions in the cash market. The most typical way is to sell a bond short in the cash market while simultaneously borrowing the same bond through an SC repo for the bond's delivery. Thus the specialness, often measured by the difference between the GC and SC rates, provides important information on short-selling pressures in the cash market. Many studies, such as Duffie's (1996), show that specialness increases with the amount of short-selling activity in the cash market and is driven by the demand for short positions, constraints on the available supply, and the liquidity of the security.

The reduction in available bonds increases the possibility of dealers being unable to close their short positions in the JGB cash market (Pelizzon et al. (2018)). Under market conditions with scarce bonds, the demand for procuring bonds in the repo market increases. The reduction in available bonds in the cash market is equivalent to the reduction of collateral for the repo market. The reduction of collateral increases the difficulty of borrowing the bonds. Therefore, the SC rate of a bond that is scarce in the market should be at a lower level and its degree of specialness should be higher (e.g., Corradin and Maddaloni (2017), D'Amico et al. (2018), Arrata et al. (2018), Brand et al. (2019)). We next describe increasing scarcity in the JGB market.

3.2   Summary of recent purchase programs

The amount traded in the JGB repo market during our sample period is increasing, which is partly attributed to increases in transactions by foreign investors and in the BoJ's JGB holdings. Purchase operations by a central bank have two different effects on the repo market: one is to increase the demand for repo transactions to cover short positions created in response to the BoJ's purchase operations, and the other is to reduce the supply of repo collateral generated by the BoJ's cumulative purchases.

Our sample period is from January 2013 to April 2018, due to the availability of the repo transaction data. A purchase program had already begun in 2013, but, on April 4, 2013, the BoJ announced the introduction of QQE, which increased its purchases of JGBs to an annual amount of about ¥50 trillion.[2] 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, approximately ¥30 trillion more than the previous amount, thus aiming to decrease interest rates across the entire yield curve and to shift its purchases further toward longer-term bonds. On January 29, 2016, the BoJ introduced QQE with a negative interest rate and revealed a policy of targeting negative interest rates and of continuing to purchase JGBs in amounts increasing by about ¥80 trillion annually. On September 21, 2016, the BoJ introduced QQE with yield curve control and announced its intent to purchase JGBs to maintain the 10-year JGB yield around 0%. The BoJ also announced the introduction of a new purchase operation tool: purchases of JGBs with yields designated by the BoJ (fixed-rate purchase operations).

Figure 1 shows the amounts (in trillions of yen) of nominal JGBs purchased by the BoJ and its holding ratio (%).

[Figure 1 about here.]

As shown in Figure 1, the BoJ gradually increased its holdings of JGBs before 2013, but accelerated its pace of bond purchases after the QQE announcement in April 2013. The monthly purchase amounts in the first QQE period (QQE-I) are approximately double the previous ones. After expansion of the QQE, in the second QQE period (QQE-II), the monthly purchase amounts increased and held at that level until the period of QQE with a negative interest rate (NI). After introducing yield curve control (YCC-I) on September 2016, the BoJ's purchase amounts decreased slightly. On the other hand, its holding ratio sharply increased after the introduction of QQE. Although the growth rate slowed according to the decline in purchases, the BoJ's holding ratio continued to increase and reached around 47% at the end of our sample period.[3]

As explained above, the BoJ accelerated its LSAPs several times during our sample period. According to the BoJ's LSAP program history, we define five subperiods, as follows:

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[2]$1 is roughly equivalent to ¥110

[3]We exclude Treasury discount bills, floating-rate bonds, and inflation-indexed bonds. Our data consist of nominal two-, five-, 10-, 20-, 30-, and 40-year JGBs.

CE-0	1-Jan-2013~	Comprehensive easing
QQE-I	4-Apr-2013~	First QQE (purchased ¥50 trillion of JGBs per year)
QQE-II	31-Oct-2014~	Second QQE (purchased ¥80 trillion of JGBs per year)
NI	29-Jan-2016~	QQE with negative interest (kept purchase amount)
YCC-I	21-Sep-2016~	QQE with yield curve control (declined purchase amount)

We set the end of the YCC-I period to be April 2018. On May 1, 2018, the JGB settlement cycle was shortened from two business days (T+2) to one business day (T+1). Although this shortening brought about interesting changes to the repo market, these are beyond the theme of this paper, so we use the sample up until this system change.

3.3   BoJ lending facility

Since the BoJ's SLF's function is similar to that of repo transactions, its relation with them is either competitive or complementary. Most SC repo transactions in the repo market are in the T+2 clearing cycle until April 2018. The BoJ offers to lend the bonds it holds on the day following the repo transaction. A dealer who wants to cover a short position and cannot find a counterparty in the repo market can therefore cover it by borrowing the bond from the BoJ the following day, although the cost is mostly higher than in the repo market.

The BoJ changed its lending requirements to ease the deterioration in liquidity caused by its LSAPs. In 2014, lending facility offers were added in the morning and thus become available twice a day. The lending amount per issue was also raised in 2015 and in 2016. After February 2016, the BoJ clarified the upper limit lending rate to be the uncollateralized overnight call rate rounded off to the first decimal place minus 0.5%. Since the overnight call rate ranged between 0% and -0.1%, the upper limits of the lending rates were set to be -0.5% or -0.6%. This BoJ lending rate may set a lower limit on the SC repo rate (upper limit of specialness). If the SC rate is currently lower than -0.5% (or -0.6%) in the repo market, dealers will reasonably choose to forgo borrowing bonds in the repo market and, instead, borrow from the BoJ the next day. We test the ceiling effect of the BoJ's lending facility on the SC repo rate in Section 5.2.7.

4   Model and empirical hypotheses

In this section, we propose a model based on the search-theoretic model introduced to the over-the-counter bond market by Duffie et al. (2002). We then describe our model prediction and the hypotheses to be examined in our empirical analyses.

4.1   Search-theoretic model

We construct a model based on a search-theoretic model. We refer to the models of Vayanos and Weill (2008) and Ferdinandusse et al. (2018) to clarify the impact of increasing central bank holdings on the repo market.

We assume three types of investors in the bond lending market: short sellers, lenders, and a central bank. Short sellers, whose measure is α_{ss}, gain profits by purchasing bonds at low prices and selling them at high prices.[4] They hold a transaction asset of value one for which they agree to sell one bond to the central bank or other investors. Since they do not hold the bond at the time they decide to sell, they try to borrow the bond either in the repo market or through the SLF. The lenders, whose measure is α_l, are non-BoJ bondholders. They hold a bond at quantity of one and do not sell their bonds, making a profit by lending their bonds in the repo market. The ratio $\frac{\alpha_{ss}}{\alpha_l}$ is the ratio of supply to demand in the repo market and represents the tightness of the repo market. The higher the ratio, the harder it is to find a counterparty in the repo market. The central bank holds the bonds it purchases to maturity and lends them through the SLF. As already mentioned, since the BoJ's SLF is implemented the day following the repo transaction and its rate is set lower than the SC repo rate in most cases, short sellers borrow bonds through the SLF when they can't find a repo counterparty with a better rate than that through the SLF. Figure 2 shows the flows in the bond lending market.

[Figure 2 about here.]

We now define our lender and short seller utility flow functions. We assume their lifetime utility is the present value of their expected utility flows, net of payments for asset transactions, discounted at a rate $r > 0$.

We assume lenders need to pay a small holding cost e_l in each period. The probability of finding a counterparty depends on the number of such counterparties on the market. A lender finds a borrower (short seller) with probability $\lambda\alpha_{ss}$ and obtains ω for the bond in a successful repo transaction. Note that λ is the Poisson arrival intensity, and lenders and short sellers are matched with intensity λ. That is, given a group of short sellers with mass α_{ss}, a particular lender meets a short seller with probability $\lambda\alpha_{ss}$. In our model, a borrower pays a positive lending fee ω to the lender. Specialness is calculated by dividing ω by the bond price, and the implied SC rate is the difference between the risk-free rate r and the specialness. If a lender cannot find a counterparty in the repo market, the lender will not make a profit and will need to pay the holding cost in the period. The lenders' utility flow function is thus

$$V_l = -e_l + \lambda\alpha_{ss}(\omega - V_l) \tag{1}$$

We next consider the utility flow of short sellers. First, we define the profits of short sellers in the bond spot market. A short seller makes a profit by purchasing bonds at low prices and selling them at higher prices in the JGB spot market. We define h_s as the profit arising from the sales and purchases of a bond. Second, we define the borrowing cost. A short seller will first try to borrow the bond to be sold in the repo market, rather than borrowing from the BoJ. That is because repo transactions are conducted the day before the BoJ's lending

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[4]Although not all borrowers are short sellers, for the sake of simplicity, no other borrowers appear in the model. The utility flow functions of borrowers besides the short sellers involve the case in which both h_s and h_f are zero in Eqs. (2) to (3).

through the SLF, and the SC repo rate is more favorable, in most cases, than the BoJ's lending rate for short sellers. The short seller finds a lender in the repo market with probability $\lambda\alpha_l$ and has a cost ω for the borrowing fee when the repo transaction succeeds, and then exits the repo market. λ is the same Poisson intensity as in Eq. (1). When a short seller cannot find a lender in the repo market (with probability $(1-\lambda\alpha_l)$), the short seller will then try to borrow the bond from the central bank. Thus, the short seller's utility flow in the repo market is in Eq. (2).

Lastly, we consider the utility flow of short sellers who could not cover their short in the repo market. We define δ as the probability that the short seller will be successful attempting to borrow through the BoJ's SLF. The term δ is assumed to remain constant for the LSAPs, because the BoJ will try to respond to investors' demand for bond lending to maintain the liquidity of the JGB market, which tends to decline due to LSAPs. Let the BoJ's lending fee be sl, which is set much higher than ω. When a short seller can borrow the bond through the SLF, the short seller exits the bond lending market and the short seller's profit is the difference between the profit h_s and the borrowing cost sl. We also consider the case in which a short seller cannot borrow in the repo market or from a central bank. If the short seller does not hold the bond on the sale date, the short seller will fail the transaction. Let $h_f(>0)$ be the cost of failure, which includes penalties such as a decline in the short seller's credit. Considering these cases together, we find that the utility flows of short sellers who intend to borrow through the SLF is in Eq. (3):

$$rV_{ss}^{repo} = \lambda\alpha_l(h_s - \omega - V_{ss}^{repo}) + (1 - \lambda\alpha_l)(V_{ss}^{cb} - V_{ss}^{repo}) \tag{2}$$

$$rV_{ss}^{cb} = \delta(h_s - sl - V_{ss}^{cb})(1 - \delta)(-h_f - V_{ss}^{cb}) \tag{3}$$

We now determine the lending fee by introducing bargaining power. When a short seller finds a lender in the repo market, they bilaterally bargain over the SC rate. We assume the SC rate is determined through Nash bargaining, which is applied by Duffie et al. (2005) and Ferdinandusse et al. (2018), among others. Under this assumption, the lending fee ω must lie between the flow utilities of the marginal lender and the marginal short seller in the repo market, that is,

$$\omega = \phi V_l + (1 - \phi)\left(V_{ss}^{cb} - V_{ss}^{repo}\right) \tag{4}$$

for some $\phi \in [0, 1]$, where ϕ measures the lenders' bargaining power and we think of it as exogenous.

We then solve the SC rates with Eqs. (1) to (4):

$$\begin{aligned}\omega = & \ h_s + \frac{(1+r)(-e_l\lambda\alpha_l\phi + h_s\lambda\alpha_l g_{ss})}{\lambda\alpha_l(-\lambda\alpha_l(r - \lambda\alpha_{ss})(1 - \phi) - (1+r)g_{ss})} \\ & + \frac{(h_f - \delta h_f - \delta h_s + \delta sl)\left(\frac{\lambda\alpha_l - 1}{\lambda\alpha_l} - \frac{-(1+r)(-\lambda\alpha_l(r - \lambda\alpha_{ss})(1 - \phi) + (1 - \lambda\alpha_l)g_{ss})}{(\lambda\alpha_l(-\lambda\alpha_l(r - \lambda\alpha_{ss})(1 - \phi) - (1+r)g_{ss})}\right)}{(1+r)}\end{aligned} \tag{5}$$

We now consider the impact of the LSAPs on the bond lending market based on our model. After the introduction of QQE, the BoJ purchased large amounts of government bonds. The

number of short sellers increases because of the high demand for short selling in response to the BoJ's purchase operations. Thus, the measure of short sellers, α_{ss}, increases after the introduction of the QQE. On the other hand, the increasing scarcity of the JGB market due to the BoJ's LSAPs diminishes decreases the number of lenders, and the measure α_l decreases.

We explore the impact on cover risk and the borrowing fee resulting from the changes in the measures of short sellers, lenders.

Proposition 1 *The probability of a lender not finding a counterparty in the repo market decreases while the probability a short seller not finding a counterparty increases with the BoJ's LSAPs.*

Proof. Since the measure of short sellers, α_{ss}, increases and the measure of lenders, α_l, decreases with LSAPs, the execution probability for a lender, $\lambda\alpha_{ss}$, increases and that for a short seller, $\lambda\alpha_l$, decreases.

We next explore the impact on search times in the repo market resulting from the LSAPs.

Proposition 2 *A lender will takes less time and a short seller will take more time to execute an order as the BoJ's holdings increase.*

Proof. Since λ is the Poisson arrival intensity and a particular lender will meet a short seller with probability $\lambda\alpha_{ss}$ in our model, $\frac{1}{\lambda\alpha_{ss}}$ reflects the lender's search time to find a counterparty. Thus, under the assumption of our model, the lender's elapsed time decreases as α_{ss} increases, depending on the BoJ's purchase operations. On the other hand, $\frac{1}{\lambda\alpha_l}$ reflects the search time for a short seller seeking a counterparty, given a group of lenders with mass α_l. A short seller takes more time as α_l decreases according to the BoJ's increase in holdings.

We next consider the effect of LSAPs on the lending fee. Since Eq. (5) has a complicated structure and it is difficult to investigate the effects of changes in the numbers of lenders and short sellers, we perform a calibration exercise. Figure 3 plots the lending fee ω as a function of the measure of lenders, α_l, or short sellers, α_{ss}. We set the parameter values as listed below Figure 3 and examine the dependence of ω on α_l or α_{ss}. We find that the lending fee rises as α_l decreases or α_{ss} increases. The decrease in the number of lenders resulting from the increase in the BoJ's holdings leads to higher lending fees. The increase in the number of short sellers due to the demand from each purchase operation also leads to higher lending fees. We thus propose the following prediction, based on our search-theoretic model:

Proposition 3 *The lending fee increases with the BoJ's LSAPs.*

[Figure 3 about here.]

4.2 Hypotheses

In this section, we describe the research questions to be tested in the empirical analyses.

In Duffie's (1996) model, specialness—the premium for procuring a specific security in the repo market—is driven by the demand for short positions, constraints on the available

supply, and the liquidity of the security. As D'Amico et al. (2018), Corradin and Maddaloni (2017) and many other empirical studies have shown, in the SC repo market, collateralized transactions are security specific, and the scarcity of the underlying collateral should be the main determinant of the SC repo rate (or specialness). Our search-theoretic model described in Section 4.1 predicts that the lending fee will increase with a decrease in the measure of lenders, and an increase in the measure of short sellers and that, when we compare two individual bonds, the SC rate of the bond with tighter supply–demand balance will be lower (specialness will be higher). This means that the cover risk of this specific bond is higher. We test the following hypothesis for the scarcity effect on repo specialness.

Hypothesis 1 *The greater the scarcity, the larger the GC–SC spread in the repo market.*

Cover risk has two aspects: the amount of time and associated incremental costs to locate a specific bond. In the calibration model proposed by Vayanos and Weill (2008), which does not consider scarcity, longer search times for borrowers are associated with greater specialness in the repo market due to the lower competition between lenders. Even though few collateral bonds are available for lending, the BoJ repeats the purchase operations in the form of an auction. If the auction bidder does not hold the bond to be sold, he will consider borrowing the bond in the repo market. As described in Section 4.1, a short seller takes longer to find a counterparty due to the increased demand for repo transactions and greater scarcity of individual bonds. In our empirical analysis, we rely on the timing of the order entries during the day to measure the time effect on specialness (opportunity cost). Based on this argument, we propose the following hypothesis.

Hypothesis 2 *The shorter the time remaining to market closure, the higher the opportunity cost of the GC–SC spread.*

We next consider the effects of the central bank's purchase and lending operations. In the case of a scarce bond, demand for repo transactions must increase as a result of the BoJ's purchase operations. An increase in short sellers will tighten the demand–supply situation, making it harder to find counterparties. This tightness of the demand–supply factor decreases the SC rate (increases specialness) according to our search and bargaining model.

Hypothesis 3 *A central bank's purchase operation increases the GC–SC spread of the purchased bond due to increased search frictions for dealers.*

A lending facility operated by the BoJ can mitigate a tight demand–supply situation. It provides the alternatives for short sellers covering their short positions. However, the lending rate through the SLF is set above the normal rate obtainable in the repo market, so that it works as a last resort to avoid short seller failure. We expect the SLF rate to create a ceiling effect on the SC repo rate. We thus test the following hypothesis for the effect of the SLF on the repo market.

Hypothesis 4 *The central bank's SLF has a ceiling effect on the SC repo rate.*

Since after February 2016 the BoJ lending rate is at the level of −50 basis points (bps)—or −60 bps—we examine the ceiling effect of the SLF on the SC rate by testing whether the SC repo rate reaches that level.

5   Empirical analysis

5.1   Data and variables for empirical analysis

5.1.1   Data

Our order submission data set, which includes the date, time, bond code, order number, rate, and volume, is obtained from the electronic platform provided by JBOND. For the empirical analyses, we use overnight SC repo transactions that are settled two business days after the transaction date, that is, 99.0% of all the transactions in our sample.

We further restrict our sample. Some bonds, such as those that were recently issued and or the cheapest to deliver, are actively traded, whereas others are rarely traded in the repo market. The rates of inactive bonds can lead to outliers, so we only use securities that are traded in more than half of the days in each subsample period. Of the approximately 307.5 bonds traded during each sample period, on average, 134.5 bonds meet the criteria when we average over the five subperiods. This represents about 44% of the eligible securities for trade. On a volume basis, highly liquid securities comprise approximately ¥2.2 trillion a day during the sample period, whereas the remaining securities comprise approximately ¥0.7 trillion, indicating that our sample represents about 76% of all JBOND SC repo transactions, by amounts.

Repo transactions are not very active in the morning session (7:30 a.m. to 11:00 a.m.), and the proportion of orders in the morning session is 10.9% during our sample period. We find that the SC rates in the morning session sometimes differ from those in the afternoon session.[5] Additionally, the way to handle the lunch break is an annoying problem when we calculate the elapsed time between a new order entry and execution, as described below.[6] We thus exclude orders placed in the morning session and use orders placed in the repo market after 12:20 p.m. for our sample. We further exclude orders with SC rates higher than GC rates, because they include orders with abnormal rates that may cause mistakes.

The GC–SC spread is defined as the difference between the GC and SC repo rates for a specific security, repo maturity, and trading day. We calculate the GC–SC spread on a daily basis—and not a deal basis—to prevent the effects of specific bonds with high numbers of transactions from becoming too strong. The daily SC repo rates for a security are calculated by the volume-weighted average of the bond over all the transaction data of the security that day. We use the Tokyo Repo Rates of the next trading day's SC transactions as our GC repo

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[5]Repo transactions in the morning session became active after the clearing cycle was shortened in May 2018.

[6]Only cancellations can be made during the lunch break on the JBOND repo system.

rates.[7] Our data cover the period from January 4, 2013, to April 30, 2018.

Figure 4 shows the time-series evolution of the GC–SC spread, averaging over all securities being traded in the repo market. We can see many spikes in the daily average GC–SC spread. Some of these are at the end of a quarter, as well as at the end of a month, caused by strong demand from financial institutions. The sizes of the spikes increase at the end of QQE-I, and the GC–SC spread remains volatile until YCC-I. The average level of the GC–SC spread rises after NI. Changes in the GC–SC spread are reflected by scarcity, maturity-specific demand, and calendar effects, such as at the end of a quarter.

[Figure 4 about here.]

To investigate the cover risk that short position dealers carry in the JGB market, in Section 5, we use the GC–SC spread at the time of placing a new order. When a bond is scarce in the market, its GC–SC spread should be wider at the time of order placement. We analyze the GC–SC spread of bid and offer orders separately, given the fact that dealers submit a bid order to cover short positions and submit an offer order to lend cash. Bids and offers thus have different motivations, which is why we distinguish bids from offers.

In addition to the GC–SC spread at the time of order placement, we propose two more measures to determine cover risk in the repo market. When a trader places a new order, we can track the order to execution, cancellation, or modification with the order ID. There are three possibilities for the order/execution results: filled, canceled, and not executed before market close (unfilled).

To investigate cover risk, we measure delays in order execution and the incremental execution costs for all the orders. We track each order's execution, cancellation, or modification by the order ID and calculate the time and rate change between a new order placement and its execution. As far as we know, we are the first to investigate search friction by tracking the search costs of individual repo orders. We examine the search times and changes for filled, canceled, and unfilled orders separately. When calculating the search times and rate concession, we again distinguish between orders initiated as a bid or as an offer. Bid orders include cases in which bidders must cover their short positions, whereas offer orders are aimed at raising money using bonds in hand. We present the statistics of the variables for bid and offer orders separately and then show the determinants of rate concession and elapsed time for bid orders in Section 5.2.5. We focus on bid orders in the aim of revealing the impact of the BoJ's LSAPs on short-selling activities in the repo market.

We further investigate the impact of the BoJ's purchase operations and lending facilities on search costs. In the case of bonds purchased by a BoJ operation today, the dealer needs to cover a short position in the repo market. We separate repo orders into bonds purchased by the BoJ and others and test the impact of each purchase operation on the repo market

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[7]The Tokyo Repo Rate is calculated as the average of the rates of the reference institutions. Since the purchase date of an SC repo is two days after the transaction but that of a GC repo (Tokyo Repo Rate) is the next trading day, we use the Tokyo Repo Rate of the next trading day of the SC transaction to calculate the GC–SC spread based on the same repo purchase date.

in Section 5.2.6. We also test in Section 5.2.7 whether the BoJ's lending facility sets a lower limit on the SC repo rate, analyzing the rate concession from the initial ordered SC rate.

5.1.2 Variables for the empirical analyses

We investigate the impact of bond scarcity on repo specialness using a panel regression method. As seen in Figure 1, the BoJ's LSAPs have a significant impact on the bond supply. The BoJ's holding ratio of nominal JGBs was around 10% until mid-2012 but then increased sharply and reached around 47% in April 2018. The reduction in available bonds increases the likelihood that dealers will be unable to close their short position in the JGB cash market. The SC rate (price) of a bond that is scarce in the market should be lower (higher) and the specialness should be greater. We construct our scarcity variable as the BoJ's security holdings n on day t as a percentage of its amount outstanding, $holding_{n,t}$. This variable indicates whether sufficient bonds exist in the market. To control the outstanding amount of a bond, we also define $outstanding_{n,t}$ as the logarithm of the outstanding amount of security n on day t.

In each purchase operation, the BoJ announces the target securities. Purchasing operations decrease the float of bonds in the secondary market. After years of operation, market liquidity conditions decrease further and further, such that the demand for procuring bonds in the repo market and repo specialness increase. To examine the effect of being purchased by the BoJ, we define $purchase_{n,t}$ as the logarithmic amount of the targeted security n purchased in day t's operation.[8]

The difficulty of execution differs, depending on the transaction size per order. We define $size_{n,t}$ as the average transaction size of bond n traded on day t. The total traded amount of a bond reflects the bond's availability. We define $tradeda_{n,t}$ as the cumulative amounts of bond n traded on day t in the repo market. A larger traded amount means that more borrowers and lenders meet in the repo market that day, or larger repo orders are placed with better availability. Repo specialness is sensitive to the JGB auction cycle, as indicated in the literature on US Treasury bonds (e.g., Sundaresan (1994), Keane (1995), D'Amico et al. (2018); see also Section A in the Appendix). To control for this effect, we use an on-the-run dummy, $ontherun$, for the most recently issued bond; an ex-on-the-run dummy, $exontherun$, for the second most recently issued bond; and age, which is defined as the number of years since issuance or the most recent reopening. We also construct a dummy variable for the cheapest-to-deliver bond, ctd, to control for its active trades. The term $outstanding_{n,t}$ is the logarithm of the outstanding amount of security n on day t.

As Figure 4 shows, repo rates have many spikes, and many of these are on days of high cash demand, such as at the end of quarters and months and in the middle of months. We add date dummies to our panel regression model in Section 5.2 to control for these effects, and other date factors, such as program announcements.

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[8]The BoJ does not disclose its purchase amounts for each operation, but it periodically discloses its JGB holding amounts. Before May 2014, the announcement frequency was once a month, and, since then, three times a month. Since the information's periodicity is longer than the period between two consecutive auctions, the variable $purchase_{n,t}$ represents estimated amounts rather than exact amounts.

5.2 Empirical results

5.2.1 Effect of scarcity on specialness

In this section, we examine how market scarcity reflects borrowing costs, which are the main constituents of cover risk. Figure 4 indicates that, after QQE-II, specialness increases and exhibits larger fluctuations (spikes) than before. If these are caused by the scarcity of individual bonds, we should observe higher costs for locating a particular bond. We predict that the greater a bond's scarcity, the more difficult the search.

We now investigate factors related to the increasing specialness. We estimate a model for initial bid specialness:

$$gcsc_{n,t} \quad = \quad \beta_1 holding_{n,t} + \beta_2 tradeda_{n,t} + \sum_j \gamma_1^j Ages_{n,t}^j + \gamma_n + \zeta_t + \epsilon_{n,t} \tag{6}$$

where $gcsc_{n,t}$ is the GC–SC spread at the time of order placement of security n on day t, $holding_{n,t}$ is the BoJ's holding rate of security n on day t, and $tradeda_{n,t}$ is the traded amount in the repo market of security n on day t. The term $Ages_{n,t}^j$ includes the number of years from the issue or reopening date, $age_{n,t}$; the on-the-run bond dummy $ontherun_{n,t}$; the ex-on-the-run bond dummy $exontherun_{n,t}$; the cross terms $ontherun_{n,t} \times age_{n,t}$ and $exontherun_{n,t} \times age_{n,t}$; and the cheapest-to-deliver bond dummy $ctd_{n,t}$. Our model includes security-level fixed effects (FEs) γ_n and time dummies ζ_t to control for security- and date-specific effects, respectively. The term $\epsilon_{n,t}$ is the error term.

[Table 1 about here.]

Table 1 shows the results of the initial bid specialness model. The BoJ's bond holding ratios have a significantly positive relation with initial bid specialness after QQE-I. In the NI and YCC-I subperiods, the values of the coefficients range from 20.75 to 25.56, respectively, which is much more than in QQE-I (2.59). This means that bidders raise initial specialness levels due to scarcity concerns after NI. The traded amount has a significantly negative coefficient in QQE-II, but a positive coefficient in NI and in YCC-I. The larger amount traded of a bond suggests its greater availability. The specialness of bonds is low in QQE-II, which indicates that the bond supply is sufficient for the borrowing demand in the repo market. However, after NI, the bond supply cannot keep up with the high borrowing demand, and the specialness of these bonds increases. We control for the effects of bond characteristics, such as age and those of on-the-run and cheapest-to-deliver bonds. After QQE-I, the initial rates of bonds that are on-the-run and ex-on-the-run increase. Additionally, *age* increases initial specialness throughout our subperiods, except for CE-0. The initial specialness of cheapest-to-deliver bonds increases by 8.65 bps in YCC-I, because these bonds were heavily owned by the BoJ at the time of being cheapest to deliver for futures contracts.[9]

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[9]In the JGB market, 10-year bonds are traded as cheapest-to-deliver bonds three years after their issuance. The YCC-I period begins in September 2016 and is three years after the introduction of LSAPs, so the BoJ holds a large proportion of cheapest-to-deliver bonds in YCC-I.

5.2.2 Order execution in the repo market

We next present the order/execution results by tracking order IDs.

[Table 2 about here.]

Panel A of Table 2 shows the numbers of orders, Panel B shows the aggregate amounts of order (billions of yen) per trading day, and Panel C shows the respective proportions. During our sample period from CE-0 through YCC-I, the number of filled bid (offer) orders increases substantially, from 64.0 (19.0) to 379.4 (158.0) orders per day. This enormous growth reflects the increasing demand for bonds on the electric platform of the Japanese repo market. The speed of growth on the bid side exceeds that on the offer side. The number of bid (offer) cancellations increases from 32.2 (27.5) to 152.5 (195.5) orders per day in the same period. Panel C shows that the probability of execution of bid (offer) orders improves from 65.1% (31.0%) to 69.1% (37.9%) between the CE-0 and YCC-I periods. The unfilled proportion of bid orders rises from 0.4% in CE-0 to 0.8% in YCC-I, and that of offer orders declines from 13.5% to 9.4% in the same period. The increasing proportion of unfilled bid orders could indicate that dealers are finding it difficult to borrow a particular bond in the repo market, whereas the decreasing proportion of unfilled offer orders could indicate strong demand for repo lending.

5.2.3 Estimation of cover risk

Cover risk can be measured by the non-execution ratio of bid orders. We split bid orders into 20-minute intervals by order entry time to determine the amount of bid orders and the unfilled proportion. Figure 5 shows the order flow for five- and 10-year bonds. In this analysis of order entry time, we use five- and 10-year JGBs that have frequent transactions during a day and across a month. The JBOND market resumes afternoon trading session at 12:20 p.m., and the total number of bid orders peaks at 12:40 p.m. and then slowly declines. Around 3:00 p.m., the number of bid orders drops sharply, and the proportion of unfilled orders increases. After 4:00 p.m., less than two hours before the market closes, the probability of non-execution exceeds 10%. Furthermore, as the order placement time approaches 6:00 p.m., the probability of non-execution increases to nearly 40%. It is clear that the later the order entry, the greater the cover risk.

[Figure 5 about here.]

[Table 3 about here.]

Panel A of Table 3 shows that the specialness of filled and unfilled orders entered after 1:00 p.m. relative to those entered between 12:20 p.m. and 1:00 p.m. are, respectively, 1.7 bps and 2.8 bps in QQE-I and 3.5 bps and 7.0 bps in YCC-I. The specialness of filled and unfilled orders entered between 3:00 p.m. and 4:00 p.m., respectively, is 2.4 bps and 7.1 bps in QQE-I and 9.3 bps and 30.8 bps in YCC-I. The specialness of bid orders increases, reflecting

the greater cover risk. It is interesting to note that those rates entered between 3:00 p.m. and 4:00 p.m. are often the highest of the day.

The BoJ holding ratios of filled and unfilled orders entered before 1 p.m. are similar, but those entered later show greater differences in the holding ratio (Table 3, Panel B). For instance, in QQE-II, the holding ratios of filled and unfilled orders entered between 12:20 p.m. and 1:00 p.m. are 33.4% and 35.9%, respectively, but the holding ratios of those entered between 5:00 p.m. and 6:00 p.m. are 35.9% and 46.7%, respectively. In YCC-I, the holding ratios for filled and unfilled orders, respectively, entered between 12:20 p.m. and 13:00 p.m. are 52.7% and 66.0%, those entered between 3:00 p.m. and 4:00 p.m. are 49.0% and 71.7%, and those entered between 5:00 p.m. and 6:00 p.m. are 39.4% and 65.2%. The peak of the holding ratio occurs between 2:00 p.m. and 4:00 p.m. It seems that after 4:00 p.m., short sellers are less willing to place bid orders for bonds with concerns of high scarcity. We investigate the formal relation between scarcity and order entry timing in the following section.

We now investigate the determinants of the probability of non-execution. We establish a probit model to predict whether a repo order is executed or not conditional on the BoJ holding ratio as a proxy for bond scarcity and the size of bid orders and the time remaining to market close. We use the time of the JBOND market close, which is 6:00 p.m. In the estimation, we again use five- and 10- year JGBs that have frequent transactions. We use filled and unfilled orders and exclude canceled orders, since they could have been executed in another venue. The model is

$$
\begin{aligned}
P(y_{n,t} = 1) \quad = \quad & \Phi(\beta_0 + \beta_1 holding_{n,t} + \beta_2 size_{n,t} + \beta_3 remaining_{n,t} \\
& \sum_j \gamma_1^j Ages_{n,t}^j + \beta_4 outstanding_{n,t} + maturity_n + \zeta_t)
\end{aligned}
\tag{7}
$$

where $y_{n,t}$ is a binary variable that equals one if the order is neither executed nor canceled before market close, and zero otherwise; $\Phi(\cdot)$ is the cumulative normal probability density function; $holding_{n,t}$ is the BoJ's holding rate of security n on day t; $size_{n,t}$ is the ordered amount per order in the repo market of security n on day t; and $remaining_{n,t}$ is the difference between the ordered time of security n on day t and the market close time, in hours. The term $Ages_{n,t}^j$ includes the number of years since the issue or reopening date, $age_{n,t}$; the on-the-run bond dummy $ontherun_{n,t}$; the ex-on-the-run bond dummy $exontherun_{n,t}$; and the cheapest-to-deliver bond dummy $ctd_{n,t}$. The variable $outstanding_{n,t}$ is the logarithm of the outstanding amount of security n on day t. Our model includes time dummies ζ_t to control for date-specific effects and maturity-level fixed effects $maturity_n$. The term $\epsilon_{n,t}$ is the error term.

[Table 4 about here.]

Panel A of Table 4 reports the maximum likelihood estimation results of a panel probit model for the five subperiods. The upper panel presents the coefficient estimates and the lower panel presents the mean unfilled probabilities and the marginal effects of *holding*, *size*, and *remaining*, calculated from the model estimates at the sample mean.

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Consistent with our expectations, the remaining time has negative coefficients throughout the five subperiods. The order entry time delays lead to an increase in the probability of short sellers not finding counterparties in the repo market. According to the marginal effects of *remaining*, the probability of non-execution increases by 1.44% in NI and by 3.62% in YCC-I when the remaining time shortens by one hour. The coefficients of the BoJ's holding ratio are positive and significant in QQE-I, QQE-II, and YCC-I. The marginal effect shows the probability of non-execution rises by 0.22% in QQE-II, and by 0.81% in YCC-I as the holding rate increases by 10%. The size ordered has a positive impact on the determination of execution/non-execution in NI and YCC-I. The probability of non-execution increases with larger ordered amounts. The average of predicted probability of non-execution is 0.50% in CE-0, and it rises to 3.67% in YCC-I.

We now consider the relation between cover risk and the borrowing fee in the repo market. As Figure 5 shows, specialness rises as the remaining time decreases. When entering an order in the repo market, a short seller could predict the probability of execution and decide on the bid rate based on the information on that bond and the time remaining to market close. Therefore, we expect that the higher the probability of non-execution, the greater the GC–SC spread. We regress the model's predicted probability of non-execution on the GC–SC spread based on the panel probit model in Eq. (7):

$$gcsc_{n,t} = \hat{P}(y_{n,t} = 1) + \epsilon_{n,t} \tag{8}$$

where $gcsc_{n,t}$ is the GC–SC spread, $\hat{P}(y_{n,t} = 1)$ is the model's estimated probability of non-execution of security n on day t, and ϵ is the error term.

Panel B of Table 4 presents the regression results of a linear regression model for the five subperiods. The coefficient estimate for the probability of non-execution is significantly positive for all the periods except CE-0, as expected. The results indicate that dealers' orders with 4.5 bps (5.3 bps) more specialness have a 10% lower probability of execution in NI (YCC-I). The magnitude of specialness increases with higher cover risk, but it is also determined by other factors specific to the security.

5.2.4 Length of negotiation

The search-theoretic model in Section 4.1 predicts that the degree of specialness is higher when a short seller submits a bid for a bond of greater scarcity. Even if the short seller posts a rate with high specialness (a low SC rate), it could take longer to find a rate that a counterparty will accept, and the short seller might have to increase the specialness in the course of negotiation. Intraday repo data allow us to track the negotiation processes of bids and offers that take place in the screen-based repo market. We compare initial and final specialness and the time needed to reach the execution rate. The rate concession is defined as the difference between the initial and final specialness of orders. We measure the negotiation time, defined as the time between an order's entry and its execution or cancellation or market closure (6 p.m.).

Table 5 shows the rate concessions for filled, canceled, and unfilled orders separately. The significance of the Welch two-sample t-test, whose alternative hypothesis is that the true

difference between the initial and final rates in means is not equal to zero, is indicated by asterisks in the rate concession columns.

[Table 5 about here.]

In Panel A of Table 5, the differences between the initial and final GC–SC spreads for bid orders are significant at the 1% level in all periods except CE-0, and these differences for offer orders are significant in NI and YCC-I. The rate concession amounts are larger for bid orders than for offer orders. The effect of scarcity is greater for bid orders than for offer orders. It is interesting to note that the level of the final offer rates is higher than that of the final bid rates in all the subperiods. This result indicates the aggressive stance of the offer side, reflecting of the increasing scarcity of government bonds. The two rightmost columns of Table 5 present the average negotiation times. The elapsed time until execution for bid orders increases from 8.9 minutes in CE-0 to 13.1 minutes in NI and then slightly declines in YCC-I, which indicates bidders' increasing difficulty finding counterparties. On the other hand, the average elapsed times of the offer orders decrease after the introduction of the QQE. Security collateral financing in the repo market became easier after the implementation of the LSAP program.

Panel B of Table 5 shows the results of the analysis of canceled orders. Similarly, the differences between the initial and final GC–SC spreads for bid orders are significant at 5% in QQE-I, at 1% in QQE-II and NI, and at 10% in YCC-I, and the differences for the offer orders are nonsignificant in all periods. The rate concession amounts for canceled bid orders are smaller than those for filled orders. Even though an electronic platform is a convenient and efficient way of disseminating trading needs, it is limited in terms of the variety of participants. Some buy-side investors, such as insurance companies, prefer a voice market to an electronic platform. Therefore, dealers might contact multiple venues to check the rates and available quantities of bonds they need to trade. Cancelled orders thus reveal the scarcity effect more broadly. The final specialness of canceled orders is significantly lower than for executed orders, as determined by Welch t-tests, not shown in Table 5. A trader placing orders in multiple venues will take a better rate if one is found in another market. This is one of the reasons why the average final specialness of canceled orders is lower than for filled orders. However, the elapsed time until cancellation is twice as long as for filled orders.

In the case of unfilled orders in Panel C of Table 5, the rate concessions are much higher than in Panels A and B. Order submitters are aware of the difficulty locating counterparties for these bonds, and they raise the degree of specialness further and wait longer. The average elapsed times for unfilled orders are 120.8 minutes in CE-0 and 163.7 minutes in NI. This result indicates that order submitters cannot find a counterparty in any venue and therefore leave the orders until the official market closes.

5.2.5 Mispricing, rate concession, and negotiation times

We next construct a model for the rate concession between a bid order entry and its execution. What factors are related to these rate changes?

The rate concession of the GC–SC rate and the search time depend on the first rate an order submitter posts. The posted rate can be above or below market expectation. The larger (smaller) the initial GC–SC spread, the larger (smaller) the rate concession. Additionally, the larger (smaller) the initial GC–SC spread, the longer (shorter) the search time. We estimate the market expected rate from the GC–SC model in Eq. (6). In the analysis on rate concessions and search times, we include a variable for mispricing that captures the deviation of the initial specialness from market expectations. The mispricing is defined as the difference between the observed GC–SC spread and the estimated GC–SC model in Eq. (6). This mispricing indicates whether the initial bid specialness is higher or lower than the model forecast. Our panel regression model is therefore as follows:

$$
\begin{aligned}
chgrate_{n,t} = {} & \beta_1 holding_{n,t} + \beta_2 tradeda_{n,t} + \beta_3 mispricing_{n,t} \\
& + \sum_j \gamma_1^j Ages_{n,t}^j + \gamma_n + \zeta_t + \epsilon_{n,t}
\end{aligned}
\tag{9}
$$

where $chgrate_{n,t}$ is the rate concession between the order placement and execution of security n on day t. The regressors are the BoJ's holding rate, $holding_{n,t}$; the traded amount in the repo market, $tradeda_{n,t}$; the mispricing of the GC–SC spread model, $mispricing_{n,t}$; and the variables included in the term $Ages_{n,t}^j$. Our model again includes security-level fixed effects γ_n and time dummies ζ_t to control for security- and date-specific effects, respectively. The term $\epsilon_{n,t}$ is the error term.

[Table 6 about here.]

Table 6 presents the results for the time and security fixed panel regressions of the rate concession for filled orders in the five subperiods. The dependent variable is the change between the initial bid rate and the final (execution) rate. We are most interested in the impact of mispricing in the initial GC–SC spread on rate concession. The coefficients for the mispricing of the initial GC–SC spread are significantly positive in the CE-0, QQE-II, and NI periods. An order placed at a level lower than the model's prediction of specialness for that bond needs a greater degree of concession, as expected.

Although the BoJ's holding ratio of a bond does not have significant explanatory power before QQE-II, its coefficient becomes significant and positive in NI and YCC-I. Short sellers have to concede a higher rate to execute highly scarce bonds.

The traded amount has a significant and negative coefficient in all the subperiods. Larger traded amounts indicate the bond's better tradability, which means the many lenders and borrowers are participating in the repo market. There are two reasons why larger rate concessions are not necessarily for bonds with many transactions. First, a dealer can easily predict rates for bonds with many transactions, so the initial rate is originally a rate that reflects the market situation. Second, there are many lenders and borrowers, so they are more likely to find each other in the repo market. The negative relation between trading volume and rate concession is observed throughout our sample period.

Next, we estimate a model for search time with the same sets of explanatory variables as in Eq. (9). We replace the dependent variable $chgrate_{n,t}$ in Eq. (9) with $etime_{n,t}$, the time elapsed until the execution of security n on day t, and we repeat the two-way fixed regression.

[Table 7 about here.]

Table 7 presents the results for the regression of the negotiation times for the filled bid orders in the five subperiods. The dependent variable is the time elapsed between the bid order placement and its execution, and the explanatory variables are the same as in Eq. (6). The coefficients of the BoJ's holding ratio until QQE-II are nonsignificant and become significantly positive after NI. The results indicate that the higher the BoJ's holding ratio, the longer the negotiation time. The coefficient estimates for NI and YCC-I are 23.514 and 8.520, respectively, which indicates that the search time increases by about 2.3 minutes and 0.85 minutes in NI and YCC-I as the BoJ holding rate rises by 10%. Bond scarcity increases search times in the repo market, just as our search-theoretic model predicted. The amounts traded in the repo market have negative coefficient estimates in all the subperiods after QQE-I. The larger the amount traded in the repo market, the shorter the search time for filled orders. Large trade volumes indicate the better availability of a specific bond. Since bonds with large trade volumes have a lower mismatch rate and many lenders and borrowers are in the repo market, a dealer can find a counterparty in less time. The coefficients for the mispricing of the initial GC–SC spread model are significant in the QQE-I, QQE-II, and NI periods. An order placed at a level lower than the valid specialness for that bond needs more time to be executed, as expected.

The results in this section support our hypothesis that the BoJ's LSAPs increase cover risk as measured by negotiation, even for filled orders.

5.2.6   Impact of the BoJ's purchase operations

We now consider another effect of the BoJ's LSAPs. Each BoJ purchase operation influences dealer activity in the repo market. When the BoJ purchases JGBs in its operations, it conducts an auction through its financial network system. The BoJ announces an auction to primary dealers at 10:10 a.m. and accepts their bids until 11:40 a.m.; the bidders are then notified of the results around 12:00 p.m. and the settlements are made in two business days.[10]

If an auction bidder does not hold the bond to be sold to the BoJ, the bidder needs to locate the bond in the repo market. Given greater scarcity, a dealer with a short position will be forced to spend longer locating a specific bond and to pay higher prices than the initial price to avoid failure to deliver. Our sample covers orders placed after 12:20 p.m. in the repo market. Bid orders from short sellers according to the purchase operations are included among the orders on the days of the operations. We investigate the effects of the purchase operations on specialness and dealer search frictions.

---

[10]Following the shortening of the JGB settlement cycle to $T+1$ on May 1, 2018, the BoJ shortened the settlement cycle of its JGB purchases from two business days ($T+2$) to one business day ($T+1$). Our sample period is prior to this system change.

We first investigate the GC–SC spread at the time of order placement and rate concessions (the differences between the initial and last rates for each order). Since demand for the bond purchased by the BoJ is expected to increase, its borrowing costs will rise that day. We first look at the initial GC–SC spread and rate concession for filled, canceled, and unfilled orders separately and then examine the impact of each purchase operation on borrowing and search costs.

[Table 8 about here.]

Table 8 shows the average GC–SC spread of bid orders and the rate concession from the time of order placement to execution, cancellation, or market close. The average GC–SC spread of the bid orders is lower for purchased bonds in CE-0 and QQE-I, but increases after QQE-II (Panel A). The rate difference between bonds that were purchased by the BoJ's operation and those that were not purchased increases to 1.12 bps in NI and then declines to 0.57 bps. Bond specialness increases as a result of the BoJ's purchase operation.

The rate concession for purchased bonds is greater than for bonds that were not purchased by the BoJ in the last three periods. The results indicate that it becomes increasingly difficult after QQE-II to execute a bid order for bonds purchased by the BoJ. Each BoJ purchase operation increases the cover risk. Panel B shows that the rate change for canceled orders is smaller than for filled orders whether the BoJ purchases the bond or not, except in CE-0. This result suggests that the cancellation occurred because the bidders located the specific bonds in other venues.

We now formally investigate the impact of each purchase operation. We add the variable $purchase_{n,t}$, the amount of security n purchased by the BoJ during t, to Eq. (6) or (9), and we repeat the regression with time and security fixed effects:

$$
\begin{aligned}
gcsc_{n,t} = {} & \beta_1 holding_{n,t} + \beta_2 tradeda_{n,t} + \beta_4 purchase_{n,t} \\
& + \sum_j \gamma_1^j Ages_{n,t}^j + \gamma_n + \zeta_t + \epsilon_{n,t}
\end{aligned}
\tag{10}
$$

$$
\begin{aligned}
chgrate_{n,t} = {} & \beta_1 holding_{n,t} + \beta_2 tradeda_{n,t} + \beta_3 mispricing_{n,t} + \beta_4 purchase_{n,t} \\
& + \sum_j \gamma_1^j Ages_{n,t}^j + \gamma_n + \zeta_t + \epsilon_{n,t}
\end{aligned}
\tag{11}
$$

[Table 9 about here.]

[Table 10 about here.]

Tables 9 and 10 present the impact of the BoJ's purchase operations on the new ordered specialness and rate concessions, respectively. We obtain a significant positive coefficient for the purchased amount in NI (Table 9). The larger the amounts of a bond the BoJ purchases, the higher the specialness at bid order entry in NI, but the relation is not shown for the other subperiods. The costs to cover the short position increase for bonds purchased by the BoJ. In Table 10, the coefficients for the purchased amounts are significant in QQE-II and YCC-I. The bonds purchased by the BoJ have higher concession rates due to their higher demand. Hypothesis 3 is supported for partial subperiods.

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5.2.7 Impact of the BoJ's lending facility

We further examine the impact of the BoJ's SLF on the repo market. As noted in Section 3.3, the BoJ tries to lend bonds in a manner that is not competitive with repo transactions, to mitigate the difficulty in lending bonds resulting from increasing its bond holdings. After February 2016, the BoJ set the upper limit of lending rates at -50 or -60 bps. If the SC rate is lower than -50 bps (or -60 bps) in the repo market today, dealers will reasonably choose to not borrow a bond in the repo market and to borrow, instead, from the BoJ the next day.

We investigate the ceiling effect of the BoJ's SLF by testing whether the rate concession is smaller when the ordered SC rate is around -50 bps. We add six dummies to Eq. (9) to represents the SC rate levels:

$$
\begin{aligned}
chgrate_{n,t} &= \beta_1 holding_{n,t} + \beta_2 tradeda_{n,t} + \beta_3 mispricing_{n,t} \\
&+ \sum_j \gamma_1^j Ages_{n,t}^j + \sum_k \gamma_2^k Dsc_{n,t}^k + maturity_n + \zeta_t + \epsilon_{n,t}
\end{aligned}
\tag{12}
$$

where $chgrate_{n,t}$ is the rate concession between the order placement and execution of security n on day t, and $Dsc_{n,t}^j$ includes six dummy variables: $d_{-10 \leq sc < -20}$, $d_{-20 \leq sc < -30}$, $d_{-30 \leq sc < -40}$, $d_{-40 \leq sc < -50}$, $d_{-50 \leq sc < -60}$, and $d_{-60 \leq sc}$, where each dummy variable equals one when the SC rate upon order entry ranges between the dummy's subscript values. The other explanatory variables are the same as in Eq. (6), except we replace security-level fixed effects with maturity-level fixed effects $maturity_n$. We perform the regressions for the two periods after February 2016, when the BoJ started to set the upper fee according to the overnight call rate and began disclosing its average lending rates.

[Table 11 about here.]

Table 11 reports the results of panel regressions of the BoJ's lending facility on SC repo rate concession. All the dummies of the rate below -20bps are significant in both periods. In the NI period, a larger coefficient is estimated as the SC rate decreases (specialness increases). The results indicate that bonds with greater specialness have higher rate concessions. There is no ceiling effect from the BoJ's lending facility. On the other hand, in YCC-I, the coefficients for the dummies increase to 1.09 as the SC rate decreases, until the rate dummies are below -60bps; however, the coefficient estimate for dummy below -60bps is 0.29. This result indicates a dealer could give up on filling an order in the repo market, intending to borrow the bond by the BoJ. The BoJ's lending facility has a ceiling effect in YCC-I.

6 Concluding remarks

In this study, we build a search-theoretic model and investigate how bond scarcity and demand from short sellers affect specialness and search frictions in the repo market. We refer to the likelihood of short sellers not being able to find a counterparty as cover risk. When bond

scarcity is high as a result of central bank LSAPs, a bond dealer who holds a short position will have difficulty finding counterparties. The scarcity effect induced by the BoJ's high holding ratio indicates a greater risk of holding a short position due to the increased difficulty of borrowing in the repo market. We introduce the interactions between short sellers, lenders, and a central bank into a search theoretic model and solve the utility flow functions for the repo borrowing fee. Our model predicts that, given the LSAPs, the borrowing fees will increase and short sellers will need more time to find a counterparty.

Our econometric analyses show that specialness is higher for bonds with greater scarcity. A short seller has to pay a higher borrowing rate to cover a short position when the bond is scarce. Tick-by-tick data from the JBOND repo platform reveal that specialness increases and the rate of unfilled orders rises for orders submitted late in the day. When posting an order closer to market close, a dealer might not be able to find a counterparty, even if the dealer posts much higher specialness. From the probit model of the order execution probability, which is our measure of cover risk, we show that cover risk rises as a bond's scarcity grows and the remaining time becomes increasingly limited. We also determine that underestimation (mispricing) of short seller bids increases the amount of rate concession and the length of negotiation. The borrowing rate deteriorates by about 0.19 bps and 0.13bps from the initial ordered rate as the BoJ holding rate rises by 10% in NI and YCC-I, respectively. Negotiation times also increase as the BoJ holding rate rises after 2016. Our results show that the greater a bond's scarcity, the longer the negotiation times in the repo market, which increases the bond's specialness, especially for buy orders.

We also investigate the impact of the BoJ's purchase operations on the repo market by analyzing the specialness and rate concessions for filled orders placed in the afternoon of the BoJ's purchase operation. The average GC–SC spread of bid orders and the rate concessions increase for bonds purchased after QQE-II. The panel regressions show that the costs to cover a short position increase for bonds purchased by the BoJ in NI. The central bank's lending facility has a ceiling effect on the SC repo rate of highly scarce bonds. In the period after September 2016, the SC rate is less likely to be lower than the lending rate through the SLF, which indicates that a dealer could give up on filling an order in the repo market, intending to borrow the bond from the BoJ. The overall results suggest that an aggressive QE carried out by the central bank weakens dealers' market-making capability.

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A   Relation between the GC–SC spread and age

In this section, we examine at the relation between the GC–SC spread of an individual bond and its age since issuance. As shown by Sundaresan (1994), Keane (1995), and D'Amico et al. (2018), the SC repo rates in the United States tend to spike downward at regular intervals, based on the auction cycle of US Treasury bonds. These studies note that, during a typical auction cycle, the supply of Treasury collateral available to the repo market is at its highest level when the security is issued and, therefore, the GC–SC spread should be close to zero. As time passes, more and more of the security can be purchased by holders who are not very active in the repo market; consequently, the security's availability can decline over time, and the repo specialness spread can increase. At the next security auction, holders of short positions will usually roll out of the outstanding issue, implying that demand for that specific collateral should decrease and that the repo specialness spread will rapidly decline.

[Figure A.1 about here.]

We examine whether the auction cycle of JGBs will cause rises and falls in repo specialness in Japan. The panels of Figure A.1 illustrate the auction cycle dynamics of the GC–SC spreads by showing their averages as a function of age (years since issuance). Since the auction cycles differ according to the original maturities, we calculate them for two-, five-, 10-, 20-, and 30-year bonds separately.

The panel for the two-year bond is different because of its monthly auction cycle without reopening. The GC–SC spreads increase as time passes, but they do not narrow, even after the issuance of the next two-year bond. The panels for the five-, 10-, 20-, and 30-year bonds show similar trends. Generally, the Japanese Ministry of Finance issues five-, 10-, 20-, and 30-year bonds quarterly and conducts two regular reopenings following each issuance. We can observe three separate auction subcycles: the dramatic run-up in the specialness spread before the first reopening; a second run-up, similar in shape but of smaller magnitude, immediately follows and peaks just before the second reopening; and, during the third subcycle, the specialness spread exhibits various levels, depending on the original maturity. This result suggests that the increased availability of on-the-run securities after each reopening diminishes the impact of the seasonal demand for short positions around these dates.

Figure 1: BoJ's monthly purchase amounts of nominal JGBs (in trillions of yen)
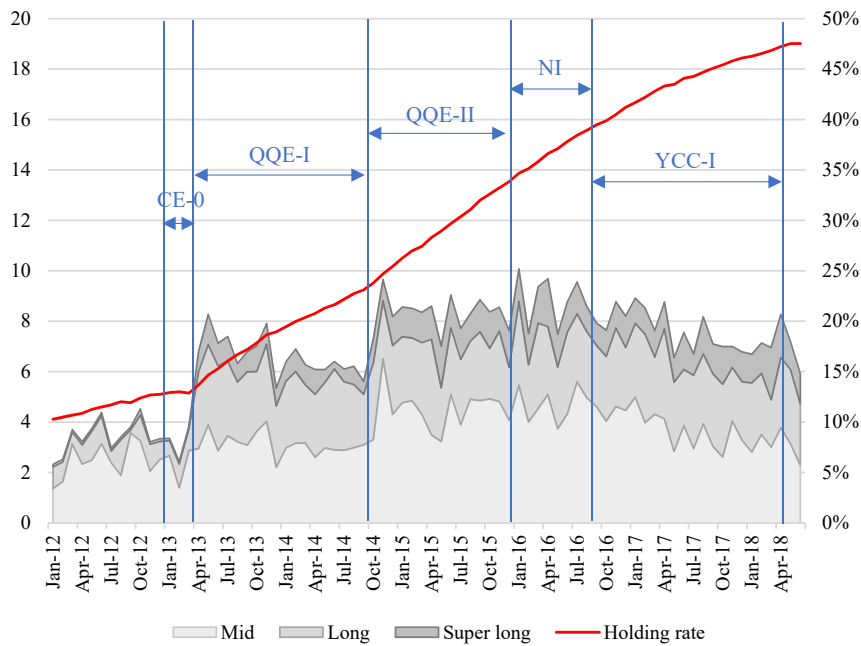
Note: The gray areas indicate the BoJ's monthly purchase amounts (in trillions of yen, left axis) of two- and five-year bonds (mid term), 10-year bonds (long term), and 20-, 30-, and 40-year bonds (super long term). We calculate these by the increments of the amounts the BoJ holds. The red line indicates the BoJ's holding ratio (as a percentage) of nominal JGBs (right axis). Our data consist of the amounts of all nominal JGBs with a fixed-rate coupon held by the BoJ from January 2012 to April 2018.

Figure 2: Flows in the bond lending market
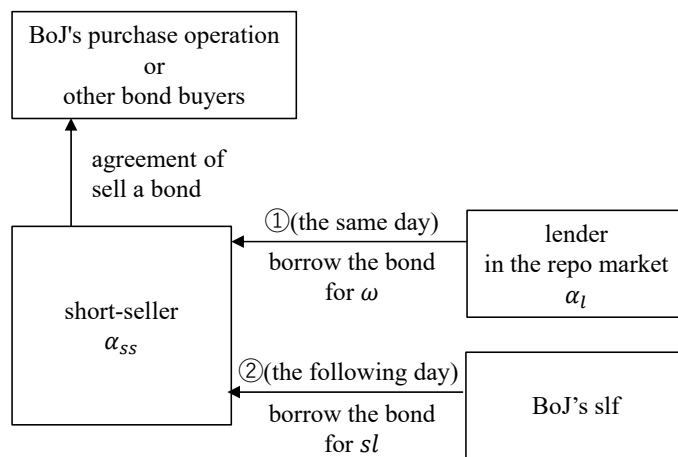
Figure 3: Lending fee as a function of the measures of lenders and short sellers
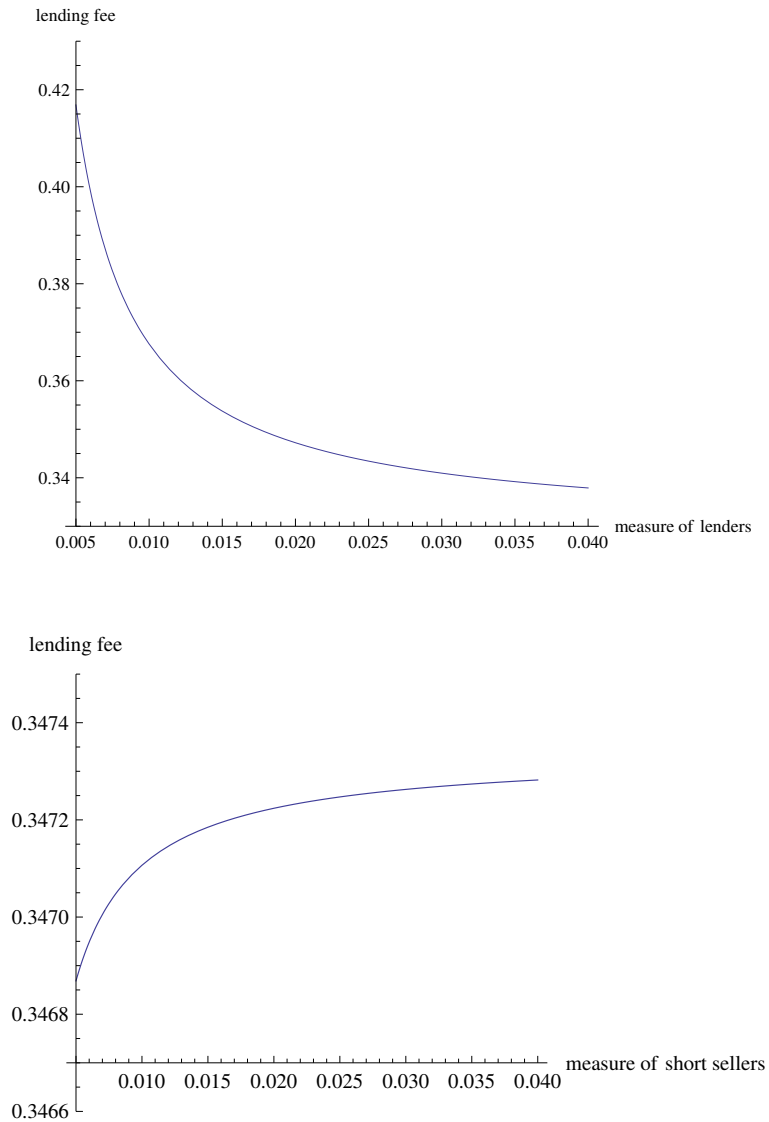
Note: This figure illustrates the dependence of the lending fee on the measures of lenders and short sellers. The top panel shows the lending fee, ω, as a function of the lender measure, α_l, and the bottom shows the lending fee, ω, as a function of the short seller measure, α_{ss}. We set the parameter values of Eq. (5) as follows: $\phi = 0.5$, $h_s = 0.5$, $sl = 0.3$, $hf = 1$, $e_l = 0.005$, $\delta = 0.99$, $\lambda = 1000$, and $r = 0.01$.

Figure 4: Historical GC–SC spread
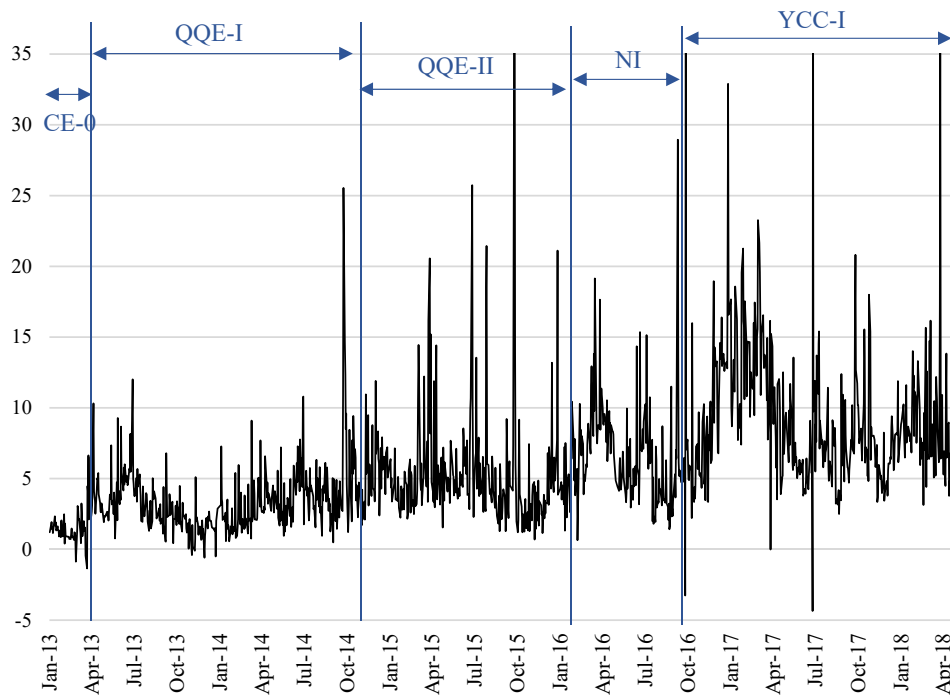
Note: This figure shows the time-series evolution of the GC–SC spread (in bps). The GC–SC repo rate is obtained from JBOND and covers the period from January 4, 2013, to April 30, 2018. Our daily average SC rate is the weighted average of the SC rate obtained by weighting each traded rate by the traded amount. The Tokyo Repo Rate is used as the GC rate.

Figure 5: Number of filled/unfilled bid orders
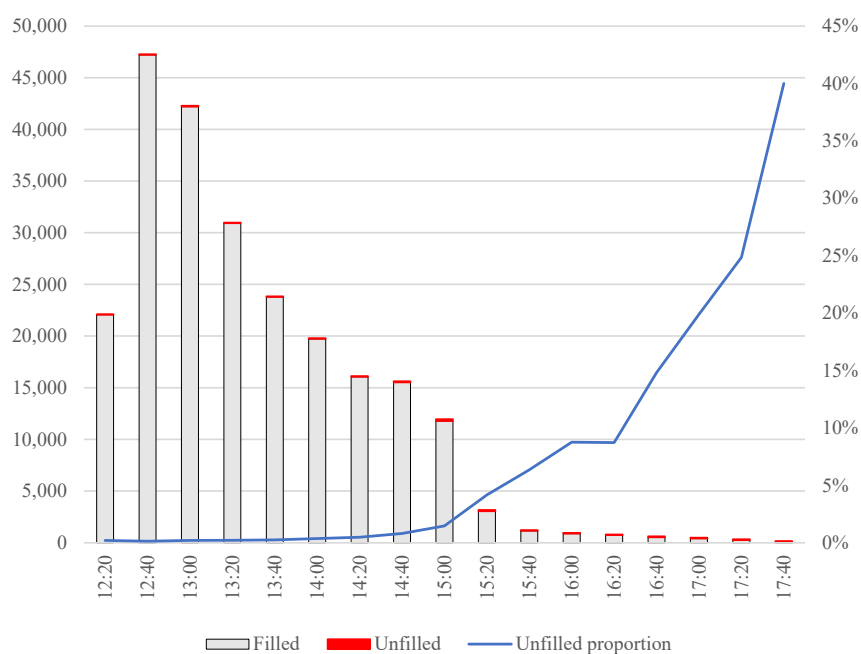
Note: This figure shows the number of filled and unfilled bid orders. The gray and red areas indicate the numbers of filled and unfilled bid orders every 20 minutes after 12:20 p.m., respectively. The blue line shows the proportion of unfilled orders. Our data consist of repo orders for five- and 10-year bonds placed after 12:20 p.m. between January 2012 and April 2018. We exclude offer orders and canceled bid orders.

Figure A.1: GC–SC spread since issuance and reopening dates
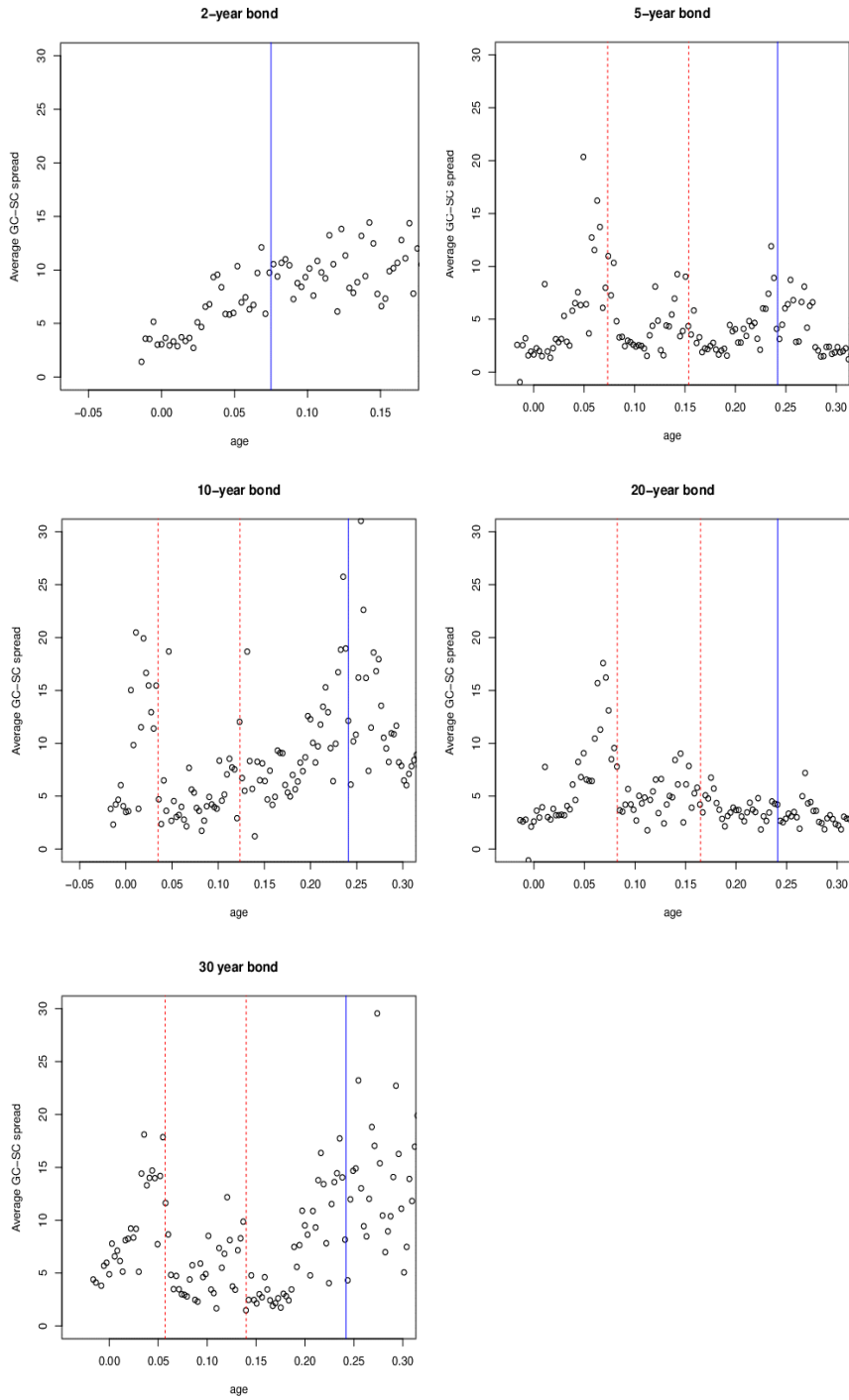
Note: These panels plot the average GC–SC spreads (in bps) as a function of age since issuance. We show the spreads for two-, five-, 10-, 20-, and 30-year bonds separately. The blue solid vertical lines indicate the timing of the next issue of a bond with the same maturity, and the red dotted vertical lines indicate the first and second reopenings. The 40-year bond has various reopening times, so we do not show its panel in this figure.

Table 1. Panel regression of the specialness of new orders

	CE-0		QQE-I		QQE-II		NI		YCC-I	
holding	0.101		2.5872	***	20.747	***	21.144	***	25.561	***
	(0.01)		(5.96)		(29.71)		(13.67)		(30.35)	
tradeda	−0.1814	**	0.0156		−0.0720	***	0.0885	**	0.1660	***
	(−2.02)		(0.89)		(−3.13)		(2.35)		(5.49)	
ontherun	2.0419	**	0.4079	**	1.6964	***	0.2227		6.6254	***
	(2.12)		(2.07)		(5.81)		(0.34)		(19.53)	
exontherun	5.0813	***	0.9889	***	2.0009	***	6.2185	***	7.0379	***
	(4.95)		(5.54)		(7.38)		(9.73)		(22.32)	
age	7.94		5.8508	***	14.451	***	17.652	***	34.901	***
	(1.29)		(7.11)		(13.38)		(4.96)		(19.18)	
ontherun × age	−0.040		26.323	***	40.626	***	40.419	***	6.6656	***
	(−0.01)		(10.94)		(14.09)		(7.34)		(4.21)	
exontherun × age	−16.895	***	3.0877	***	4.334	***	−19.768	***	−6.8447	***
	(−4.45)		(4.49)		(4.53)		(−8.25)		(−7.98)	
ctd	0.510		3.1408	***	1.4967	***	0.4322		8.6459	***
	(0.49)		(19.26)		(6.25)		(0.88)		(25.49)	
Time FE	Yes		Yes		Yes		Yes		Yes	
Security FE	Yes		Yes		Yes		Yes		Yes	
R-Squared	0.3584		0.6298		0.7362		0.6722		0.6333	
Adjusted *R*-squared	0.3016		0.6196		0.7300		0.6645		0.6265	
F-Statistic	6.316		61.580		119.600		88.150		94.140	
Observations	2129		19083		18160		14034		30036	

Note: This table presents the results for the regression of the GC–SC spreads. The dependent variable is the GC–SC spread (in bps) and the regression equation is Eq. (6). Security-level fixed effects and daily time dummies are not shown. The *t*-values are in parentheses and are calculated for cluster-robust standard errors. The superscripts ***, **, and * indicate statistical significance at the 1%, 5%, and 10% levels, respectively.

Table 2. Ordered amount

Panel A: Number of orders

| | BID | | | | OFFER | | | |
	Total	Filled	Canceled	Unfilled	Total	Filled	Canceled	Unfilled
CE-0	96.2	64.0	32.2	0.0	46.6	19.0	27.5	0.0
QQE-I	191.6	131.9	59.7	0.1	68.5	29.0	38.5	1.1
QQE-II	330.1	224.0	105.5	0.6	137.8	48.8	70.1	18.9
NI	490.3	335.3	153.3	1.7	320.8	106.3	178.8	35.7
YCC-I	532.9	379.4	152.5	0.9	367.1	158.0	195.5	13.5

Panel B: Ordered amount

| | BID | | | | OFFER | | | |
	Total	Filled	Canceled	Unfilled	Total	Filled	Canceled	Unfilled
CE-0	374	243	129	1.5	229.1	71	127	31
QQE-I	583	392	190	1.3	293.2	95	144	54
QQE-II	881	617	263	1.4	455.1	150	230	75
NI	1175	796	372	7.4	942.3	297	502	144
YCC-I	1344	928	405	10.6	1109.1	421	584	104

Panel C: Filled proportion

| | BID | | | OFFER | | |
	Filled	Canceled	Unfilled	Traded	Canceled	Unfilled
CE-0	65.1%	34.5%	0.4%	31.0%	55.5%	13.5%
QQE-I	67.2%	32.5%	0.2%	32.4%	49.1%	18.5%
QQE-II	70.0%	29.9%	0.2%	33.0%	50.4%	16.5%
NI	67.7%	31.6%	0.6%	31.5%	53.2%	15.3%
YCC-I	69.1%	30.2%	0.8%	37.9%	52.6%	9.4%

Note: This table shows the numbers and proportions of orders and amounts ordered per trading day. Panel A shows the total numbers of orders and the numbers of filled, canceled, and unfilled orders per day. Panel B shows the total ordered amounts (in billions of yen) and the ordered amounts (in billions of yen) filled, canceled, and unfilled per day, and Panel C shows the respective proportions (%). We compute the statistics of for bid and offer orders separately. The statistics for bid orders are presented in the left-hand columns, and those for offer orders are presented in the right-hand columns.

Table 3. Cover risk until market close

Panel A: Hourly average GC–SC spread

	Filled						Unfilled					
	12–1 p.m.	1–2 p.m.	2–3 p.m.	3–4 p.m.	4–5 p.m.	5–6 p.m.	12–1 p.m.	1–2 p.m.	2–3 p.m.	3–4 p.m.	4–5 p.m.	5–6 p.m.
CE-0	1.2	2.1	1.7	1.6	1.1	NA	NA	4.0	0.3	10.8	0.5	0.9
QQE-I	1.7	2.5	3.0	2.4	2.5	1.9	2.8	5.5	6.9	7.1	5.7	4.2
QQE-II	2.3	3.5	4.6	5.4	4.2	3.6	3.3	12.3	12.4	19.5	7.1	14.5
NI	2.4	3.4	5.4	4.2	2.3	2.7	12.2	19.7	15.2	19.0	22.6	12.2
YCC-I	3.5	6.3	9.2	9.3	3.5	3.2	7.0	23.3	24.9	30.8	21.9	16.6

Panel B: Scarcity

	Filled						Unfilled					
	12–1 p.m.	1–2 p.m.	2–3 p.m.	3–4 p.m.	4–5 p.m.	5–6 p.m.	12–1 p.m.	1–2 p.m.	2–3 p.m.	3–4 p.m.	4–5 p.m.	5–6 p.m.
CE-0	12.7%	7.1%	5.3%	5.0%	8.0%	NA	NA	0.0%	5.9%	3.5%	6.6%	9.4%
QQE-I	17.2%	20.4%	20.7%	18.8%	17.8%	15.4%	14.2%	22.0%	19.3%	20.9%	28.9%	23.1%
QQE-II	33.4%	37.5%	34.0%	31.9%	30.7%	35.9%	35.9%	47.1%	49.4%	49.9%	41.0%	46.7%
NI	41.4%	49.2%	47.4%	41.4%	37.0%	38.7%	67.5%	60.3%	46.7%	58.7%	53.8%	47.0%
YCC-I	52.7%	59.3%	56.9%	49.0%	39.9%	39.4%	66.0%	71.6%	68.1%	71.7%	67.4%	65.2%

Note: Panel A presents the average hourly GC–SC spread for filled and unfilled bid orders. Panel B presents the BoJ's holding ratio averaging over the bid orders placed for the time period. We calculate filled and unfilled orders separately. Our data consist of bid orders for five- and 10-year bonds placed after 12:20 p.m. between January 2012 and April 2018.

Table 4. Probability and specialness of non-execution

Panel A: Panel probit regression of the probability of non-execution

	CE-0		QQE-I		QQE-II		NI		YCC-I	
holding	18.410	**	1.135	**	2.074	***	0.586		2.212	***
	(1.97)		(2.39)		(4.06)		(0.90)		(7.60)	
size	0.010		0.004		−0.022	***	0.011	***	0.008	***
	(0.55)		(1.45)		(−4.73)		(3.68)		(5.83)	
remaining	−5.672	**	−0.937	***	−0.969	***	−1.054	***	−0.987	***
	(−2.42)		(−13.45)		(−14.01)		(−11.85)		(−31.33)	
ontherun	6.604	**	1.047	***	0.901	***	0.424		0.574	***
	(2.35)		(4.66)		(3.26)		(1.12)		(3.78)	
exontherun	3.156	**	0.414		0.782	***	0.507	**	0.4368	***
	(2.37)		(1.61)		(3.17)		(2.05)		(4.09)	
age	−0.484		0.001		−0.087		−0.307	***	−0.039	
	(−1.22)		(0.03)		(−1.37)		(−3.08)		(−1.23)	
ctd	4.830	**	0.321	**	0.119		0.525	***	−0.219	***
	(2.03)		(2.17)		(0.74)		(2.89)		(−3.28)	
outstanding	−2.084		−0.2862		−0.7586	***	−0.3480		−0.4296	***
	(0.00)		(−1.97)	0.0000	(−4.77)		(−1.61)		(−4.50)	
intercept	−6.775		3.469	**	4.208		5.426	**	4.213	***
	(0.00)		(2.15)		(0.00)		(2.20)		(3.53)	
Maturity FE	Yes		Yes		Yes		Yes		Yes	
Time FE	Yes		Yes		Yes		Yes		Yes	
Observation	1537		14709		12847		6970		17711	
Wald chi-squared	168.21		701.60		800.55		623.92		2857.81	
Pseudo-*R*-squared	0.86		0.55		0.62		0.64		0.55	
Avr. non-execution rate	0.498%		1.055%		1.038%		1.370%		3.670%	
ME of *holding*	9.169%	**	1.197%	**	2.153%	***	0.803%		8.117%	***
ME of *size*	0.005%		0.004%		−0.023%	***	0.015%	***	0.029%	***
ME of *remaining*	−2.824%	**	−0.989%	***	−1.006%	***	−1.444%	***	−3.622%	***

Panel B: Probability of non-execution and the GC–SC spread

	CE-0		QQE-I		QQE-II		NI		YCC-I	
$\hat{y}$	7.800	.	9.106	***	37.260	***	45.170	***	53.034	***
	(1.82)		(5.80)		(12.37)		(11.74)		(31.79)	
intercept	1.592	***	2.340	***	3.305	***	3.043	***	4.741	***
	(13.43)		(75.98)		(67.70)		(51.64)		(67.31)	
R-Squared	0.003		0.011		0.071		0.147		0.155	

Note: Panel A presents the results for the panel probit regression of the probability of non-execution. The dependent variable is a binary variable that equals one if and only if the order is neither executed nor canceled before market close, and the explanatory variables are presented in Eq. (7). Maturity-level fixed effects and daily time dummies are not shown. The z-values are in parentheses. The means of the predicted non-execution probabilities are presented in the Avr. non-execution rate column, and the marginal effects (MEs) of *holding*, *size*, and *remaining* are presented in the last three columns. Panel B presents the results for the regression of the GC–SC spread in Eq. 8. The dependent variable is the GC–SC spread in bps, and the explanatory variable is the predicted probability of non-execution based on the probit regression. The t-values are in parentheses. The superscripts ***, **, and * indicate statistical significance at the 1%, 5%, and 10% levels, respectively.

Table 5. Order modification

Panel A: Filled orders

	BID				OFFER				BID	OFFER
	Initial spread	Final spread	Rate concession		Initial spread	Final spread	Rate concession		Elapsed time	Elapsed time
CE-0	1.61	1.75	0.14		2.38	2.50	0.11		8.9	28.6
QQE-I	2.53	2.74	0.21	***	4.00	3.91	−0.09		11.6	26.6
QQE-II	3.75	4.12	0.37	***	5.65	5.51	−0.14		10.4	20.4
NI	4.52	5.22	0.70	***	6.52	6.20	−0.32	*	13.1	23.8
YCC-I	5.20	5.62	0.41	***	7.10	6.80	−0.30	**	11.1	22.7

Panel B: Canceled orders

	BID				OFFER				BID	OFFER
	Initial spread	Final spread	Rate concession		Initial spread	Final spread	Rate concession		Elapsed time	Elapsed time
CE-0	1.89	1.99	0.10		2.86	2.86	0.00		26.6	56.2
QQE-I	2.63	2.78	0.15	**	4.68	4.63	−0.05		29.5	66.2
QQE-II	3.56	3.77	0.21	***	5.92	5.88	−0.04		24.4	53.4
NI	4.30	4.65	0.35	***	5.94	5.72	−0.23		27.7	54.0
YCC-I	5.48	5.67	0.19	*	6.35	6.23	−0.12		29.1	73.9

Panel C: Unfilled orders

	BID				OFFER				BID	OFFER
	Initial spread	Final spread	Rate concession		Initial spread	Final spread	Rate concession		Elapsed time	Elapsed time
CE-0	3.06	3.09	0.04		2.80	2.83	0.04		120.8	223.6
QQE-I	5.77	6.19	0.43		4.80	4.83	0.02		158.7	240.5
QQE-II	12.11	13.49	1.38		5.37	5.38	0.01		151.0	255.3
NI	22.48	24.36	1.88		6.77	6.75	−0.02		163.7	264.1
YCC-I	21.44	21.95	0.51		8.74	8.70	−0.04		155.4	232.3

Note: This table shows the average GC–SC spreads, rate concessions, and elapsed times. Six leftmost columns show the average GC–SC spreads at the time of order entry and at the order execution or cancellation or market close, and the rate differences (rate concessions). We compute the statistics for the bid and offer orders separately. The two groups of three columns show the average elapsed time between the order's placement and its execution or cancellation or market close for bid and offer orders. Panels A to C cover filled, canceled, and unfilled orders, respectively.

Table 6. Panel regression of the rate concession for filled orders

	CE-0		QQE-I		QQE-II		NI		YCC-I	
holding	−1.072		0.1022		0.4281	*	1.912	***	1.302	***
	(−0.56)		(1.03)		(1.81)		(2.62)		(6.80)	
tradeda	−0.0294	***	−0.0362	***	−0.0727	***	−0.1007	***	−0.1267	***
	(−2.63)		(−9.08)		(−9.34)		(−5.68)		(−18.44)	
mispricing	−0.0087	***	0.0022		−0.0177	***	−0.0348	***	0.0019	
	(−3.08)		(1.32)		(−6.96)		(−8.66)		(1.43)	
ontherun	0.2403	**	−0.0978	**	−0.0335		−0.1554		0.3086	***
	(2.01)		(−2.16)		(−0.34)		(−0.50)		(4.00)	
exontherun	0.14		−0.0743	*	−0.152	*	−0.061		0.259	***
	(1.11)		(−1.82)		(−1.65)		(−0.20)		(3.61)	
age	0.204		0.682	***	−0.711	*	14.290	***	0.6790	
	(0.27)		(3.61)		(−1.95)		(8.53)		(1.64)	
ontherun × age	−0.278		1.9557	***	1.083		−3.351		−0.5730	
	(−0.26)		(3.55)		(1.11)		(−1.29)		(−1.59)	
exontherun × age	−0.156		0.1985		1.0068	***	0.2306		−0.3919	**
	(−0.33)		(1.26)		(3.11)		(0.20)		(−2.01)	
ctd	0.133		0.0926		0.0449		0.0122		0.1567	**
	(1.03)		(2.48)		(0.55)		(0.05)		(2.03)	
Time FE	Yes		Yes		Yes		Yes		Yes	
Security FE	Yes		Yes		Yes		Yes		Yes	
R-Squared	0.2456		0.2330		0.3591		0.2313		0.1901	
Adjusted *R*-squared	0.1785		0.2118		0.3441		0.2134		0.1752	
F-Statistic	3.658		10.980		23.950		12.900		12.770	
Observations	2129		19083		18160		14034		30036	

Note: This table presents the results for the regression of the rate concession. The dependent variable is the change in the SC rate until execution (in bps), and the regression equation is presented in Eq. (9). Security-level fixed effects and daily time dummies are not shown. The *t*-values are in parentheses and are calculated with cluster-robust standard errors. The superscripts ***, **, and * indicate statistical significance at the 1%, 5%, and 10% levels, respectively.

Table 7. Panel regression of the time until execution

	CE-0		QQE-I		QQE-II		NI		YCC-I	
holding	−71.010		−1.4883		4.6930		23.514	***	8.520	***
	(−1.05)		(−0.54)		(1.59)		(3.95)		(3.78)	
tradeda	−1.0850	***	−1.6131	***	−1.6239	***	−1.7605	***	−2.0396	***
	(−2.73)		(−14.50)		(−16.71)		(−12.16)		(−25.21)	
mispricing	−0.1173		−0.2283	***	−0.1757	***	−0.1934	***	−0.0162	
	(−1.18)		(−4.87)		(−5.54)		(−5.89)		(−1.04)	
ontherun	7.2500	*	−0.4296		−3.2520	***	−5.5851	**	−0.6146	
	(1.71)		(−0.34)		(−2.64)		(−2.20)		(−0.68)	
exontherun	6.15		−0.8243		−4.338	***	0.757		1.347	
	(1.36)		(−0.72)		(−3.79)		(0.31)		(1.60)	
age	16.560		8.618		2.068		65.649	***	6.6119	
	(0.61)		(1.64)		(0.45)		(4.80)		(1.36)	
ontherun × *age*	−36.220		15.8342		14.252		10.409		3.4616	
	(−0.95)		(1.03)		(1.17)		(0.49)		(0.82)	
exontherun × *age*	−12.150		6.6885		17.0723	***	−14.8488		−5.2043	**
	(−0.72)		(1.52)		(4.23)		(−1.61)		(−2.27)	
ctd	3.443		−0.3154		0.0668		0.0684		1.1089	
	(0.75)		(−0.30)		(0.07)		(0.04)		(1.22)	
Time FE	Yes		Yes		Yes		Yes		Yes	
Security FE	Yes		Yes		Yes		Yes		Yes	
R-Squared	0.3473		0.3897		0.3982		0.4422		0.3773	
Adjusted *R*-squared	0.2892		0.3728		0.3841		0.4291		0.3659	
F-Statistic	5.978		23.070		28.290		33.970		32.980	
Observations	2129		19083		18160		14034		30036	

Note: This table presents the results for the regression of the elapsed time until execution. The dependent variable is the time elapsed between the order placement and execution, in minutes, and the explanatory variables are the same as in Eq. (9). Security-level fixed effects and daily time dummies are not shown. The *t*-values are in parentheses and are calculated with cluster-robust standard errors. The superscripts ***, **, and * indicate statistical significance at the 1%, 5%, and 10% levels, respectively.

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Table 8. BoJ's purchase operations and order modification

Panel A: Filled orders

	Initial GC–SC spread				Rate concession			
	Unpurchased	Purchased	Diff	Test	Unpurchased	Purchased	Diff	Test
CE-0	1.63	1.19	−0.44	***	0.15	0.13	−0.02	
QQE-I	2.57	2.16	−0.41	***	0.21	0.16	−0.05	**
QQE-II	3.71	4.10	0.38	**	0.35	0.46	0.11	***
NI	4.41	5.53	1.12	***	0.65	0.81	0.16	***
YCC-I	5.16	5.73	0.57	***	0.36	0.47	0.11	***

Panel B: Canceled orders

	Initial GC–SC spread				Rate concession			
	Unpurchased	Purchased	Diff	Test	Unpurchased	Purchased	Diff	Test
CE-0	1.92	1.40	−0.52	*	0.09	0.18	0.09	
QQE-I	2.68	2.27	−0.41	***	0.15	0.12	−0.03	**
QQE-II	3.54	3.75	0.21		0.20	0.31	0.11	**
NI	4.17	5.33	1.16	***	0.34	0.43	0.09	*
YCC-I	5.44	5.95	0.51	**	0.19	0.20	0.02	

Panel C: Unfilled orders

	Initial GC–SC spread				Rate concession			
	Unpurchased	Purchased	Diff	Test	Unpurchased	Purchased	Diff	Test
CE-0	3.06	NA	−	−	0.04	NA	−	−
QQE-I	5.75	5.86	0.11		0.42	0.49	0.07	
QQE-II	12.52	8.88	−3.64		1.43	0.92	−0.52	
NI	21.72	25.59	3.87		2.18	0.64	−1.54	***
YCC-I	21.53	20.78	−0.75		0.50	0.63	0.13	

Note: This table shows the means and two-sample t-test results for the initial GC–SC spreads and order modifications until execution. Panels A to C show the average GC–SC spreads at the time of order placement (in bps) and the rate concessions (in bps) until execution, cancellation, or market close, respectively. In each panel, the statistics for the securities that were not purchased by the BoJ's operation (unpurchased bonds) are presented in the left-hand columns, and those for the securities that were purchased by the BoJ's operation (purchased bonds) are presented in the middle columns. The "diff" and "test" columns show, respectively, the differences between unpurchased and purchased bonds and the significance of the Welch two-sample t-test, whose alternative hypothesis is that the true difference in means is not equal to zero. The GC–SC spread and rate concession are calculated from the bid orders placed after 12:20 p.m. The superscripts ***, **, and * indicate statistical significance at the 1%, 5%, and 10% levels, respectively.

Table 9. Impact of the BoJ's purchase operations on the specialness of new orders

	CE-0		QQE-I		QQE-II		NI		YCC-I	
holding	0.497		2.5319	***	20.7600	***	21.231	***	25.512	***
	(0.03)		(5.82)		(29.69)		(13.73)		(30.28)	
tradeda	−0.1835	**	0.0160		−0.0722	***	0.0875	**	0.1675	***
	(−2.04)		(0.92)		(−3.13)		(2.33)		(5.54)	
purchase	0.0314		−0.0229	*	0.0054		0.0726	**	−0.0456	
	(0.40)		(−1.89)		(0.29)		(2.40)		(−1.63)	
ontherun	2.0437	**	0.4297	**	1.6910	***	0.1654		6.6840	***
	(2.12)		(2.17)		(5.79)		(0.25)		(19.59)	
exontherun	5.09	***	1.0006	***	2.002	***	6.203	***	7.041	***
	(4.95)		(5.60)		(7.38)		(9.71)		(22.33)	
age	7.947		5.833	***	14.450	***	17.769	***	34.8488	***
	(1.29)		(7.08)		(13.38)		(5.00)		(19.15)	
ontherun × age	−0.026		26.2973	***	40.660	***	40.683	***	6.6023	***
	(0.00)		(10.93)		(14.10)		(7.39)		(4.17)	
exontherun × age	−16.893	***	3.0677	***	4.3370	***	−19.7220	***	−6.8372	***
	(−4.44)		(4.46)		(4.53)		(−8.23)		(−7.97)	
ctd	0.513		3.1221		1.4990	***	0.4388		8.6303	***
	(0.49)		(19.11)		(6.25)		(0.90)		(25.44)	
Time FE	Yes		Yes		Yes		Yes		Yes	
Security FE	Yes		Yes		Yes		Yes		Yes	
R-Squared	0.3584		0.6299		0.7362		0.6723		0.6333	
Adjusted *R*-squared	0.3013		0.6196		0.7300		0.6646		0.6265	
F-Statistic	6.277		61.480		119.300		87.920		93.970	
Observations	2129		19083		18160		14034		30036	

Note: This table presents the results for the regression of the GC–SC spreads. The dependent variable is the GC–SC spread (in bps), and the regression equation is presented in Eq. (10). Security-level fixed effects and daily time dummies are not shown. The *t*-values are in parentheses and are calculated with cluster-robust standard errors. The superscripts ***, **, and * indicate statistical significance at the 1%, 5%, and 10% levels, respectively.

Table 10. Impact of the BoJ's purchase operations on rate concessions

	CE-0		QQE-I		QQE-II		NI		YCC-I	
holding	−1.058		0.1115		0.4479	*	1.904	***	1.317	***
	(−0.55)		(1.12)		(1.90)		(2.61)		(6.88)	
tradeda	−0.0295	***	−0.0363	***	−0.0730	***	−0.1006	***	−0.1272	***
	(−2.63)		(−9.09)		(−9.38)		(−5.67)		(−18.50)	
mispricing	−0.0087	***	0.0022		−0.0177	***	−0.0348	***	0.0019	
	(−3.08)		(1.34)		(−6.97)		(−8.65)		(1.45)	
purchase	0.0011		0.0039		0.0104	*	−0.0068		0.0145	**
	(0.12)		(1.40)		(1.67)		(−0.48)		(2.28)	
ontherun	0.24	**	−0.1015	**	−0.044		−0.150		0.290	***
	(2.01)		(−2.24)		(−0.44)		(−0.48)		(3.74)	
exontherun	0.142		−0.076	*	−0.150		−0.059		0.2581	***
	(1.11)		(−1.86)		(−1.64)		(−0.20)		(3.60)	
age	0.204		0.6847	***	−0.704	*	14.280	***	0.6955	*
	(0.27)		(3.63)		(−1.93)		(8.52)		(1.68)	
ontherun × age	−0.277		1.9600	***	1.1427		−3.3760		−0.5529	
	(−0.26)		(3.56)		(1.17)		(−1.30)		(−1.54)	
exontherun × age	−0.156		0.2019	**	1.0124	***	0.2262		−0.3943	**
	(−0.33)		(1.28)		(3.13)		(0.20)		(−2.02)	
Time FE	Yes		Yes		Yes		Yes		Yes	
Security FE	Yes		Yes		Yes		Yes		Yes	
R-Squared	0.2456		0.2331		0.3592		0.2313		0.1902	
Adjusted *R*-squared	0.1781		0.2118		0.3441		0.2133		0.1753	
F-statistic	3.635		10.960		23.910		12.850		12.760	
Observations	2129		19083		18160		14034		30036	

Note: This table presents the results for the regression of changes in the SC rate until execution. The dependent variable is change in the SC rate until execution (in bps), and the regression equation is presented in Eq. (11). Security-level fixed effects and daily time dummies are not shown. The *t*-values are in parentheses and are calculated with cluster-robust standard errors. The superscripts ***, **, and * indicate statistical significance at the 1%, 5%, and 10% levels, respectively.

Table 11. Impact of the BoJ's lending facility on rate concession

	NI		YCC-I	
Intercept	1.785	***	0.7663	***
	(6.40)		(4.46)	
holding	0.5904	***	0.5193	***
	(3.96)		(7.91)	
tradeda	−0.0795	***	−0.1271	***
	(−4.79)		(−19.28)	
mispricing	0.1045	***	0.0205	***
	(13.34)		(9.56)	
purchase	−0.017		0.0151	**
	(−1.10)		(2.39)	
$d_{-10 \leq sc < -20}$	0.059		0.056	*
	(0.93)		(1.82)	
$d_{-20 \leq sc < -30}$	0.844	***	0.3743	***
	(5.81)		(7.78)	
$d_{-30 \leq sc < -40}$	1.908	***	0.9624	***
	(8.06)		(14.08)	
$d_{-40 \leq sc < -50}$	1.933	***	1.0697	***
	(6.54)		(13.67)	
$d_{-50 \leq sc < -60}$	1.7398	***	1.0940	***
	(5.36)		(10.00)	
$d_{-60 \leq sc}$	7.1252	***	0.2903	**
	(13.65)		(2.00)	
ontherun	0.6726	***	0.1565	***
	(3.55)		(2.77)	
exontherun	−0.5193	*	0.1790	***
	(−1.93)		(2.61)	
age	0.0635	***	0.0025	
	(5.90)		(0.40)	
ontherun × age	−7.6480	***	−0.1957	
	(−3.02)		(−0.72)	
exontherun × age	2.5749	**	−0.2489	
	(2.31)		(−1.35)	
ctd	−0.0996		−0.0695	
	(−0.49)		(−0.94)	
Time FE	Yes		Yes	
Maturity FE	Yes		Yes	
R-Squared	0.1316		0.1162	
Adjusted R-squared	0.1202		0.1038	
F-Statistic	11.590		9.427	
Observations	13020		30036	

Note: This table presents the results for the regression investigating the impact of the BoJ's lending facility on search costs. The dependent variable is the change in the SC rate until execution (in bps), and the regression equation is presented in Eq. (12). Original maturity-level fixed effects and daily time dummies are not shown. The t-values are in parentheses and are calculated with cluster-robust standard errors. The superscripts ***, **, and * indicate statistical significance at the 1%, 5%, and 10% levels, respectively.