Yield Curve Control*

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This is one of the first studies to analyze the Bank of Japan's (BOJ) yield curve control since 2016. The BOJ set a target range for 10-year Japanese government bond (JGB) yields and introduced distinct policy instruments. A fixed-price (i.e., unlimited-amount) purchase operation for the 10-year JGBs effectively reduces yields to the target range, although this effect may not immediately extend to the interest swap rate. The BOJ has also made regular fixed-amount purchase operations endogenous to yields and adjusted the growth rate of its balance sheet. These instruments, together with the enhanced forward guidance, have made investors' expectations convergent, and yields have become stationary and less volatile.

JEL Codes: E43, E52, E58, G12.

1. Introduction

In September 2016, the Bank of Japan (BOJ) started an innovative monetary policy regime termed yield curve control (YCC). To control short- and long-term yields of Japanese government bonds (JGBs), the BOJ set a goal to keep 10-year yields within a certain range at zero (e.g., between -0.1 percent and 0.1 percent). To achieve this goal, the BOJ launched a dual bond purchase program consisting of both traditional fixed-amount bond auctions and

*We thank Yuichi Fukuda, Harrison Hong, Yoshio Nozawa, Nao Sudou, Kozo Ueda, Tsutomu Watanabe, Jing Cynthia Wu, and seminar and conference participants at the Bank of Japan, Japanese Ministry of Finance, Japanese Economic Association, and 2020 AEA/ASSA Meeting for their helpful comments. This paper is financially supported by Japan Society for the Promotion of Science (JSPS) KAKENHI Grant-in-Aid (21K13321). Author contact: Hattori: hattori0819@gmail.com. 7-3-1 Hongo, Bunkyo-ku, Tokyo 113-0033, Japan. Yoshida: jiro@psu.edu, 368 Business Bldg., University Park, PA 16802 USA.

newly introduced fixed-price (i.e., unlimited-amount) purchases of 10-year JGBs termed "Sashi-Neh" operations. The YCC is a far bolder regime than the previous large-scale asset purchases (LSAPs), which began in 2001 before other central banks' LSAPs (Ueda 2012; Krishnamurthy and Vissing-Jorgensen 2013; Heckel and Nishimura 2020; Ito and Hoshi 2020). Recently, the YCC has attracted significant attention since the U.S. Federal Reserve System (Fed) actively discusses this policy (e.g., Yellen 2018; Clarida 2019; Brainard 2020). The Reserve Bank of Australia adopted the YCC in March 2020 (e.g., Lucca and Wright 2022).

The YCC regime is similar to the bond-price support regime adopted by the U.S. Federal Reserve System during the 1940s (Amamiya 2017). In April 1942, the Fed and the Treasury Department agreed on a program to control interest rates (Woodford 2001). Specifically, yields on 90-day Treasury bills were strictly pegged at 3/8 of a percent until June 1947, while yields on 25-year Treasury bonds were maintained below 2.5 percent until 1951. The stationary long-term yield expectations under the bond-price support regime led to mean-reverting short-term interest rates. However, since the Treasury-Fed Accord concluded this regime in 1951, no central bank other than the BOJ has adopted a similar policy. A notable difference is that the BOJ sets a target yield range around zero (i.e., bond price floors and caps) instead of completely pegging yields.

The present research is one of the first studies that analyze the BOJ's yield curve control. It demonstrates how the BOJ's new monetary policy works in the modern financial system. The BOJ's innovation is targeted at endogenizing its monetary policy by timing the JGB market. Not specifying a bond purchase schedule is a unique feature of YCC. Combined with its contrarian approach to purchasing exchange-traded funds and real estate investment trusts (Hattori and Yoshida 2021, 2022), this monetary policy regime is qualitatively different from the previous unconventional monetary policy which included quantitative easing (QE) and LSAPs.

To analyze the largest fixed-price purchase operation (July 30, 2018), we use high-frequency data. Specifically, we test whether the effect of the BOJ's operation is confined to the 10-year JGB market or whether it also extends to the interest rate swap markets. In addition, we contrast this effect with that of smaller operations on February 3, 2017, and July 27, 2018. Subsequently, we analyze the long-term effect of the YCC regime over six years by testing whether YCC changes investor expectations and the statistical properties of JGB yields. Specifically, we test the convergence of investor expectations under YCC and whether yields become mean reverting, stationary, and less volatile across the entire yield curve, using the methodology proposed by Mankiw, Miron, and Weil (1987) and Hutchinson and Toma (1991).

Our findings are summarized as follows. First, the BOJ endogenizes its open market operations under YCC, unlike other central banks' QE. Under the zero lower bound (ZLB), endogenous QE can be more effective than conventional monetary policy (Sims and Wu 2020). In addition to inherently endogenous fixed-price operations, the BOJ also makes its fixed-amount operations endogenous to JGB yields. The 10-year yield Granger-causes the 10-year JGB auction amount under YCC (i.e., a high yield Granger-causes an auction). Before the YCC, causality runs in the opposite direction; an auction decreases 10-year yields. Similar results are also obtained for JGB yields of other maturities. Furthermore, as a result of endogenized fixed-amount operations, there is a reduction in the growth of the BOJ's balance sheet, which correlates with yields.

Second, fixed-price operations effectively reduce 10-year JGB yields down to the target range. However, the effect can be confined to the JGB market for a significant period, especially during a large operation. Although the relationship between the 10-year JGB yield and the 10-year LIBOR (London interbank offered rate) swap rate tends to be stable before and after a small fixed-price operation, the spread increased significantly and remained high after the largest operation. Using the difference-in-differences approach, we find that the largest fixed-price operation decreased 10-year JGB yields but not the 10-year LIBOR swap rate. This result suggests that the fixed-price operation exerted its effect through the scarcity channel, which is based on limits to arbitrage and market segmentation.

Third, investors' yield expectations converge under YCC. The dispersion of expert yield forecasts significantly decreased under YCC when the BOJ imposed a narrow yield target range and enhanced forward guidance. Moreover, the dispersion of yield forecasts is consistent across all maturities. Within these periods, the BOJ conducted only three fixed-price operations. Therefore, the BOJ's YCC exerts its effects through investor expectations instead of frequent fixed-price operations. However, the dispersion increased when yields drifted within a widened yield target range.

Fourth, as a result of endogenous interventions and convergent expectations, the stochastic property of 10-year JGB yields changed during YCC. Specifically, based on the trend-cycle decomposition, the cyclical component of 10-year yields became less volatile under YCC, especially when a narrow target range made forecasts less dispersed. Moreover, 10-year yields—which were non-stationary before YCC despite QE and LSAPs—become stationary in the low-volatility environment under YCC. However, yields become non-stationary when investor expectations diverged due to drifting yields in a wide target range.

Last, JGB yields across the entire yield curve, including shorter- and longer-maturity JGBs, likewise become stationary when a narrow target range reduces forecast dispersion under YCC. Overall, the BOJ effectively controls the entire JGB yield curve. However, consistent with 10-year yields, shorter- and longer-term yields also become non-stationary when the BOJ has a wide target range.

In summary, YCC is characterized by stable and stationary JGB yields that are aligned with investor expectations. YCC is effective when the BOJ combines (i) its balance sheet growth management through endogenized fixed-amount operations, (ii) a yield cap maintained by fixed-price operations, and (iii) enhanced forward guidance. These results suggest that the YCC regime is considered a credible and effective means of controlling the yield curve. In particular, fixed-price (Sashi-Neh) operations are essential in changing investors' expectations and stabilizing JGB yields below the target levels.

JGB yields are tightly related to the 10-year LIBOR swap rate around a small fixed-price operation, but this no-arbitrage relationship can temporarily break down in a large operation. Given the significance of swap rates in pricing financial contracts and securities such as corporate bonds and over-the-counter derivatives, mitigating limits to arbitrage would be a viable policy to improve YCC.

Endogenous monetary policies can reduce asset price volatility by offsetting the change in economic fundamentals but can also destabilize the asset market (Yang and Zhu 2021). We find that YCC significantly stabilizes interest rates by making investors' expectations align with the BOJ's. Although the BOJ does not expressly state when bonds should be purchased, investors widely share the bank's endogenous intervention rule. Thus, the bank effectively communicates its commitment to achieving a target rate through its consistent behavior. Less volatile JGB yields can have large spillover effects on other financial markets (Yang and Zhou 2017).

The remainder of this paper is organized as follows. Section 2 reviews the literature. Section 3 outlines the institutional background of the BOJ's YCC. Upon clarifying our conceptual framework in Section 4, we present the results in Section 5. Finally, Section 6 concludes the paper.

2. Literature Review

Studies identify several channels through which LSAPs can affect long-term interest rates: (i) the expectations/signaling channel, (ii) the scarcity channel, and (iii) the duration risk channel (D'Amico et al. 2012; Krishnamurthy and Vissing-Jorgensen 2013). The expectations/signaling channel is based on the expectations hypothesis, i.e., that the expected path of short-term rates determines long-term rates. A central bank's bond purchases affect long-term rates through the bank's signaling of future short-term rate policies and the state of the economy. In contrast, the scarcity channel is based on the preferred-habitat theory, which states that investors with unique preferences for certain maturities create segmented bond markets (e.g., Modigliani and Sutch 1966; Wallace 1981; Greenwood and Vayanos 2014; Sudo and Tanaka 2021). A central bank's demand for long-term bonds increases bond prices in that maturity segment. (Equivalently, a central bank's purchases make long-term bonds scarcer for investors.) Lastly, the duration risk channel is based on the change in risk-averse arbitrageurs' aggregate exposure to risky longer-term bonds. As a central bank purchases long-term bonds, arbitrageurs' aggregate exposure to longer-term bonds decreases, leading to a decrease in duration risk premiums for the entire duration spectrum.

The literature on the Fed's bond-price support regime of the 1940s is also relevant to our research. Friedman and Schwartz (1963) frame this policy as the setting of price-level targets and point to price expectations as the crucial factor supporting the Fed's ability to maintain the program. Eichengreen and Garber (1991) build a model where a target zone for the price level and an intervention rule create a target zone for the interest rate. Hutchinson and Toma (1991) find that short-term interest rates were mean reverting under the bond-price support regime. Alternatively, McCallum (1986) and Barro (1989) show that a policymaker can peg the nominal rate by committing to a particular money supply time path. Several studies emphasize the relation with fiscal policy. Toma (1991) shows that the credibility of the Fed's bond-price support program depended on the expected duration of the war and the government's expected use of tax income for postwar expenditures. More recently, Woodford (2001) uses the bond-price support regime to illustrate the role of fiscal developments in inflation determination under a non-Ricardian paradigm.

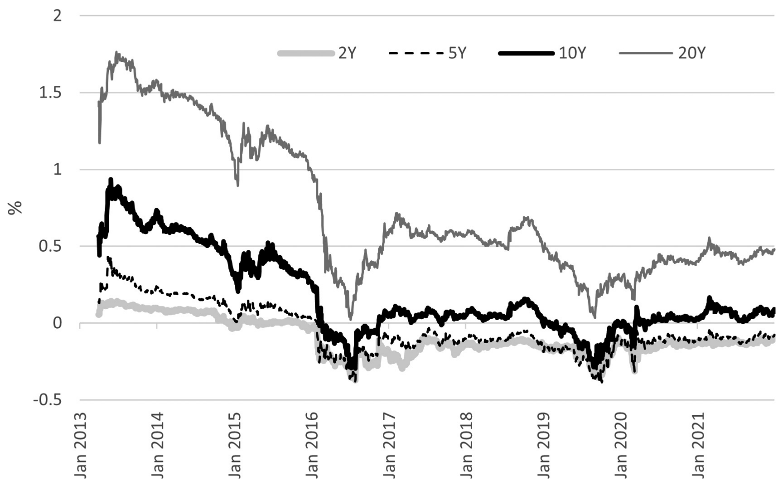
Methodologically, our study is most closely related to Mankiw, Miron, and Weil (1987) and Hutchinson and Toma (1991). Mankiw, Miron, and Weil (1987) focus on the creation of the Fed and argue that a change in policy regime affects the public's expectation of the future interest rate. In particular, they show that the nominal interest rate switched from a stationary to a non-stationary process after the creation of the Fed. Hutchinson and Toma (1991) extend the work of Mankiw, Miron, and Weil (1987) and conclude that the peg for long-term interest rates under the bond-price support program of the 1940s led to the interest rate becoming a stationary process.

3. Institutional Background

The BOJ introduced its qualitative and quantitative monetary easing (QQE) policy in April 2013 to meet its 2 percent consumer price index (CPI) inflation target in an aggressive time frame (Hattori 2020). Figure 1 depicts the time series of the 2-, 5-, 10-, and 20-year JGB yields since the BOJ began implementing its QQE policy in April 2013. Since then, the BOJ has annually increased the monetary base by approximately 80 trillion yen through open market operations, i.e., the purchase of assets such as JGBs. In January 2016, the BOJ announced a negative interest rate (−10 basis points) on the current accounts held by financial institutions at the BOJ.[1]

[1]Introduction of "Quantitative and Qualitative Monetary Easing with a Negative Interest Rate," https://www.boj.or.jp/en/about/press/koen_2016/data/ko160203a1.pdf.

Figure 1. Japanese Government Bond Yields



Note: This figure depicts constant-maturity yields for the Japanese government bonds (JGBs) of different maturities (2, 5, 10, and 20 years) between April 1, 2013, and December 31, 2021.

In September 2016, the BOJ introduced "QQE with Yield Curve Control," a policy aimed at controlling interest rates of various terms through market operations.[2] The BOJ set a target to keep 10-year yields within a certain range under YCC. Here, we define three YCC phases: narrow-range YCC, wide-range YCC, and YCC with indefinite forward guidance. In the first phase (between October 2016 and July 2018), the BOJ had a target yield range between -0.1 percent and 0.1 percent. The second phase (between August 2018 and October 2019) is characterized by a doubled target range.[3] In the third phase, the BOJ additionally removed the time horizon for its forward guidance; namely, "the Bank expects short- and long-term interest rates to remain at their present or lower levels as long

[2]New Framework for Strengthening Monetary Easing: "Quantitative and Qualitative Monetary Easing with Yield Curve Control," https://www.boj.or.jp/en/mopo/mpmdeci/mpr_2016/k160921a.pdf.

[3]"Strengthening the Framework for Continuous Powerful Monetary Easing," https://www.boj.or.jp/en/mopo/mpmdeci/state_2018/k180731a.htm/. The BOJ further increased the target range to 0.25 percent in March 2021.

as it is necessary to pay close attention to the possibility that the momentum toward achieving the price stability target will be lost."[4]

To control the yield curve, the BOJ has employed two major policy measures. First, the BOJ has pledged to increase the monetary base until the year-over-year CPI inflation rate consistently remains above a 2 percent target rate ("inflation-overshooting commitment"). This policy measure is similar to the "average inflation targeting," which was subsequently adopted by the Fed. Forward guidance for the policy rates is part of this policy measure. Second, the BOJ influences both short- and long-term interest rates through two methods of outright purchase operations: the competitive auction method (Kai-Kiri) and the newly introduced fixed-price method (Sashi-Neh). The competitive auction method is the primary method of purchasing 80 trillion yen in JGBs annually under QQE. Fixed-price operations—introduced in September 2016 to better control the yield curve—are conducted only when long-term interest rates (typically 10-year JGB yields) approach or hit the BOJ's target rate.

3.1 Competitive Auction Method (Fixed-Amount Operation)

For the competitive auction method, the BOJ determines the purchase amount based on the differentials between the bid and reference rates. The BOJ has conducted outright purchase operations almost every business day (except when there are monetary policy meetings and JGB auctions) to divide the large required amount of money supply into smaller amounts.

Like the Fed, the BOJ conducts multiple-security auctions. The BOJ first announces specific maturity buckets that it will purchase (i.e., less than 1 year, 1–3 years, 3–5 years, 5–10 years, 10–25 years, and over 25 years). Subsequently, primary dealers and qualifying financial institutions can submit their offer prices for JGBs in the maturity bucket. The BOJ then purchases JGBs from the lowest-price offer until it meets the target.

Under the YCC regime, the BOJ changed its behavior in regular bond-auction operations. Before YCC, each auction amount was stable at approximately 400 billion yen. Under YCC, however, auction

[4] "Statement of Monetary Policy," https://www.boj.or.jp/en/mopo/mpmdeci/mpr_2019/k191031a.pdf.

Table 1. Granger Causality Tests

	Number of Lags	Pre-YCC Apr. 2013– Sep. 2016 (1)	YCC Oct. 2016– Dec. 2021 (2)	Change in Probability Values (3)
BOJ's Auction Amount → 10-Year JGB Yield	1	0.0058 (858)	0.1588 (1282)	0.1530
	2	0.0117 (857)	0.2360 (1282)	0.2243
10-Year JGB Yield → BOJ's Auction Amount	1	0.5837 (858)	0.0184 (1282)	–0.5653
	2	0.6513 (857)	0.0074 (1282)	–0.6439

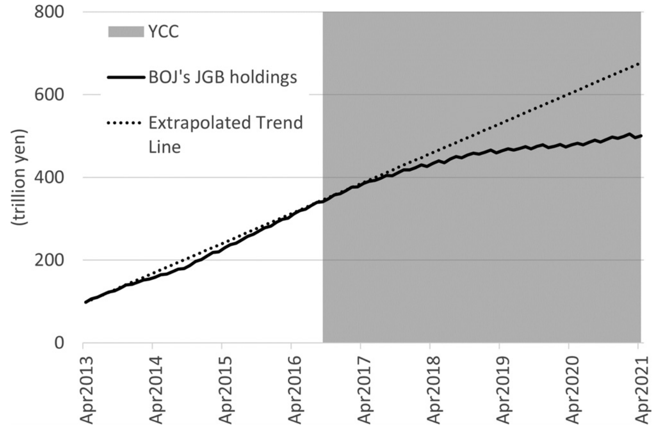
Note: This table shows the results of the Granger causality tests. The entries in columns 1 and 2 are p-values for the null hypothesis that the first-named series does not Granger-cause the second-named series. The number of observations is in parentheses.

amounts have fluctuated more frequently. Although an amount is typically fixed for approximately six months, it is sometimes revised at a monthly or shorter frequency (e.g., in July and August 2017 as well as in June, July, and August 2018).

Table 1 shows Granger causalities between auction amounts and 10-year JGB yields. Before YCC, the auction amount Granger-caused 10-year yields but not vice versa (column 1). Thus, regular fixed-amount auctions were conducted regardless of the market yield and affected subsequent yields. Under YCC, however, the Granger causality of an auction amount on yields was insignificant, whereas the Granger causality of yields on an auction amount was statistically significant at least at the 2 percent level (column 2). Using simple linear regressions, we confirm that the BOJ actively manages auction amounts under YCC by increasing the purchase amount when the 10-year yield is high. In other words, the BOJ controls the yield curve by endogenizing its fixed-amount purchase decisions based on market JGB yields.[5]

[5]This endogenous intervention behavior is not observed in the subsample during QQE with a negative interest rate either. Thus, it is a unique feature of YCC. In addition, Table A.2 in the appendix shows that the BOJ's intervention

Figure 2. Bank of Japan's JGB Holdings



Note: This figure depicts the amount of JGBs held by the Bank of Japan under QQE and YCC. The shaded area represents the YCC period. The dotted line represents an extrapolated trend line based on the average JGB holding growth rate before YCC.

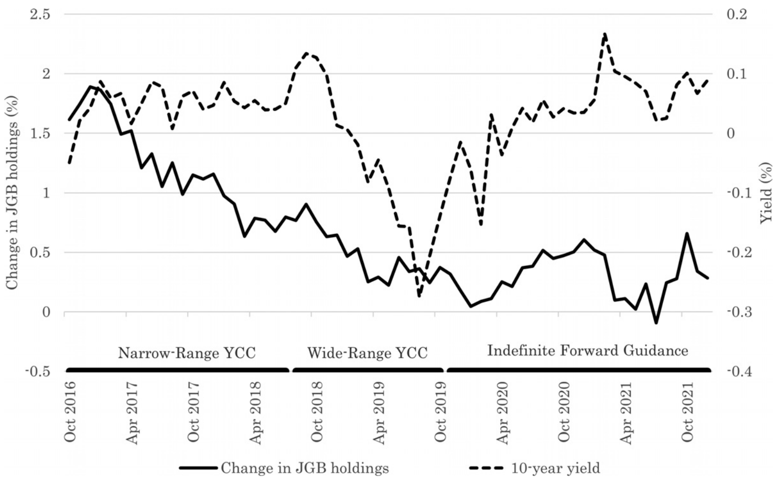
3.2 BOJ's Balance Sheet Management

The BOJ manages its balance sheet growth during YCC by controlling the total JGB purchase amount. Figure 2 depicts the BOJ's JGB holdings during QQE (pre-YCC) and YCC. Relative to the trend line extrapolated from the pre-YCC period, the speed of the balance sheet growth has decreased during YCC. The growth of BOJ's JGB holdings has been particularly mild since 2020. Figure 3 depicts the growth rate of three-month average JGB holdings and 10-year JGB yields. The balance sheet growth rate steadily decreased during the narrow-range and wide-range YCC and became positively correlated with 10-year yields during YCC with indefinite forward guidance (the correlation coefficient is 0.30).

This balance sheet growth management is likely a consequence of BOJ's endogenized bond purchase operations. Under YCC, the BOJ does not increase its balance sheet significantly as long as yields fall within the target range but does do so when yields increase toward

is also endogenous to 5- and 20-year yields under YCC. Therefore, by focusing on 10-year yields, the BOJ effectively responds to the entire yield curve.

Figure 3. Change in the BOJ's JGB Holdings and 10-Year Yields under YCC



Note: This figure depicts the percentage change in the Bank of Japan's three-month average holdings of JGBs (solid line) and 10-year JGB yields (dashed line) under YCC. The three monetary policy regimes are narrow-range YCC (from October 2016 to July 2018), wide-range YCC (from August 2018 to October 2019), and YCC with indefinite forward guidance (from November 2019 to December 2021).

the upper bound of the target range. For example, the BOJ increased its JGB holdings by 5.0 percent between February 2020 and February 2021 when yields increased from −0.153 percent to 0.168 percent. Similarly, the BOJ accelerated its balance sheet growth rate between July 2021 and October 2021 while yields increased from 0.022 percent to 0.101 percent.

3.3 Fixed-Price Method

For the fixed-price method, the BOJ purchases JGBs at a specified price by accepting all offers except under special circumstances. The Bank of Japan (2019) states that the BOJ stands ready to offer fixed-price operations when the yield curve shifts significantly. Since announcing this new type of operation in September 2016 until the end of 2021, the BOJ has announced a total of six fixed-price purchase operations for 10-year JGBs, although the bank has conducted only three in actuality. The yield cap is set at 0.1 percent–0.11 percent. The six announcements were made on February 3, 2017 (723.9 billion yen), July 7, 2017 (no purchase), February 2, 2018 (no purchase), July 23, 2018 (no purchase), July 27, 2018 (94 billion yen), and July 30, 2018 (1.64 trillion yen). The time of each announcement was either 10:10 or 14:00, except on February 3, 2017.

4. Conceptual Framework and Hypotheses

In a standard general-equilibrium model, the interest rate is determined for each period in a Walrasian equilibrium where the firm sector's total bond supply is equated with the household sector's total bond demand. This class of models does not provide an ideal framework for analyzing a central bank's open market operations, which do not change the total amount of bond supply or demand.

Thus, an alternative approach for understanding a central bank's bond purchases is the preferred-habitat theory, which states that unique investor preferences for certain maturities create segmented bond markets (e.g., Modigliani and Sutch 1966; Wallace 1981; Greenwood and Vayanos 2014). In a segmented bond market, demand and supply are imperfectly elastic because investors' reservation values are heterogeneous and based on differences in beliefs, information sets, risk preferences, portfolio holdings, and investment objectives.[6] In this framework, a central bank's fixed-amount operations can be modeled as a parallel shift of the demand for long-term bonds (Vayanos and Vila 2020). However, these models do not consider fixed-price operations.

Our key insight is that the BOJ shifts the demand curve to the right by a fixed-amount operation but changes the shape of the demand curve by a fixed-price operation. In a fixed-amount operation, the BOJ takes all ask quotes until it buys the specified amount. Thus, transaction prices move up along the supply curve represented by the ask-price schedule. By contrast, in a fixed-price operation,

[6]In the actual customer-broker market, a downward-sloping demand curve and an upward-sloping supply curve are represented by brokers' bid-price and ask-price curves, respectively (e.g., Lyons 2008). We abstract from the market microstructure.

the BOJ does not shift the demand curve but makes the demand curve flat at the target price. In other words, the BOJ changes investors' price expectations by providing a put option. By combining both fixed-amount and fixed-price operations, the BOJ creates a floor on bond prices (i.e., a cap on bond yields). However, it is difficult to disentangle the effects of fixed-amount and fixed-price operations because investors' price expectations are always affected by the possibility of fixed-price operations, even without actual purchases.

Effective YCC can also affect non-JGB interest rates through arbitrage. In particular, the spread between 10-year LIBOR swap rates and 10-year JGB yields will be stable regardless of the BOJ's JGB purchases if arbitrageurs actively take rate discrepancies away between these two markets. However, if markets are segmented because of limits to arbitrage or asset-specific demand, the swap spread will increase after BOJ operations. For example, Jermann (2020) develops a model to explain a negative swap spread in the United States when frictions for holding bonds limit arbitrage. Klinger and Sundaresan (2019) instead focus on the demand for interest rate swaps and demonstrate that a negative swap spread can be rationalized when pension funds use interest rate swaps to hedge duration risks. The aforementioned studies suggest that the JGB–swap relationship can be unstable when one of these markets has a shock to demand or frictions. A negative swap spread has been consistently observed for Japanese yen interest rate swaps and has fluctuated more widely than USD interest rate swaps (Figure A.1 in the appendix). Thus, a large demand shock to the JGB market may affect the swap spread significantly. Consequently, our hypothesis is as follows.

Hypothesis 1. *After the BOJ purchases of 10-year JGBs, the LIBOR swap spread increases.*

Regarding 10-year JGB yields, we expect four potential impacts of YCC. First, investors will have more homogeneous valuations, as the BOJ's yield cap will align investors' expectations with those of the central bank.

Hypothesis 2. *Investor expectations on 10-year yields will converge to the BOJ's expectations.*

Second, we expect yields to be less volatile when the target yield range is binding.

HYPOTHESIS 3. *Yields on 10-year JGBs become less volatile under YCC if the target yield range is binding.*

Third, bond yields will become stationary when the target yield range is binding. Moreover, as Mankiw, Miron, and Weil (1987) and Hutchinson and Toma (1991) argue, if YCC is credible and stabilizes investor expectations, bond yields will be stationary without frequent fixed-price operations. Thus, our hypothesis under credible YCC is as follows:

HYPOTHESIS 4. *Yields on 10-year JGBs follow a stationary process under YCC even without regular fixed-price operations.*

Fourth, a corollary is that bond yields can become non-stationary if the yield target range is wide and slack. In this case, yields can be non-stationary while the YCC target range is satisfied.

HYPOTHESIS 5. *Yields on 10-year JGBs become non-stationary when the yield target range is wide and slack.*

Furthermore, for YCC to be effective, the BOJ's price impact needs to be transmitted to other maturities. Based on expectations theory, the 10-year JGB yield $R_{10,t}$ depends on the weighted average of the expected short-term rates (Hutchinson and Toma 1991):

$$R_{10,t} = c_{10,t} + \frac{r_t + E_t\left(\sum_{i=1}^{9} r_{t+i}\right)}{10}, \tag{1}$$

where E_t denotes the expectation formed at time t, r_t denotes the nominal short rate, and $c_{10,t}$ denotes a term premium on the 10-year bond. The BOJ's purchase of 10-year JGBs can affect shorter-term yields through two channels. First, the controlled 10-year yields restrict the path of expected short-term rates (the expectations/signaling channel). The expectations theory also extends to longer maturities by a similar argument. Second, term premiums will decrease across the entire yield curve (the duration risk channel) if the BOJ's operations decrease risk-averse arbitrageurs' aggregate exposure to long-term bonds (Vayanos and Vila 2020). Therefore, the following hypotheses will hold if YCC is effective.

HYPOTHESIS 6. *Investors' expectations are consistent between 10-year yields and yields of other maturities.*

HYPOTHESIS 7. *The stationarity property is consistent between 10-year yields and yields of other maturities.*

5. Result

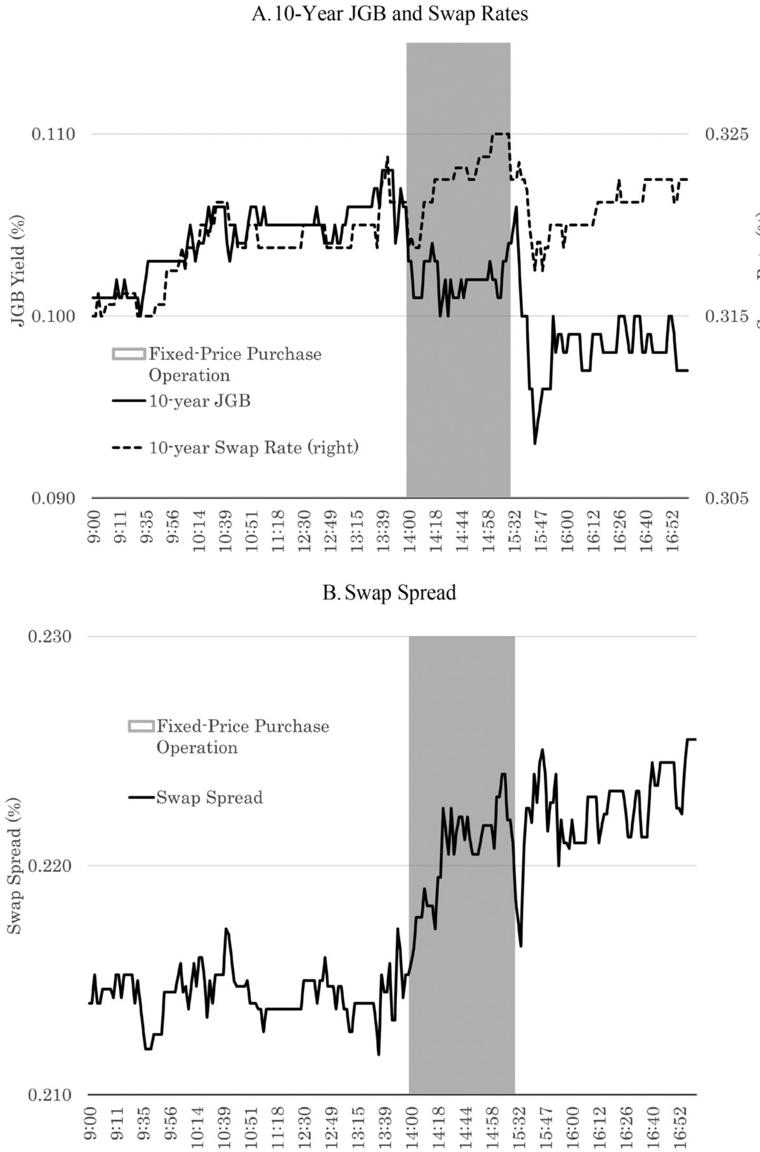
5.1 Intraday Analysis

We test Hypothesis 1 regarding the no-arbitrage relation between JGBs and the same-maturity LIBOR swap rate by analyzing intraday data from the date of the largest fixed-price operation (July 30, 2018). A tight relation between government bonds and the same-maturity LIBOR swap rate is an important underpinning of financial markets, as Krishnamurthy, Nagal, and Vissing-Jorgensen (2018) note. In particular, the 10-year swap rate is widely used for various long-term financial contracts because of its liquidity and nearly risk-free nature through central counterparty (CCP) settlements.

On July 30, 2018, the BOJ purchased 10-year JGBs at a 0.1 percent yield with no restriction on the purchase amount. At 14:00 on the same day, the BOJ announced that it would purchase an unlimited amount of 10-year JGBs through a fixed-price operation. The BOJ continued to purchase bonds at 0.1 percent until 15:30. It eventually purchased approximately 1.6 trillion yen worth of JGBs.

Figure 4 depicts the time series of the on-the-run 10-year JGB yield and the 10-year swap rate from 09:00 to 17:00. JGB yields consistently increased from the opening yield of 0.101 percent and reached 0.108 percent before 14:00. When the operation started at 14:00, JGB yields decreased sharply and stayed just below the target rate of 0.1 percent. A 1.1 basis point decrease from the peak yield to the ending yield (0.097 percent) is significant in this low-rate environment. Conversely, swap rates increased during the operation period and ended at a 0.8 basis point higher rate than at the opening. The spread of the 10-year swap rate over the 10-year JGB yield significantly increased during the fixed-price operation from 21.4 to 22.6 basis points. The BOJ's operation in the JGB market did not instantaneously propagate into the entire financial market.

Figure 4. JGB and LIBOR Swap Rates during the Largest Fixed-Price Operation



Note: This figure depicts the time series of the on-the-run 10-year JGB yield and the 10-year swap rate (panel A) and the swap spread (panel B) from 09:00 to 17:00 on July 30, 2018. At 14:00, the BOJ announced a fixed-price operation to purchase an unlimited amount of 10-year JGBs. The BOJ continued to purchase bonds at 0.1 percent until 15:30. The minute-by-minute data are obtained from Bloomberg.

We test the change in the spread using the difference-in-differences method, with 10-year swaps as the control group and on-the-run 10-year JGBs as the treatment group. We use minute-by-minute data from Bloomberg.

$$\begin{aligned} y_{i,t} = \underset{(0.0004)}{0.3186} \; &\underset{(0.0006)}{-0.2144} JGB_{i,t} \; \underset{(0.0006)}{+0.0030} Post_{i,t} \\ &\underset{(0.0009)}{-0.0075} JGB_{i,t} \times Post_{i,t} + \varepsilon_{i,t}, \end{aligned} \tag{2}$$

where $y_{i,t}$ denotes yields, $JGB_{i,t}$ denotes a dummy variable for JGBs, and $Post_{i,t}$ denotes a dummy variable that takes the value of one after 14:00 and zero before 14:00. The Newey-West heteroskedasticity- and autocorrelation-consistent standard errors are in parentheses. The largest fixed-price operation created an additional 0.75 basis point spread between the 10-year JGB yield and the 10-year swap rate. This result is consistent with Hypothesis 1, suggesting that arbitrage between these two markets is limited to some extent. Although the 0.75 basis point effect may not be large, it significantly affects pricing when yields are approximately 10 basis points. A 0.75 basis point change is equivalent to a 7.5 percent change in the current yield.[7]

We also examine the intraday yield data for two smaller fixed-price operations on February 3, 2017, and July 27, 2018. Figure A.2 depicts 10-year JGB yields on the day of the first fixed-price operation.[8] At 10:10, the BOJ announced its fixed-amount operation but surprised investors for not including an anticipated fixed-price operation. Yields sharply increased to 0.15 percent soon after this announcement and hovered around 0.14 percent until the morning market closed. As the afternoon market started at 0.151 percent, the BOJ announced at 12:30, instead of the regular 14:00, their purchase of an unlimited amount of 10-year JGBs at 0.11 percent. Yields dropped to 0.11 percent within a few minutes and remained at this level until around 14:00. Then yields slightly decreased further

[7]The 10-year swap spread remained large during August. It took more than 30 days for the spread to return to the original level of 21 basis points.

[8]The data are available on Bloomberg only until 15:00. In addition, we could not obtain the intraday swap rate data for this day.

to 0.10 percent by the end of the market. The bank eventually purchased 723.9 billion yen of JGBs. Thus, the first fixed-price operation effectively imposed a yield cap at 0.11 percent.

Figure A.3 shows the intraday yields and swap rates around a fixed-price operation on July 27, 2018, a few days before the largest fixed-price operation. Yields increased to 0.107 percent in the morning market before dropping to 0.100 percent by the end of the morning market. The figure shows a tight no-arbitrage relation between JGB and swap rates in the morning market. When the BOJ announced a fixed-price operation at 14:00 at a lower yield (0.10 percent) than the previous level, yields immediately decreased to 0.087 percent and remained within the target range. Thus, the BOJ purchased only 94 billion yen, 5.7 percent of the largest operation size, on July 30. The swap rate tightly followed JGB yields except for the temporary divergence around the end of the operation period. The swap spread was largely stable on this day.

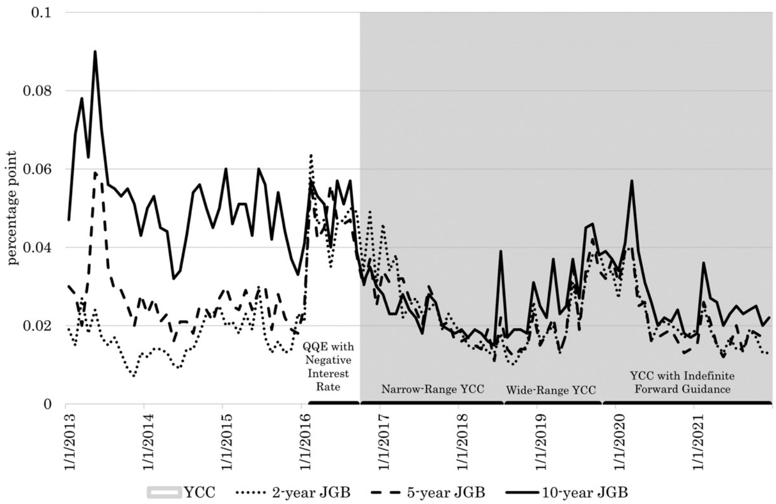
Figure A.4 depicts intraday JGB yields for different maturities on the days of three fixed-price operations (February 3, 2017; July 27, 2018; and July 30, 2018). As soon as an operation started, yields for all maturities decreased from the values observed just before the start of a purchase operation. Yields were already negative for two- and five-year JGBs; thus, an additional decrease was limited. However, yields for most maturities tended to stay lower than the values before an operation.

Overall, our intraday analysis shows that the BOJ's fixed-price operation affects JGB yields for different maturities, although the effect tends to be the largest on 10-year yields. The no-arbitrage relation between JGB yields and swap rates generally holds but can break down immediately after a large-scale intervention in the JGB market.

5.2 Expectation Dispersion

Hypotheses 2 and 6 involve investors' expectations. YCC can align investors' expectations with those of the central bank (Hypothesis 2) and make them consistent across maturities (Hypothesis 6). We use the QUICK Monthly Market Survey, which is Japan's largest expert survey regarding the stock, bond, and foreign exchange markets. In this survey, experts at securities firms, banks, and other institutional

Figure 5. Dispersion of Forecast Yields



Note: This figure depicts the standard deviation of experts' one-month-ahead forecasts of 2-, 5-, and 10-year JGB yields for each survey month. The data are obtained from the QUICK Monthly Market Survey.

investors provide their one-month-ahead forecasts of 2-, 5-, and 10-year JGB yields. We use the standard deviation of forecasts among experts to measure the different expectations of investors.

Figure 5 depicts the time series of monthly standard deviations. Before YCC, there was consensus among forecasters on 2-year yields; however, forecasters disagreed on 5- and 10-year yields. For example, standard deviations were less than 2 basis points for 2-year yields but were 5 basis points for 10-year yields. Under YCC, however, investor expectations converged significantly in two ways. First, the standard deviation level decreased from approximately 5 basis points at the start of YCC to 1.5 basis points in June 2018. This result supports Hypothesis 2. Second, expectation dispersion becomes consistent across maturities. Forecast standard deviations for 2-year yields are indistinguishable from those for 10-year yields under YCC. This result supports Hypothesis 6. In addition, these results suggest that convergent investor expectations are significant in stabilizing JGB yields.

Moreover, we note that the dispersion of investor expectations increased during the QQE with a negative interest rate (between February 2016 and September 2016), a period marked by non-stationary yields across the entire yield curve (Table 3). Dispersion also increased when the YCC target range was widened (between August 2018 and October 2019), a period similarly marked by non-stationary yields. Thus, we observe a link between elevated expectation dispersion and non-stationary yields. In contrast, the dispersion of investor expectations decreased under the narrow-range YCC and the YCC with indefinite forward guidance, both of which were characterized by stationary yields. Overall, the narrow-range YCC and the indefinite forward guidance are effective in aligning investor expectations.

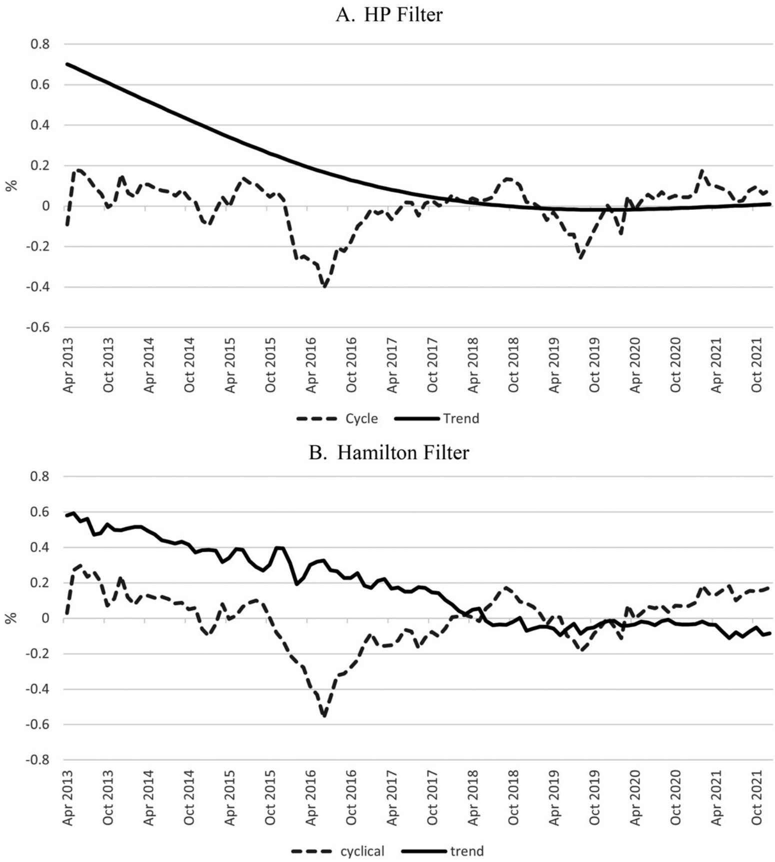
5.3 The Stochastic Property of 10-Year JGB Yields

Through fixed-price operations, the BOJ places an option-like cap on 10-year JGB yields at the 0.1 percent target rate. Thus, credible YCC will make 10-year yields hover around the target rate. For more than 3 years before the start of YCC, 10-year JGB yields had displayed a secular downward trend. Under YCC, however, yields markedly stabilized, particularly by the end of 2018. In 2019, 10-year yields remained negative.

Hence, we decompose JGB yields into cyclical (stationary) and stochastic trend (non-stationary) components to better understand the change in the stochastic property. We use monthly data and follow Ravn and Uhlig (2002) in applying the Hodrick–Prescott (HP) and Hamilton filters (Hamilton 2018).[9] The Hamilton (2018) filter is a robust detrending method based on an OLS regression. Specifically, we regress the current yield on the distributed one-year lag of yields from two years ago. Figure 6 demonstrates that the HP- and Hamilton-filtered trends are qualitatively identical. Panels A and B of Figure 6 show the results of the decomposition. Both filters show a steady decrease in the stochastic trend component before YCC and during the narrow-range YCC. It reached zero in mid-2018 and hovered around zero thereafter.

[9] The HP filter is applied with the smoothing parameter $\lambda = 1600(3)^4$.

Figure 6. Decomposed 10-Year JGB Yields



Note: This figure depicts the decomposed 10-year JGB yields by the Hodrick–Prescott (HP) filter (panel A) and the Hamilton (2018) filter (panel B) from April 2013, when the BOJ started implementing its QQE policy. The monthly data are obtained from Japan's Ministry of Finance. For the HP filter, $\lambda = 1600(3)^4$ based on Ravn and Uhlig (2002). For the Hamilton filter, we regress the current yield on the distributed one-year lag of yields from two years ago. The predicted error provides the cyclical component.

Hypothesis 3 states that bond yields become less volatile under YCC. To allow for regime-specific stochastic properties, we divide the sample into five periods: (i) QQE (from April 2013 to January 2016), (ii) QQE with a negative interest rate (from February 2016 to September 2016), (iii) narrow-range YCC (from October 2016 to July 2018), (iv) wide-range YCC (from August 2018 to October 2019), and (v) YCC with indefinite forward guidance (from November 2019 to December 2021). Table 2 shows that pre-YCC volatility was particularly large under the QQE with a negative interest rate when 10-year yields became negative (column 2). We measure volatility by the square root of the mean squared deviation from the unconditional mean (i.e., zero). The volatility of the HP-filtered cyclical component significantly decreased from 0.150 percent before YCC to 0.082 percent under YCC (columns 6 and 7). The Hamilton filter also suggests a decrease in volatility from 0.208 percent to 0.115 percent. F-tests strongly reject equal variances in both cases (p-value equals 0.000). Thus, the YCC regime significantly stabilized the JGB market, supporting Hypothesis 3.

Hypothesis 4 states that 10-year yields follow a stationary process under YCC even without regular fixed-price operations. Simultaneously, we also hypothesize that 10-year yields can be non-stationary when yields can freely drift within a wide target range (Hypothesis 5). We test the stationarity of JGB yields by following the unit-root tests developed by Mankiw, Miron, and Weil (1987) and Hutchinson and Toma (1991).

Table 3 shows the results of the augmented Dickey-Fuller (ADF) and Phillips-Perron (PP) unit-root tests based on the daily yield data for 2-, 5-, 10-, and 20-year JGBs. The 10-year yield data show significant differences in stationarity among these five periods. For the initial QQE (columns 1 and 2), both tests fail to reject the null hypothesis of a unit root. The p-values are 0.895 for the ADF test and 0.929 for the PP test. Thus, 10-year yields were non-stationary during the initial QQE. Yields continued to decrease below zero percent during QQE with a negative interest rate (columns 3 and 4). The tests marginally reject a unit root at the 10 percent level but fail to reject it at the 5 percent or lower level. Yields were generally non-stationary before YCC although they hit the zero lower bound (ZLB). Thus, ZLB does not make yields stationary.

To confirm that yields around ZLB do not cause stationarity, we also conduct unit-root tests for German federal bond yields (Table A.3). Our sample period is between April 2015 and December 2021 because German bond yields hit ZLB in April 2015. Although a unit root is rejected at the 5 percent level for 2-year bonds, it cannot be

Table 2. Volatility of the Cyclical Component

	QQE		YCC			QQE	YCC
		With Negative Interest Rate	Narrow Range	Wide Range	With Indefinite Forward Guidance	Total	Total
	Apr. 2013–Jan. 2016 (1)	Feb. 2016–Sep. 2016 (2)	Oct. 2016–Jul. 2018 (3)	Aug. 2018–Oct. 2019 (4)	Nov. 2019–Dec. 2021 (5)	Apr. 2013–Sep. 2016 (6)	Aug. 2018–Dec. 2021 (7)
HP Filter	0.091	0.287	0.055	0.122	0.073	0.150	0.082
Hamilton Filter	0.136	0.386	0.122	0.111	0.111	0.208	0.115

Note: This table shows the volatility of the cyclical component from the Hodrick–Prescott (HP) and Hamilton filters. Volatility is measured by the square root of the mean squared deviation from the unconditional mean. The sample is divided into five subperiods: QQE (from April 2013 to January 2016), QQE with a negative interest rate (from February 2016 to September 2016), narrow-range YCC (from October 2016 to July 2018), wide-range YCC (from August 2018 to October 2019), and YCC with indefinite forward guidance (from November 2019 to December 2021).

Table 3. Unit-Root Tests of JGB Yields

	QQE				YCC					
			With a Negative Interest Rate		Narrow Range		Wide Range		With Indefinite Forward Guidance	
	Apr. 2013–Jan. 2016		Feb. 2016–Sep. 2016		Oct. 2016–Jul. 2018		Aug. 2018–Oct. 2019		Nov. 2019–Dec. 2021	
	ADF (1)	PP (2)	ADF (3)	PP (4)	ADF (5)	PP (6)	ADF (7)	PP (8)	ADF (9)	PP (10)
2-Year JGB	–0.043	–0.123	–3.425	–3.468	–2.843	–2.684	–1.423	–3.4	–4.488	–32.517
	(0.955)	(0.947)	(0.010)	(0.009)	(0.052)	(0.077)	(0.571)	(0.626)	(0.000)	(0.000)
5-Year JGB	–0.892	–0.751	–3.092	–3.158	–4.199	–4.231	–1.132	–2.278	–5.018	–37.511
	(0.791)	(0.833)	(0.027)	(0.023)	(0.001)	(0.001)	(0.702)	(0.734)	(0.000)	(0.000)
10-Year JGB	–0.485	–0.273	–2.599	–2.581	–4.007	–4.056	–0.818	–1.381	–3.666	–20.671
	(0.895)	(0.929)	(0.093)	(0.097)	(0.001)	(0.001)	(0.814)	(0.823)	(0.005)	(0.004)
20-Year JGB	–0.473	–0.171	–2.63	–2.659	–3.112	–3.082	–0.507	–0.746	–2.35	–9.012
	(0.897)	(0.942)	(0.087)	(0.081)	(0.026)	(0.028)	(0.891)	(0.886)	(0.156)	(0.150)

Note: This table provides the results of the ADF and PP unit-root tests for 2-, 5-, 10-, and 20-year JGB yields. The tests are based on the daily data obtained from the Ministry of Finance, Japan. The sample is divided into five subperiods: QQE (from April 2013 to January 2016, columns 1 and 2), QQE with a negative interest rate (from February 2016 to September 2016, columns 3 and 4), narrow-range YCC (from October 2016 to July 2018, columns 5 and 6), wide-range YCC (from August 2018 to October 2019, columns 7 and 8), and YCC with indefinite forward guidance (from November 2019 to December 2021, columns 9 and 10). The intercept is included in these tests. P-values are shown in parentheses.

rejected for 5-, 10-, and 20-year yields. Thus, German data also show that ZLB does not make long-term bond yields stationary.

However, when the BOJ started YCC, 10-year yields hovered just below the upper bound of the BOJ's narrow target range. The BOJ actively announced fixed-price operations in this period when yields exhibited a significant upward move. Both tests reject the null of a unit root with p-values of 0.001 (columns 5 and 6). A stationary yield process is also observed under YCC with the indefinite forward guidance (columns 9 and 10). Both tests reject a unit root at the 1 percent level. In this regime, the BOJ did not conduct a fixed-price operation. Thus, stationarity is attributed to forward guidance and endogenized fixed-amount operations. Thus, the data support Hypothesis 4 on stationarity under YCC, especially when a target range is binding on the upper bound. Interestingly, yields became non-stationary even under YCC when the BOJ widened its target range (columns 7 and 8). In this period, yields decreased to a negative range and reached the lower bound of the widened range. The data are consistent with Hypothesis 5 about non-stationarity when the target range is slack. Overall, stationary yields are observed when the YCC target range is binding at the upper bound.

In addition, we estimate autocorrelations by following Mankiw, Miron, and Weil (1987) and Hutchinson and Toma (1991). Before YCC (from April 2013 to September 2016), autocorrelations for 10-year yields were consistently greater than 0.96 from the first (0.996) to the tenth (0.964) order. Conversely, under the YCC regime (from October 2016 to December 2021), autocorrelations decayed from 0.987 in the first order to 0.907 in the tenth order (Table A.1). Similarly, autocorrelations for five-year yields decayed under YCC from 0.982 in the first order to 0.849 in the tenth order. This result suggests that JGB yields became a mean-reverting process under YCC. This mean-reversion result is analogous to what was observed in the United States during the gold standard and the bond-price support regime (Mankiw, Miron, and Weil 1987; Hutchinson and Toma 1991).

5.4 JGBs of Other Maturities

The BOJ expects to control the entire yield curve through no-arbitrage relationships between different maturities, although the direct target is for 10-year yields. If YCC is effective, JGB yields should also be stationary for other maturities (Hypothesis 7). Table 3 shows the results of ADF and PP unit-root tests for 2-, 5-, and 20-year JGB yields. The table shows the co-movement of test statistics for different maturities over policy regimes. Under QQE until January 2016, JGB yields were non-stationary across the entire yield curve despite aggressive LSAPs (columns 1 and 2). For example, the p-values were 0.955 and 0.947 for two-year JGBs. After the BOJ implemented a negative interest rate, ADF and PP test statistics significantly increased in magnitude, and a unit root was rejected for two- and five-year yields. However, a unit root was not rejected for 10- and 20-year yields at the 5 percent level (columns 3 and 4). Thus, long-term yields were non-stationary before YCC under QQE.

However, after the narrow-range YCC was implemented, 5-, 10-, and 20-year yields became stationary at least at the 5 percent level (columns 5 and 6). For example, the p-value is 0.001 for five-year yields. For two-year yields, a unit root was rejected at the 10 percent level, although it was not at the 5 percent level (the p-values are 0.052 and 0.077). Stationary yields are also observed during YCC with indefinite forward guidance for 2-, 5-, and 10-year JGBs (columns 9 and 10). However, 20-year yields are non-stationary in this period. Investors may not have expected an expansionary monetary policy beyond the 10-year horizon. Yields are also non-stationary for the entire yield curve under the wide-range YCC between August 2018 and October 2019 (columns 7 and 8). Thus, the binding YCC makes a large part of the yield curve stationary, particularly when 10-year yields are on the upper bound of the target yield range. These results support Hypothesis 7. Overall, YCC has a qualitatively different effect on the yield curve from the previous QQE when the yield target range is binding. This result supports Hypotheses 4, 5, and 7 and implies that the BOJ has maintained the credibility of the YCC among investors.

6. Conclusion

The BOJ's YCC, which is equipped with fixed-price bond purchases, is qualitatively different from the previous unconventional monetary policy with quantitative easing and LSAPs. The BOJ effectively controlled the yield curve by introducing an endogenous intervention rule instead of a fixed purchase schedule. Investors' yield expectations converged under YCC, making JGB yields of all maturities stationary and less volatile under YCC. Although a small fixed-price operation affects swap markets through the no-arbitrage relation between JGB and swap markets, the effect of a large fixed-price operation is confined to the JGB market immediately after the intervention. Overall, these results confirm the credibility of the monetary policy of the BOJ.

Appendix. Additional Tables and Figures

Table A.1. Autocorrelation Coefficients

	Pre-YCC				YCC			
	April 2013–September 2016				October 2016–December 2021			
	2-Year	**5-Year**	**10-Year**	**20-Year**	**2-Year**	**5-Year**	**10-Year**	**20-Year**
First	0.994	0.994	0.996	0.997	0.979	0.982	0.987	0.995
Second	0.988	0.989	0.991	0.993	0.956	0.964	0.976	0.990
Third	0.981	0.983	0.987	0.989	0.932	0.949	0.968	0.986
Fourth	0.974	0.977	0.984	0.986	0.910	0.931	0.958	0.982
Fifth	0.969	0.972	0.981	0.984	0.892	0.914	0.948	0.977
Sixth	0.964	0.968	0.977	0.981	0.877	0.900	0.939	0.973
Seventh	0.959	0.963	0.974	0.978	0.860	0.885	0.930	0.969
Eighth	0.953	0.958	0.970	0.975	0.845	0.872	0.922	0.966
Ninth	0.947	0.954	0.967	0.972	0.832	0.861	0.915	0.962
Tenth	0.941	0.950	0.964	0.969	0.818	0.849	0.907	0.959

Note: This table shows the autocorrelation coefficients from the first to the tenth order for 2-, 5-, 10-, and 20-year JGB yields.

Table A.2. Granger Causality

	Number of Lags	Pre-YCC Apr. 2013– Sep. 2016 (1)	YCC Oct. 2016– Dec. 2021 (2)	Change in Probability Values (3)
BOJ's Auction Amount → 2-Year JGB Yield	1	0.1413 (858)	0.5723 (1282)	0.431
	2	0.2758 (857)	0.7078 (1282)	0.432
2-Year JGB Yield → BOJ's Auction Amount	1	0.7261 (858)	0.2862 (1282)	–0.4399
	2	0.8951 (857)	0.3405 (1282)	–0.5546
BOJ's Auction Amount → 5-Year JGB Yield	1	0.0228 (858)	0.4335 (1282)	0.4107
	2	0.0207 (857)	0.4409 (1282)	0.4202
5-Year JGB Yield → BOJ's Auction Amount	1	0.6786 (858)	0.0458 (1282)	–0.6328
	2	0.901 (857)	0.0333 (1282)	–0.8677
BOJ's Auction Amount → 20-Year JGB Yield	1	0.0729 (858)	0.8696 (1282)	0.7967
	2	0.2424 (857)	0.9812 (1282)	0.7388
20-Year JGB Yield → BOJ's Auction Amount	1	0.6032 (858)	0.0001 (1282)	–0.6031
	2	0.266 (857)	0 (1282)	–0.2660

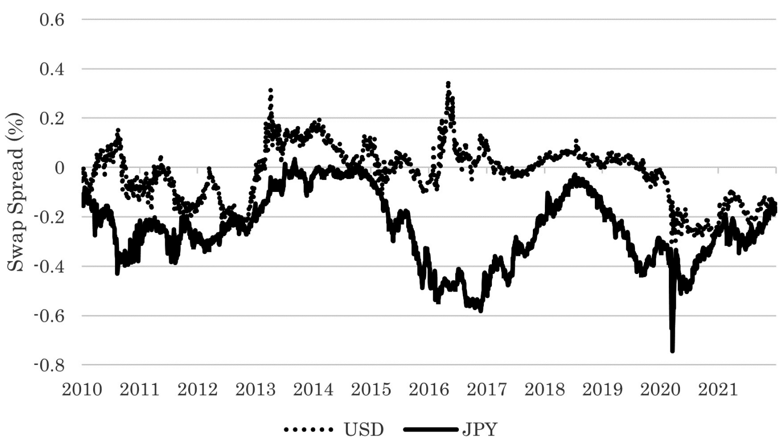
Note: This table shows the results of the Granger causality tests. The entries in columns 1 and 2 are probability values for the null hypothesis that the first-named series does not Granger-cause the second-named series. The BOJ's auction amount is for 10-year JGBs. The number of observations is in parentheses.

Table A.3. Unit-Root Tests of German Federal Bond Yields

	ADF	PP
2-Year Yield	–2.940	–2.976
	(0.041)	(0.037)
5-Year JGB	–2.395	–2.398
	(0.143)	(0.142)
10-Year JGB	–1.766	–1.719
	(0.397)	(0.421)
20-Year JGB	–1.497	–1.476
	(0.535)	(0.545)

Note: This table presents the results of the ADF and PP unit-root tests for 2-, 5-, 10-, and 20-year German federal bond yields. The tests are based on daily data. The sample period begins in April 2015 when yields hit the zero lower bound. The intercept is included in these tests. P-values are shown in parentheses.

Figure A.1. USD and JPY Swap Spread

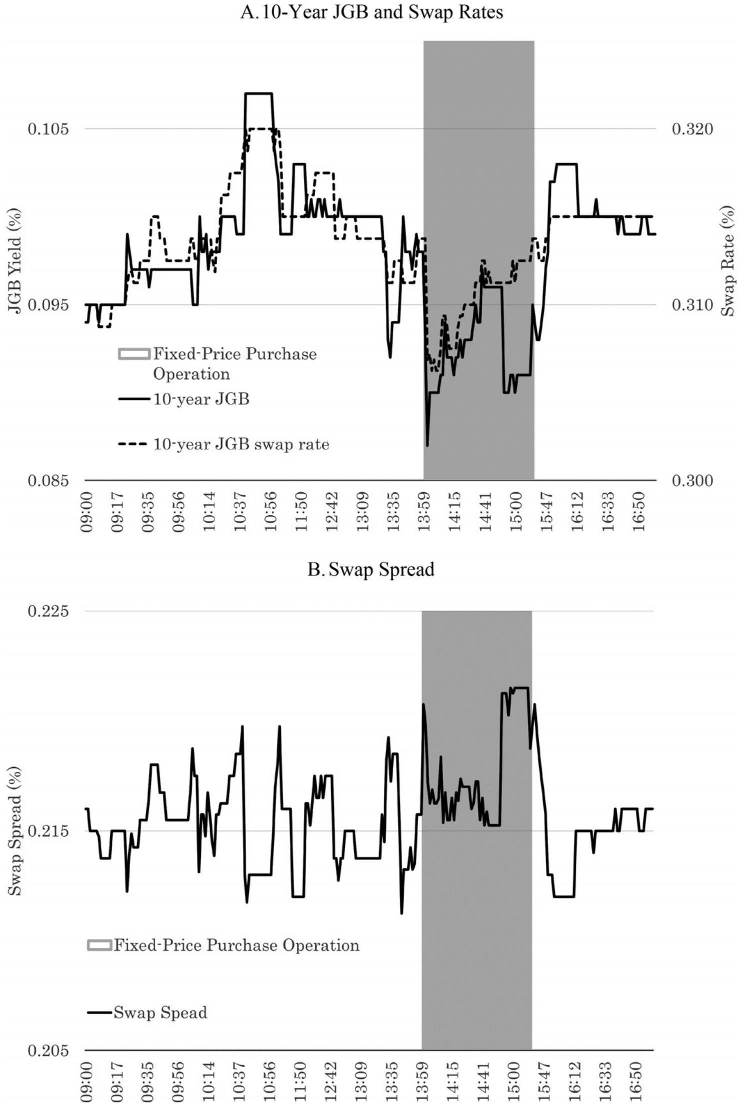


Note: This figure depicts a swap spread for USD and JPY from 2010 to 2021. The swap spread is consistently negative for JPY throughout the sample period.

Figure A.2. JGB Yields during the First Fixed-Price Operation

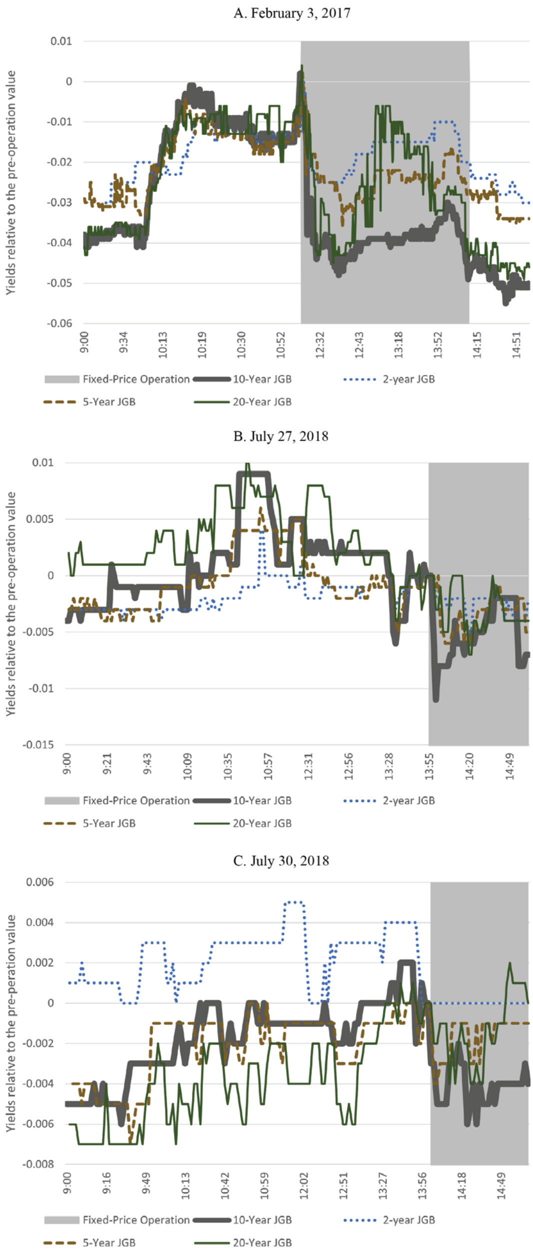
Note: This figure depicts the time series of the on-the-run 10-year JGB yield from 09:00 to 17:00 on February 3, 2017. At 12:30, the BOJ announced a fixed-price operation to purchase an unlimited amount of 10-year JGBs at 0.11 percent and bought 723.9 billion yen of JGBs. The minute-by-minute data are obtained from Bloomberg.

Figure A.3. JGB and LIBOR Swap Rates during a Small Fixed-Price Operation



Note: This figure depicts the time series of the on-the-run 10-year JGB yield and the 10-year swap rate (panel A) and the swap spread (panel B) from 09:00 to 17:00 on July 27, 2018. At 14:00, the BOJ announced a fixed-price operation to purchase an unlimited amount of 10-year JGBs at 0.10 percent. The BOJ purchased 94 billion yen of JGBs until 15:30. The minute-by-minute data are obtained from Bloomberg.

Figure A.4. JGBs of Different Maturities during Fixed-Price Operations



Note: This figure depicts the time series of the relative yields for 2-, 5-, 10-, and 20-year JGBs on February 3, 2017 (panel A), July 27, 2018 (panel B), and July 30, 2018 (panel C). The yields are relative to the last value before the start of an operation. The shaded region indicates the period of the BOJ's fixed-price operations. The minute-by-minute data are obtained from Bloomberg.

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