ISSN 0956-8549

Low Rates and Bank Loan Supply: Theory and Evidence from Japan

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DISCUSSION PAPER NO 884

August 2023

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March 2023

Abstract

In this paper, we explore the consequences of low nominal interest rates for credit supply, macroeconomic outcomes and policy. Using the protracted period of negative rates and detailed micro data from Japan, we show that banks with higher ex-ante market power face relatively higher funding costs, have lower profitability, and decrease loan supply in a low nominal rate environment. We build a macroeconomic model that rationalizes our key empirical findings and characterizes optimal long-run rates. Market power in deposits helps mitigate lending frictions, but is sensitive to nominal rates due to the existence of cash. Under such lending frictions, the optimal nominal rate is higher than suggested by the Friedman rule. Calibrating the model with cross-sectional panel evidence, we find that low rates resulted in significantly lower aggregate lending, negatively affecting output. Tiering bank reserves only marginally alleviates the negative effects of low rates on credit supply, while taxing cash is more effective.

*We would like to thank Markus Brunnermeier, Stephen Redding, Mark Aguiar, Atif Mian, and Motohiro Yogo for invaluable discussions, guidance, and support over the course of this project. We also thank Martin Guzman, Kimie Harada, Takatoshi Ito, Nobu Kiyotaki, Oleg Itskhoki, Moritz Lenel, Ernest Liu, Adrien Matray, Sebastian Merkel, Randall Morck, Jonathan Payne, Julian Richers, Etsuro Shioji, Joseph Stiglitz, Mauricio Ulate, Takashi Unayama, Olivier Wang, David Weinstein, Christian Wolf, and participants in the Princeton Finance seminar and the Japan Economics Seminar at Columbia Business School for helpful advice and comments. We thank Nicholas Garvey for excellent research assistance. This work was supported by the Julis-Rabinowitz Center for Public Policy & Finance at Princeton's Woodrow Wilson School, the Macro Financial Modeling Project at the Becker Friedman Institute, and the Institute for New Economic Thinking.

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1 Introduction

An important economic phenomenon of recent decades has been the decline of nominal interest rates. Policymakers and practitioners have expressed concerns that this environment puts pressure on financial intermediaries' profitability and ability to lend, threatening financial stability and monetary policy transmission.[1] Several papers have proposed that environments with low nominal rates can reduce or even reverse the effects of monetary stimulus because of this intermediary profitability channel (Brunnermeier and Koby, 2018; Eggertsson et al., 2019; Ulate, 2021b). Recent increases in inflation and interest rates have not smoothly restored bank profitability, pointing to potential repercussions of low rates even outside that environment. However, a challenge in studying the implications of low nominal rates is that other macroeconomic shocks typically occur at the same time, and may both drive and conflate the effects of policy rates.

In this paper, we examine the case of Japan, where nominal rates reached low levels well before the United States and Europe, to explore the consequences of low nominal rates for bank lending, output, and optimal policy. Our empirical approach allows us to identify distortions in credit supply that result from long-term changes in nominal interest rates. We then build a theoretical environment that rationalizes these empirical results, allows us to draw formal conclusions about the efficiency of these observed changes, and provides a novel explanation for why optimal long-run rates are higher than zero. The model is disciplined by empirical moments to estimate the aggregate effect of low nominal interest rates on lending and output for Japan, and allows us to test policy tools in a low interest rate environment.

The first contribution of the paper is to provide novel empirical evidence on the detrimental long-term effects of low nominal interest rates on bank profits and lending, based on micro data. In Japan, aggregate bank profitability significantly decreased after the onset of the low interest rate environment. The aggregate spread between banks' interest expense and the risk-free rate decreased from close to one percent in the early 1990s to roughly zero after 2000. In contrast, the spread banks earn on assets over the risk-free rate only increased by 0.2 percent, resulting in a 0.8 percent decrease in net interest margins.

[1] See Coeure (2016); Lane (2016); Kuroda (2017).

We show that banks' exposure to low nominal rates is heterogeneous, and that banks' historical liabilities structure is a strong quasi-exogenous predictor of this exposure. Due to the segmentation of Japan's banking industry prior to the 1980s, certain banks built strong local deposit customer bases, which allowed them to pay lower deposit rates.[2] In 1990, the range of funding spreads is large: banks charged a spread of between 0.2 and 4.8 percent on deposits (mean 4.0; s.d. 0.9).

We use bank heterogeneity to show that exposure is associated with losses in bank profitability, capitalization, and lending in a low interest rate environment. As exposed banks paid low interest rates on liabilities ex-ante, a reflection of their market power, they are less able to pass through interest rate cuts to liabilities as rates decline. To assess the effect of low rates on banks, our main empirical test is a difference-in-difference regression with exposure, measured as the deposit spread in 1990, as a continuous treatment variable, comparing the 1990s (pre) to the decade after 2000 (post). We control for time fixed effects, which absorb macroeconomic variation that is common to all banks, time-invariant bank fixed effects, and bank characteristics that may affect bank profitability and be correlated with our measure of exposure: non performing loans and bank size. Although the collapse of real estate prices in the early 1990s and subsequent banking crisis had large effects on banks, controlling for non performing loans and size has little impact on our empirical results.[3] After 2000, the least exposed banks cut interest expenses by 4.1 percentage points, on average. By contrast, the most exposed banks only reduced interest expenses by 1.7 percentage points.

To interpret our results as the effect of the low rate environment, our identification assumption is that no macroeconomic factors differentially affect banks along the measure of exposure, aside from interest rates. One threat to identification is potential trends in bank competition that particularly affect exposed banks. To address this potential concern, we show that our main results hold within region-years, as well as among regional banks alone.

[2]Prior to the 1990s, Japanese banks faced both interest rate controls and restrictions on the types of liabilities that could be raised, which depended on bank type. The deregulation of the Japanese financial system was driven by rising fiscal deficits that required government bonds to pay market rates of return, as well as pressure from the U.S., and was largely implemented during the 1970s and 1980s (Hoshi and Kashyap, 2004; Hotori, 2021).

[3]Zombie lending was most pronounced during the mid-1990s, among banks with low equity and an incentive to evergreen loans rather than report losses that would result in losses to equity (Peek and Rosengren, 2005; Caballero et al., 2008).

Region-time fixed effects absorb time-varying variation at the prefecture level, including rising competition. That our results hold within regional banks indicates that banks' business models are not driving the empirical findings, since regional banks' business models are similar. Our results are robust to weighting by initial total bank assets. We also show the robustness of our findings to alternate measures of deposit market power as the exposure variable: (i) the 1990 share of deposits in liabilities (Heider et al., 2019; Ampudia and den Heuvel, 2019; Eggertsson et al., 2019), (ii) the deposit spread in 1980, and (iii) the estimated sensitivity of deposit spreads to the level of and changes in the policy rate (Drechsler et al., 2017, 2021). To strengthen the argument that our results are driven by interest rates, we also run regressions with interactions between exposure and the level of nominal rates, which yield consistent results. We consequently conclude that exposed banks' ability to generate funding profits was significantly reduced by the low interest rate environment.

Using the same empirical framework, we then show that exposed banks' overall margins decrease when rates decline: lower funding profits are not offset by increases in fees, non-interest income, or decreases in costs. Net interest income and net ordinary income over assets of the most exposed banks decrease, on average by 1.3 and 1.0 percentage points more than the least exposed bank, respectively. Next, we show that the lower net income of exposed banks translates into lower equity, as neither dividends nor capital issuance change enough to reverse losses in interest income. Ultimately, the loan spread of exposed banks rises. The estimated coefficients imply that for each percentage point increase in funding costs, roughly 30 basis points passes through to lending rates in the low rates environment.

A final empirical exercise shows in bank-firm matched loan-level data that firms' borrowing from the most exposed banks declines by 6.4 percent on average, relative to the least exposed banks in the sample. These estimates control for firm demand through the inclusion of firm-year fixed effects and rule out demand-driven explanations for the results above. At the firm level, this results in declining bank borrowing, total borrowing, and reductions in firm size measured by assets and employment. In addition to confirming the presence of strongly negative long-run effects on credit supply, our empirical results are also informative for theories proposing that monetary policy cuts are less expansionary at low rates.

Our second contribution is to build a macroeconomic model with heterogeneous banks that rationalizes our cross-sectional findings, characterizes aggregate effects, and provides a theory of optimal long-run rates under testable assumptions. In the model, differences in the quality of banks' savings products generates heterogeneous exposure to the low rate environment. Banks' market power on liabilities alleviates lending frictions by raising banks' capitalization. Low nominal interest rates decrease banks' market power, reducing net worth and lending in equilibrium. Consequently, the optimal inflation target is higher than suggested by the Friedman rule: the long-term nominal policy rate is strictly positive in the welfare-maximizing equilibrium. In the model, the effects of low rates on bank intermediation in the aggregate operate through the same channels as in the cross-section, so our identified empirical moments are informative about the aggregate credit supply mechanisms at play, in the spirit of Nakamura and Steinsson (2018). As such, our cross-sectional empirical evidence can be used to discipline the model and make quantitative predictions.

Specifically, we extend a standard macroeconomic model with heterogeneous banks that provide liquid savings products to households, raise equity, and invest in loans and bonds. Firms use bank loans and bonds to finance capital purchases. Households provide labor, consume, and save using bonds, deposits, and currency. Money and deposits provide liquidity benefits, but are imperfect substitutes. Bank deposits are also imperfect substitutes across banks, and heterogeneity in banks' deposit quality results in heterogeneity in market power.[4]

Banks' market power also depends on the relative returns to bank savings and cash. Banks invest in bonds at the margin, and hence pay a deposit rate equal to the bond rate times a mark-down that depends on the elasticity of deposit supply. We consider the implications of changes in long-term nominal interest rates induced by changes in the inflation target, such that the real rate stays constant. The pass-through of nominal rate changes to interest expenses is incomplete if and only if the elasticity of substitution between cash and deposits is higher than the elasticity of substitution between liquid savings and bonds. That incomplete pass-though is documented in our empirical results confirms the assumed relative elasticity. Intuitively, when rates are low, cash is more attractive, and banks earn lower profits per unit of deposits.

[4]Our approach relates to the heterogeneity in the quality of banks savings' products and structural estimates of banks' market power on liabilities documented by Egan et al. (2017a,b).

Bank lending is constrained by financial frictions, which bank market power helps to mitigate by raising banks' net worth. The loan rate is the sum of the bond rate, a mark-up, and a shadow price associated with banks' leverage constraint. Bank equity is raised from households, who require their discount factor and an additional premium, pinning down bank equity at a sub-optimal quantity, which limits loan supply. This builds on the idea that banks' exposure to interest rate risk or other sources of net worth variations have real consequences for bank lending (Gropp et al., 2018; Gomez et al., 2021). Market power on deposits alleviates these frictions by raising the return on equity.

Following a decline in the inflation target that decreases nominal rates, we show that bank profits decrease if and only if the pass-through of nominal rates to deposit rates is incomplete. Under the same condition, bank equity falls and – through financial frictions – lending falls as well. Relative to Drechsler et al. (2017), who focus on deposit inflows from bond savings, our model highlights the potential of outflows to cash as a countervailing force, which occurs when substitution between cash and deposits is greater than substitution from bonds to liquid savings. The decline in lending results in lower investment, capital and output.

Absent financial frictions, households benefit from lower inflation that allows them to increase savings in cash and deposits, and the Friedman rule holds: optimal nominal rates are zero. With financial frictions, the welfare-maximizing inflation target is higher than suggested by the Friedman rule, resulting in strictly positive nominal rates at the optimum. While other authors have shown positive inflation to be optimal, prior work emphasizes achieving a reduced frequency of hitting the zero lower bound (Christiano et al., 2011; Coibion et al., 2012). By contrast, the mechanism driving higher optimal nominal rates in our setting is the distortion to bank lending caused by deposit market power.

A third contribution of this paper is to demonstrate quantitatively that the frictions we highlight generate an economically significant decline in bank lending in Japan, and to measure the impact of policies that in theory mitigate these effects. We discipline the model using our empirical estimates of funding spreads in the pre-period, cross-section, and low rates environment. Importantly, we do not incorporate information regarding aggregate changes in equity, lending, or investment as model inputs, instead comparing the model predictions of these variables as a test of the model.

In the quantitative model, the frictions generated by low nominal rates cause a significant decrease in equilibrium lending and output. We change the nominal rate from the early 1990s average of 3.4 percent to the post-2000s low rate environment of 0.2 percent, assuming inflation adjusts to keep the real rate constant. Cash holdings as a percent of households' total financial assets increase, in line with aggregate Japanese data. As a result, bank market power decreases significantly. The change results in a four percent permanent decrease in loans and a 0.5 percent permanent decrease in output, with effects of similar magnitude on wages and consumption. This effect is non-linear: it is three times larger during the last percentage point decrease than during the first percentage point decrease. There may thus be substantial costs to keeping nominal rates near zero for extended periods of time. This finding provides support for the idea proposed in Brunnermeier and Koby (2018) and Eggertsson et al. (2019) that monetary policy cuts that result in very low interest rates can be contractionary, especially in the long-run.

We quantify the effect of two policy counterfactuals. First, we model reserve tiering closely to how it was implemented by the Bank of Japan in 2016. Bank reserves were tiered according to outstanding balances in 2015, such that 80-90 percent of reserves earned a 0.15 percent higher rate than marginal balances. In the model, we add reserves to banks' investments and apply subsidies to infra-marginal units. This has quantitatively small effects: lending increases by 0.25 percentage points in the low rate steady state.

By contrast, taxing cash significantly improves efficiency. In a second counterfactual experiment, we show that a decrease in the return on cash savings undoes four times more of the negative effects of low nominal rates. We model Agarwal and Kimball (2015)'s proposal, where currency is replaced by electronic money as the unit of account, and central banks set an exchange rate between electronic and paper currency, effectively controlling the nominal return on cash. Setting this nominal return to a modest negative 0.1 percentage points increases lending by 1 percent while producing negligible feedback on liquidity.

The remainder of the paper is structured as follows. The rest of this section summarizes related literature. Section 2 describes the empirical strategy, sources of data used, and empirical results. Section 3 presents the model. The key mechanisms are described in

Section 4. The calibration is set out in Section 5, as are the results on the aggregate effects and counterfactual experiments. The final section concludes.

Related literature. Existing empirical work on the consequences of low interest rates for banks includes evidence on the pass-through of negative policy rates to other interest rates (Jackson, 2015; Claessens et al., 2018; Bech and Malkhozov, 2016) as well as to bank equity and lending (Ampudia and den Heuvel, 2019; Heider et al., 2019; Eggertsson et al., 2019), but primarily focuses on Europe and the United States.[5] Two papers study Japan's negative interest rates episode in 2016 (Nakashima and Takahashi, 2021; Hong and Kandrac, 2022); we focus on the low interest rate period that began in the 2000s. Wang et al. (2022) show that bank market power is quantitatively important in explaining the short-run transmission of U.S. monetary policy to lending when rates are low and positive, relative to regulatory constraints and financial frictions. By contrast, our model focuses on the long-run steady state and aggregate outcomes including output and optimal policy, and is calibrated to long-run cross-sectional empirical evidence under the assumption that frictions exist in the steady state. Our approach has advantages relative to short run analysis because identification in the short term is complicated by the endogeneity of monetary policy and banks' interest rate hedges. Although banks actively match the interest rate risk of their liabilities and assets (Drechsler et al., 2021), permanent declines in interest rates cannot be hedged.

Several recent papers explore the general equilibrium effects of low and negative interest rates, typically focusing on a balance of short-run effects.[6] Brunnermeier and Koby (2018) demonstrate the existence of a policy "reversal rate," below which interest rate cuts are contractionary for lending. The reversal rate crucially depends on banks' capitalization and bond holdings, which they quantify using a New Keynesian closure and European data. Unlike their paper, we assume banks' ability to hedge interest rate risk disappears in the long-run, and that bank equity follows different dynamics.[7] Our results however relate to the idea that the long-run reversal rate is essentially high and positive: in the long-run, positive nominal rates and higher inflation than suggested by the Friedman rule are optimal. Ulate

[5] Heider et al. (2021) and Balloch et al. (2022) survey the literature on negative rates.
[6] See also Rognlie (2016); Eggertsson et al. (2019); de Groot and Haas (2021); Onofri et al. (2021).
[7] Monetary policy cuts stealthily recapitalize banks in the short-run (Brunnermeier and Sannikov, 2016).

(2021b) estimates reduced positive welfare benefits of monetary policy below a threshold low level of interest rates and in negative territory, and calibrates his model to European data. In the U.S., Wang (2019) finds that low nominal rates increase lending spreads in a model with perfect bank competition and a constraint that restricts banks' ability to raise deposits. Our focus is on market power rather than liquidity premia, and our constraint limits lending rather than deposits, which is closer to a capital requirement and allows for large deposit inflows as observed in low rate environments globally.

Compared to the existing theoretical literature, we develop a testable theory of the optimal trade-off between liquidity benefits and decreased bank intermediation through market power, augment the model with bank heterogeneity to discipline it using novel cross-sectional data, and find that the negative effects of bank disintermediation strongly dominate in the long run for Japan.

2 Empirical evidence

In this section we present empirical evidence that the spread between the policy rate and banks' interest expenses decreases with the level of rates, resulting in lower aggregate net interest margins. This holds both in the aggregate and across banks that are heterogeneously exposed to the level of interest rates, through their historical liability structure. We then project exposures on other outcomes of interest such as profits, equity, and lending, and show that they all decline for more exposed banks.

2.1 Data

We use three main sources of data for this project.

At the bank level, our data comes from Nikkei NEEDS Financial Quest, which includes regulatory filings of listed commercial banks in Japan. Since not all banks report fully in every quarter, we rely primarily on fiscal year end reporting in March of each year. Our data starts in 1975 and ends in 2017. During that period, a significant number of mergers and acquisitions occur, and twelve banks fail. For banks involved in mergers, we calculate pro-forma balance sheets for combined entities throughout our sample.[8] This allows us to trace current performance to historical exposure despite substantial merger activity, and allows us to include more banks. This approach is more accurate because the unmerged sample of banks has many banks that do not have a clear historical counterpart, or the historical counterpart may not reflect the current business model due to acquiring other banks.[9] We exclude the Japan Post Bank, due to lack of data prior to 2006, and Shinkin credit cooperatives. Table 1 shows summary statistics for the Japanese banking sector in 2000. There is substantial heterogeneity in bank size, and banks are on average highly dependent on deposits and highly leveraged. Loans are by far banks' main assets.

In addition to bank level data we use firm-level reporting of borrowing from specific banks to run loan-level regressions. This data is included in listed firms' regulatory filings and is collected by the Development Bank of Japan at an annual frequency. Our sample includes the universe of listed firms. Firms' disclosures include the quantities of long-term and short-term borrowing from all major financial institutions in Japan, as well as firms' annual financial data.

Finally, we supplement our micro data with aggregate data on banks and macroeconomic variables from the Bank of Japan.

2.2 Aggregate evidence

Since the 1970s, banks' aggregate net interest income per assets has decreased alongside nominal rates. This decline took a sharp turn in the late nineties following the collapse of the real estate bubble, and after that rates essentially stayed close to zero. Despite business cycle fluctuations and the early 1990s real estate crisis, net interest income per asset of Japanese banks has steadily trended down since the mid-1970s.

In this environment, banks have been unable to fully pass through declines in nominal rates to the rate they pay for their liabilities, while the realized spread between loan rates

[8] For example, to calculate the historical deposits to liabilities ratio of Mizuho Financial Group, we use the sum of the balance sheets of the Industrial Bank of Japan (IBJ), Dai-Ichi Kangyo Bank, and Fuji Bank, which were merged in 2002.

[9] Appendix B explains the exact procedure we use for mergers, and Appendix C shows that our results hold even when using the unmerged sample of banks.

and nominal rates has steadily increased. Figure 1 panel (a) displays a plot of nominal rates against the aggregate realized interest rate banks pay on their liabilities. As rates fell, banks began paying rates closer to the nominal rate, reducing their margin relative to the risk-free rate from close to one percent in the early 1990s, to roughly zero after 2000.[10] Importantly, these trends are not driven by business cycle fluctuations, and appear stronger when business cycle components are taken out using an HP filter. Figure 1 panel (b) displays a plot of nominal rates against the aggregate realized spread banks charge on their loans.[11] The low level of nominal rates seem to coincide with a high level of realized loan spreads. As was the case for interest expenses, these trends are not driven by business cycle fluctuations. Aggregate bank profitability and lending as a share of GDP also declined.[12] However, these declines could reflect secular changes in the provision of credit which coincide with long-run changes in nominal rates. We cannot exclude, for example, that the collapse of the real estate bubble had extremely persistent effects on Japanese banks. For these reasons, in the remainder of our empirical analysis we use variation in the cross-section of banks, to rule out secular trends.

2.3 Empirical Strategy

Exposure variable. Banks' exposure to the low interest rate environment differs by the extent of market power in local deposit markets, which we denote using α_j. Our main empirical measure of α_j is the markup banks charge on deposits in 1990:

$$\hat{\alpha}_{j,1990} = i_{1990} - i^d_{j,1990}, \tag{1}$$

[10]The evolution of three-month Yen Libor is shown in Appendix Figure A1 panel (a). The relevant marginal rate, in our theory, is the risk-free rate, but this empirical fact holds – and is in fact stronger – if rates with higher maturity are used, given the duration of banks' liabilities.

[11]Interest rates in Japan were liberalized over the course of the 1980s. Prior to this, interest rate controls led banks to charge artificially low interest rates on loans. To compensate, banks sometimes required banks to hold deposits at zero interest. In addition, interest rates on deposits were controlled to provide an implicit subsidy to banks. Interest rate deregulation began in the mid-1970s, and interest rate ceilings on deposits were lifted between 1984 and 1989. Although our analysis focuses on the period after liberalizations, our empirical results are robust to using the full sample.

[12]Appendix Figure A1 panel (b) shows the decline in aggregate bank net interest income per asset since 1975. Appendix Figure A2 panel (a) shows the evolution in bank loans to non-financial corporations as a percentage of GDP since 1980.

where i_{1990} is the nominal interest rate in 1990, and $i^d_{j,1990}$ is the nominal rate charged on bank j's deposits in that year. In our model, α_j correlates one-for-one with the elasticity of banks' deposit supply, and hence with market power. Regressions of this ex-ante markup on prefecture and type fixed effects explains 94 percent of the variation across banks, as seen in Table A2 in the Appendix.

Geography drives part of the ex-ante markup. This is in part due to attributes of depositors in markets where banks were historically dominant, and in part driven by historical restrictions that existed on bank entry and branch expansion. Income per capita, population density, and the number of other banks headquartered in a prefecture can be shown to explain 50-60 percent of the variation in 1990 markups. This is because local market conditions and competition influence the ability of banks to charge a spread on deposit services. Bank types also play a role. Historical regulatory restrictions and market segmentation was imposed on banks by type, and had persistent effects on banks' market power. Up to the late 1970s, restrictions limited the types of liabilities banks could issue, depending on bank type (e.g. long-term credit banks, city, trust, regional).

One alternate measure of exposure is the ratio of bank deposits to total liabilities in 1990. The deposits to liabilities ratio of banks measures to what extent banks rely on deposits for funding, and is a measure of market power because banks typically do not have market power over other sources of funds, such as wholesale funding. Banks in regional areas, for example, had more ordinary deposits and less wholesale funding than city banks. The markup banks are able to charge in 1990 is highly correlated with the 1990 deposits to liabilities ratio. The deposits to liabilities ratio is also highly persistent.[13]

We can also measure exposure in the data by estimating the sensitivity of funding spreads to the level of interest rates. There is significant heterogeneity in the exposure of individual banks to long-run changes in the aggregate level of interest rates. These ex-ante historical measures of market power aim to identify banks' exposure to monetary policy. This can be thought of as the extent to which banks' spreads depend on the level of interest rates. Both alternative measures generate similar results to our main findings, as shown in Appendix C.

[13]For the persistence of deposits, see Appendix Figure A4 panel (a); the correlation of markups and deposit dependence is shown in panel (b).

Regression specification. We use 1990 as our starting point, as there were considerable interest rate controls prior to the 1990s.[14] Not only were banks unable to charge market interest rates on loans prior to 1990, but also common practices such as requiring borrowers to make deposits that did not earn interest also distorts bank income and profitability in prior periods.[15]

Our regression specifications test whether banks that are more exposed through their market power are differentially affected once Japan enters the low-rate environment. We first assess this in regressions of bank outcomes y_{jt} on our measure of bank exposure (the spread on deposits in 1990), a dummy variable that equals one in the years of the low-rate environment (Post), and the interaction of exposure and the post dummy. Our regressions hence take the form:

$$y_{jt} = \beta_0 + \beta_1 \,\mathrm{Post}_t + \beta_2 \,\hat{\alpha}_{j,1990} + \delta \,\mathrm{Post}_t \times \hat{\alpha}_{j,1990} + \mathrm{Controls}_{jt} + \epsilon_{jt}, \tag{2}$$

where we set Post_t equal to 1 in the years after 2000. The coefficient of interest δ indicates whether banks that are more exposed to the monetary policy environment have different outcomes in the low rate environment (i.e. after 2000). We add time fixed effects to control for macroeconomic variation (that replace $\beta_1 \,\mathrm{Post}_t$ with a β_t for each year), controls for bank size and non-performing loans interacted with the post variable, and bank fixed effects to control for other time-invariant differences across banks (that replace $\beta_2 \,\hat{\alpha}_{j,1990}$ with a time-invariant β_j for each bank). Standard errors are clustered at both the bank and pre/post level, our main sources of variation. The identification assumption these regressions rely on is that there are no macroeconomic factors that differentially affect banks along the measure of exposure, other than the effects of interest rates.

Table 2 compares the characteristics of banks according to whether they have high or low $\hat{\alpha}_{j,1990}$, splitting the group at the median (4.26). These groups differ particularly along bank size, exposure to NPLs, and the share of regional banks. To address these concerns, we

[14] Changing this starting point and including the full sample does not change our results, as shown in Appendix Table A3.

[15] In addition, the 1980s were a period of substantial deregulation which we believe to be orthogonal to level of nominal interest rates, but which did affect bank lending (Hoshi and Kashyap, 2004; Balloch, 2022).

include initial bank size and the maximum level of nonperforming loans as control variables, as well as an interaction of these variables with a post dummy, and in some regressions restrict the sample to only regional banks.

One threat to identification is that the decrease in nominal rates coincided with the collapse of Japanese real estate prices in the 1990s, which was followed by a major banking crisis. This concern, however, biases our coefficient towards zero: indeed, banks with large non-performing loans as a percent of their balance sheet typically had smaller deposit spreads prior to the crisis.[16] Nevertheless, we include controls for non-performing loans (interacted with our Post_t variable) in our regressions. These controls typically increase the magnitude of the estimated coefficients.

Another concern is that secular trends across bank types threaten identification. Indeed, some of the regulations that gave regional banks more deposit market power were removed in the 1970s and 1980s, and could have affected these banks beyond that. Moreover, secular trends towards urbanization might also result in spatial heterogeneity unfavorable to regional banks and uncorrelated with low nominal interest rates. To address these concerns, we show that our results hold when we allow for an interaction of the post dummy with banks' initial size and run regressions using only variation within regional banks.

Our data is sufficiently detailed to allow us to further explore these effects in dynamics at an annual frequency. To understand more precisely the timing in which the low rate environment affects banks, we also run dynamic regressions which examine the relative outcomes of exposed banks in each year. These regressions take the form:

$$y_{j,t} = \beta_t + \beta_j + \sum_{s=1990}^{2010} \delta_s \cdot \mathbf{1}_{t=s} \cdot \hat{\alpha}_{j,1990} + \text{Controls}_{jt} + \epsilon_{jt}, \tag{3}$$

where the coefficients of interest δ_s are now estimated for each year. This allows us to determine whether changes in outcomes occur gradually or suddenly.

[16] The correlation between $\hat{\alpha}_{j,1990}$ and bank maximum NPLs over assets is -0.18.

2.4 Empirical results

Effect on spreads and net interest margins. Banks with high initial deposits spreads are less able to pass-through interest rate cuts once Japan enters the low interest rate environment. In Table 3, the coefficient on Post in column (1) of panel A indicates that the interest expense rate of banks with $\hat{\alpha}_{j,1990} = 0$ fell by 4.2 percentage points after 2000. The coefficient on $\hat{\alpha}_{j,1990}$ must be multiplied by the initial markup, which ranges from 0.2 to 4.8, to be interpreted as a magnitude. This indicates that the most exposed bank initially paid an interest rate on its liabilities that was $(0.67 \times (4.8 - 0.2) =)$ 3.1 percentage points lower than the least exposed bank. The estimated coefficient on the interaction term is large and statistically significant, indicating that banks with high deposit spreads in 1990 are less able to reduce their interest expenses in the low nominal rates period. This implies that while the least exposed bank could reduce its interest expense by $(4.23 - 0.2 \times 0.52 =)$ 4.1 percentage points, the most exposed bank could only afford a reduction of 1.7 percentage points. Column (2) adds year fixed effects, to control for macroeconomic factors. This leaves the coefficients essentially unchanged. Column (3) adds controls for bank size and non-performing loans interacted with post, as well as bank fixed effects, which control for time-invariant bank characteristics. In column (4) we additionally control for region-year fixed effects and weight the regression by the log of initial total assets; this demonstrates that the results are not being driven by increased competition, rising inequality between regions, or only small banks.

Columns (5) and (6) show the same specifications as columns (2) and (3), using only the sample of regional banks. That these effects hold using only the sample of regional banks is a good robustness check, as regional banks are most similar in terms of business model. We are encouraged that within this narrow category of bank types, our main results remain statistically and economically significant.

We run several additional robustness tests, including four alternate measures of deposit market power as the exposure variable. Specifically, we show our findings are robust to using as the exposure variable: (i) the 1990 share of deposits in liabilities, as in Heider et al. (2019); Ampudia and den Heuvel (2019); Eggertsson et al. (2019), (ii) the deposit spread in 1980,

(iii) the estimated sensitivity of deposit spreads to the level of the policy rate, and (iv) the estimated sensitivity of deposit spreads to changes in the policy rate, as in Drechsler et al. (2017) and Drechsler et al. (2021). The results are also robust to using unmerged banks and the full sample period (1975-2017). Finally, to strengthen the argument that this is driven by interest rates and not other factors, we also run regressions with interactions between the exposure variable and the level of nominal interest rates.[17] The results of these regressions for interest expenses and net interest margins are shown in columns (2) and (3) in Appendix Table A3. We consequently conclude that exposed banks' ability to generate funding profits was significantly reduced in the low interest rate environment.

This result is driven by the fact that while banks with high initial spreads pay lower interest rates on liabilities in the high rates environment relative to banks with lower exposure, this advantage is no longer present once interest rates become low. In fact, both groups essentially pay the same price for their liabilities in the post environment. This is most evident in Figure 2 panel (a), which plots the coefficients δ_t of regression (3).

Figure 3 panel (a) provides a visual representation of our baseline result, by plotting the change in the effective interest rate on liabilities for each bank against its spread on deposits in 1990. This shows that banks with low exposure have reduced their interest expenses significantly, while banks with higher exposure are less capable of reducing their interest expenses. The relationship between the change and exposure appears approximately linear, which supports the implicit linearity assumption in regressions (2) and (3).

Next we show that exposed banks do pass through some of their increased interest expenses into rates they charge (or earn) on their assets. Panel B of Table 3 shows the results of regression (2) for interest income, normalized by total assets. The significant and positive coefficient on the interaction term confirms the relative rise in interest income for exposed banks. Importantly, the size of this change is smaller than the effect of low rates on the pass through of interest expenses. This qualifies the results of Drechsler et al. (2021), which show that banks actively hedge interest rate risk using the duration of their assets: banks simply cannot use that hedge against "low-for-long" interest rate environments.

[17]Controlling explicitly for trends interacted with exposure in this regression further strengthens the results. These results are available upon request.

It follows from our two previous results that exposed banks' net interest margins must be falling. We define banks' net interest margin is the difference between banks' interest income divided by total assets and interest expenses: $\text{NIM}_{j,t} = \frac{\text{Interest income}_{j,t}}{\text{Assets}_{j,t}} - \frac{\text{Interest expenses}_{j,t}}{\text{Liabilities}_{j,t}}$. The results of regression (2) with net interest margin as the dependent variable are shown in Table 3 panel C. In terms of economic magnitudes, the results imply that the net interest margin of the most exposed bank in the sample is roughly one percentage point lower in the low rate environment, relative to a hypothetical bank without exposure (e.g. a fully wholesale funded bank, whose initial spread on deposits is zero). As the average bank in the sample in 2000 has a net interest margin of 1.85 percent, this effect is economically significant. Figure 3 panel (b) provides a plot of this result.

The estimated coefficients of the dynamic regression (3) displayed in Figure 2 panel (c) shows the change in relative net interest margin by $\alpha_{j,1990}$. Following a decade of stable relative profitability during the 1990s, the relative profitability of exposed banks declines sharply in the early 2000s, and continues to decline, without recovery, until the present. This result suggests that the detrimental effects of negative interest rates may take years before showing up in financial statements.

Effects on profits and retained earnings. In this section we show that the significant relative decrease in net interest margins of exposed banks is not undone by non-interest sources of income and expenses, such as an increase in fees or a decrease in costs. If banks were able to increase non-interest income or dramatically reduce costs, then the decline in net interest income would not affect net income, retained earnings, or equity. We conclusively rule this out in the Japanese case.

Table 4 shows that the relative decline in exposed banks' profitability remains statistically and economically significant across multiple definitions of profitability, in Panel A. In the post environment, annual net interest income per asset declines by 1.3 percentage points more for the most exposed bank relative to the least exposed, on average. This relative decline is 1.0 percentage points for net ordinary income per asset, which is inclusive of non-interest income such as fees or trading income as well as expenses such as costs or provision for loan losses. The results are consistent across all samples and specifications:

exposure predicts strong effects on net ordinary income. Finally, the results inclusive of extraordinary income, which includes write-offs, is less precisely estimated, likely due to the noise introduced by extraordinary income, but consistently yields negative estimated coefficients. Overall, exposed banks' lower net interest income is not compensated by other income items, decreasing relative net income.

Table 4 provides additional results in panel B for income sources that have been suggested as having the potential to help banks cope with a low interest rate environment: fees and general and administrative expenses. In the low interest rate environment in Japan, exposed banks have been unable to compensate for their relatively higher interest expenses by charging higher fees. In only one of the main specification is the response of fees significant. This gives the impression that fees are not convincingly increasing for those banks whose interest income is most impacted by low interest rates.

Exposed banks have managed to decrease their costs in response to their higher interest expenses, albeit insufficiently to overturn net interest income losses. General and administrative expense per asset shows a statistically and economically significant decline. The response, however, is only about a half of the loss in net ordinary income over assets, and hence is unable to overturn the decline in net interest income.

Effects on equity. We then evaluate to what extent banks' equity decreases following the decline in profitability due to the low interest rate environment. As banks' net income decreases, so does retained earnings. Given the documented relative decline described above, we expect bank equity to be affected unless banks can reduce dividend payments or increase equity issuance. Having shown a decline in net profits, we can examine whether dividends and/or equity issuance have changed by enough to prevent a decline in equity.[18]

Table 4 shows in panel C that exposed banks' dividend payments per asset declined relative to banks with low exposure, after 2000. Banks with high initial deposit spreads decrease their dividend payments in relative terms, compensating part of their decrease in

[18]In the data, book equity is given by the accounting identity: $\text{Equity}_{j,t+1} = \text{Equity}_{jt} + \text{Net profits}_{jt} + \text{Equity Issuance}_{jt} - \text{Dividends}_{jt}$. Cross-sectional identification is particularly important here, as the implementation of Basel regulations and the collapse of asset prices during our sample period makes aggregate trends in bank capitalization uninformative for our purposes.

net earnings. The magnitude of the effect, however, is very small relative to the losses in retained earnings that exposed banks face. Banks also do not raise additional equity. This is consistent with our theoretical analysis, where banks' lower net profits leads to lower capitalization, allowing banks to maintain a high return on equity despite being less profitable. This lack of capital issuance is likely a specificity of the long horizon of our analysis: at short horizons and for temporary changes in interest rates, banks would have incentives to issue capital in order to take on risk.[19]

Overall, declining profitability and limited adjustment to dividends and equity issuance imply that banks' equity declines. This pattern is shown in Figure 4, where the dynamic coefficients from regression (3) are shown for the dependent variable equity divided by assets (i.e. inverse leverage). Despite some fluctuations in the 1990s, there is a marked and persistent decline in the level of equity relative to assets for exposed banks in the sample after 2000.

Effects on lending. We run regression (2) at the bank level using lending outcomes, and also conduct regressions at the loan-level to rule out the possibility that our results are driven by demand. As low interest rates can also be expected to stimulate (in a savings glut) or mitigate (secular stagnation) loan demand, aggregate identification is infeasible. Cross-sectional regressions allows us to make progress. The main threat to identification in this setting is that the macroeconomic environment weighs particularly heavily on banks that have high exposure because of how the low rate environment affects these banks' borrowers. This could be the case if borrowers were sorted across bank types and demand fell disproportionately for borrowers of exposed banks, e.g. due to secular trends in urbanization. We can rule this out using loan-level data and firm-year fixed effects to control for demand.

The decline in interest rates is also associated with an increase in loan spreads for banks with high initial deposit spreads after 2000, relative to banks with lower deposit spreads in 1990, as shown in panel C of Table 4. These cross-sectional results are consistent with aggregate behavior of loan rates documented in Figure 1 panel (b), suggesting that in response

[19] Models with financial frictions typically assume capital issuance frictions in the short term to maintain a role for the lack of profitability (e.g., Brunnermeier and Koby, 2018).

to lower bank profitability the spread between bank loan rates and nominal rates increases. The estimated coefficients for the increase in loan rates imply that for each percentage point increase in real funding costs, between 27 and 33 basis points passes through to real lending rates.

We provide additional consistent results in matched bank-firm loan-level data. When projecting exposure to low rates on loan growth, our regressions follow equation 2 with $\Delta \log \ell_{ijt}$ as the dependent variable, where $\ell_{ij,t}$ is the loan volume from bank j to firm i in year t, and include firm-year fixed effects $\eta_{i,t}$ as additional controls. In this case, the coefficient on the interaction term tests whether firms borrow less from exposed banks, relative to how much they borrow from other banks, post-2000.

The results of the loan-level regressions are shown in Table 5. These tests control for demand by including firm-year fixed effects. These fixed effects absorb variation in lending that is due to firm-specific demand, yet we still find a persistent effect on exposed banks. Interestingly, the estimated coefficients grow larger as we include firm-year fixed effects, suggesting that trends in firm demand favor exposed banks. In column (3) we control for a host of bank characteristics including non-interest income, extraordinary income, non-performing loans, and changes to equity due to mergers, acquisitions, and recapitalizations, and the results are then statistically significant. Given the range of $\alpha_{j,1990}$ is 4.6, the coefficient in column (3) implies firms' bank borrowing from the most exposed banks declines by 6.9 percent on average, relative to the least exposed bank in the sample. In column (4) we control for time-invariant bank fixed effects, which capture the average lending growth rate of each bank over all the years in the sample. This makes the coefficient on the interaction term larger, and more strongly statistically significant. In column (5) we control for time-invariant bank-firm fixed effects, which should further alleviate concerns about endogenous matching driving the results.

Firm level effects. We can further explore whether firms that borrow from exposed banks have any measurable real effects. Since loan-level regressions measures relative borrowing, we can calculate a measure of firms' overall exposure to the low rate environment via banks by taking the weighted average of $\hat{\alpha}_{j,1990}$ across all banks lending to each firm:

$\tilde{\alpha}_{it} = \sum_j \theta_{ijt}\hat{\alpha}_{j,1990}$ where $\theta_{ijt} = \ell_{ijt}/\sum_j \ell_{ijt}$. Then, for firm level outcomes y_{it}, one can run a regression similar to regression (2) to test whether borrowing more from banks that are more exposed ex-ante leads to changes in overall firm bank borrowing, leverage, assets, or employment:

$$\Delta \log y_{it} = \beta_0 + \beta_1 \, \text{Post} + \beta_2 \, \tilde{\alpha}_{i,t-1} + \delta \, \text{Post} \times \tilde{\alpha}_{i,t-1} + \epsilon_{it} \tag{4}$$

The firm-level results are shown in Table 6. In column (1), the coefficient on the interaction term indicates that firms with a larger share of borrowing from exposed banks borrowed 6.0 percentage points less on average per unit of additional exposure; recall that the range of $\hat{\alpha}_{j,1990}$ is 4.6 so this indicates a significant relative decline in firm-level bank borrowing. The effect on total borrowing is muted, but still statistically and economically significant, as shown in column (2). This is striking because our sample of firm level data covers listed firms, which should in principle be the most able of any firms to substitute other sources of financing for bank lending. In columns (3) and (4) we measure smaller but still statistically significant estimates for effects on asset growth and employment growth, which indicate that on average, the bank credit supply shocks we document above do have real effects at the firm level. To estimate the aggregate implications of these effects, however, requires a model.

3 Model

We now present a macroeconomic model with banks that demonstrates how market power over deposits together with financial frictions can rationalize the empirical findings presented in Section 2. We use the model to assess the aggregate impact of low nominal rates on bank lending and conduct counterfactual policy analysis.

Time is discrete, infinite, and indexed by t. The model is deterministic. The economy is populated by three types of agents: households, firms, and banks. We first describe these agents and the markets they interact in, and then describe the equilibrium.

3.1 Households

A unit continuum of identical households choose consumption and assets to maximize their lifetime utility over consumption, which takes the usual form:

$$U_0 = \sum_{t=0}^{\infty} \beta^t u(c_t),$$

where β is the discount factor of households, and c_t is consumption.

Households can save using three assets: bonds, bank deposits, and money. We denote by $q_t = \frac{1}{1+r_t} = \frac{1+\pi_t}{1+i_t}$ the real price of a bond g_t that delivers one unit of consumption good in $t+1$, where r_t is the real rate, i_t is the nominal rate, and π_t is inflation, respectively between time t and $t+1$.[20] Let $j \in \mathcal{J}$ index bank deposits d_j and $\mathcal{J}$ the set of such products available to households. We denote the price of such a bank product q_{jt}. The price of money m_t is denoted by $q_{mt} = 1 + \pi_t$. Finally, each household supplies one unit of labour inelastically at wage w_t. Given initial savings s_t and transfers T_t, households' budget constraint is:

$$w_t + s_t + T_t = c_t + q_t g_t + q_{mt} m_t + \sum_j q_{jt} d_{jt}$$

Total household savings is the sum of proceeds from government bonds and a function of liquid savings $\Phi(\mathcal{L}_t)$:

$$s_{t+1} = g_t + \Phi(\mathcal{L}_t). \tag{5}$$

where $\Phi(\cdot)$ is increasing up to a satiation point $\overline{\mathcal{L}}$, with $\Phi'(\mathcal{L}) < 1$ for all $\mathcal{L} > \overline{\mathcal{L}}$, $\lim_{\mathcal{L}\to 0} \Phi'(\mathcal{L}) = \infty$, and $\Phi'' < 0$. This function is a reduced form for the returns to liquid savings, which mitigate transaction costs, for example. It is always efficient to have some liquidity, as captured by the Inada condition. These extra returns are in units of consumption goods, and are decreasing at the margin with the quantity of liquid savings. Above the satiation point, liquid holdings start imposing a marginal cost: at some point increasing liquidity imposes

[20] The bonds g_t include government bonds as well as other financial products whose net return equals the real rate r_t, such as corporate bonds or bank equity.

some costs (e.g. storage, decreased returns) that offset benefit.[21]

We then assume that the savings instruments offered by banks are differentiated products of heterogeneous quality α_j. These bank accounts aggregate into an aggregate bank deposit d_t given by:

$$d_t = N^{-\frac{1}{\varepsilon-1}} \left(\sum_j \alpha_j d_{jt}^{\frac{\varepsilon-1}{\varepsilon}} \right)^{\frac{\varepsilon}{\varepsilon-1}}$$

where $\varepsilon > 1$ is the elasticity of substitution across banks and N is the number of banks.[22] When $\varepsilon < \infty$, banks' products are imperfect substitutes.

In a similar fashion, money m_t and aggregate bank deposits d_t provide imperfectly substitutable liquidity services, which yield a liquid savings aggregate $\mathcal{L}_t$:

$$\mathcal{L}_t = 2^{-\frac{1}{\eta-1}} \left(\alpha_d d_t^{\frac{\eta-1}{\eta}} + \alpha_m m_t^{\frac{\eta-1}{\eta}} \right)^{\frac{\eta}{\eta-1}}$$

where $\eta > 1$ is the elasticity of substitution between bank deposits and money, and α_d and α_m measure the quality of bank savings and money, respectively. Without loss of generality, we normalize $\alpha_d = 1$. We also assume that $\eta < \varepsilon$, since bank deposits are arguably closer substitutes products.

Solving households' portfolio allocations We now solve the consumption-saving problem of the households and state the optimal portfolio allocations. Government bond holdings g_t enter the expression for next-period savings s_{t+1} linearly, so a standard Euler equation holds:

$$u'(c_t) = \beta \left(\frac{1}{q_t} u'(c_{t+1}) \right),$$

[21] Satiation allows the model to theoretically consider negative nominal interest rates.

[22] This CES aggregator can be micro-founded by having a continuum of household members solve a discrete choice problem where each member chooses a bank, given that it wants to invest an amount d_t. Alternately, Ulate (2021a) shows models that deliver non-unitary pass-through to deposit rates while assuming a continuum of banks.

and the (net) holdings of bonds are then given by the household budget constraint. The price index of liquid savings $q_{\mathcal{L}_t}$ takes a standard CES price index form:

$$q_{\mathcal{L}_t} = \left(\frac{q_{dt}^{1-\eta} + \alpha_m^\eta q_{mt}^{1-\eta}}{2} \right)^{1/(1-\eta)}$$

where q_{dt} is itself an index that aggregates prices from banks' differentiated products:

$$q_{dt} = \left(\frac{1}{N} \sum_j \alpha_j^\varepsilon q_{jt}^{1-\varepsilon} \right)^{1/(1-\varepsilon)} .$$

First order conditions imply that the quantity of liquid assets holdings only depends on its price relative to that of bonds:

$$\Phi' \left(\mathcal{L}_t \right) = \frac{q_{\mathcal{L}_t}}{q_t},$$

which equivalently yields $\mathcal{L}_t = \Phi'^{-1} \left(q_{\mathcal{L}_t} / q_t \right)$, where we define $\varepsilon^{\mathcal{L}}$ as the elasticity of liquid savings with respect to its price. From there we can now derive the quantities of cash savings:

$$m_t = \alpha_m^\eta q_{mt}^{-\eta} q_{\mathcal{L}_t}^\eta \frac{\mathcal{L}_t}{2}.$$

Similarly we can obtain the quantity saved in bank savings:

$$d_t = q_{dt}^{-\eta} q_{\mathcal{L}_t}^\eta \frac{\mathcal{L}_t}{2},$$

and from there we can derive the quantity of savings supplied to an individual bank j:

$$d_{jt} = \alpha_j^\varepsilon q_{jt}^{-\varepsilon} q_{dt}^\varepsilon \frac{d_t}{N} \tag{6}$$

as a function of prices. This expression is taken as given by banks.

3.2 Firms

A continuum of identical firms use labor n_t and capital k_t, and produces output to sell on a competitive market:

$$y_t = A_t \left(k_t^{\alpha} n_t^{1-\alpha}\right)^{\nu},$$

where α is the capital share, and $\nu < 1$ indicates decreasing returns to scale. Labor is paid wage w_t.

Firms live for two periods. First, they borrow their capital and install it. Next, they produce, repay what they borrowed, sell their capital, and close.

Two types of capital are required in production: pledgeable and non-pledgeable, which form k_t according to a Cobb-Douglas function with pledgeable share ρ:

$$k_t = k_{P,t}^{\rho} k_{NP,t}^{1-\rho}$$

Pledgeable capital is borrowed directly from households, at rate r_{t-1}, i.e. the interest rate between $t-1$ and t. This borrowing can be thought of as corporate bonds, or other non-bank lending. Non-pledgeable capital is financed using bank loans, which are differentiated products sold by banks, similar to bank liabilities:

$$\ell_t = \left(N^{-1/\varepsilon^{\ell}} \sum_j \ell_{jt}^{\frac{\varepsilon^{\ell}-1}{\varepsilon^{\ell}}}\right)^{\frac{\varepsilon^{\ell}}{\varepsilon^{\ell}-1}}$$

where ε^{ℓ} is the elasticity of substitution between loans, and each loan ℓ_{jt} offered by bank j has the (real) rate $r^{\ell}_{j,t-1}$. Both types of capital depreciate at rate δ.[23]

The problem of the firm is therefore to choose both capital types, labor, and loans to maximize profits, which are given by:

$$p_t y_t + (1-\delta)(k_{P,t} + k_{NP,t}) - w_t n_t - (1 + r_{t-1})k_{P,t} - \sum_j (1 + r^{\ell}_{j,t-1})\ell_{jt}$$

[23]Bond prices are determined by the discount factor of the households, which in steady-state equals $q_t = \frac{1}{1+r_t}$. While bank loans are assumed to be differentiated, we do not assume that banks' market power over loans is associated with the quality of their liabilities α_j. This is to emphasize the role of deposit margins as central to bank constraints in a low interest rate environment.

where p_t is the price of output, inflation and prices are related according to $1 + \pi_t = \frac{1+p_{t+1}}{1+p_t}$, and firms' non-pledgeable capital is subject to the constraint:

$$k_{NP,t} \leq \ell_t,$$

which always binds in equilibrium.

3.3 Banks

Each bank invests in loans ℓ_{jt} and government bonds g_{jt}, funded by households' deposits d_{jt} and equity e_{jt}. The balance sheet identity of the banks is given by:

$$\ell_{jt} + g_{jt} = d_{jt} + e_{jt}. \tag{7}$$

Banks provide differentiated savings instruments and set the interest rate on their liabilities, taking households' savings supply as given in equation (6). The quality of banks' deposit services is heterogeneous and given by α_j, which alters the appeal of investing at a particular bank.[24] Banks may therefore pay different interest rates on their liabilities. These liabilities are a composite of both deposits and wholesale funds. Similarly, loan products are differentiated. For both liabilities and loans, banks set prices taking demand for loans and households' savings supply as given. Banks take the return on bonds i_t as given.

For a given amount of equity e_{jt}, banks' set the interest rates of loans and liabilities, and choose a quantity of bonds to maximize the net return in each period:

$$\max_{i^{\ell}_{jt}, i^{d}_{jt}, g_{jt}} (1 + i^{\ell}_{jt})\ell_j(i^{\ell}_{jt}, \cdot) + (1 + i_t)g_{jt} - (1 + i^{d}_{jt})d_j(i^{d}_{jt}, \cdot)$$

[24]For example, a high alpha bank could be a regional bank that has many branches and few competitors. In contrast, city banks face intense competition in urban areas. Other possible quality differences include customer service, 24 hour ATMs, or geographic proximity. These differences lead banks to have different degrees of market power, which banks use to charge a larger deposit spread. We take this as exogenous, but it can also be endogenized as the result of a problem in which banks invest in building their deposit franchise, but have different investment technology.

subject to a financial constraint that ties up their lending to their equity:

$$\ell_j(i^{\ell}_{jt}, \cdot) \leq \gamma e_{jt}. \tag{8}$$

This constraint captures regulatory constraints or agency issues, and generates a feedback from bank net worth to bank lending.[25]

Deposit supply $d_j(i^d_{jt}, \cdot)$ and loan demand $\ell_j(i^{\ell}_{jt}, \cdot)$ are derived from the household and firm problems described above, respectively, with $\frac{1+i^{\ell}_{jt}}{1+\pi} = 1 + r^{\ell}_{jt}$ and $\frac{1+i^d_{jt}}{1+\pi} = q^{-1}_{jt}$.

The balance sheet constraint (7) can be used to solve out g_{jt}. The lending and the funding problems of banks are separable:

$$\underbrace{\max_{i^{\ell}_{jt}} (i^{\ell}_{jt} - i_t)\ell(i^{\ell}_{jt}, \cdot)}_{\text{Lending profits: } \Pi^{\ell}_{jt+1}} + \underbrace{\max_{i^d_{jt}} (i_t - i^d_{jt}) d_j(i^d_{jt}, \cdot)}_{\text{Funding profits: } \Pi^d_{jt+1}} + (1 + i_t)e_{jt}. \tag{9}$$

and where total profits at $t+1$ in nominal terms are the sum of profits from the lending side and the funding side:

$$\Pi_{jt+1} = i_t e_{jt} + \Pi^{\ell}_{jt+1} + \Pi^d_{jt+1} \tag{10}$$

At the margin, the return on both loans and deposits must equal that of a government bond (an opportunity cost). Focusing on the lending problem first, we obtain that:

$$1 + i^{\ell}_{jt} = \underbrace{\frac{\varepsilon_{jt}}{\varepsilon_{jt} - 1}}_{\text{Mark-up}} (1 + i_t + \lambda_{jt})$$

where the elasticity ε_{jt} is the semi-elasticity of loan demand, and λ_{jt} is the Lagrangian multiplier on the net worth constraint.

From the funding problem, we obtain:

$$1 + i^d_{jt} = \frac{\varepsilon^d_{jt}}{\varepsilon^d_{jt} + 1}(1 + i_t)$$

[25]In the calibrated model, we make this constraint a smooth cost to keep the economy continuous.

where the elasticity $\varepsilon^d_{jt} = \frac{d \log d_j(\cdot)}{d \log(1+i^d_{jt})}$ is derived from the households' problem and takes the following form:

$$\varepsilon^d_{jt} = (1-\omega^d_{jt})\varepsilon + \omega^d_{jt}\omega^m_t \eta + \omega^d_{jt}(1-\omega^m_t)\varepsilon^{\mathcal{L}}_t \tag{11}$$

where $\omega^d_{jt} = \frac{q_{jt}d_{jt}}{q_{dt}d_t}$ is bank j's market share in the funding market, $\omega^m_t = 1 - \frac{q_{dt}d_t}{q_{\mathcal{L}t}\mathcal{L}_t}$ is the share of liquid savings that households hold in cash, and $\varepsilon^{\mathcal{L}}_t = -\frac{\partial \log \mathcal{L}_t}{\partial \log q_{\mathcal{L},t}}$ is the elasticity of liquid savings with respect to its price. Banks with higher α_j have higher local market share, face a lower elasticity of funding supply, and hence have larger market power. All banks face decreased market power when ω^m_t rises. However, this is stronger for banks with higher market shares. These forces are central to mapping the model to our diff-in-diff results.

Finally, banks raise equity directly from households. We assume that bank equity has similar properties as government bonds from the households' perspective, and hence should yield the same return to them by arbitrage. We posit that a friction prevents them from obtaining the full return on banks' profits, so that the return on equity that banks must offer is the risk-free rate plus an additional (real) spread ϱ.[26] Hence we have:

$$1 + r_t + \varrho = \frac{\Pi_{jt+1} + e_{jt}}{(1+\pi_t)e_{jt}},$$

where π_t is inflation between period t and $t+1$. This gives an equation for equity:

$$e_{jt} = \frac{\Pi^\ell_{jt+1} + \Pi^d_{jt+1}}{(1+\pi_t)\varrho},$$

where equity is tied to the level of lending and funding profits. Consequently, banks retain only earnings that exceed the risk-free rate and spread.

3.4 Closure and Equilibrium

Supply of cash and bonds. We assume that cash is elastically supplied by the government, and backed by lump-sum taxes.[27] Similarly, we assume that the government elastically

[26]There is extensive empirical evidence that bank managers target a fixed return on equity above the risk-free rate (e.g., Begenau and Stafford, 2019).

[27]It would be equivalent to assume that a central bank invests cash against bonds, and rebates the proceeds to the government.

supplies bonds to match banks' demand. The demand for bonds by households is not pinned down, but plays no role in our analysis (bonds do not provide liquidity services).

Nominal rates and inflation. The path of nominal rates $\{i_t\}_{t=0,1,..}$ is exogenously chosen by the central bank and taken as given by all other agents. Given these rates, inflation adjusts so that the Euler equation of households' holds. We assume that the central bank understands this Fisherian mechanism, and chooses a long-run inflation target $\bar{\pi}$ implemented by manipulating the path of nominal interest rates. In the analysis below, we discuss variation in this target.

Equilibrium. An equilibrium is a set of (a) household decisions rules: portfolio choices for cash, bank savings, bonds, and bank equity; consumption demand; capital supply; (b) firm decision rules: labor demand; capital demand; loan demand; output supply; (c) bank decisions rules: prices of loans and bank savings; demand for bonds; demand for bank equity; (d) government decisions rules: supply of cash and bonds, (e) prices: prices of bonds, cash (inflation); wages; bank equity return; such that (1) households optimize; (2) firms optimize; (3) banks optimize; (4) all markets clear.

4 Model implications

In this section we characterize the implications of changes in long-run nominal rates induced by a change in the inflation target for the economy presented in Section 3. To do so, we compare steady states for different values of the long-term inflation target $\bar{\pi}$. As the real rate stays constant, this induces an equivalent change in the nominal rate i. We drop t indices as we discuss steady-state values.

We first state an assumption, and show that it is equivalent to an easily verifiable empirical moment: the pass-through to deposit rates is incomplete. We then show formal results under that assumption. Our main result is that a low inflation target results in unambiguously negative effects on banks, as well as aggregate outcomes. We show that as a consequence, the optimal nominal interest rate is strictly positive, in contrast to the Friedman rule.

4.1 Elasticities and pass-through, i.e. an identified assumption

To consider the implications of a decline in the inflation target, we first state an assumption regarding the elasticities of substitution in the household savings problem:

Assumption 1. $\eta > \varepsilon^{\mathcal{L}}$,

which amounts to assuming that households elasticity of substitution between cash and bank savings is always larger than the elasticity of liquid savings with respect to its price. This is reasonable if liquidity and wealth are complements, or if the returns to liquid savings are low.[28]

These elasticities are difficult to estimate in the data, and moreover $\varepsilon^{\mathcal{L}}$ is an endogenous object. Fortunately, we show in our next proposition that Assumption 1 is equivalent to an easily testable proposition: that the pass-through of nominal rates to deposit rates is incomplete.

Proposition 1 (Identification of Assumption 1)**.** *In response to a change in the inflation target $\bar{\pi}$, the pass-through of a change in the level of nominal rates i to interest expense rates i^d is incomplete:*

$$\left.\frac{d\log(1+i^d)}{d\log(1+i)}\right|_{di=d\bar{\pi}} < 1$$

if and only if Assumption 1 holds.

Proof. All proofs are provided in Appendix D. □

Intuitively, declining inflation makes money more attractive as a savings instrument. This increases the elasticity of deposit supply if and only if the elasticity of substitution between cash and deposits is higher than the elasticity of substitution between liquid savings and bonds. Faced with a more elastic supply curve, banks then optimally choose to reduce their mark-downs, resulting in a low pass-through. Figure 5 panel (a) shows this graphically. This also leads to an increase in real funding costs for banks: as the spread decreases, the real deposit rate increases. This is consistent with the empirical findings of Section 2, providing support for Assumption 1.

[28] In our setup, $\varepsilon^{\mathcal{L}}$ is low when $\Phi' \approx 1$: an extra unit of liquid assets has low returns.

A cross-sectional implication of Proposition 1 is that banks with greater ex-ante market power will have lower pass through. In response to a change in the inflation target $\bar{\pi}$, the pass-through of a change in the level of nominal rates i to interest expense rates i^d is decreasing in α_j. Figure 5 panel (b) shows this graphically. When rates are high, banks with high ex-ante market power pay a lower rate on their deposits. However, as rates decrease, these banks are less able to reduce the interest expenses associated with their funding. Because the interest rate paid on funding such as deposits at these banks is relatively low, customers are more likely to substitute to cash. This mirrors the empirical finding of lower pass-through for banks with higher ex-ante market power in Section 2, and further implies differential effects for banks' relative profits, equity and lending.

4.2 Bank profits and lending

We show in our next result that Assumption 1 is also equivalent to lower nominal interest rates decreasing banks' profitability, equity, and lending, as we establish in Proposition 2.

Proposition 2 (Long-run bank effects)**.** *Following a decrease in the inflation target* $\bar{\pi}$*:*

(i) bank real funding profits $\frac{\Pi^d}{1+\pi}$ *decrease;*

(ii) real total profits $\frac{\Pi^\ell+\Pi^d}{1+\pi}$ *decrease and bank equity* e *decreases; and,*

(iii) the real loan rate r^ℓ *increases and the quantity of loans* ℓ *decreases,*

if and only if Assumption 1 holds.

The intuition is that a decrease in the inflation target and nominal rates, from the point of view of banks, makes cash a more attractive alternative to deposits. This increase in competition is harmful to bank profits if and only if the outflow of liquid supply towards cash is greater than the inflow out of bonds and into liquid savings holding the bank's deposit rate constant, by the envelope theorem. This is what Assumption 1 guarantees. Importantly, the result that deposit profitability declines does not imply that the equilibrium volume of deposits necessarily decreases, as we show in Section 4.5.

The decrease in banks' profits on funding activities translates into declining total profits, triggering a decrease in equity to keep the real return on equity constant. Recall that banks' total profits can be separated in a funding component and lending component. Holding the response of general equilibrium variables constant, the change in i has no direct effect on lending profits. Total profits of banks hence go down. To keep the real return on equity constant, banks must then decrease equity. Figure 5 panel (c) shows this result graphically. General equilibrium feedback only worsens the picture for banks, as loan demand declines.

Part (iii) of Proposition 2 demonstrates a further consequence of the decrease in the inflation target and hence nominal rates: the cost of bank loans increases and lending decreases. As bank equity decreases, the leverage constraint binds, leading to a higher shadow price λ_{jt} that passes through to credit spreads. Equilibrium lending unambiguously decreases, as shown in Figure 5 panel (d). General equilibrium only modulates the magnitude of the response, but does not change its direction.

4.3 Optimal inflation target

There are two opposing forces when inflation declines: negative investment effects and positive liquidity benefits. The negative investment effect triggers from the decline in banks' ability to intermediate funds from deposits to loans following low rates, resulting in less lending, investment and output.

Lemma 1 (Aggregate implications)**.** *Following a decrease in the inflation target $\bar{\pi}$,*

(i) both capital types (non-pledgeable k_{NP} and pledgeable k_P) and total capital k decrease;

(ii) the ratio of pledgeable capital k_P to non-pledgeable capital k_{NP} increases; and,

(iii) steady-state output y and wages w decrease.

On the other hand, lower inflation decreases the cost of money and also decreases banks' market power in the deposit market. This results in more liquidity and hence more transaction benefits (or less transaction costs), provided inflation is above the discount factor, which is the relevant case to understand for our proposition below.[29] These benefits increase the share of output available for consumption and hence improve welfare.

[29] If inflation was below the discount factor, i.e. lower than minus the real rate, households would hold liquidity past the satiation point to equate the net return on liquidity to the real rate, and hence transaction benefits would decrease. This is of course not efficient.

Lemma 2 (Liquidity implications)**.** *Suppose that $1 + \bar{\pi} > \beta$. Then following a decrease in the inflation target $\bar{\pi}$, the price of liquidity $q_{\mathcal{L}}$ decreases, liquidity $\mathcal{L}$ increases and transaction benefits $\Phi(\mathcal{L})$ increase.*

Our last formal result shows that the optimal inflation target is strictly positive if and only if banks are strictly constrained when nominal interest rates are zero.. This deviates from the Friedman rule, suggesting instead that optimal long-run interest rates are strictly positive. This is stated formally in Proposition 3.

Proposition 3 (Optimal inflation)**.** *Suppose that $\alpha_m = 1$ and that banks receive a per-deposit subsidy such that $q_d = q$ always holds in equilibrium.*

(i) If the bank net worth constraint is slack at $i = 0$, then the welfare-maximizing inflation target is such that the optimal nominal interest rate is zero:

$$i = 0$$

which is obtained by setting $1 + \bar{\pi}^* = \beta$ (Friedman rule).

(ii) If instead the bank net worth constraint strictly binds at $i = 0$, then the welfare-maximizing inflation target is such that the optimal nominal interest rate is strictly positive and finite:

$$i > 0$$

i.e. $1 + \bar{\pi}^* > \beta$, and moreover the bank net worth constraint binds for $\bar{\pi} = \bar{\pi}^*$.

To help intuition, we first highlight conditions under which the Friedman rule is optimal. To make deposits and cash equally desirable assets at equal prices, we set $\alpha_m = 1$, and remove the distortion that market power causes with the subsidy. Then, in the absence of lending frictions, optimal inflation must be such that nominal interest rates are zero, since this equates the returns on money and deposits. With nominal rates above zero, cash would be relatively too expensive, and vice-versa below zero.

When the constraint binds, however, the marginal return to an extra unit of bank profits and equity is strictly positive, while the marginal loss in *net* liquidity benefits is zero, since liquidity is already optimally allocated between cash and deposits. Therefore, it must be optimal to raise nominal interest rates above zero. However, it cannot be optimal to raise the inflation target beyond where banks' net worth constraint is slack, since this has no benefits for bank intermediation and costs liquidity.

The assumption that banks receive a deposit subsidy serves to highlight the role of the bank net worth constraint in generating optimal inflation such that the nominal interest rate is positive. Indeed, when banks have market power and there is no subsidy, the optimal nominal rate is always strictly positive regardless of the bank capital constraint, because of the distortion caused by deposit market power. Our model therefore provides a second rationale for deviating from the Friedman rule.

4.4 Effects of other shocks

A decrease in nominal interest rates triggered by other changes, such as an increase in the discount factor β (e.g. aging, risk aversion) or a decrease in productivity growth (i.e. secular stagnation) would have different implications for aggregate variables than our inflation target shock. However, the resulting decrease in nominal rates would have exactly the same effects as described above. These effects arise due to bank frictions, and would be neutral absent bank market power and net worth constraints. As a result, financial frictions would lead to additional relative outcomes that follow the patterns in the Propositions above, irrespective of the source of the shock.

4.5 Implications for deposit volumes

One further implication of the model that fall outside our main results is that we provide predictions for the volume of deposits, which explain some patterns in the data. The model predicts deposits to be non-monotonic in the level of the inflation target. As nominal rates decline, bonds become less attractive relative to liquid savings. This generates an increase in bank deposits, consistent with the main result of Drechsler et al. (2017). However, as the cost of holding cash also decreases, the share of bank deposits in household liquid savings declines. These two forces together determine the total quantity of bank deposits d, which is conditional on the inflation target, as we show in Proposition 4.

Proposition 4 (Hump-shaped deposit volumes)**.** *There exists a unique* $\widetilde{\pi}$ *such that:*

(i) if $\bar{\pi} > \widetilde{\pi}$*,* d_j *is decreasing in* $\bar{\pi}$*; and,*

(ii) if $\bar{\pi} \leq \widetilde{\pi}$*,* d_j *is increasing in* $\bar{\pi}$*.*

Importantly, this implies that the deposits channel of monetary policy in Drechsler et al. (2017) weakens and eventually reverses. We observe both forces at play in the Japanese data: bank liabilities to GDP has steadily increased as rates declined. At the same time, the share of currency as a percent of household liquid savings has increased. These dynamics are shown in Appendix Figures A2 and A3.

5 Quantitative results and counterfactuals

To demonstrate quantitatively that the frictions we highlight generate an economically significant decline in bank lending in Japan, we calibrate the model at steady-state to match moments from the beginning of our empirical analysis, 1990, as well as identified moments from our empirical analysis. We then decrease equilibrium nominal rates by changing the central bank's inflation target and compute the new equilibrium. We additionally conduct two counterfactual policy experiments.

5.1 Parametrization

Macro parameters. The model is calibrated annually. We normalize labor supply to 1. The scale parameter ν is set to 0.85. The labour share in production is set to $65\% \times \nu$. We set the Cobb-Douglas share of non-pledgeable capital in total capital ρ at 0.5, which yields a loans-to-GDP ratio of 125%. Depreciation is set to 8%. We set $\beta = .98$, aiming for a real rate of 2%. The initial steady-state nominal rate is set at 3.4%, the value of the one-year rate on Japanese government bonds in 1990, filtered out of its business cycle component.[30] Inflation hence is 1.4%. The macro parameters are summarized in Table 7.

Bank parameters. We choose the parameters listed in Table 8 to match the empirical moments reported in Table 9. Importantly, none of the moments we target encompass

[30]To filter we use an hp filter with smoothing parameter of 100.

information regarding the long-term aggregate effects of the nominal rates change through bank total profits, equity, or lending, which we instead recover from the model. The identified model allows us to identify these aggregate effects through model simulation. Due to non-linearities imposed by the structure of the model, the moments cannot be matched exactly.

Our first set of parameters govern the properties of the assets that households invest in. The demand for liquid savings is a function of the price of bonds q and the price index of liquid savings $q_{\mathcal{L}}$, which is independent of the quantity purchased. First order conditions of the households' problem yields $\mathcal{L}_t = \Phi'^{-1}\left(\frac{q_{\mathcal{L}}}{q}\right)$. We assume that this function is log-linear in its price, so that $\log \mathcal{L} = \log \overline{\mathcal{L}} - \varepsilon^{\mathcal{L}} \log\left(\frac{q_{\mathcal{L}}}{q}\right)$, yielding a shifter parameter $\overline{\mathcal{L}}$ and an elasticity $\varepsilon^{\mathcal{L}}$ to estimate.[31] Next, to generate demand for cash even when rates are high, we assume that a subsistence amount $\underline{m}$ must be held. We obtain cash holdings from the Japanese flow of funds and estimate that cash holdings represented roughly 4% of household liquid asset holdings in 1990, which increased to 11% by the end of our sample. We thus target an initial cash allocation of 4% and an increase of 7% going into the low rate equilibrium. With this the model yields three parameters to estimate: the subsistence amount $\underline{m}$, the quality of cash relative to bank assets α_m, and the elasticity of substitution between cash and bank deposits η.

To parameterize the competition between banks, we assume there are two bank types, with high and low exposure to the interest rate environment through quality parameter α_j. This reduces the bank parameters to estimate to a relative quality advantage of exposed banks α_H, and the elasticity of substitution between banks ε.

To fit these parameters we target corresponding moments from the market for liquid assets. We relate high exposure banks to their counterparts in Japan, which can be thought of as banks with strong deposit franchises that were able to charge high initial markups, such as regional banks. Low exposure banks are those with less deposit dependence, such as city banks and trust banks. We target the spread of the median bank in the initial equilibrium ($i_0 = 3.4\%$). The median bank $\hat{\alpha}_{1990}$ is 4.26. Using the coefficients reported in Table 3, we calculate predicted interest expense of $5.10 - 0.67 * 4.26 = 2.2458$. This implies

[31] This functional form implies the existence of a Φ function that satisfies our theoretical assumptions, in particular that of a satiation point.

a spread of $i - i^d = 3.4 - 2.2458 = 1.154$. We also target the reduction in this spread in the low rate equilibrium ($i_1 = 0.2\%$). In the post period, the predicted interest rate is $0.87 - (0.67 - 0.52) * 4.26 = 0.231$, which leads to a predicted spread of $i - i^d = 0.2 - 0.231 = -0.031$. This implies a median change in the spread of $-0.031 - 1.154 = -1.185$. We also target the "difference-in-difference" in spreads across a one-standard deviation change in $\hat{\alpha}_{1990}$: the spread across non-exposed banks decreased by 0.52*0.87 = 0.4524% more relative to the exposed bank group.

Finally, we target the ratio of bank liabilities relative to bank loans in the initial equilibrium, which is 65%, as well as the growth of bank liabilities as a fraction of GDP, which grew 30%, to match the relative attractiveness of bank liabilities relative to bond holdings in equilibrium.

Our second set of parameters concern the lending market and its frictions. The elasticity of substitution ε^ℓ governs the substitutability of bank lending products. Next, we parametrize the credit spread implied by the asset management costs directly, that is we assume that $c_j^\ell(\ell_j, e_j) = \kappa / (\gamma - \zeta_j \ell_j / e_j)$. This expression is a smooth version of the leverage constraint in equation (8), in which $\zeta_j \ell_j \leq \gamma e_j$. We normalize $\zeta_H = 1$ and estimate $\zeta_L \leq 1$, capturing the fact that less exposed banks' loan portfolios are potentially more diversified.[32] This gives us four parameters to estimate (ε^ℓ, γ, κ, ζ_L).

We target moments from the initial equilibrium to inform the four lending parameters. We match an average loan spread over the risk-free rate of 1.64% and an aggregate loans to assets ratio of 58%. The lending shares of the low exposure banks is 63% in the initial equilibrium. Finally, we need to discipline how credit responds to a change in equity – the asset management cost function. For that purpose we collect data on public equity injections conducted in Japan during our sample period. We compute the lending response of an equity injection equivalent to 1% of assets, and find an average response of lending of 1.66% of assets.[33] We target that elasticity directly in the model.

Finally, the last parameter governs the required return on bank equity in excess of the return on bonds ϱ, which disciplines the equity held by banks. We target a real return on

[32]Alternatively, we could have just let these banks make more profits from non-deposit sources, as is clear from our data, where less-exposed banks typically have more diversified banking activities.

[33]For details, see Appendix E.

equity of 8%, the long-term average equity return of Japanese banks.

5.2 Computing aggregate effects

In this section we analyze the aggregate effects of a decrease in the inflation target, which decreases the nominal interest rate.[34] Our goal is to estimate the resulting changes in loan spreads, aggregate lending and output.

Figure 6 (a) shows that lower nominal rates are associated with lower spreads (distance to the 45 degrees line), as cash becomes a stronger competitor to bank deposits. Since exposed banks always charge a lower spread, the decrease occurs sooner for these banks. The lower panel shows that net funding profits Π^d are affected, despite the fact that the demand for bank liabilities actually rise in the model.[35] This loss is larger for banks with higher exposure. At very low rates, low exposure banks gain loan market shares.

Figure 6 (b) shows that equilibrium steady-state lending by both types of banks decreases, and that this decline in non-pledgeable capital also affects output, despite substitution (i.e. the ratio of pledgeable capital to non-pledgeable capital increases). The effects are large, amounting to a four percent decrease in steady-state non-pledgeable capital going from the 3.4 percent nominal rate initial equilibrium to the 0.2 percent nominal rate for the period 2000-2017. These effects translate to a permanent 0.5 percent reduction in output.

5.3 Policy tools

Tiering. The first counterfactual experiment we implement using the model is to consider tiering the interest rate on reserves. Tiering in Japan was introduced in January 2016. The implemented policy applied different interest rates to different categories of reserves, depending on bank-specific historical reserve balances. Banks' "basic balance" outstanding in 2015 would continue to earn 0.1 percent. This represents roughly 50 percent of reserves. An additional 30-40 percent of reserves qualified as part of a "macro add-on" and earned zero. Beyond this, any "excess balance" of reserves would earn negative 0.1 percent. This is

[34] As discussed in Section 4.4, a decrease in nominal rates triggered by a change to the real rate would have qualitatively similar effects as a shock to inflation target.

[35] The reduction in the spreads banks charge induces a substitution away from bonds towards bank deposits.

roughly 10 to 20 percent of reserves, depending on the bank.

We split banks' bond holdings into government bonds and reserves, and assume that reserves earn i at the margin but inframarginal units get a subsidized rate.[36] We set reserves to 20 percent of assets when $i = 0$, and apply a subsidized rate of 0.15 percent on 80 percent of reserves.

Figure 7 panel (a) displays the response of bank profits by group as well as capital following the introduction of tiering. This experiment suggests small impact on loan quantities. In the presence of tiering, lending increases by 0.25 percent in the low rate steady state, a marginal amount relative to the overall four percent decrease we document as resulting from bank frictions absent tiering.

Cash Tax. Our second counterfactual experiment considers a cash tax. This idea follows the proposal of Agarwal and Kimball (2019), in which electronic money is established as the unit of account, and central banks establish establish an exchange rate at the window between electronic currency and paper currency. We test the impact of setting the nominal return on money to negative 0.1 percent.

Figure 7 panel (b) displays the response of bank profits by group as well as loans following the introduction of a cash tax. This increases lending by one percent. Relative to tiering, at a plausible level cash taxes are more successful in mitigating the negative effects of low interest rates on lending. Because the liquidity benefits of cash are small at the margin, this has limited repercussions for household savings.

6 Conclusion

That low interest rates affect bank intermediation is a subject of high importance and continued debate. In this paper, we demonstrate this empirically in the case of Japan, where interest rates have been low since the 1990s. This channel had a marked impact on bank lending, both in the aggregate and particularly for banks whose historical dependence on deposits makes it difficult to pass interest rate cuts through to expenses. Taken together, our

[36]Government bonds and reserves otherwise offer the same returns for banks.

evidence also suggests that low nominal interest rates reduce the effectiveness of monetary policy, particularly when rates remain low for long periods of time.

Overall, these findings raise questions for policymakers in selecting the optimal level and path of policy rates, or equivalently inflation targets. Also relevant is the extent to which other policies such as tiering, a tax on cash, or other central bank lending facilities help stimulate lending in the long run in a low interest rate setting. In plausible calibrations, we show that policies such as tiering and cash taxes help to mitigate the effects of low rates on bank profitability, but with differing degrees of effectiveness.

There are a number of additional questions not addressed in the current paper. We assume that banks' assets include loans and securities, and that there is no risk in banks' portfolios. As loan demand declines, banks with growing deposits increase investing in securities, and may "reach for yield" – in securities or in lending – to increase their income. This poses a potential unmodeled risk. There may be in certain settings different dynamics of substitution between bank and non-bank financing, and potential shifts in bank business models that do not follow the path of Japan. These possibilities are important to keep in mind, and are promising areas for future work.

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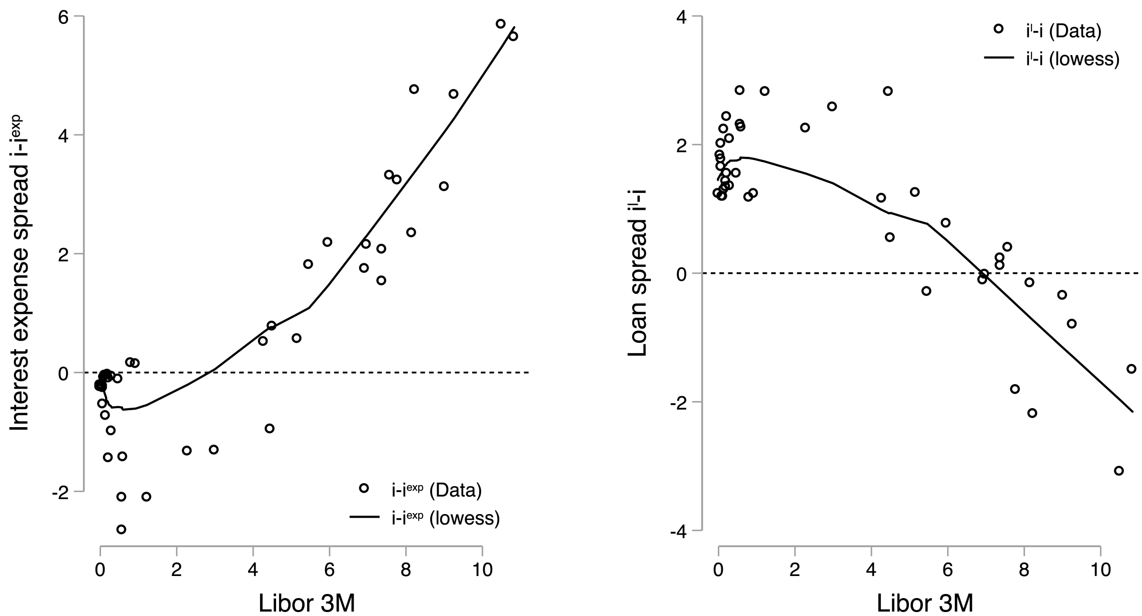
Figure 1: Bank interest rate spreads

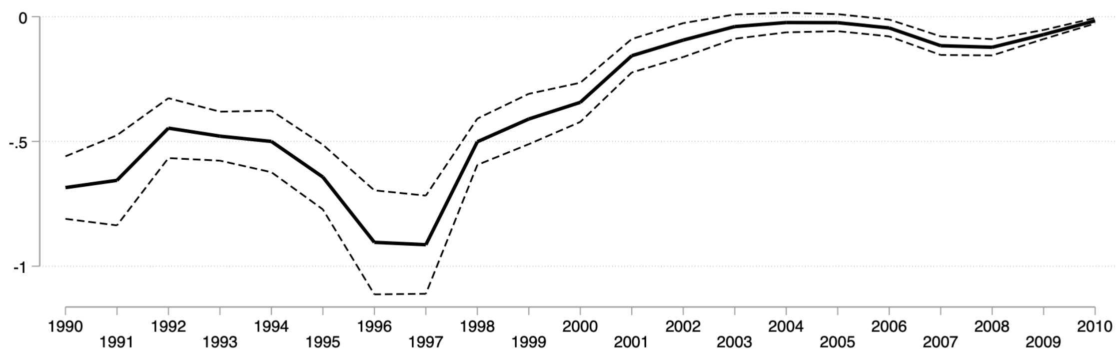


(a) Interest expense spread

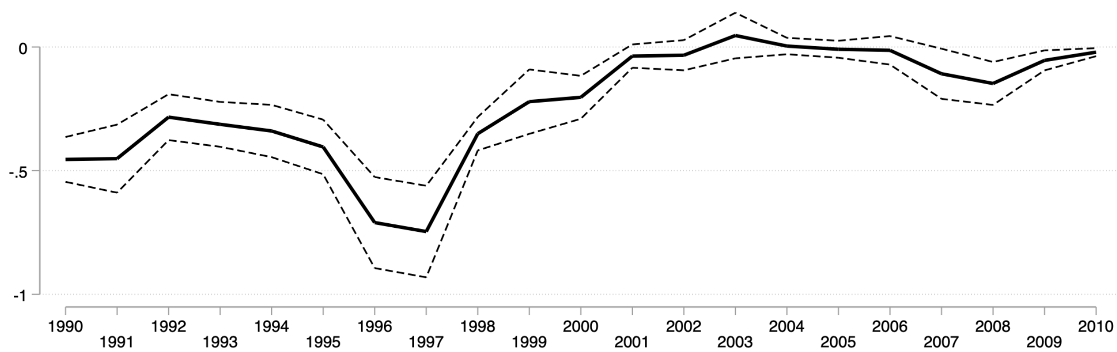
(b) Loan rate spread

Notes: Panel (a) plots the nominal rate as measured by three month Yen Libor against the spread between the nominal rate and realized aggregate bank interest expenses, that is, the ratio of interest expenses to total liabilities. Prior to deregulation during the 1980s, interest rates on deposits were controlled. Panel (b) plots the nominal rate against the spread between the nominal rate and the aggregate realized bank loan rate, that is, the ratio of interest income from loans to total outstanding loans. The smoothed line is the locally weighted scatterplot smoothing (lowess). The negative spreads in the lower right portion of panel (b) reflect that until the mid 1980s, loan rates were also controlled, at artificially low levels. Banks sometimes required firms to hold deposits at zero interest to compensate.

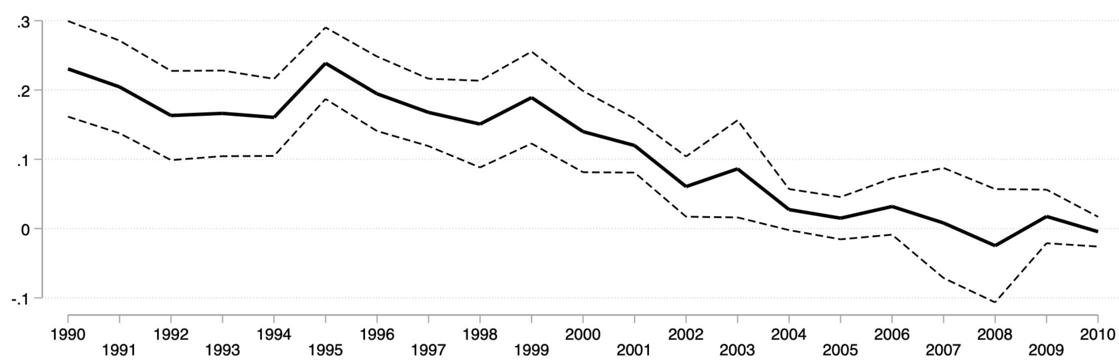
Figure 2: Interest income and interest expense dynamics



(a) Interest Expense / Liabilities



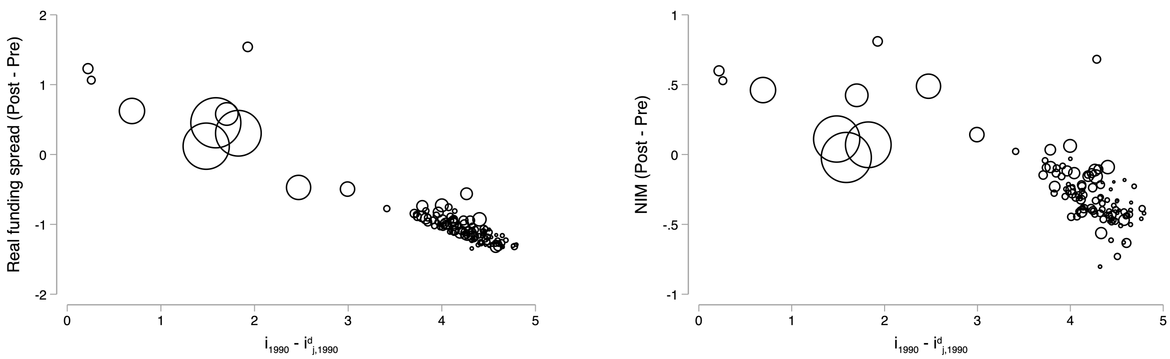
(b) Interest Income / Assets



(c) Net Interest Margin

Notes: Panel (a) shows coefficients δ_t from regression (3) with interest expenses as the dependent variable, and confidence bands for clustered standard errors (bank×post) at 95 percent levels. The coefficients show that banks with more market power earned a larger spread on liabilities in the 1990s, relative to banks with less market power. This advantage is significantly reduced in the 2000s. The results for the same regression with interest income as the dependent variable is shown in panel (b). Interest income is lower for exposed banks during the 1990s, although the size of the difference is smaller than for expenses, and the difference also declines in the 2000s. Taken together, these dynamics amount to a reduction in the relative net interest expense earned by banks with ex-ante higher deposit market power, which persists throughout the sample, as shown in the coefficients of the regression with net interest margins as the dependent variable, in panel (c).

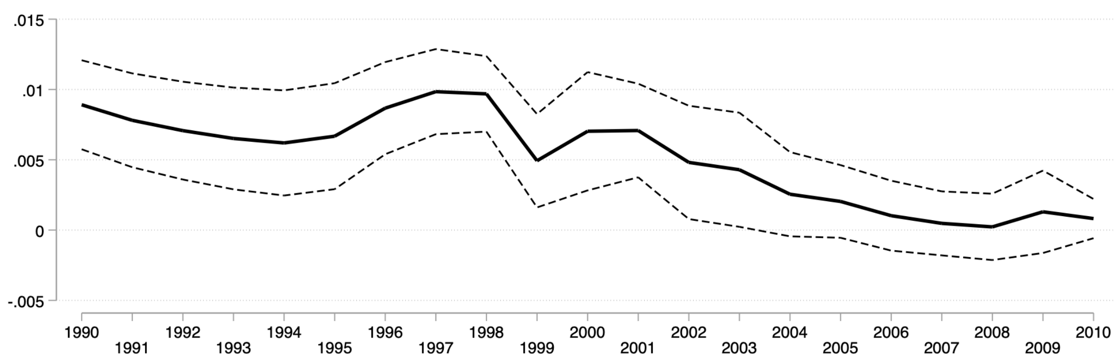
Figure 3: Changes by historical deposit spread



(a) Δ Interest Expense / Liabilities (b) Δ Net Interest Margin

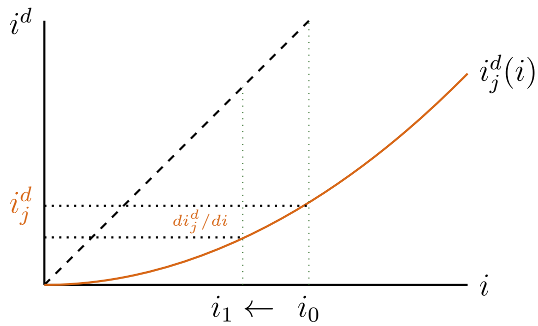
Notes: Panel (a) plots the change in the interest rate on liabilities for each bank against its spread on deposits in 1990. The size of the bubbles indicates bank size, measured by total assets. Panel (b) plots the change in net interest margins against the 1990 deposit spread. Although the main source of cross-sectional variation is between large and small banks, our results hold within the sample of regional banks, which are the majority of small banks.

Figure 4: Equity dynamics

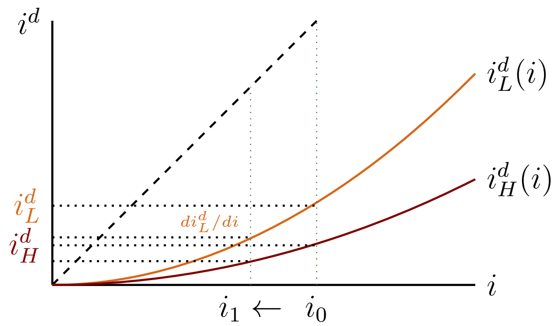


Notes: Shows coefficients δ_t from regression (3) with bank equity divided by assets as the dependent variable, and confidence bands for clustered standard errors (bank×post) at 95 percent levels. The coefficients show that banks with more market power had higher equity in the 1990s, relative to banks with less market power. This advantage is significantly reduced in the 2000s.

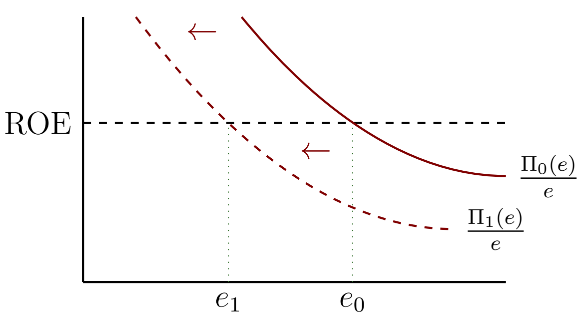
Figure 5: Model mechanisms



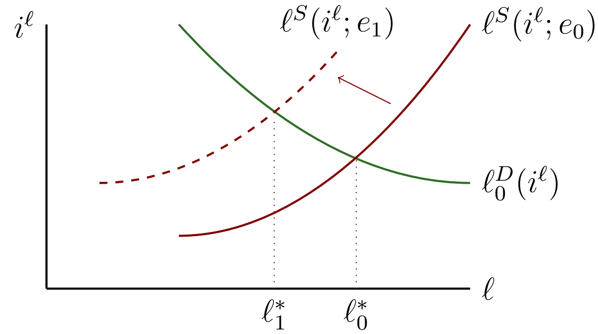
(a) Pass-through to deposits



(b) Cross-sectional implications ($\alpha_H > \alpha_L$)



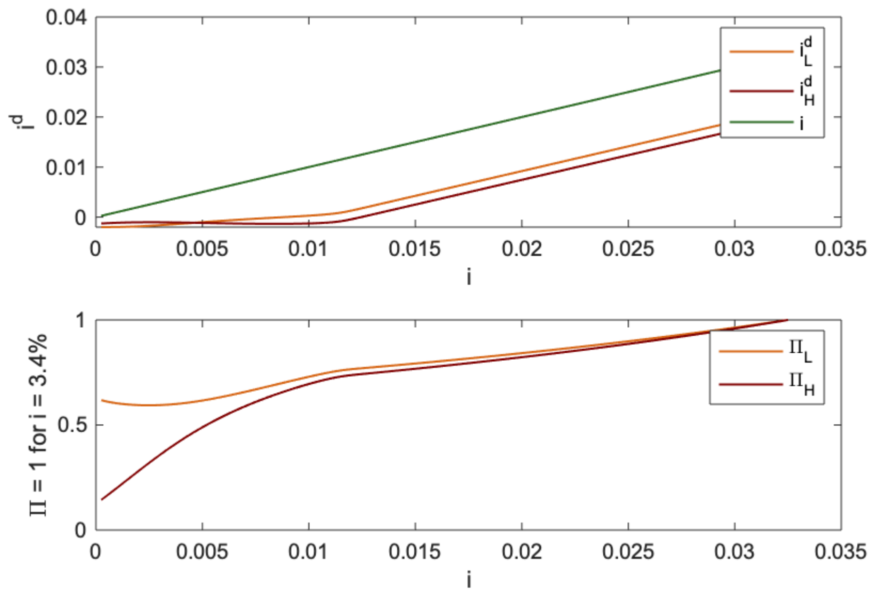
(c) Effects on equity



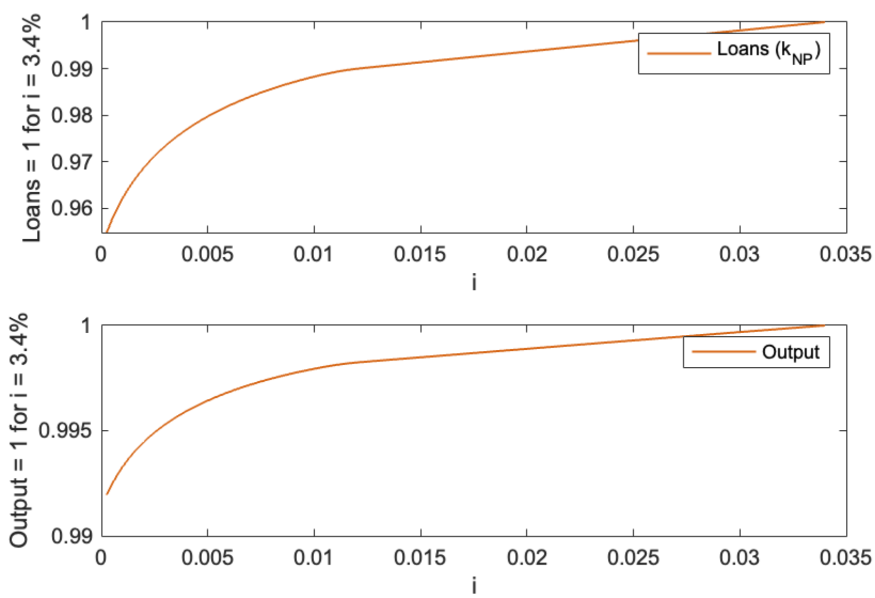
(d) Lending effects

Notes: Panel (a) shows the incomplete passthrough of changes in the nominal interest rate. As the interest rate declines from i_0 to $i_1 < i_0$, the interest rate banks charge on deposits declines by less than one-for-one; this result is proved formally in Proposition 1. In panel (b) the cross-sectional implications are shown for two banks, one that corresponds to a bank with high exposure to the monetary policy environment (H), and one that is less exposed (L). As shown, the exposed bank charges a higher initial spread, but is less able to pass-through changes to the nominal rate when interest rates are low. The effects on equity are shown in panel (c); as profits fall, provided investors require a set return on equity (ROE $= 1 + r_t + \varrho$), equilibrium equity falls. With bank frictions, this reduces loan supply, as shown in panel (d). Panels (c) and (d) correspond to the formal results in Proposition 2.

Figure 6: Calibrated model



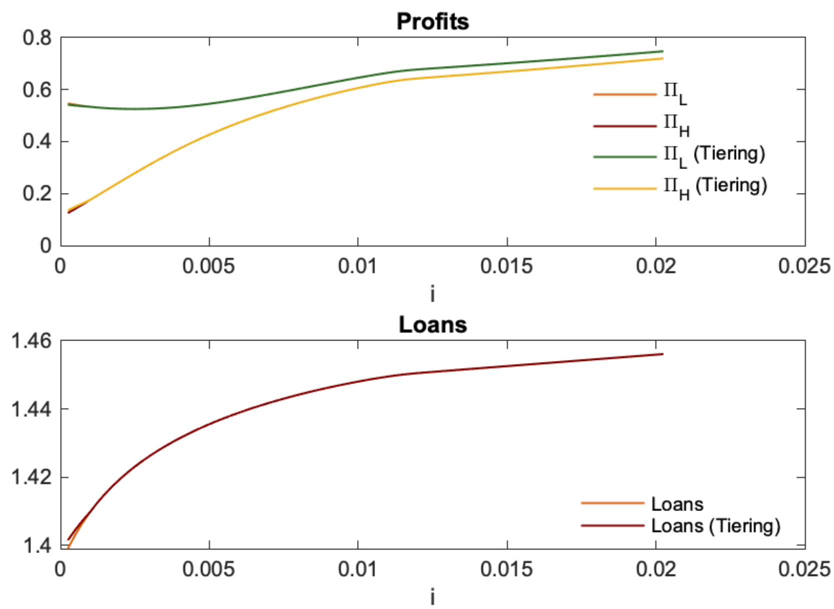
(a) Bank deposit rates and profits



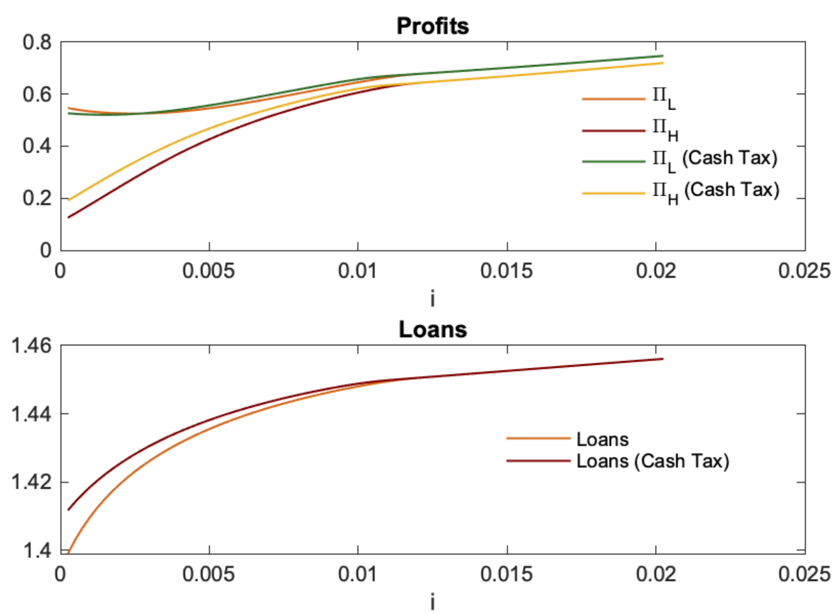
(b) Loans and output

Notes: Panel (a) plots the equilibrium bank deposit rates and profits for banks with high (H) and low (L) exposure to the policy rate against different levels of the policy rate in steady state. The model is calibrated to match the higher profitability of less exposed banks that we observe in the data. This is modeled as a higher leverage limit for less exposed banks, which captures the fact that less exposed banks in this setting also have more diversified banking activities. Panel (b) plots the equilibrium quantity of loans and output as a percentage of the steady state when $i = 3.4\%$.

Figure 7: Counterfactual response of bank profits and lending



(a) Tiering



(b) Cash tax

Notes: Panel (a) plots the response of bank profits and lending in the baseline model relative to the counterfactual in which central bank reserves earn different interest rates, i.e. tiering. This is modeled as a subsidy of 0.15 percent on 80 percent of reserves (assumed to be 20 percent of bank assets). Panel (b) plots the response of profits and loans in response to a tax on cash of 0.1 percent, as nominal rates decline.

Table 1: Summary statistics (2000)

	Mean	Median	S.D.	N
Total assets (tr)	6,055	2,124	17,527	110
Net Interest Margin	1.85	1.90	0.47	110
Ordinary Profits / Assets	-0.14	0.21	2.52	110
Deposits / Liabilities	0.90	0.95	0.14	110
Loans / Assets	0.70	0.70	0.09	110
Assets / Equity	29.5	21.7	70.9	109
$\max_j$(Non-performing loans / Assets, %)	4.09	3.62	2.83	110
Regional banks (%)	92	100	28	110
$\hat{\alpha}_{j,1990}$	4.02	4.26	0.87	110

Notes: Net interest margin is interest income divided by assets minus interest expense divided by liabilities. Ordinary profits include all earnings before taxes, divided by assets. Equity is measured using book value, i.e. book assets minus liabilities. Non-performing loans are taken at the highest level reported by each bank relative to assets over all years in the sample. The empirical measure of banks' markup on deposits in 1990 is given by the difference between nominal rates and the bank interest rate on deposits: $\hat{\alpha}_{j,1990} = i_{1990} - i^d_{j,1990}$.

Table 2: Balance of covariates (2000)

	All banks		Regional banks	
	High $\hat{\alpha}_j$	Low $\hat{\alpha}_j$	High $\hat{\alpha}_j$	Low $\hat{\alpha}_j$
Total assets (tr)	1,615	9,893	1,848	3,227
Net Interest Margin	2.02	1.70	2.00	1.91
Ordinary Profits / Assets	0.09	-0.34	0.10	-0.56
Deposits / Liabilities	0.95	0.86	0.95	0.93
Loans / Assets	0.69	0.70	0.69	0.72
Assets / Equity	23.3	34.9	23.0	38.6
$\max_j$(Non-performing loans / Assets, %)	3.76	4.38	3.81	4.31
Regional banks (%)	100	85	100	100
$\hat{\alpha}_{j,1990}$	4.49	3.61	4.47	3.99

Notes: Columns compare means for banks above and below the median bank markup on deposits in 1990 $\hat{\alpha}_{j,1990} = i_{1990} - i^d_{j,1990}$: 4.26 for all banks, 4.29 for regional banks. Net interest margin is interest income divided by assets minus interest expense divided by liabilities. Ordinary profits include all earnings before taxes, divided by assets. Equity is measured using book value, i.e. book assets minus liabilities. Non-performing loans are taken at the highest level reported by each bank relative to assets over all years in the sample.

Table 3: Interest income and interest expenses

	All banks				Regional banks	
	(1)	(2)	(3)	(4)	(5)	(6)
A. Dependent variable: Interest Expense / Liabilities (%)						
Post	-4.23***					
	(0.18)					
$\hat{\alpha}_{j,1990}$	-0.67***	-0.67***			-0.55***	
	(0.04)	(0.04)			(0.03)	
Post $\times\ \hat{\alpha}_{j,1990}$	0.52***	0.52***	0.52***	0.48***	0.46***	0.40***
	(0.04)	(0.04)	(0.04)	(0.04)	(0.04)	(0.03)
Constant	5.10	3.09	0.44	0.53	2.74	0.72
Observations	2,309	2,309	2,309	2,114	2,082	2,082
R-squared	0.54	0.97	0.98	0.99	0.99	0.99
B. Interest Income / Assets (%)						
Post	-3.51***					
	(0.14)					
$\hat{\alpha}_{j,1990}$	-0.23***	-0.23***			-0.10	
	(0.03)	(0.03)			(0.08)	
Post $\times\ \hat{\alpha}_{j,1990}$	0.32***	0.32***	0.36***	0.34***	0.17	0.12***
	(0.03)	(0.03)	(0.03)	(0.05)	(0.11)	(0.04)
Constant	5.02	3.35	2.15	2.25	3.18	2.83
Observations	2,309	2,309	2,309	2,114	2,082	2,082
R-squared	0.56	0.95	0.97	0.98	0.96	0.99
C. Net Interest Margin (%)						
Post	0.73***					
	(0.17)					
$\hat{\alpha}_{j,1990}$	0.45***	0.45***			0.45***	
	(0.03)	(0.04)			(0.07)	
Post $\times\ \hat{\alpha}_{j,1990}$	-0.20***	-0.20***	-0.16***	-0.13***	-0.30***	-0.27***
	(0.04)	(0.04)	(0.02)	(0.02)	(0.10)	(0.04)
Constant	-0.08	0.27	1.71	1.72	0.44	2.11
Observations	2,309	2,309	2,309	2,114	2,082	2,082
R-squared	0.51	0.61	0.88	0.93	0.34	0.83
Controls (all panels):						
Year f.e.s		Y	Y		Y	Y
Bank f.e.s			Y	Y		Y
Post$\times$max(NPL)			Y	Y		Y
Post$\times$Log Assets$_{j,1990}$			Y	Y		Y
Region$\times$year f.e.s				Y		
Weighted by Log Assets$_{j,1990}$				Y		

Notes: Regression specification (2), post equals 1 after 2000, and $\hat{\alpha}_{j,1990} = i_{1990} - i^d_{j,1990}$ is the spread on deposits measured in 1990. Standard errors clustered at the bank × pre/post level. Significance follows * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$.

Table 4: Effects on net profitability, other income and expenses, bank equity and lending

	All banks				Regional banks	
	(1)	(2)	(3)	(4)	(5)	(6)
A. Effects on net profitability						
Net Interest Income / Assets						
Post × $\hat{\alpha}_{j,1990}$	-0.29***	-0.29***	-0.28***	-0.26***	-0.25**	-0.27***
	(0.05)	(0.05)	(0.03)	(0.04)	(0.12)	(0.04)
Net Ordinary Income / Assets						
Post × $\hat{\alpha}_{j,1990}$	-0.34***	-0.34***	-0.22**	-0.13	-0.60**	-0.22***
	(0.09)	(0.09)	(0.09)	(0.17)	(0.30)	(0.08)
Net Income / Assets						
Post × $\hat{\alpha}_{j,1990}$	-0.14***	-0.14***	-0.05*	0.06*	-0.30	-0.07
	(0.03)	(0.03)	(0.03)	(0.03)	(0.25)	(0.09)
B. Effects on other income and expenses						
Fees / Assets						
Post × $\hat{\alpha}_{j,1990}$	0.02	0.02	0.06***	0.06*	-0.04	-0.01
	(0.07)	(0.07)	(0.02)	(0.04)	(0.03)	(0.01)
General and administrative expenses / Assets						
Post×$\hat{\alpha}_{j,1990}$	-0.10***	-0.10***	-0.08***	-0.08*	-0.09	-0.07**
	(0.03)	(0.03)	(0.03)	(0.05)	(0.08)	(0.03)
C. Effects on bank equity and lending						
Dividend payments / Assets						
Post × $\hat{\alpha}_{j,1990}$	-0.02***	-0.02***	-0.01**	0.002	-0.02***	-0.02***
	(0.01)	(0.01)	(0.005)	(0.01)	(0.01)	(0.004)
Equity issuance / Assets						
Post × $\hat{\alpha}_{j,1990}$	0.004	0.003	-0.02	-0.06**	0.05*	0.02
	(0.02)	(0.02)	(0.02)	(0.03)	(0.02)	(0.02)
Interest on loans / Loans						
Post × $\hat{\alpha}_{j,1990}$	0.14***	0.14***	0.17***	0.19***	0.14	0.11***
	(0.04)	(0.04)	(0.02)	(0.03)	(0.13)	(0.04)
Observations (all panels)	2,309	2,309	2,309	2,114	2,082	2,082
Controls (all panels):						
Year f.e.s		Y	Y		Y	Y
Bank f.e.s			Y	Y		Y
Post×max(NPL)			Y	Y		Y
Post×Log Assets$_{j,1990}$			Y	Y		Y
Region×year f.e.s				Y		
Weighted by Log Assets$_{j,1990}$				Y		

Notes: Regression specification (2), post equals 1 after 2000, and $\hat{\alpha}_{j,1990} = i_{1990} - i^d_{j,1990}$ is the spread on deposits measured in 1990. Coefficients on Post in column (1) and $\hat{\alpha}_{j,1990}$ in columns (1), (2), and (4) are estimated but not shown. Standard errors clustered at the bank × pre/post level. Significance follows * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$.

Table 5: Loan-level results ($\Delta \log \ell_{ijt}$)

	(1)	(2)	(3)	(4)	(5)
$\hat{\alpha}_{j,1990}$	0.011***	0.011**	0.014***		
	(0.004)	(0.005)	(0.005)		
Post$\times\hat{\alpha}_{j,1990}$	-0.013	-0.014	-0.015*	-0.021***	-0.027***
	(0.009)	(0.009)	(0.009)	(0.008)	(0.010)
Firm fixed effects	Y				
Year fixed effects	Y				
Firm-year fixed effects		Y	Y	Y	Y
Bank controls$_{j,t}$			Y	Y	Y
Bank fixed effects				Y	
Firm-bank fixed effects					Y
Constant	-0.021	-0.021	0.005	0.053	0.062
Observations	219,251	217,909	196,666	196,666	193,655
R-squared	0.04	0.23	0.24	0.25	0.34

Note: The dependent variable is $\Delta \log_{ijt}$ where $\ell_{ij,t}$ is the loan volume from bank j to firm i in year t. Sample includes 1990-2010, firms reporting fiscal year ends in March. Bank controls include non-interest income, extraordinary income, non-performing loans, and changes to equity due to mergers, acquisitions, and recapitalizations. Regressions are weighted by total firm borrowing. Standard errors clustered at the bank$\times$pre/post level. Significance follows * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$.

Table 6: Firm-level results ($\Delta \log y_{it}$)

Dependent variable y_{it}	Bank debt (1)	Total debt (2)	Assets (3)	Employees (4)
Post	0.074***	0.022*	0.004	0.007
	(0.018)	(0.013)	(0.007)	(0.008)
$\tilde{\alpha}_{i,t-1}$	0.044***	0.018***	0.013***	0.011***
	(0.009)	(0.007)	(0.004)	(0.004)
Post$\times\tilde{\alpha}_{i,t-1}$	-0.060***	-0.036***	-0.015***	-0.009*
	(0.013)	(0.010)	(0.005)	(0.005)
Constant	-0.041	-0.004	0.010	-0.024
Observations	29,262	29,458	29,881	29,459
R-squared	0.004	0.002	0.007	0.004

Note: All dependent variables are in $\Delta \log y_{it}$. Sample includes 1990-2010, firms reporting fiscal year ends in March. Regressions are weighted by total firm assets. Results in columns (1), (2) and (3) are robust to including year fixed effects and region$\times$year fixed effects; columns (1) and (3) are also robust to including industry$\times$year fixed effects. Standard errors clustered at the firm$\times$pre/post level. Significance follows * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$.

Table 7: Macroeconomic parameters for initial steady state

Parameter	Description	Value
$\bar{n}$	Labor supply	1
δ	Depreciation	0.08
α	Capital share	0.35
ν	Scale parameter	0.85
ρ	Non-pledgeable capital share	0.5
β	Discount factor	0.98
i_0	Nominal rate	3.4%

Notes: Macro parameters used in model calibration. Labor supply is normalized to 1. The labor share implies a capital share of 0.65. The Cobb-Douglas share of non-pledgeable capital is set to obtain a loans-to-GDP ratio of 125%. Depreciation is set to 8%. We set $\beta = .98$, aiming for a real rate of 2%. The initial steady state has a nominal rate of 3.4%, the value of the one-year rate on Japanese government bonds in 1990, filtered out of its business cycle component using an hp filter with smoothing parameter 100. Inflation hence is 1.4%.

Table 8: Fitted parameters

Parameter	Description	Value
Savings		
$\log \overline{\mathcal{L}}$	Liquid savings shifter	3.5
$\varepsilon^{\mathcal{L}}$	Elasticity of liquid savings	43.0
$\underline{m}$	Minimum cash holdings	0.11
$\frac{1-\alpha_m}{\alpha_m}$	Cash shifter	-0.04%
$\alpha_H - 1$	H (exposed) bank deposit advantage	0.26%
$\frac{1}{\varepsilon-1}$	EOS across bank savings	0.58%
$\frac{1}{\eta-1}$	EOS across bank and cash	2.2%
Lending		
γ	Maximal equity-to-capital ratio	15.87%
κ	Asset cost parameter	0.21%
ζ_L	L bank leverage advantage	0.53
$\frac{1}{\varepsilon^{\ell}-1}$	EOS across bank loans (mark-up)	0.7
Equity		
ϱ	Equity spread	7.27%

Notes: Fitted parameters chosen to match the empirical moments reported in Table 9. Household demand for liquid savings is determined by the first order condition $\mathcal{L}_t = \Phi'^{-1}(q_{\mathcal{L}}/q)$; we assume this function is log-linear in its price such that $\log \mathcal{L} = \log \overline{\mathcal{L}} - \varepsilon^{\mathcal{L}} \log (q_{\mathcal{L}}/q)$ where $\overline{\mathcal{L}}$ shifts liquidity demand and $\varepsilon^{\mathcal{L}}$ is the elasticity. To generate demand for cash even when rates are high, a minimum amount of cash $\underline{m}$ is imposed; this is necessary to match the high levels of cash observed in the data. To map the model to the empirical results, we assume two bank α_j types high (H) and low (L). Bank costs are modeled as a smooth functional form of equation (8) such that $c_j^{\ell}(\ell_j, e_j) = \kappa / (\gamma - \zeta_j \ell_j / e_j)$. We normalize $\zeta_H = 1$ and estimate $\zeta_L \leq 1$ to match the higher leverage of low α_j banks in the data.

Table 9: Calibration targets and model values

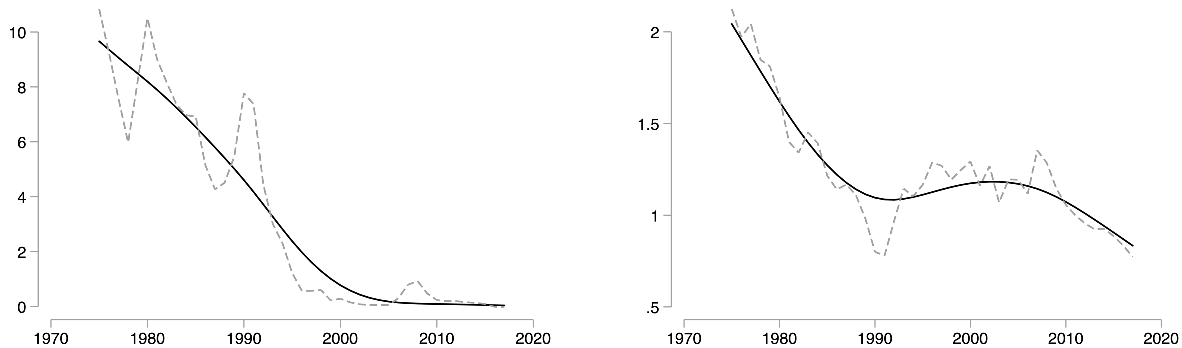
Moment	**Data**	**Model**
Savings		
$i - i^d$ spread, initial equilibrium	1.15%	1.18%
$i - i^d$ spread, change	−1.19%	−0.84%
$i - i^d$ spread, relative change	0.45%	0.26%
Cash holdings, initial equilibrium	4.10%	4.83%
Cash holdings, change	7.00%	7.50%
Loans-to-Liabilities	65.0%	60.1%
Bank liabilities to GDP, change	30%	33%
Lending		
$i^\ell - i$ spread, initial equilibrium	1.64%	1.61%
Loans-to-Assets ratio	58%	53%
Loan market share of low exposure banks	63%	63%
Lending response to equity injection	1.66%	1.42%
Equity		
Return on Equity	8.00%	9.31%

Notes: The first three targets in the model calibration map to the empirical results in Section 2. The median bank $\hat{\alpha}_{j,1990}$ is 4.26. Using the coefficients in Table 3 column (1), the predicted interest expense for the median bank in the pre-period is $5.10 - 0.67 * 4.26 = 2.2458$. This implies a spread of $i - i^d = 3.4 - 2.2458 = 1.154$. In the low rate equilibrium ($i_1 = 0.2\%$), the predicted median interest rate is $0.87 - (0.67 - 0.52) * 4.26 = 0.231$, which leads to a predicted spread of $i - i^d = 0.2 - 0.231 = -0.031$. This implies a change in the spread of $-0.031 - 1.154 = -1.185$. We also target the difference-in-difference in spreads across a one-standard deviation change in $\hat{\alpha}_{1990}$: the spread across less exposed banks decreased by 0.52*0.87 = 0.4524% more relative to more exposed banks.

Appendix

A Aggregate trends

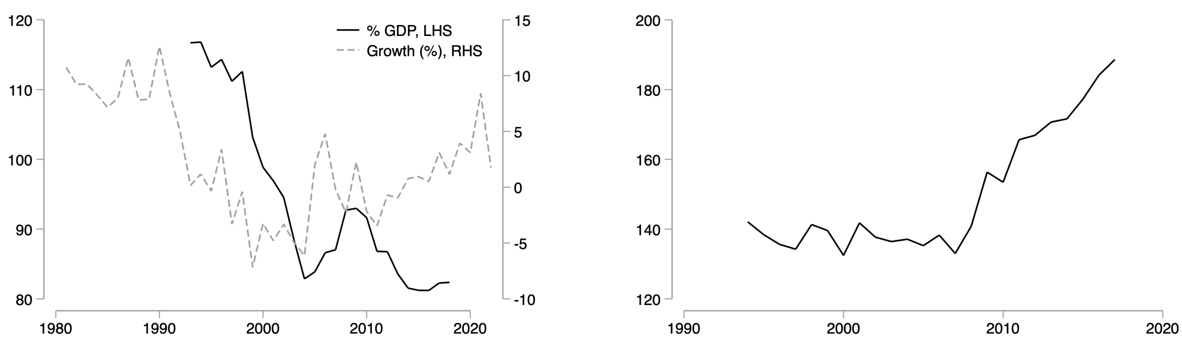
Figure A1: Interest rates and bank profitability



(a) Three-month Yen Libor (b) Bank net interest income per asset

Notes: Panel (a) plots the three-month Yen Libor. Prior to 1986, before the publication of the Libor, we fit the equivalent return on Japanese T-bills. Panel (b) displays aggregate bank net interest income divided by aggregate bank asset for our sample of banks, which excludes Shinkin banks, government banks, and Japan Post Bank. The smoothed line represents the trend component of the respective HP filtered series.

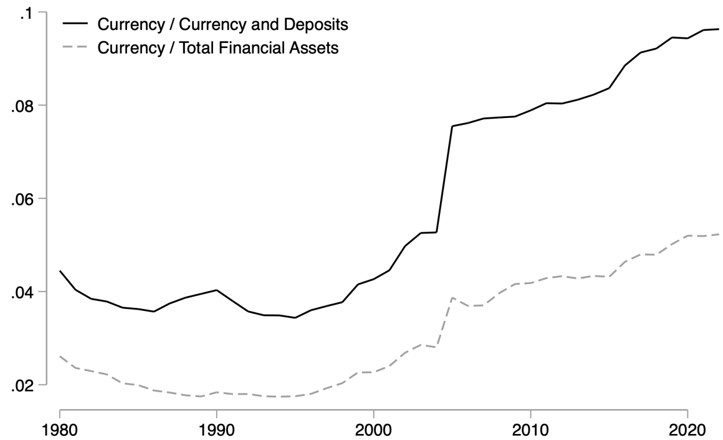
Figure A2: Bank Loans and Liabilities to GDP



(a) Loans to corporations (FoF) (b) Bank liabilities (% of GDP)

Notes: Panel (a) shows shows bank loans to non-financial corporations. Panel (b) shows total bank liabilities as a percent of GDP. Aggregate lending from the flow of funds, aggregate liabilities and nominal GDP from Bank of Japan.

Figure A3: Currency holdings of households



Notes: Household currency holdings as a percent of deposits and currency as well as a percent of total financial assets of households. Source: Flow of funds.

B Details on mergers

We manually track the mergers, acquisitions, and failures of all banks in our sample. Where banks merge, we add together the historical balance sheet components of the post-merger bank to compare the post-merger performance to a pro-forma sum of parts, before the merger.

The list of mergers accounted for in this way is summarized in Table A1. For example, Kyowa Bank and Saitama Bank merge in 1991 to form Asahi Bank, which merges with Daiwa Bank in 2002. The combined bank is then reorganized into Saitama Resona and Resona Holdings. We do not assess the reorganization but rather combine all the pre-merger banks and post merger banks into a single entity for the entire sample. Our results are robust to using individual banks, without adjusting for mergers.

Twelve banks fail and their assets cannot be clearly traced to a single entity. We remove these from the analysis. These are Toho Sogo Bank (1992q1), Taiheiyo Bank (1996q1), Hanwa Bank (1997q1), Hokkaido Takushoku Bank (1998q1), Tokuyo City Bank (1998q1), Kyoto Kyoei Bank (1998q3), Namihaya Bank (2000q1), Kofuku Bank (2000q1), Kokumin Bank (2000q1), Niigata Chuo Bank (2001q1), Ishikawa Bank (2002q3) and Chubu Bank (2002q3).

Table A1: Mergers and Acquisitions

Acquiror	Bank acquired	Date
Fukuoka Financial Group	Kyushu-Shinwa Holdings	2007q2
Hokuto Bank	Akita Akebono Bank	1993q1
Juroku Bank	Gifu Bank	2012q1
Kansai Urban Banking	Biwako Bank	2009q4
Kanto Tsukuba Bank	Tsukuba Bank	2003q2
Kinki Osaka Bank	Bank Of Kinki	2000q1
Kirayaka Bank	Yamagata Shiawase Bank	2007q1
Kirayaka Bank	Kirayaka Holdings	2008q3
Kiyo Bank	Wakayama Bank	2006q3
Kiyo Bank	Kiyo Holdings	2013q3
Kumamoto Bank	Higo Family Bank	1992q1
Kyushu Financial Group	Kyushu Bank	2003q1
Michinoku Bank	Hirosaki Sogo Bank	1976q3
Minato Bank	Hyogo Bank	1995q3
Minato Bank	Midori Bank	1999q1
Mitsubishi UFJ	Bank Of Tokyo	1996q1
Mitsubishi UFJ	Tokai Bank	2001q3
Mitsubishi UFJ	Nippon Trust Bank	2001q3
Mitsubishi UFJ	UFJ Holdings	2005q3
Mitsubishi UFJ	Toyo Trust Bank	2005q3
Mitsubishi UFJ	Sanwa Bank	2005q4
Mizuho Financial Group	Industrial Bank Of Japan	2002q1
Mizuho Financial Group	Dai-Ichi Kangyo Bank	2002q1
Mizuho Financial Group	Fuji Bank	2002q1
Namihaya Bank	Bank Of Naniwa	1998q3
Namihaya Bank	Fukutoku Bank	1998q3
Nishi-Nippon City Bank	Takachiho Sogo Bank	1984q1
Nishi-Nippon City Bank	Fukuoka City Bank	2004q3
North Pacific Bank	Sapporo Bank	2008q3
North Pacific Bank	Ibaraki Bank	2009q4
North Pacific Bank	Sapporo Hokuyo Holdings	2012q3
Kyowa Bank	Saitama Bank	1991q1
Resona (Daiwa)	Asahi Bank (Kyowa)	2002q4
Resona	Nara Bank	2005q4
Resona	Resona Trust & Banking	2009q1
San-In Godo Bank	Fuso Bank	1991q1
Senshu Ikeda Bank	Senshu Bank	2010q1
Sumitomo Mitsui Financial Group	Heiwa Sogo Bank	1986q1
Sumitomo Mitsui Financial Group	Taiyo Kobe Bank	1990q1
Sumitomo Mitsui Financial Group	Sakura Bank (Mitsui)	2001q1
Sumitomo Mitsui Financial Group	Sumitomo Banking	2002q3
Sumitomo Mitsui Trust Bank	Mitsui Trust And Banking	2000q1
Sumitomo Mitsui Trust Bank	Chuo Mitsui Asset Trust & Bank	2012q1
Sumitomo Mitsui Trust Bank	Chuo Mitsui Trust & Banking	2012q1
Tokyo Star Bank	Tokyo Sowa Bank	2001q1
Yamaguchi Financial Group	Setouchi Bank	2004q1
Yamaguchi Financial Group	Momiji Holdings	2006q3

Notes: When banks merge, we list as the acquirer the bank with a financial reporting identifier that is used by the combined entity after the merger. Where bank names are changed we list the previous name in parentheses.

C Additional empirical results

In Table A2, we show that variation in the 1990 spread is strongly driven by differences across prefectures and bank types. This can be linked to regional characteristics such as population density, income per capita, population, and the number of banks with headquarters in that prefecture in 1990. These factors individually explain between 50 and 64 percent of the variation across banks. Fixed effects for regions and types explain 94 percent of the variation across banks, as shown in column (5). Among the sample of regional banks alone, shown in column (6), time-invariant regional factors still explain a substantial portion of the variation.

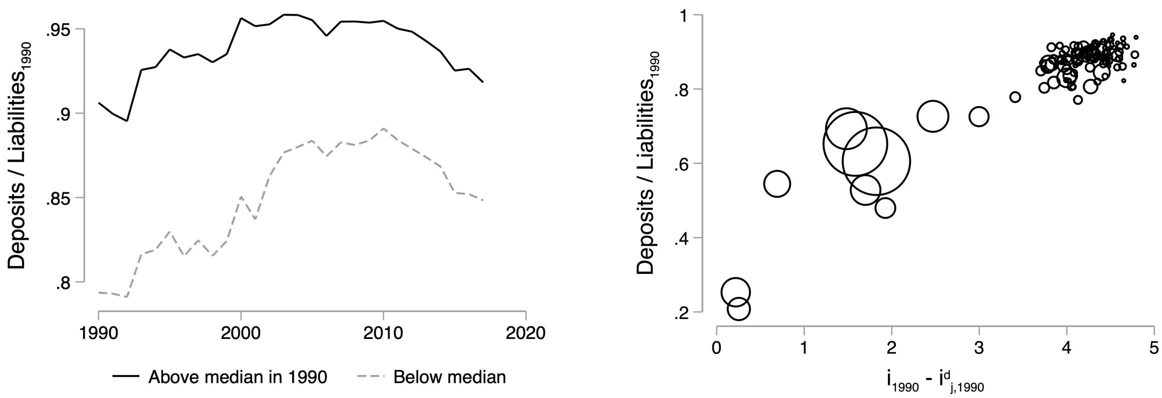
Table A2: Dependent variable: $\hat{\alpha}_{j,1990} = i_{1990} - i^d_{j,1990}$

	All banks					Regional banks
	(1)	(2)	(3)	(4)	(5)	(6)
Density	-0.42***					
	(0.07)					
Income p.c.		-0.41***				
		(0.06)				
Population			-0.44***			
			(0.08)			
# bank HQ				-0.11***		
				(0.02)		
Prefecture fixed effects					Y	Y
Type fixed effects					Y	
Observations	110	110	110	110	110	101
R-squared	0.60	0.62	0.51	0.64	0.94	0.54

Note: Density, income per capita, and population are standardized to have mean 0 and standard deviation 1. Bank headquarters and population is measured in 1990, income per capita in 2001 and density in 2010 (due to data availability). Robust standard errors. Significance follows $^{*}p < 0.1,^{**}p < 0.05,^{***}p < 0.01$.

In our mechanism, banks with more market power are more exposed to low nominal interest rates. One alternate measure of market power is the deposits-to-liabilities ratio. A maintained assumption of this setting is that banks' market power is highly persistent (and in the model, permanent). Panel (a) of Figure A4 shows that banks' deposits to liabilities ratio in 1990 is highly persistent throughout the sample. Panel (b) shows that the spread on bank deposits charged in 1990 is highly correlated with the 1990 deposits to liabilities ratio.

Figure A4: Deposits to Liabilities ratio, 1990



(a) Deposits to Liabilities ratio$_t$ (b) Comparison to $\hat{\alpha}_{j,1990}$

Notes: In panel (a), deposit dependence as measured by the ratio of deposits to liabilities is both high on average and highly persistent over the sample period, as measured in groups of banks above and below the 1990 median. Panel (b) shows that deposit dependence is also highly correlated with $\hat{\alpha}_{j,1990}$.

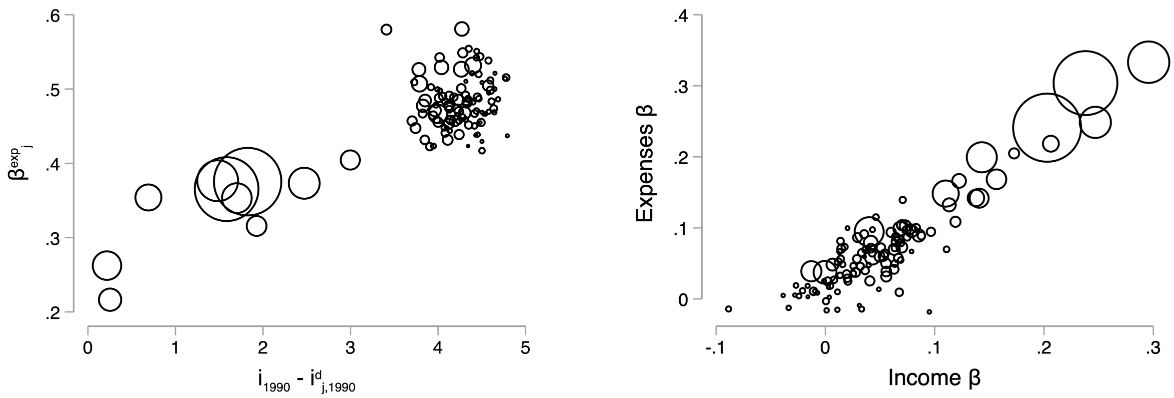
We can also measure exposure in the data, by defining bank exposure as bank j's associated parameter β_j^{exp} estimated from the regression:

$$i_t - i_{jt}^{exp} = \beta_0 + \beta_j^{exp} i_t + \epsilon_{jt}, \tag{A1}$$

where i_t is the three month Yen Libor and i_{jt}^{exp} is the realized interest expense of bank j. A large β_j^{exp} indicates a bank with long-term spreads that are highly dependent on the level of nominal rate, for example because it funds itself with deposits over which it has market power. In contrast, a wholesale funded bank would be expected to have $\beta_j^{exp} = 0$. In our sample, β_j^{exp} ranges from about 0.2 to 0.6, with a standard deviation of 0.06. A high β_j^{exp} correlates with large spreads in the high rates environment. Figure A5 shows in panel (a) that the spread on bank deposits charged in 1990 is highly correlated with the β^{exp} measure of exposure. By running regression (A1) in levels at an annual frequency, we capture the long-run exposure of banks' interest expense spreads to the level of interest rates.

The interpretation of β_j^{exp} is different from that of Drechsler et al. (2021), who estimate a similar regression in changes, picking up business cycle frequency fluctuations in both variables. The results of Drechsler et al. (2021) nonetheless hold among Japanese banks, as

Figure A5: Estimated measures of exposure



(a) Estimated exposure β_j^{exp}

(b) Banks hedge

Notes: Panel (a) shows the estimated exposure β_j^{exp} coefficients estimated from equation (A1) run bank by bank, using data since 1975, plotted against the initial spread $\hat{\alpha}_{j,1990}$. The size of the bubbles indicates bank size in 1990, measured by total assets. In panel (b), the y-axis plots coefficients of bank-level regressions of equation (A2) of the change in interest expenses scaled by liabilities on changes in the 1 year JGB interest rate, for 1975-2017. The x-axis is the corresponding coefficient from a regression of interest income scaled by bank assets.

we show by estimating the expense and income beta from a regression:

$$\Delta i_{jt}^k = \alpha + \beta_j^{\Delta,k} \Delta i_{jt} + \epsilon_{jt} \tag{A2}$$

for $k =$ income, expenses. In our sample, $\beta_j^{\Delta,exp}$ ranges from roughly 0 to 0.3, with a standard deviation of 0.06. A high $\beta_j^{\Delta,exp}$ indicates that interest expenses change when nominal rates change, i.e. deposit market power is decreasing in $\beta_j^{\Delta,exp}$. The resulting estimates of interest income betas and interest expense betas are shown in Figure panel (b) of A5, which line up close to the 45 degree line. This shows that in Japan, banks hedge and equalize their income and expense betas. While this is true in a stable environment, we focus in our results on the long term, rather than the short term, and look at the level of interest rates rather than banks' reactions to changes. In the low interest rate environment, banks are no longer able to hedge effectively.[37]

[37] Drechsler et al. (2017) run a similar regression using the change in the deposit spread as the dependent variable. They show the betas estimated in this case to increase with concentration as measured by the Herfindal index (HHI), i.e. market power.

Our empirical results are robust to these alternative measures of banks' exposure to low interest rates. We re-run regressions corresponding to column (2) of the regression results tables in the main text. As outcomes, we consider (1) the spread $\mu_{ijt}^{exp} = i_t - i_{jt}^{exp}$ where i_{jt}^{exp} is the measured interest expense and where μ_{ijt}^{exp} has its business cycle component removed, the interest expense i_{jt}^{exp}, the net interest margin, net operating income, and the realized loan rate. Table A3 compares the results of the baseline specification in the main text in panel A, using $\hat{\alpha}_{j,1990} = r_{1990} - r_{j,1990}^{d}$ as the exposure variable, to several alternatives.

Panel B shows the results when using the deposits to liabilities ratio in 1990 as the exposure variable. The results are consistent with our main analysis, supporting the idea that the market power embedded in the deposit franchise is highly persistent due to historical reasons. Panels C and D display the robustness results when using the deposit spread in 1980 as the exposure variable and using the baseline sample and full sample of data, respectively. These results are consistent with our main analysis, giving support to the idea that banks that charge high initial spreads – banks we interpret as having high market power – lose these advantages in the post low rates era.

Our results also hold when using the estimated measure of exposure β_j^{exp} defined in equation (A1), as shown in panel E. Banks with large β_j^{exp} suffer larger declines in their mark-ups, pay higher interest expenses, have lower net interest margins, lower net ordinary income, and charge higher loan rates. Panel F shows that our results are robust to using the DSS β as computed in equation (A2) as an exposure variable. The estimated coefficients are consistent with our main analysis but the signs of the coefficients are reversed, since low values indicate higher market power. Panel G shows that when we do not consolidate banks, we find very similar point estimates as in our main sample.

We also run one specification that allows us to test elasticities, using the level of nominal rates as an explanatory variable and interacting the level of rates with the treatment $\hat{\alpha}_{j,1990}$ (instead of pre/post). Panel H shows that the main results hold when instead of using pre/post we use the three month Yen Libor, from which we remove the business cycle component using a standard HP filter. Following a decrease in rates, banks with a high deposit spread in 1990 have lower spreads, higher interest expenses, lower net interest margins, and higher loan rates.

Table A3: Robustness regressions

Dependent variable:	μ_{jt}^{exp} (1)	i_{jt}^{exp} (2)	NIM$_{jt}$ (3)	NOI$_{jt}$ (4)	i_{jt}^{ℓ} (5)
A. Baseline results					
$\hat{\alpha}_{j,1990}$	0.62**	-0.67**	0.45**	0.29**	0.01
	(0.01)	(0.01)	(0.02)	(0.02)	(0.02)
Post $\times\ \hat{\alpha}_{j,1990}$	-0.43***	0.52***	-0.20**	-0.34**	0.14**
	(0.01)	(0.00)	(0.01)	(0.01)	(0.01)
Observations	2,288	2,309	2,309	2,309	2,309
R-squared	0.90	0.97	0.61	0.13	0.95
C. Exposure measure: $\hat{\alpha}_{j,1980}$					
$\hat{\alpha}_{j,1980}$	0.84**	-0.90**	0.54**	0.33**	-0.05
	(0.04)	(0.03)	(0.04)	(0.02)	(0.03)
Post $\times\ \hat{\alpha}_{j,1980}$	-0.60**	0.72**	-0.22*	-0.33*	0.24**
	(0.02)	(0.01)	(0.02)	(0.05)	(0.01)
Observations	2,288	2,309	2,309	2,309	2,309
R-squared	0.78	0.96	0.44	0.11	0.95
E. Exposure measure: β_j^{exp}					
β_j^{exp}	7.66*	-8.15**	5.18*	2.53	0.15
	(0.61)	(0.56)	(0.52)	(0.45)	(0.41)
Post $\times\ \beta_j^{exp}$	-5.69**	6.70**	-1.96*	-2.52	2.34**
	(0.25)	(0.23)	(0.21)	(1.08)	(0.17)
Observations	2,288	2,288	2,288	2,288	2,288
R-squared	0.66	0.94	0.40	0.10	0.95
G. Sample of unmerged banks					
$\hat{\alpha}_{j,1990}$	0.63**	-0.67***	0.46**	0.19**	0.02
	(0.01)	(0.01)	(0.02)	(0.01)	(0.02)
Post $\times\ \hat{\alpha}_{j,1990}$	-0.44***	0.52***	-0.18**	-0.21**	0.15**
	(0.00)	(0.00)	(0.01)	(0.00)	(0.01)
Observations	2,752	2,843	2,843	2,843	2,843
R-squared	0.87	0.97	0.65	0.08	0.95
Controls (all panels):					
Year f.e.s	Y	Y	Y	Y	Y

Dependent variable:	μ_{jt}^{exp} (1)	i_{jt}^{exp} (2)	NIM$_{jt}$ (3)	NOI$_{jt}$ (4)	i_{jt}^{ℓ} (5)
B. Deposits / Liabilities$_{j,1990}$					
D/L 1990	4.49**	-4.87**	3.12*	2.45**	-0.07
	(0.17)	(0.16)	(0.25)	(0.19)	(0.14)
Post $\times$ D/L	-3.06**	3.78**	-1.41**	-2.74**	0.93**
	(0.07)	(0.07)	(0.10)	(0.08)	(0.06)
Observations	2,288	2,309	2,309	2,309	2,309
R-squared	0.86	0.97	0.54	0.14	0.95
D. Exposure measure: $\hat{\alpha}_{j,1980}$ (1975-2017)					
$\hat{\alpha}_{j,1980}$	0.86**	-0.88**	0.57**	0.16*	-0.15
	(0.02)	(0.02)	(0.04)	(0.02)	(0.03)
Post $\times\ \hat{\alpha}_{j,1980}$	-0.69***	0.74***	-0.30**	-0.20	0.30**
	(0.01)	(0.01)	(0.02)	(0.06)	(0.01)
Observations	4,577	4,618	4,618	4,618	4,618
R-squared	0.97	0.97	0.66	0.17	0.97
F. Exposure measure: $\beta_j^{\Delta,exp}$ Drechsler et al. (2021)					
$\beta_j^{\Delta,exp}$	-4.36**	4.94**	-3.79**	-1.97*	-0.45
	(0.29)	(0.26)	(0.26)	(0.27)	(0.23)
Post $\times\ \beta_j^{\Delta,exp}$	2.80**	-3.73**	1.65**	2.79	-0.90*
	(0.12)	(0.11)	(0.11)	(0.66)	(0.10)
Observations	2,288	2,309	2,309	2,309	2,309
R-squared	0.54	0.93	0.40	0.11	0.95
H. Nominal rate elasticity					
$\hat{\alpha}_{j,1990}$	0.22***	-0.21***	0.26***	0.14	0.17***
	(0.04)	(0.05)	(0.03)	(0.13)	(0.04)
Rate $i_t \times \hat{\alpha}_{j,1990}$	0.15***	-0.16***	0.07***	-0.01	-0.07***
	(0.02)	(0.02)	(0.01)	(0.03)	(0.02)
Observations	2,288	2,309	2,309	2,309	2,309
R-squared	0.87	0.97	0.60	0.10	0.95
Controls (all panels):					
Year f.e.s	Y	Y	Y	Y	Y

Notes: Significance follows * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$. Standard errors are clustered at the bank $\times$ pre/post level. $\mu_{jt}^{exp} = i_t - i_{jt}^{exp}$ where i_{jt}^{exp} is the interest expense rate and i_t is the three-month libor. We extract the business cycle component of μ_{jt}^{exp} bank-by-bank using an HP filter and remove it. NIM is interest income rate minus the interest expense rate. NOI is net ordinary income, the sum of net interest income and net non-interest income, divided by assets. i_{jt}^{ℓ} is the realized loan rate.

Effect on Total Assets. One concern, particularly regarding our liability results, is the scenario in which bank profits is growing yet bank assets is growing faster, resulting in potentially lower profitability metrics but still positive outlook for bank loans-to-equity ratios, the relevant measure of leverage in our model. Table A4 shows the results of regression (2) with the change in the log of total bank assets as the dependent variable. Although more exposed banks had higher growth on average, if anything this growth was significantly lower in the post period. With the controls added to the main regressions the rate of growth does not differ in an economically or statistically significant manner, which indicates that this concern does not drive our results.

Table A4: Effects on Δ Log Total Assets

	All banks				Regional banks	
	(1)	(2)	(3)	(4)	(5)	(6)
Post	0.052**					
	(0.021)					
$\hat{\alpha}_{j,1990}$	0.017***	0.017***			0.032***	
	(0.002)	(0.002)			(0.008)	
Post $\times$ $\hat{\alpha}_{j,1990}$	-0.015***	-0.015***	-0.002	0.006	-0.031***	-0.008
	(0.005)	(0.005)	(0.004)	(0.006)	(0.009)	(0.005)
Year f.e.s		Y	Y		Y	Y
Bank f.e.s			Y	Y		Y
Post$\times$max(NPL)			Y	Y		Y
Post$\times$Log Assets$_{j,1990}$			Y	Y		Y
Region$\times$year f.e.s				Y		
Weighted by Log Assets$_{j,1990}$				Y		
Constant	-0.047	-0.022	-0.049	-0.073	-0.054	-0.021
Observations	2,309	2,309	2,309	2,114	2,082	2,082
R-squared	0.04	0.27	0.33	0.53	0.32	0.38

Notes: Regression specification (2), post equals 1 after 2000, and $\hat{\alpha}_{j,1990} = i_{1990} - i^d_{j,1990}$ is the spread on deposits measured in 1990. Standard errors clustered at the bank $\times$ pre/post level. Significance follows * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$.

D Proofs

Proof of Proposition 1

Proof. From the banking problem recall that the rate charged by banks is given by:

$$1 + i_j^d = \frac{\varepsilon_j^d}{\varepsilon_j^d + 1}(1+i)$$

Where ε_j^d takes the following form:

$$\varepsilon_j^d = (1-\omega_j^d)\varepsilon + \omega_j^d \omega^m \eta + \omega_j^d (1-\omega^m)\varepsilon^{\mathcal{L}}$$

where ω_j^d is bank j's market share in the local market, ω^m is the share that households save in cash, and $\varepsilon^{\mathcal{L}} \geq 0$ is the elasticity of liquid savings to the price index of these savings. In the symmetric equilibrium $\omega_j^d = 1/N$. Hence the elasticity increases and the pass-through is less than one if and only if $\frac{d\omega^m}{d\bar{\pi}}(\eta - \varepsilon^{\mathcal{L}}) < 0$. Because cash and deposits are substitutes ($\eta > 1$), $\frac{d\omega^m}{d\bar{\pi}} < 0$ is always true: an exogenous decrease in the price of cash (i.e. a decrease in the inflation target) must increase its share of total liquid savings. Hence the pass-through is less than one if and only if $\eta > \varepsilon^{\mathcal{L}}$. □

Proof of Proposition 2

Proof. To show (i), the funding problem of the bank in real terms can be written:

$$\frac{\Pi^d}{1+\pi} = \max_{q_j}(q^{-1} - (q_j)^{-1}) d_j(q_j, q_d, q_m, q_{\mathcal{L}})$$

We can apply the envelope theorem following a change in $\bar{\pi}$, hence ignoring the spread term. Importantly, $d_j(\cdot)$ also depends on the prices of competing saving products, q_d, q_m and q, the respective prices of aggregate deposits, inflation and real bonds (and q_d contains the bank's own price). Because inflation adjusts to keep the real bond rate constant, q is unchanged.

Taking logs and differentiating with respect to $\log(1+\bar{\pi})$ we obtain:

$$\begin{aligned}
\left.\frac{d\log d_j}{d\log(1+\bar{\pi}))}\right|_{dq_j=0} &= (\varepsilon-\eta)\left.\frac{d\log q_d}{d\log(1+i)}\right|_{dq_j=0} + (\eta-\varepsilon^{\mathcal{L}})\left.\frac{d\log q_{\mathcal{L}}}{d\log(1+i)}\right|_{dq_j=0} \\
&= \frac{d\log q_d}{d\log(1+\bar{\pi})}\frac{N-1}{N}\left(\varepsilon-\eta+(\eta-\varepsilon^{\mathcal{L}})(1-\omega^m)\right)+(\eta-\varepsilon^{\mathcal{L}})\omega^m
\end{aligned}$$

Viewing the expression above as a function of ω^m, it is then useful to see that:

$$\begin{aligned}
\lim_{\omega^m\to 0}\left.\frac{d\log d_j}{d\log(1+\bar{\pi}))}\right|_{dq_j=0} &= \frac{d\log q_d}{d\log(1+\bar{\pi})}\frac{N-1}{N}\left(\varepsilon-\varepsilon^{\mathcal{L}}\right) \\
\lim_{\omega^m\to 1}\left.\frac{d\log d_j}{d\log(1+\bar{\pi}))}\right|_{dq_j=0} &= \frac{d\log q_d}{d\log(1+\bar{\pi})}\frac{N-1}{N}(\varepsilon-\eta)+(\eta-\varepsilon^{\mathcal{L}})
\end{aligned}$$

Both expressions are positive if and only if $\eta > \varepsilon^{\mathcal{L}}$, as $\varepsilon > \eta$ by assumption and $\frac{d\log q_d}{d\log(1+\bar{\pi})} > 0$ if and only if $\eta > \varepsilon^{\mathcal{L}}$ by Proposition 1, i.e. a decrease in the inflation target leads to cheaper deposits due to incomplete pass-through. But now, realize that $\left.\frac{d\log d_j}{d\log(1+\bar{\pi}))}\right|_{dq_j=0}$ is continuous in ω^m, proving the result by the intermediate value theorem.

For (ii), first note that, holding equity e constant and general equilibrium quantities constant, a change in i such that $di = d\bar{\pi}$ has no direct impact on banks' profits on lending, as the elasticity of loan supply faced by banks does not depend on the nominal rate i, only the real loan rate. Next, note that holding equity e and general equilibrium quantities constant has no impact on this result: by the envelope theorem a decrease in e decrease the profits that banks make, and general equilibrium responses can only dampen the response of a loan supply in the first place, but not overturn it, by contradiction. Since bank funding profits decrease by part (i), total bank profits must decrease.

Recall now that equity is the solution to:

$$e = \frac{\Pi^{\ell}(e)+\Pi^{d}}{(1+\pi)\varrho}$$

Hence if Π^d decreases, then so does e. Since $\Pi^{\ell}(e)$ is increasing in e, the decrease is further amplified by losses on the asset side of banks.

For (iii), the proof is straightforward: a decrease in e can only tighten the constraint.

When it binds, the real loan rate increases and loan demand decreases. General equilibrium changes the magnitude of that response, but cannot undo it. □

Proof of Lemma 1

Proof. These results are immediate from the increase in the real loan rate, which is essentially a permanent negative supply shock to the economy. Note that the changes in transaction benefits translate one for one to changes in consumption, and hence the increase in liquidity from Lemma 2 has no impact on other real quantities. □

Proof of Lemma 2

Proof. That the price of liquidity $q_{\mathcal{L}}$ decreases is immediate from the decline in q_m and q_d, and as $q_{\mathcal{L}}$ decreases, the household's first order condition implies that $\mathcal{L}$ increases (recall q is constant). Since $1+\bar{\pi} > q \iff q_m > q$, $\Phi' \geq 0$ (we are below the satiation point), meaning that liquidity benefits increase. □

Proof of Proposition 3

Proof. We first show conditions under which optimal inflation is such that the optimal nominal interest rate is zero, i.e. the Friedman rule applies. Since $\alpha_m = 1$, households optimally want to hold equal shares of cash and deposits, and want the price to of liquid assets to be the price of bonds to reach the satiation point in the liquidity aggregator. Since $q_d = q$ always hold because of the subsidy, it suffices to set $q_m = q = \beta$ to maximize welfare, as there are no distortions on bank lending. Any deviation strictly decreases liquidity, decreasing transaction benefits and decreasing welfare.

Next, suppose banks' net worth constraint strictly binds at zero, so that loans are undersupplied in equilibrium due to the scarcity of bank equity. At $q_m = q$, the equal allocation between cash and deposits would still be optimal, and the marginal cost of an increase in the price of cash q_m is zero. To see this, define the net benefit of liquidity as the difference between Φ and $\mathcal{L}$: $\phi = \Phi(L) - \mathcal{L}$ when $q_m = q_d = q$, $q_{\mathcal{L}} = q$. From the first order conditions this implies $\Phi' = \frac{q_{\mathcal{L}}}{q} = 1$. This implies additional units of liquidity do not provide any marginal additional or benefit or cost, besides the liquidity itself: the marginal net benefit is zero, i.e. $\frac{d\phi}{d\mathcal{L}} = 0$. In contrast, since banks' net worth constraint strictly binds at zero by assumption, they still strictly binds for a small ϵ-ball around zero, and hence the marginal benefit of reducing the constraint is positive. We conclude that the optimal inflation target is above minus the real rate, and hence resulting nominal interest rate must be strictly positive. Optimal inflation is also finite, because as $\pi \to \infty$, $m \to 0$ and hence $\mathcal{L} \to 0$, which by assumption implies losses (recall the Inada condition $\lim_{\mathcal{L}\to 0} \Phi'(\mathcal{L}) \to \infty$).

It is immediate that the banks' net worth constraint must bind at the optimal inflation target: if it did not, there would be no cost of decreasing inflation by some ϵ, while benefiting from better liquidity. □

Proof of Proposition 4

Proof. Differentiating equilibrium d_j with respect to the inflation target one obtains:

$$\frac{d\log d_j}{d\log(1+\bar{\pi})} = \frac{d\log q_d}{d\log(1+\bar{\pi})}\left(-\eta + (\eta - \varepsilon^{\mathcal{L}})(1-\omega^m)\right) + (\eta - \varepsilon^{\mathcal{L}})\omega^m.$$

Note that unlike Proposition 2, we do not hold the bank price constant. Taking limits with respect to ω^m we have:

$$\lim_{\omega^m \to 0} \frac{d\log d_j}{d\log(1+\bar{\pi})} = -\frac{d\log q_d}{d\log(1+\bar{\pi})}\varepsilon^{\mathcal{L}}$$
$$\lim_{\omega^m \to 1} \frac{d\log d_j}{d\log(1+\bar{\pi})} = (\eta - \varepsilon^{\mathcal{L}})$$

Where we have used the fact that $\lim_{\omega^m \to 1} \frac{d\log q^d}{d\log(1+\bar{\pi})} = 0$. Clearly, the first expression is negative, while the second one is positive: when inflation is high ($\omega^m \approx 0$), banks benefit from the overall increase in liquidity that their mark-up reduction generates after a decrease in the inflation target, and so deposits increase; in contrast, when inflation is already low ($\omega^m \approx 1$), do not benefit at all from the overall increase in liquidity, and hence their deposits decrease. Since the expression $\frac{d\log d_j}{d\log(1+\bar{\pi})}$ is continuous and increasing in ω^m, there exists a unique $\widetilde{\pi}$ such that $\frac{d\log d_j}{d\log(1+\bar{\pi})} = 0$.

□

E Public equity injections

In this section we show that equity is an important component of bank loan supply by showing that public equity injections into (distressed) banks results in increases in bank lending. Our goals are both to show that equity matters and to use the resulting elasticity to calibrate the strength of the lending frictions in our model. When the government injects new equity into banks, this relaxes banks' net worth constraints, facilitating additional lending. Japanese bank recapitalizations occurred during the late 1990s, early 2000s, and around the Great Recession – and affected both large and small banks.

We collect data on public equity injections from the Deposit Insurance Corporation of Japan website. We then run a regression:

$$\frac{\Delta L_{jt+1}}{A_{jt}} = \alpha_j + \alpha_t + \beta \frac{\Delta E_{jt}}{A_{jt}} + Controls_{jt} + \epsilon_{jt} \tag{A3}$$

where L_{jt} is lending, ΔL_{jt+1} is the change in lending $L_{jt+1} - L_{jt}$, E_{jt} is book equity at period t, and $\Delta E_{jt} = E_{jt} - E_{jt-1}$. Controls include public bond injections, non-performing loans at the bank level, and bank size (log total assets). Table A5 shows the results from a regression in which we instrument for the change in bank equity using the recapitalization data.

Table A5: Dependent variable: Change in bank lending / assets

	All banks				Regional banks
	(1)	(2)	(3)	(4)	(5)
$\Delta E_{jt}/A_{jt}$	1.66***	1.57***	1.32**	0.82	1.34**
	(0.50)	(0.48)	(0.52)	(0.50)	(0.62)
Year f.e.s	Y	Y	Y		Y
Bank f.e.s	Y	Y		Y	Y
Bond injections	Y		Y	Y	Y
Observations	3,000	3,000	3,001	3,000	2,732
R-squared	0.01	0.02	0.06	0.09	0.03
First-stage F stat	50.2	52.4	48.0	38.4	31.4

Notes: All columns include controls for both bank size and the rate of reported non-performing loans. Significance follows * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$.