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Micro-level transmission of monetary policy shocks: The trading book channel

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We open the black box of the monetary policy transmission mechanism with a granular model that considers the balance-sheet composition and network relationships of each economic agent. Though there are several well-documented channels through which monetary policy operates, we focus on the overlooked trading book channel, which arises because of adjustments in the accounting value of trading book exposures on banks’ balance sheets that have to be marked to market when interest rates change. Variations in banks’ net worth due these adjustments are used as input to a network model that incorporates the financial and corporate sectors. The framework permits us to determine the effects of interest rate changes on every bank and firm in the economy and any second-round (contagion) effects in the short run. We apply the model to a comprehensive database of Brazilian banks and firms from 2015 to 2020. We find that interest rate shocks affect more strongly financial stability in periods of monetary policy tightening. We also find notable asymmetric effects of positive and negative interest rate shocks in the Brazilian economy, with positive interest rate shocks affecting more financial stability. Finally, our results also suggest a non-linear relationship between interest rate changes and financial stability, reinforcing the need to mitigate monetary policy shocks through interest rate smoothing and adequate communication and transparency to society.

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1. Introduction

The global financial crisis highlighted how monetary policy, banks’ financial conditions, and the financial system structure interconnect in non-trivial ways. Existing research focuses typically on monetary policy transmission to the economy or the

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structure of the financial system as a driver of financial instabilities.\footnote{1} This paper lies at the intersection of both themes and documents on how monetary policy affects financial stability using network modeling with micro-level supervisory data. Network-based models have gained increased attention precisely because they offer a flexible and elegant way of constructing granular models with several heterogeneous agents while not abstracting away from their particularities, such as non-trivial connections patterns.

Monetary policy shocks impact the economy through a variety of transmission channels.\footnote{2} In this paper, we are concerned with adjustments in the accounting value of trading book exposures on banks’ balance sheets that have to be marked to market when interest rates change. While existing research on agent-based models considers individual banks and firms that interact with each other as well as a central bank, in which monetary policy can affect the economy through a variety of channels,\footnote{3} none of them has explicitly incorporated the trading book channel. To evaluate how interest rate changes transmit to the entire economy through revaluation in banks’ trading books, we build upon Silva et al. (2017a)'s contagion model and extend it in three relevant ways. First, we add a policy-maker layer to allow for monetary policy shocks in the model. Second, we model bank-specific financial exposures to interest rate changes by recalculating the new fair value of the entire cash flow attached to the interest rate at different maturities in terms of banks’ capitalization levels. Third, as banks may incur losses or profits due to interest rate changes, we adapt the Silva et al. (2017a)'s inner stress transmission mechanism to accommodate positive and negative shocks.\footnote{4}

Our contagion model considers individual particularities of firms and banks, and also bilateral exposures among them. Banks that experienced trading book losses cut credit to the corporate sector due to macroprudential regulatory constraints and internal risk management. Depending on firms’ current liquidity conditions and ability to substitute banks, they may not pay back the bank credit, leading banks into additional losses. These events create a vicious loss cycle fed by successive credit crunches and credit defaults. As output, the model permits us to determine the net worth reduction on every bank and firm due to these second-round (contagion) effects. This paper considers the net worth reduction as a proxy for economic agents’ financial instability. With this tool, we can identify economic and financial sectors that would be more sensitive to sudden interest rate changes from the viewpoint of financial instability.

There are two broad channels through which interest rate shocks may directly affect banks (Kashyap and Stein, 2000): (i) the risk-taking channel\footnote{5} and (ii) the credit channel through bank lending\footnote{6} and balance sheet changes. In the short run, the balance-sheet channel works mainly through the revaluation of banks’ trading books due to marking-to-market assets and liabilities. While the balance-sheet channel has an immediate impact on banks’ net worth, the other channels take time to kick in because they involve changes in economic agents’ behaviors and expectations. In this paper, we are concerned with the short-term consequences of monetary policy shocks to financial stability. Hence, we focus on the balance-sheet channel through trading book variations. As Basel III recommends that banks meet minimum capital requirements continuously (BCBS, 2015), trading book variations are of concern as banks may immediately run into insolvency following the shock and hence impair the stability of the entire financial system.

Trading book activities were one of the primary sources of financial losses in the 2008 financial crisis.\footnote{7} While accounting data on the trading book is scarce, the few data available attest to the non-negligible representativeness of trading book positions. According to Ramon et al. (2017), the share of trading book assets increased over time since 1996 for the largest UK banks, reaching nearly 30% in 2013. The main German bank, Deutsche Bank (2014) reported that its trading book positions accounted for 56.7% (46.3%) of total assets (liabilities). In Brazil, the trading book position of commercial, investment, and development banks reached up to 35% (37%) of the total assets (liabilities) in 2015. Given the relevance of the trading book, the Basel Committee on Banking Supervision (BCBS, 2013) revised the capital framework for trading book exposures, recognizing the interest rate was one of its five broad risk factors (together with credit, foreign exchange, equities, and commodities). This normative change reflects the importance of understanding the impact of monetary policy shocks—which directly operate through revaluation of tradable instruments attached to the interest rate—on financial stability. For instance, interest rate changes caused considerable losses in the trading book of Indian banks after a rise in the yields of Indian benchmark securities in 2004–2005 (Saha et al., 2009).

\begin{footnotesize}
\begin{itemize}
\item \footnote{1} Research dealing with monetary policy transmission either use micro-level data in a reduced panel-data format (Kashyap and Stein, 2000) or a structural macroeconomic model (Bernanke and Gertler, 1995). The strand in the literature dealing with financial contagion and stability relies typically on the theory of complex networks to trace how shocks propagate throughout the network (Eisenberg and Noe, 2001; Battiston et al., 2012).
\item \footnote{2} There are several well-documented channels through which monetary policy can influence the course of the financial and corporate sectors. Among them, we highlight Kashyap and Stein (2000); Bernanke and Gertler (1995); Diamond and Rajan (2012).
\item \footnote{3} See Dawid and Delly Gatti (2018) for a comprehensive review on agent-based models.
\item \footnote{4} For instance, Silva et al. (2017a) only study the effects of negative events in the economy, such as bank defaults. In contrast, trading book variations can generate profits or losses in such a way that banks can be better off after the interest rate change. We account for this particularity in the model by introducing a “better off” state for banks besides the traditional “distressed” and “in default” states found in stress-based contagion models.
\item \footnote{5} The risk-taking channel refers to the impact of prolonged accommodative monetary policy on the risk perception and tolerance of banks. It works through the “search-for-yield” mechanism and the impact on valuations, incomes and cash flows that may decrease the banks’ probability of default and thus incentive more risky positions (Jiménez et al., 2014; Dell’Arcia et al., 2014).
\item \footnote{6} The bank lending channel relates to the opportunity cost of bank liabilities. For instance, rises in the interest rate make government bonds more attractive than bank loans, which may ignite a substitution effect of loans to government bonds.
\item \footnote{7} In 2008, the Bank of America, the Royal Bank of Scotland, and the UBS Group AG reported trading book losses amounting to USD 5.9 billion, GBP 8.5 billion, and CHF 25.8 billion, respectively (Alexander et al., 2013). Losses originated mainly from derivative instruments, such as credit default swaps (CDS) and collateralized debt obligations (CDO), in banks’ trading book portfolios (D’Errico et al., 2018).
\end{itemize}
\end{footnotesize}
The trading book composition of banks is relatively rigid. Basel III strictly limits banks’ ability to move instruments between the trading book and the banking book by their own choice after initial designation to bypass financial regulatory requirements and recover from accounting losses (BCBS, 2015). In practice, switching is rare and allowed by regulators only in extraordinary circumstances. This highlights the trading book channel’s relevance as a potential medium of stress transmission in the economy that we explore in this work.

To show the applicability of the model, we use a comprehensive database encompassing Brazilian banks and firms, as well as their bilateral credit exposures. The Brazilian case is an interesting case study due to numerous reasons. First, the trading book of Brazilian banks is sizable and is mainly composed of instruments attached to the interest rate (roughly 70% of the trading book). Therefore, interest rate changes can substantially affect banks’ net worth. Second, capital markets are underdeveloped, and hence bank credit turns out to be a significant (or the only) funding option for firms. Third, Brazilian experienced tremendous credit growth after 2008, making banks more exposed to firms and the business cycle. These two last characteristics increase firms’ dependency on bank credit and enhance the way interest rate changes can transmit from the financial to the corporate sector through credit rationing. Fourth, Brazil has a comprehensive database containing detailed information on all loans made by banks to firms and between banks themselves and bank-specific net cash flows for maturities from 1 day up to 30 years. Such setup permits us to track how interest rate changes affect banks’ net worth and how they transmit to the economy at a very granular level.

Overall, Brazilian banks have a positive net trading book (trading assets minus liabilities) and incur losses when interest rates increase. For the same interest rate shock, foreign private banks (state-owned banks) have the most (least) sensitive trading book to interest rates and thus lose/profit more (less) than other banks. We find that a 10% increase in the interest rate can generate losses up to 5% of foreign banks’ aggregate net worth only due to trading book variations.

We perform a sensitivity analysis of interest rate changes on banks and firms’ financial instability, measured in terms of aggregate net worth losses originating from the trading book revaluation (direct impact) and financial contagion (indirect impact). In our model, while banks are subject to losses in both components, firms are only susceptible to financial contagion through credit rationing from the financial sector. We find strong asymmetric effects of interest rates on the financial instability of banks and firms. While negative interest rate shocks have a small impact on banks’ capitalization and, therefore, on financial contagion, net worth losses become sizable for positive interest rate shocks. This effect is explained by the fact that Brazilian banks usually hold positive net trading books.

In our simulations, for a 10% increase in the interest rate, banks lose up to 5% of their aggregate net worth due to financial contagion (besides the 5% loss from trading book variations), while listed firms lose 0.8% of their aggregate net worth. This effect is heterogeneous across different banks and firms. While the least affected by trading book variations, state-owned banks endure losses amounting up to 12.5% of their net worth due to financial contagion. In contrast, foreign private banks (the most affected in terms of trading book variations) only lose up to 2.5%. State-owned banks are more susceptible to financial contagion because they are more exposed to the interbank market than foreign private banks. In the corporate sector, the agriculture and chemical sectors lose up to 10% and 15% of their net worth, respectively, for the same shock.

We analyze the period from the beginning of 2015 to March 2020. This time frame encompasses periods of high interest rates (14.25% at the beginning of the sample) and the historical lowest interest rates in Brazil (3.75% by the end of the sample). These opposing pictures enable us to understand how monetary policy shocks affect financial stability during times of high and low interest rates. Our results reveal that interest rate shocks affect more financial stability during periods of monetary policy tightening, both in terms of direct and indirect impacts.

Our results point to a non-linear relationship between interest rate changes and financial stability, measured in terms of aggregate losses of the financial and corporate sectors. This finding reinforces the conclusions of the classical work by Clarida et al. (1999), who advocate that central banks need to smooth interest rate changes to minimize disruptions in financial markets. By smoothing interest rate changes, the shocks tend to be smaller, and the impact becomes roughly linear. Managing expectations with proper communication and transparency to society also reduce the surprise component of changes in the interest rate.

2. Related literature

There is an ongoing debate on the role of interconnectedness in the amplification of shocks through contagion. Several papers have attempted to estimate different systemic risk measures using the information on financial networks. Methods that use financial networks to estimate systemic risk fall into two broad categories: loss-based methods (Eisenberg and Noe, 2001) or stress-based methods (Battiston et al., 2012). While the first evaluates real losses for a given shock, the second

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8 For further details, Fig. 3d shows the composition of Brazilian banks’ trading books in terms of instruments attached to the interest rate, foreign exchange rate, stocks, and commodities.
9 As of March 2020, more than 21 million firms were operating in Brazil, of which less than 500 had access to capital markets.
10 A 10% shock represents a percentage of the before-shock interest rate level and not an interest rate increase of an additional 10% per year. To exemplify, a 10% interest rate shock in a moment when interest rates are 5% would result in a stressed interest rate of 5.5%. In this case, the 10% interest rate shock corresponds to a 0.5 p.p. increase of the current interest rate.
11 Chinazzi et al. (2013) also find strong evidence of non-linear effects in a related study of the interbank financial network.
measures financial stress inside the network, which may not necessarily materialize. Loss-based methods are particularly useful for large initial shocks, such as significant bank defaults. In contrast, stress-based methods are more appropriate for small shocks and for capturing systemic risk buildup. Their complementary nature highlights that a set of systemic risk measures is often necessary to capture imbalances comprehensively. Our model is based on stress propagation because we are particularly interested in understanding the effect of small interest rate changes in the economy. Loss-based models would not be suitable in this setup because banks will most likely not default if these shocks occur.

The classical literature on systemic risk estimation using network-based models has focused on the traditional interbank market. Recently, after Glasserman and Young (2015)’s critique, there seems to be an effort in incorporating other sources of contagion into the analysis, such as the corporate sector (Silva et al., 2017a), common assets exposures (Poledna et al., 2018), among other contagion transmission channels. In our case study using Brazil, due to the high dependency of the corporate sector with the financial sector, we use an adaption of Silva et al. (2017a)’s model.

Papers dealing with monetary policy normally investigate its macroeconomic effects. For instance, Bernanke and Blinder (1992) target the macroeconomic aspect of monetary policy by examining the strength of the federal funds rate as a tool of monetary policy to adjust output and price using a vector autoregression model. In turn, Jiménez et al. (2014), Dell’Ariccia et al. (2014), and Maddaloni and Peydró (2011) study the effects of monetary policy on credit risk-taking in environments of prolonged low interest rates.

In contrast, research that mainly deals with financial stability focuses on the role that financial networks play in amplifying losses. For instance, Acemoglu et al. (2015) show that contagion in financial networks exhibits a form of phase transition. In this respect, more densely connected networks enhance financial stability as long as the magnitude of the negative external perturbation is sufficiently small. However, beyond a certain critical point, dense interconnections serve as a medium that favors the propagation of shocks, leading to more fragile financial systems. In the same vein, Elliott et al. (2014) study cascades of failures in financial networks and find that the effects of increasing dependence on counterparts (integration) and more counterparts per organization (diversification) have different and non-monotonic effects on the extent of financial contagion.

Network modeling enables us to trace how macroeconomic events disseminate through the economy at a very granular level. Notwithstanding recent advances in the literature, opening the black box of the monetary policy transmission mechanism with granular models to assess the heterogeneous effects on individual agents and understand how risks propagate in networks are still at the early stages. In this effort to link micro-founded models with macroeconomics, Dawid and Delli Gatti (2018) provide a comprehensive review of agent-based models used to analyze macroeconomic behavior. In turn, Ragot (2018) explore Heterogeneous Agent New Keynesian (HANK) models in incomplete markets. Our paper also deals with heterogeneous agents models with macroeconomic inspiration (monetary policy). However, our model significantly differs from them in that we study monetary policy transmission through the trading book channel. To the best of our knowledge, our work is the first to analyze such a channel using granular data of an economy.

Still in the agent-based modeling, Georg (2013) and Bluhm et al. (2014) share similarities with our research, as they analyze the central bank as a liquidity provider in an interbank network. Liquidity provision makes banks more resilient to shocks. However, it is detrimental to financial stability because it encourages risk-taking and results in a more interconnected financial system, in which the shock transmission is facilitated. Our paper differs from these works in significant ways. First, we are interested in understanding the trading book channel through which monetary policy can operate. Second, they do not include the corporate sector, which is a relevant source of loss amplification (Silva et al., 2017a).

3. Methodology

In this section, we discuss the intuition and underpinnings of our methodology. As mentioned before, our model is closely related to Silva et al. (2017a)’s model but adds three significant methodological contributions: (i) the inclusion of the policy-maker; (ii) the introduction of financial exposures of banks to the policy-maker, representing the sensitiveness to interest rate changes in their trading books; and (ii) the adaption of the stress transmission mechanism because the initial shock (trading book variation) can generate losses or profits for banks. While the first two are differences concerning the network structure (discussed in Section 3.1), the latter pertains to the stress transmission mechanism (see Section 3.2, the contagion component).

3.1. Network components

We design our framework using multilayer networks, in which each layer comprises a set of economic agents of the same nature and links connote bilateral financial exposures. Any multilayer network model dealing with stress propagation is completely described by defining the network layers, vertices, links, and stress transmission rules. We detail them the first three in this section and present the microfoundations of the last in the following section.

Network layers: Our model has three layers: the policy-maker layer, financial, and corporate sectors. Fig. 1 exhibits an illustrative three-layer network, where the top, middle, and bottom layers constitute the policy-maker, financial sector, and corporate sector layers, respectively. Network vertices: Each network layer contains economic agents of the same nature. The financial sector layer encompasses the collection of banks in the economy, the corporate sector layer includes firms, and the policy-maker layer embodies the central bank. As illustrated in Fig. 1, banks, and firms can be of any numbers, are allowed
to have heterogeneous balance sheet profiles, and can take any interconnection pattern to other members in the economy. The policy-maker layer, in contrast, has a single vertex.

Network links: a link originating in A (creditor) and ending in B (debtor) embodies bilateral financial exposure of the former to the latter. The link weight quantifies the magnitude of financial exposure. These financial exposures represent the contagion transmission channels through which stress propagates from one economic agent to another. Fig. 1 illustrates the possible bilateral financial exposures. The policy-maker has no outgoing links and therefore has no vulnerabilities. Besides links connecting to the policy-maker, every other link is bidirectional because it models vulnerability in the asset side of the creditor's balance sheet and an associated vulnerability in the liability side of the debtor's balance sheet. We model counterparty risk in the asset side: if A lends to B, then a financial exposure arises in the asset side of A's balance sheet. We model funding risk in the (opposite) liability side: in the same example, B has a funding vulnerability to A in the case the loan is due in the short term. Both link weights need not be identical: while the vulnerability due to counterparty risk relates to the full loan/credit (outstanding short- and long-term loans/credit), that due to funding risk is proportional to the outstanding short-term loan/credit. Table 1 compiles all potential bilateral financial exposures among economic agents (policy-maker, banks, and firms).

The financial sector layer communicates with the policy-maker layer only unidirectionally. Banks are exposed to variations in the interest rate promoted by the central bank. These changes transmit instantaneously to bank balance sheets due to the daily mark-to-market updates on their tradable instruments attached to the interest rate. Examples include securities or derivatives attached to the interest rate, such as federal bonds and other fixed-rate contracts. In the interbank market, financial exposures arise from unsecured lending to other bank counterparts. Common instruments in the interbank market include interfinancial deposits, on-lending, and credit. Bank lending to the corporate sector includes non-collateralized
earmarked and non-earmarked credit for general (e.g., working capital) and specific (e.g., financing to infrastructure, and exports & import operations) purposes. Firm-to-firm operations include trade credit transactions.

3.2. Stress transmission mechanism

Our model is particularly useful for understanding the short-term consequences of interest rate shocks in the economy, in that it assumes that the network topology does not change after the shock. However, the model allows for simple actions by firms. For instance, when firms experience credit rationing by the financial sector, they may replace the bank rationing credit for a counterparty willing to lend outside the network.

The model has two sequential steps:

1. The risk-taking component (initial shock): the risk-taking component represents the change in banks’ trading books when a policy-maker enacts an interest rate change. The mechanism is immediate and works through marked-to-market accounting of tradable assets/liabilities. Such changes reflect directly in banks’ net worth and represent the initial shock to the next step of the model. The risk-taking component is a contribution of this work to existing models.

2. The financial contagion and amplification components (second-order effects): due to the financial exposures (links) among banks and firms, losses/gains arising from the trading book in view of an interest rate shock do not dissipate entirely on the directly affected banks. Financial frictions, such as internal risk management and regulatory limits, enable stress transmission to other economic agents. These frictions allow trading book changes to propagate to the corporate sector.

3.2.1. The risk-taking component

The risk-taking component shapes the sensitivity of banks’ net worth to interest rate variations. Banks’ net worth changes according to trading book gains and losses arising from the tradable instruments attached to the interest rate. The marking-to-market of trading books is crucial for the validity of our results. In our application to Brazil, the Circular 3354, 27/6/2007 enacted by the Central Bank of Brazil enforces daily marking-to-market of the trading book. Otherwise, banks could keep the value fixed until a convenient moment and only then revalue their trading book, invalidating our analysis of the short-term effects of interest rate changes on financial stability.

To capture a comprehensive view of banks’ sensitiveness to interest rate changes, we consider the present value of the balance between cash inflows and outflows attached to the interest rate maturing at the following twelve vertices of the interest rate term structure: 1 day, 1 month, 2 months, 3 months, 6 months, 1 year, 2 years, 3 years, 4 years, 5 years, 10 years, and 30 years. Following BCBS (2013), if a financial instrument’s maturity does not fall into any of these vertices, we decompose their constituent cash flows and assign it to the nearby vertices on a proportional basis.

An interest rate shock causes an immediate change in the present value of banks’ balance of cash inflows and outflows. Net cash flows with longer maturities are more sensitive to interest rate changes. If the policy-maker changes the interest rate to \( i_{\text{stressed}} \) from the original value of \( i_{\text{original}} \), bank \( i \) recalculates the new fair present value of its net flow of cash maturing \( v \) days ahead \( r_{i}^{\text{stressed}}(v) \) as follows (BCBS, 2013):

\[
r_{i}^{\text{stressed}}(v) = \frac{i_{i}^{\text{original}}(v)(1+i_{\text{original}})^{v}}{(1+i_{\text{stressed}})^{v}},
\]

in which \( i_{i}^{\text{original}}(v) \) is the present value of the net cash flow evaluated with the original interest rate \( i_{i}^{\text{original}}(v) \) maturing \( v \) days ahead. If \( i_{\text{stressed}} > i_{\text{original}} \), then the new cash flow is smaller than the original value. In this situation, when inflows (assets) surpass outflows (liabilities), i.e., when \( r_{i}^{\text{stressed}}(v) > 0 \), the bank incurs losses in the net cash flow maturing \( v \) days ahead. When outflows (liabilities) are larger than inflows (assets), i.e., when \( r_{i}^{\text{stressed}}(v) < 0 \), then the bank profits at the net cash flow maturing \( v \) days ahead.

We compute the total gain/loss of the trading book attached to the interest rate of bank \( i \) by summing the differences of the fair net present value after the interest rate change (according to Eq. (1)) and the original net present value over all vertices (maturing days). Mathematically, bank \( i \)’s total gain/loss is given by:

\[
\Delta r_{i} = \sum_{v \in V} \left[ \frac{i_{i}^{\text{original}}(v)(1+i_{\text{original}})^{v}}{(1+i_{\text{stressed}})^{v}} - r_{i}^{\text{original}}(v) \right],
\]

in which \( V \) stands for the set of vertices with the following maturing days: 1 day, 1 month, 2 months, 3 months, 6 months, 1 year, 2 years, 3 years, 4 years, 5 years, 10 years, and 30 years. The change in bank \( i \)’s net worth \( \Delta r_{i} \) is used as input to the next step of our framework, detailed in the following.

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\(^{12}\) To understand the medium- and long-term effects of monetary policy shocks in the economy, we would have to consider the network topology as endogenous. In that configuration, each bank and firm would be allowed to create and sever links to each other based on their utility functions. As a robustness check, we analyze the resilience of our results to random reattachment of links in the interbank market during the stress propagation mechanism in Section 5.3.

\(^{13}\) In general terms, the interest rate could also depend on the maturity of the cash flow. In this paper, we assume that both the original and stressed interest rates are independent of the vertex. However, the proposed model can encompass such dependency provided that data is available.
3.2.2. The financial contagion and amplification component

We treat banks and firms indistinguishably as economic agents. After banks revalue their tradable instruments following the interest rate shock, we remove the policy-maker because: (i) it is not exposed to any economic agents and, hence, it is insensitive to second-order (contagion) effects; and (ii) we are dealing with the short-term consequences of the interest rate shock, in such a way that we can assume that the rate remains fixed during the financial contagion and amplification process. Putting these facts together, the central bank is an exogenous entity in the model. The model then reduces to describing the net worth dynamic of banks and firms following the interest rate shock.

Although our model consists of a single-period economy, we represent the shock propagation process as a dynamic system that may take several iterations before converging. We notate as $t$ the current iteration of the dynamic system. For mathematical convenience, we assume that $t = 0$ represents the economy’s state before the interest rate change. At $t = 1$, the policy-maker changes the interest rate, and banks revalue their trading books, recognizing losses or profits in their net worth according to Eq. (2). At $t > 1$, the net worth change transmits forward in the network in the form of downward investment repricing (counterparty risk) and increased financing costs (funding risk). Since economic agents hold positive equities, the shock always dissipates as it travels along with the network. Hence, the dynamic system has a contracting map as the update rule, and therefore it converges to a fixed point.

The balance sheet of economic agent $i$ at iteration $t$ consists of three elements: assets ($A_i(t)$), liabilities ($L_i(t)$), and net worth ($E_i(t)$). In the case of firms, the net worth is $E_i(t) = A_i(t) - L_i(t)$. In the case of banks, it is the capital buffer, which is the net worth parcel that is above the minimum capital requirements established by the regulator (more details in Section 4). In both cases, the economic agent default at $t$ when $E_i(t) \leq 0$. We split the economic agent assets and liabilities in the following disjoint quantities: inside-network assets ($A_i^{(in)}(t)$), outside-network assets ($A_i^{(out)}(t)$), inside-network short-term liabilities ($L_i^{(in-st)}(t)$), inside-network long-term liabilities ($L_i^{(in-h)}(t)$), and outside-network liabilities ($L_i^{(out)}(t)$).

**Losses due to counterparty and funding risks:** We decompose net worth losses of economic agent $i$ by using a differential version of the fundamental accounting equation:

$$\Delta E_i(t) = \Delta A_i^{(in)}(t) + [\Delta A_i^{(out)}(t) - \Delta L_i(t)] = \Delta E_i^{(ct)}(t) + \Delta E_i^{(f)}(t)$$

in which $\Delta E_i^{(ct)}(t) = \Delta A_i^{(in)}(t)$ and $\Delta E_i^{(f)} = \Delta A_i^{(out)}(t) - \Delta L_i(t)$ indicate potential losses due to counterparty risk and funding risk, respectively.

Counterparty risk losses arise from the repricing of inside-network assets due to decreased creditworthiness of debtors. Fluctuations in the probability of default lead to changes in debtors’ creditworthiness. When economic agents monitor these changes, they register accounting losses in their balance sheets due to changes in their debtors’ riskiness. The model proxies the economic agent’s probability of default proportionally to the amount of its net worth loss relative to the initial net worth. Under this repricing mechanism, Silva et al. (2017a) demonstrate that losses due to counterparty risk of $i$ are:

$$\Delta E_i^{(ct)}(t + 1) = \sum_{j \in A_i(t-1)} \frac{A_j^{(in)}(0)}{E_j(0)} [E_j(t) - E_j(t-1)]$$

in which $A_j^{(in)}(0)$ and $E_j(0)$ are exogenous variables representing initial exposure of $i$ to $j$ and the net worth of $j$, respectively. The term $A_i(t-1)$ indicates the set of economic agents that have not defaulted up to iteration $t - 1$.

Funding risk losses arise from the inability to rollover short-term debt, forcing the fireselling of illiquid assets. Gai et al. (2011) document that banks hoard liquidity to control their uncertainty over their ability to roll over their debt or even to survive. Therefore, we assume that economic agents ration credit proportionally to their amount of net worth loss relative to the initial net worth (our proxy for probability of default). Under such hypothesis, Silva et al. (2017a) demonstrate that losses due to funding risk of economic agent $i$ are:

$$\Delta E_i^{(f)}(t + 1) = \sum_{j \in A_i(t-1)} \frac{\alpha_{ij}^{(in-st)}(0)}{E_j(0)} [E_j(t) - E_j(t-1)],$$

in which $L_{ij}^{(in-st)}(0)$ is the initial short-term liabilities of $i$ to $j$ that is exogenous to the model and $\alpha_{ij} \geq 0$ modulates the funding risk arising from the short-term liability. When economic agent $i$ is liquid or can replace the funding counterparty $j$ easily, then $\alpha_{ij}$ is small. Otherwise, this coefficient is larger. This coefficient is estimated using past data.

**Shock propagation rule:** Our model also departs from Silva et al. (2017a)’s in how shocks propagate throughout the network. In their model, since only negative events are studied, banks cannot have net worth larger than their initial values by construction. In our case, banks can potentially profit from the interest rate shocks. In this way, we use the following

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14 In our application to Brazilian data, we also observe this behavior within the analyzed period (2015–2020). Brazil had a deep recession in 2015–2016 with substantial increase in delinquency rates and therefore credit losses to banks. Concurrent to that, we observed an increase in the average Liquidity Coverage Ratio (LCR) of large banks of 24.86% in 2016 compared to 2015. Large foreign private banks performed a more pronounced precautionary liquidity hoarding, with an average increase of 27.73% in 2016 compared to 2017. When conditions improved in 2017, the LCR of these banks decreased 8.22% in that year when compared to 2016.
propagation model for economic agent $i$:

$$s_i(t + 1) = \min \left[ 1, s_i(t) + \sum_{j \in S} V_{ij}(AS) \max \left[ 0, \Delta s_j(t) \right] + V_{ij}(LS) \max \left[ 0, \Delta s_j(t) \right] \right].$$

(6)

in which $S$ is the set of all economic agents and $s_i(t)$ represents the financial stress of economic agents that we evaluate as:

$$s_i(t) = \frac{E_i(0) - E_i(t)}{E_i(0)}.$$  

(7)

and $V(AS)$ and $V(LS)$ are the vulnerability matrices that numerically translate how financial contagion spills over and impacts economic agents from their asset and liability sides, respectively. These matrices are exogenous to the model and are computed as follows:

$$V_{ij}(AS) = \frac{A_{ij}(0)}{E_i(0)},$$  

(8)

$$V_{ij}(LS) = \frac{\alpha_i L_{ij}^{(in-st)}(0)}{E_i(0)}.$$  

(9)

In our framework, we monitor how financial stress of economic agents in Eq. (7) increases as shocks propagate across the network. Note that the numerator in Eq. (7), $E_i(0) - E_i(t)$, quantifies the losses of economic agent $i$ up to iteration $t$. It can happen that banks profit from the interest rate shock, in a way the banks’ stress levels become negative. In-between values represent partial financial distress. Default occurs when $s_i(t) = 1$, which denotes an upper limit due to the min(.) operator in Eq. (6).

Economic agents in the network model can attain three different states that are important in terms of stress propagation. We depict them in the state machine illustrated in Fig. 2. We can identify them simply looking at the current stress levels of economic agents in Eq. (7). A description of the states is given below:

- **In default state** ($s_i(t) = 1$): the net worth of economic agents in this state has been completely depleted. Economic agents cannot propagate any further stress throughout the network when they default.
- **Distressed state** ($s_i(t) \in [0, 1]$): economic agents in this state have positive net worth but smaller than its original value ex-ante the interest rate shock. They propagate losses through the network in accordance with Silva et al. (2017a)'s contagion mechanism.
- **Better off state** ($s_i(t) < 0$): economic agents attain this state when their net worth is larger than their original values ex-ante the interest rate shock. Only banks can attain this state when they receive trading book profits following the interest rate shock.

This state machine contrasts with the economic agents’ dynamics of Silva et al. (2017a)'s model. Therein, since the authors only study negative events, such as bank defaults, economic agents are only allowed to attain the “distressed” or “in default” states. In our extended model, banks (but not firms) can assume the “better off” state, representing the case in which they end up more capitalized after the interest rate change. In this state, they do not cut lending nor propagate any stress to the interbank market. Instead, they stay latent in the model and are only susceptible to receiving stress from other bank and firm counterparts. Only when their net worth drops below the original values ex-ante the interest rate shock they
will transit to the “distressed” state and will start propagating losses. The mechanism of enabling or disabling stress propagation of economic agents creates a non-linear behavior in the model that will become evident in our empirical section.¹⁵

Systemic risk estimation: We evaluate systemic risk in terms of the aggregate net worth loss experienced by economic agents. Take a sufficient large iteration \( t = t_c \gg 1 \) in a way that the dynamic system settles down after the interest rate shock. Then, the systemic risk \( SR \) arising from an interest rate shock is:

\[
SR = \sum_{i \in S} s_i(1)E_i(0) + \sum_{i \in S} (s_i(t_c) - s_i(1))E_i(0) = SR_{\text{risk-taking}} + SR_{\text{contagion}},
\]

in which \( SR_{\text{risk-taking}} = \sum_{i \in S} s_i(1)E_i(0) \) and \( SR_{\text{contagion}} = \sum_{i \in S} (s_i(t_c) - s_i(1))E_i(0) \). Observe that both \( SR_{\text{risk-taking}} \) and \( SR_{\text{contagion}} \) are in monetary values, since stress levels are normalized by the net worth ex-ante the interest rate shocks. The systemic risk due to the risk-taking component is evaluated only at \( t = 1 \), which is the instant that we apply the exogenous monetary policy shock. The systemic risk due to financial contagion and amplification is the additional system-wide financial stress caused by the negative spillovers to the economy.

*Linking the interest rate change as the initial shock of the contagion model: As discussed before, \( t = 0 \) represents the current economy’s state. At \( t = 1 \), the policy-maker changes the interest rate, causing changes in banks’ trading books. We need to translate such losses in terms of financial stress relative to their initial net, as defined in Eq. (7). Therefore, we set:

\[
s_i(1) = \begin{cases} 
1 - \Delta r_i & \text{if } i \text{ is a bank} \\
0 & \text{if } i \text{ is a firm} 
\end{cases},
\]

in which \( \Delta r_i \) is the net trading book variation, which we evaluate in accordance with Eq. (2). If the interest rate generates losses to bank \( i \), then \( s_i(1) > 0 \); otherwise, \( s_i(1) \leq 0 \). If the bank loses more than its initial net worth, then the minimum operator caps the financial stress at \( s_i(1) = 1 \), indicating that it has defaulted.

4. Data

We collect, pre-process, and match several unique Brazilian databases with supervisory and accounting data. We extract monthly information from January 2015 through March 2020 in all data sources.¹⁶ Next, we discuss how we build the network components using the terminology exhibited in Fig. 1.

4.1. Bank & policy-maker connection

This represents the interlayer connections between banks and the policy-maker. Connections are unilateral from banks to the policy-maker and represent banks’ net trading book sensitiveness to interest rates changes. Brazil adopts Basel III recommendations regarding the treatment of the trading book. In this way, the Central Bank of Brazil has established rules that oblige banks to mark-to-market any tradable instrument daily. We take monthly supervisory data from the Risk Market Statements database (Demonstrativo de Risco de Mercado - DRM) maintained by the Central Bank of Brazil. The DRM contains bank-specific information on cash flows (in and outflows) subject to market risk at different maturity dates ranging from one day to 30 years (twelve vertices).

Fig. 3 a shows the aggregate size of the banking and trading books in terms of the total assets of the entire financial sector from 2015–2020. Trading assets and liabilities are more representative and correspond to 25% and 22%, respectively, of the financial system’s total assets. The net trading book is positive, suggesting that increases in interest rate generate losses to banks. At the beginning of the sample, when interest rates were high, the trading book was slightly larger due to the attractiveness of federal bonds attached to the interest rate. When interest rates decreased, the trading book size reduced as well. Fig. 3b portrays the trading and banking books as a share of the sum of both books.¹⁷ The trading book takes 60% of the size of both books during the period. Fig. 3c shows monetary values of the net trading and banking books (assets - liabilities) of the entire financial system. The net trading book remains stable in the period with a net positive

¹⁵ The main difference of our shock propagation rule in Eq. (6) from the Silva et al. (2017a)’s model is the introduction of the \( \max[.\ldots] \) operator in the stress differentials \( \Delta s \). In their model, \( \Delta s \geq 0 \) by construction because only negative events are considered. However, if banks profit from the interest rate change, we could have \( \Delta s < 0 \). To prevent this, we take the \( \max[.\ldots] \) operator. This construction is also important to guarantee the convergence of the dynamic system. While the economic agents’ financial stress has clear upper bounds—represented by their default—there is no clear lower bound, in such a way that the convergence of the model would be compromised. By restricting negative stress propagation of “better off” banks, we guarantee convergence because stress levels take a non-decreasing behavior and have an upper limit.

¹⁶ The sample period is defined due to data availability. The lower limit occurs due to a substantial change in how financial institutions started to consolidate and report their balance sheets in 2015 brought by the Carta-Circular 3,687, 26/12/2014, issued by the Central Bank of Brazil. With this regulatory change, financial institutions had to consolidate all controlled firms’ balance sheets regardless of whether they were regulated or unregulated (such as consortium administrators, payment institutions, credit society, and securitizer over which the institution had direct or indirect control). These were termed as prudential conglomerates, as opposed to financial conglomerates before the entrance of this regulatory change, in which balance-sheet consolidation was limited to controlled financial firms directly supervised by the Central Bank of Brazil. Therefore, data on conglomerate-level market exposures became more comprehensive since 2015.

¹⁷ The total assets contain elements that are not classified neither in the trading nor banking books, such as cash, permanent assets, deferred tax credit, and other assets that do not have a market risk component. By eliminating these terms, we can compare the relative sizes of both books.
position of R$ 1 trillion (about 14% of the Brazilian GDP in 2019). In contrast, the banking book seems to change from a net short position to a long position in the period.

In this paper, monetary policy shocks transmit to banks’ balance sheets through the revaluation of tradable instruments attached to that rate rather than the entire trading book. Fig. 3d breaks down the components of banks’ trading books in terms of instruments attached to the interest rate, foreign exchange rate, commodities, and stocks. Values are in shares of the total tradable assets/liabilities. Interest rates are the most representative portion of both the trading book’s asset and liability sides, with an average share of 70% in 2015–2020. Foreign exchange rates follow with an average share of 30%. Most of the foreign exchange exposures are overhedge operations to offset the difference in taxation between hedging in Brazil and foreign investment. The shares of tradable assets/liabilities representing commodities and stocks held by Brazilian banks are negligible. Monetary policy changes transmit through the tradable instruments attached to the interest rate, which are the most important parcel held by Brazilian banks.

The interest rate shock effect will depend on the portfolio formed by tradable instruments, the net position, and the duration gap, defined as a difference between the weighted maturity of the portfolio’s assets and liabilities. Ceteris paribus, the greater the difference in duration, the greater the variation in the portfolio value.\footnote{Bluhm et al. (2016) argument that the interbank book in Germany shrinks the underlying client book, like a mirror image. In Brazil, this case is also possible, as changes in the trading portfolio may indirectly affect the interbank market. The direct variation of the interbank market due to the revaluation of the trading book is negligible, as banks have little exposure to instruments attached to the interest rate in the interbank market.}

4.2. Bank layer

The Brazilian interbank market is composed of secured and unsecured financial operations. Due to domestic regulatory norms, financial institutions must register and report all securities and credit operations to the Central Bank of Brazil, which
reinforces the data representativeness and quality. From January 2015 to March 2020, 86% of the financial operations were not collateralized. Most of the unsecured lending are on-lending (91.4% of the total unsecured lending in the period), followed by credit (61%), and interfinancial deposits (1.7%).

The most common secured lending operations among banks are short-term re-purchase agreements (repos) collateralized with Brazilian federal bonds (99.8% of the total secured lending). Since the vast majority of secured lending are backed by federal bonds—which are very liquid—creditors could sell off these bonds with roughly no losses even in the very short term if debtors default. Therefore, we remove secured lending during the contagion transmission process as they are unlikely to convey counterparty risk.

The Brazilian interbank market has significantly changed since 2015. Before, most transactions were collateralized with federal bonds, and the primary transactions were repos, on-lending, interbank deposits, financial bills, and debentures. This structural change may be partly due to the onset of the Brazilian recession in 2015, which may have led banks to redirect credit from the real sector to the interbank market. According to Bluhm et al. (2016), the inflow and outflow of non-bank customers are correlated with the interbank market.

These operations are registered and controlled by different custodian institutions, which raises the complexity of gathering, pre-processing, and matching the data across different systems. Among the custodian institutions, we extract data from the Cetip, which holds operations with private securities, the Central Bank of Brazil’s Credit Risk Bureau System (SCR), which registers credit-based operations, and the Brazilian stock exchange (BM&FBovespa), which records swaps and options operations. On March 30th, 2017, BM&FBovespa, and Cetip merged into a new company named B3.

We consider financial exposures among different conglomerates or individual financial institutions that do not belong to conglomerates. In Brazil, conglomerates must account for all the counterparty risk of their branches, subsidiaries, and other entities within the group, such as consortia. Therefore, we remove intra-conglomerate exposures in the analysis as they are more related to internal liquidity management and less to risky operations. We contemplate all banking institutions in Brazil, encompassing commercial banks, investment banks, development banks, federal savings banks, and universal banks. There are, on average, 131 active banking institutions in our sample for the analyzed period. We do not include non-banking institutions, such as credit unions, because their contribution to stress transmission is negligible.

Following Silva et al. (2017b), we take as bank capital only that fraction above the minimum capital requirements that Brazilian banks must continuously hold (the capital buffer). That is, the bank defaults when its total capital buffer relative to its risk-weighted assets (RWA) falls below the 8% Basel regulatory requirement. Since the total RWA also accounts for the interest rate risk held in the trading book (inside the market risk component), our capital buffer also includes the capital requirements arising from banks’ risk-taking component besides the counterparty risk in the interbank and corporate markets.

4.3 Firm layer

In this section, we only describe the set of firms used in the analysis. We do not model firm-to-firm links (trade credit) due to data unavailability.

Our model requires firms’ accounting data. Unlike the financial sector in which we have complete information on bank exposures, data on the corporate sector is scarcer and is available only for listed companies in BM&FBovespa. Due to legal enforcement, listed firms must report balance-sheet data, such as financial statements and financial indicators, quarterly. We use Economatika to extract consolidated balance sheet information from these firms. Table 2 reports the number of firms in each economic sector that we use in our analyses. Although firms can coexist with negative equities, such as those facing judicial recovery, we remove them because our model uses equities as the primary resource of loss absorption.

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19 While this argument holds for Brazil, in which secured lending is mainly through repo operations collateralized by federal bonds, counterparty risk does exist, in general, in secured lending. A clear example is the global financial crisis. Gorton and Metrick (2012) argue that the 2008 financial crisis was a system-wide bank run in the “securitized-banking” system, rather than in the traditional banking system. They find that securitization and repo financing were at the core of the crisis. The contagion led to en masse withdrawals, causing high haircuts in the repo markets. Unlike the US case, in which repo markets are more developed and diversified with private securities used as collateral, repo operations in Brazil mainly take place with federal bonds, which are guaranteed by the federal government and hence much less prone to haircuts.

20 Cetip is a depositary of mainly private fixed income, state and city public securities, and other securities. As a central securities depositary, Cetip processes the issue, redemption, and custody of securities, and, when applicable, the payment of interest and other related events. Eligible institutions that participate in Cetip include commercial banks, multiple banks, savings banks, investment banks, development banks, brokerage companies, securities distribution companies, goods, and futures brokerage companies, leasing companies, institutional investors, non-financial companies (including investment funds and private pension companies) and foreign investors.

21 SCR is a comprehensive data set that records every single credit operation within the Brazilian financial system worth R$200 or above. Up to June 30th, 2016, this lower limit was R$1,000. SCR has the tax identifier of the bank and client, the loan’s maturity, modality, interest rate, risk classification, origin (earmarked or non-earmarked), and the parcel that is overdue.

22 BM&FBovespa is a privately-owned company created in 2008 through the integration of the São Paulo Stock Exchange (Bolsa de Valores de São Paulo) and the Brazilian Mercantile & Futures Exchange (Bolsa de Mercadorias e Futuros). As Brazil’s central intermediary for capital market transactions, the company maintains electronic systems for trading equities, equity derivatives, fixed-income securities, federal government bonds, financial derivatives, spot FX, and agricultural commodities.

23 For more details, we refer the reader to Silva et al. (2016), who study the structure and systemic risk issues of the Brazilian interbank market in terms of the type of the financial institution (credit unions, commercial, investment, development banks).
To facilitate the reading, we limit our discussion to six sectors that we select by the extent of the interest rate shock effect. We choose the three most affected (agriculture, chemical, and electric electron) and least affected sectors (mining, oil & gas, and technology). Firms in these six sectors have high relevance to the Brazilian economy, such as those in the mining, oil & gas, and agriculture sectors. As for the impact of negative shocks, as will be discussed in the results Section 5, contagion is low and negligible for financial stability.

Fig. 4a and 4b depict the average net worth (equities) and total equities of the six selected economic sectors from January 2015 to March 2020. During the COVID-19 crisis in 2020, total sector-level capitalization mainly dropped, especially for the chemical sector. As firm capitalization serves a loss-absorption mechanism, these firms in the chemical sector become more exposed to credit rationing from the financial sector. The technology sector has a higher heterogeneity regarding firm size since the total capital is high, and the average capital is relatively low.

4.4. Bank & firm connection

For each firm, we identify its economic conglomerate, which encompasses all controlled firm branches of the listed firm. We then extract the outstanding bank credit of each firm economic conglomerate from January 2015 to March 2020 monthly using the SCR. We also consider the maturity of the loans, such as to identify the short- (less than one year) and long-term bank funding. This division is important because funding risk operates through short-term loans, while counterparty risk works through total outstanding loans (short + long).

Firm perspective: Fig. 5a and 5b portray the outstanding (short and long term) bank debt and the average share of short-term bank debt of firms, respectively. Sectors with the highest share of short-term debt, chemical and agriculture, have the lowest bank credit volume and are most prone to credit rationing (funding risk). Overall, firms increased their short-term debt during the COVID-19 crisis mainly by borrowing working capital to withstand potential liquidity constraints, as capital markets were facing high volatility. Bank perspective: We now look at how economic sectors are connected to banks. In our model, banks that endure large losses in view of changes in interest rate are those that will restrain more credit to the corporate sector. Thus, firms that are connected to these banks will be the ones most affected. Since financial stress transmits from banks to firms through credit rationing, we focus on short-term bank credit.
Due to the importance of state-owned banks for the Brazilian economy and financial system, we depict in Fig. 6a the share of bank credit that is due in the short term to the corporate sector broken down by bank control (domestic private, foreign private, and state-owned). Most of the short-term bank credit to Brazilian listed firms comes from foreign private banks (roughly 80%). Hence, if foreign private banks endure large trading book losses due to interest rate changes (risk-taking component), firms relying on their credit will be most affected by credit rationing. State-owned credit is mainly long term, as they aim to finance long-term infrastructure projects from listed firms. We also report the share of short-term bank credit to the corporate sector in Fig. 6b broken down by bank size (large, and medium/small). The bank size component is important because larger banks are the most important institutions for the financial stability.24 Firms that borrow from medium/small size are more susceptible to bank funding risk and, therefore, to contagion.

5. Empirical results

We start this section by performing a sensitivity analysis of economic agents’ financial stability to interest rate shocks. After, we present a more granular view of interest rate consequences on financial stability. Finally, we report some robustness tests.

24 We classify banks as large or medium/small as follows. We first construct a cumulative distribution function (CDF) on the banks’ total assets and classify them depending on the region in which they fall in the CDF. We consider as large those banks that fall in the 0% to 75% region, and as medium/small, otherwise.
5.1. Sensitivity analysis of the financial stability of economic agents to interest rate shocks

We start this section by performing a sensitivity analysis of the potential net worth loss of banks and firms to different interest rate shocks. Our exercise consists of three sequential and independent steps: (i) vary the interest rate from -90% to 90% relative to its true nominal rate at that time, with steps of 10 percentile points, (ii) revalue the stressed cash flow attached to the interest rate of banks using the methodology in Section 3.2.1, and then (iii) estimate potential net worth losses—i.e., our proxy for the financial stability of the economic agent—of every bank and firm in the economy through financial contagion using the guidelines in Section 3.2.2.

Fig. 7 a depicts the trajectory of Brazil’s policy rate (Selic) rate. Our sample covers an interesting period in Brazil. It starts with a period of monetary tightening (January 2015 to May 2017), followed by a period of significant reduction in the interest rate until it entered a period of monetary easing (March 2018 to March 2020). In this last period, the Selic rate reached 3.75%—its lowest historical value since the beginning of the time series in 1996 up to March 2020. Our sample also encompasses the beginning of the COVID-19 crisis in Brazil, which led to further monetary easing.

Fig. 7 b shows the direct impact of interest rate shocks on banks’ trading books due to the immediate revaluation of their cash flows attached to the interest rate. In turn, Fig. 7 c and 7 d show the indirect impact on the financial and corporate sectors due to financial contagion. We report losses/profits as a fraction of the current net worth of economic agents. We only report curves with data from March of each analyzed year.

Our sensitivity analysis points to a piece-wise linear relationship between trading book losses and interest rate shocks (Fig. 7b). The sign of the interest rate shock separates the linear segments of this relationship. The trading book’s sensitivity to interest rates is more pronounced for positive shocks, as we can observe from the larger curve slopes for positive interest rate shocks when compared to negative shocks. Roughly, the slope relationship between the positive and negative segments is 2. Interest rate shocks cause substantial variations of banks’ net worth, especially in periods of high interest rate (March 2015). For instance, in March 2015, a 10% shock would cause a 10% decrease in the capitalization of the entire financial
system. In turn, in a period of low interest rates such as March 2020, the same shock would cause a 4% reduction. For comparability, the delinquency rate of 3% observed in 2015 corresponded to about 22% of the financial system’s net worth. While losses arising from credit default are aggregate within the year, the interest rate shock must be registered within the day. Therefore, these observed net worth losses are relevant.

In contrast, we observe a non-linear relationship between interest rate changes and contagion & amplification losses for both financial and corporate sectors (Fig. 7c and 7d). While the impact of negative shocks is stable, the impact of positive interest shocks on net worth losses grows non-linearly as we distance from the current state of the economy (no interest rate shock). The non-linearity arises from the network topology among economic agents. Some banks may lose, and others may profit from the interest rate shock. The way they interconnect with other banks and firms will determine how shocks will propagate. The marginal sensitivity of economic agents’ net worth to interest rate shocks due to the indirect impact decreases for larger shocks because there are important banks to which firms/banks are exposed that end up better off due to the large interest rate shock. Therefore, they attenuate the overall contagion effect.

We also highlight an interesting observed feature. Even though interest rates in March 2016 were higher than in March 2015, the effect of interest rate changes on banks’ trading books (direct impact) is higher in the former date. One explanation is that Brazil was in a phase of increasing (already high) interest rates, which incentive position-taking in tradable instruments attached to the interest rate. However, we observe a different profile for indirect impact, with contagion being higher than trading book losses in 2016. This fact occurs because some foreign private banks are more affected by interest rate shocks in 2016 than in 2015. Since they are the main drivers of funding risk to the corporate sector (see Fig. 6a), they end up transmitting more financial stress to the entire economy.

To better exemplify the relevance of monetary policy shocks to the financial stability, Fig. 8a and 8b exhibit aggregate net worth losses of the financial and corporate sectors for +10% and +40% interest rate shocks. We do not consider negative interest rate shocks when analyzing the financial contagion because net worth losses are negligible during 2015–2020 (see Fig. 7b). We choose the +10% and +40% shocks due to the significant interest rate variations in the analyzed period. Although shocks of 10% over the nominal interest rate are feasible over the entire sample period, the magnitude of this shock becomes irrelevant at the end of our sample, when the Selic rate reached 3.75%. Therefore, we also investigate the financial stability implications of a 40% interest rate shock, which would be feasible at the end of the sample, given the historical changes in the Selic rate promoted by the policy-maker.

We can see that the financial and corporate sectors are more sensitive to interest rate shocks in periods of monetary tightening. The direct impact of a +40% interest rate shock reaches up to 4 times the net worth variation caused by a +10% interest rate shock from 2015 to 2017. After this period, there is greater stability in the net worth variation caused by these two shocks, even though Brazil’s policy rate decreased during the period. Overall, the net worth variations caused by the +40% interest rate shock is about 3 times greater than the +10% interest rate shock after 2017. Regarding the indirect impact, we observe the same phenomenon for both the financial and corporate sectors. Also, capital losses from financial contagion are higher than from the trading book in the first half of 2016. These results indicate that, in addition to the interconnections in the real and financial sectors, macroeconomic conditions are relevant to the relationship between monetary policy and financial stability.

We can also draw some policy implications given this non-linear relationship between monetary policy and financial stability. First, policy-makers should be aware of the financial system’s current capitalization levels when conducting monetary policy. Big swings in the interest rate can cause considerable adverse consequences for banks’ net worth through trading book variations and the network effect, which could spillover to the corporate sector. Second, our findings reinforce the con-

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![Graph](image-url)

**Fig. 8.** Trajectory of the short-term sensitiveness of the (a) financial and (b) corporate sectors’ aggregate net worth to +10% and +40% interest rate shocks from January 2015 to March 2020. Higher sensitivities imply larger losses in their net worth when interest rate changes.
clclusions of the classical work by Clarida et al. (1999), who advocate that central banks need to smooth interest rate changes to minimize disruptions in financial markets. By smoothing interest rate changes, shocks tend to be smaller, and the impact becomes roughly linear.

5.2. A more granular view on the consequences of monetary policy shocks to financial stability

The previous aggregate analysis is useful for a system-wide view of the financial system’s resilience to monetary policy shocks. However, it does not allow us to identify particularities arising from banks’ and firms’ financial conditions and the network structure. This section analyzes the effects of interest rates on these economic agents in a more granular way.

5.2.1. Interest rate sensitiveness of banks by control and size

In this section, we break down the effects of interest rate shocks on the financial sector by looking at which banks are more susceptible to these shocks in terms of control and size.

Direct effects: Fig. 9a and 9b display the average banks’ net worth variation caused by the direct effect when we simulate a +10% and −10% interest rate shock broken down by bank control and bank size, respectively. Foreign private banks are more sensitive to both positive and negative interest rate shocks. While in the aggregate analysis (Fig. 8a) losses from trading book variations are less than 5% of the financial system’s net worth, losses for foreign private banks reach almost 9% for a +10% interest rate shock (Fig. 9a). Private foreign banks are also the ones that show the greatest capital gain in the event of a negative interest rate shock, reaching almost double the earnings of other types of banks. A possible explanation for these results is the business niche of these banks. Many are investment banks and, therefore, operate with a larger trading book and act more strongly when interest rates are high in Brazil.

In contrast, state-owned banks experience fewer losses and gains in the trading book mainly because of their institutional purposes. State-owned banks are conduits of public policies in Brazil and tend to have smaller net trading books. For instance, in Brazil, they operationalize subsidized and long-term credit programs to mitigate market failures in certain sectors. Domestic private banks, in contrast, have in-between losses comparatively to state-owned and foreign private banks. However, at the end of the sample, domestic and foreign private banks have similar losses/gains, possibly because they increase their position-taking as a result of the reduction of Brazil’s policy rate. This fact highlights the importance of having a more detailed view of the financial system so that a shock does not cause unintended imbalances.

We do not observe sizable differences on the trading book variation by bank size until 2019. In this year, medium/small banks show high sensitiveness to positive and negative interest rate shocks (Fig. 9b). Finally, in case of a −10% interest rate shock, there will be capital gains on average for banks. Roughly speaking, the potential capital losses trajectories due to positive and negative 10% shocks are very similar. However, they start at different levels. In 2015, the potential capital gains for a −10% interest rate shock were about half of the potential losses for a positive shock of the same magnitude. At the end of the sample period, both percentages of potential gains and losses on average are similar. Indirect effects: We now analyze the indirect short-term consequences of interest rate shocks in the corporate and financial sectors. We take the trading book variations explored in the previous in this section as input to the network model. As discussed in the previous section, we analyze contagion regarding shocks of +10% and +40% on interest rate due to the negligible indirect impact of negative interest rate shocks.

As in the case of direct impact, we note that net worth losses are smaller when monetary policy is looser. This fact reinforces the perception that the policy-maker must also take contagion into account when establishing monetary policy.
interest rates. Unlike trading book variations, state-owned banks and large banks are more susceptible to contagion (Fig. 10a and 10b) because they are the largest creditors of listed firms and play a central position in the interbank market. Therefore, the likelihood of receiving financial stress from any other agent in the network is higher.

5.2.2. Interest rate sensitiveness of firms by economic sector

In this part, we evaluate the corporate sector’s short-term sensitiveness to +10% and +40% interest rate shocks. Recall that firms are exposed to interest rate shocks in the model through credit rationing from the financial sector. Therefore, they only have a non-zero indirect effect (financial contagion).

Fig. 11a portrays the short-term sensitiveness of the three most affected economic sectors to +10% and +40% interest rate shocks (indirect effect). All losses are in terms of the sector-specific total net worth. The granular analysis reveals that losses in some economic sectors can be significantly higher than those estimated by the aggregate analysis. While in the latter net worth losses were limited to a maximum of 1% and 2% of the entire corporate sector’s net worth for +10% and +40% interest rate shocks, respectively, sector-specific net worth losses can be substantially higher. For instance, the chemical sector would lose up to 40% of its total capitalization. Even though total losses in the granular analysis must coincide with the aggregate analysis if we sum across all economic sectors, our results evidence the high level of heterogeneity that monetary policy can affect the corporate sector through credit rationing. We can also notice that the aggregate losses are similar to the losses of the sectors least affected by contagion (Fig. 11b).

Unlike other sectors and even the financial sector, whose net worth sensitivity follows Brazil’s policy rate, the agriculture sector becomes more sensitive when the Selic rate is at its lowest levels. One possible explanation is the increase in bank loans taken by firms in the sector, as shown in Fig. 5, especially short-term credit. The sectors least affected by interest rate shocks are the most capitalized.
The granular analysis of the firms’ net worth sensitivity to interest rate shocks reinforces the idea that the policy-maker has to make a comprehensive analysis before taking monetary policy decisions. In addition to assessing the impact on the financial sector, one has to estimate second-order effects, such as on the corporate sector. Monetary policy and financial stability have a non-trivial relationship, with ties that depend on the conditions of economic agents in the corporate and financial sector, and also the underlying network structure that defines the relationships among them. Our methodology applied to Brazil highlights a potential expressive financial contagion in the agriculture sector through credit rationing in periods of monetary policy easing. The agriculture sector is heavily dependent on bank financing and is of great importance for the Brazilian economy. Although the aggregate analysis indicates a low effect of monetary policy on the financial stability of the corporate sector, the agriculture sector has a significant loss of capital in a period when the model indicates decreasing losses in an aggregate manner.

5.3. Robustness tests

Mutable network structure: our financial contagion & amplification model assumes the network structure as fixed. Even in the short term, links among banks/firms may be created or severed, depending on several factors. In this section, we perform a simple exercise in which we allow links in the interbank market to change stochastically while shocks transmit across the network. Following the interest rate shock in the economy, we perform a random reattachment of all interbank links before each iteration of the shock transmission rule in Eq. (6). We use a uniform distribution to reassign the links, but we prevent the creation of self-loops. Fig. 12 displays a sensibility analysis of the aggregate net worth losses to interest rate shocks, similar to the setup in Fig. 7. For each date and interest rate shock, we perform 100 independent runs and report the quantiles 0.50 (median), 0.75, 0.9, and 0.99 of the aggregate net worth loss distribution of (a) the financial sector in March 2015; (b) the financial sector in March 2020; (c) the corporate sector in March 2015; and (d) the corporate sector in March 2020. The random reattachment of links does not seem to interfere with our results in qualitative terms. However, we should note that link reattachments are not random and rather strategic in reality. Despite this, our results provide a first idea of the robustness of our results to different network structures. Paying out profits from interest rate shocks: banks
may be tempted to pay out gains from re-valuation caused by interest rate changes, thus eliminating any positive effects on their net worth. To simulate this behavior, we assume that banks’ initial net worth does not increase when they profit from an interest rate shock as they immediately pay out their gains to shareholders. Hence, they do not enter the “better off” state as in Fig. 2. Our results remain qualitatively and almost quantitatively the same as in Fig. 7.

6. Conclusions

This paper investigates how monetary policy shocks transmit to the economy, considering a very granular model comprising each individual bank and firm and their connection patterns. Though there are several transmission channels through which monetary policy operates, we are concerned with adjustments in the accounting value of trading book exposures on banks’ balance sheets that have to be marked to market when interest rates change. While there are increasing efforts in linking macroeconomic behavior with granular models in the literature, primarily through network models, none of them has explicitly incorporated the trading book channel that we explore in this work. Such a detailed understanding of how monetary policy is transmitted can help decision-makers design better policies to steer the economy and mitigate financial imbalances.

To evaluate how interest rate changes transmit to the economy, we extend Silva et al. (2017a)’s model by encompassing a policy-maker and introducing the trading book channel. Interest rate changes can generate losses or profits for banks, depending on their trading book exposures and duration gap. Profiting banks increase their capitalization levels while banks registering losses become financially distressed. The extended granular model permits us to open the black box of the monetary policy transmission and to determine the effects on every bank and firm in the economy and any second-round (contagion) effects. With this tool, we can identify economic sectors and banks that would be more sensitive to sudden interest rate changes. We use a comprehensive database of Brazilian banks and firms to show the applicability of the model. Our results reveal that interest rate shocks affect more financial stability during periods of monetary policy tightening, both in terms of direct and indirect impacts.

Our granular network model also abstracts away from some contagion transmission channels. For instance, interest rate increases not only affect firms’ cost of funding but also reduce consumer demand. While our model indirectly captures the first component through successive credit crunches as a function of the firm creditworthiness, we do not integrate the second risk channel. As future work, we could apply a similar model to study potential capital outflows. In general, this is an existing risk in emerging markets, such as Brazil.

Declaration of Competing Interest

All authors declare no financial and personal relationships with other people or organizations that could inappropriately influence (bias) their work.

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