Enhancing Stress Tests by Adding Macroprudential Elements[*]

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February 15, 2022

Abstract

The use of stress testing for macroprudential objectives is advanced by modeling spillovers within the financial sector or between the real and financial sectors. In this chapter, we discuss several macroprudential elements that capture these spillovers and how they might be added to stress test frameworks. We show how funding spillovers can be modeled as an add-on, using a reduced-form relation between banks' funding cost, bank capital and economic activity. Using a calibration to US data, we project very modest funding spillovers conditional on the DFAST 2018 severely adverse scenario. We describe the pros and cons of modeling different types of spillovers using this approach.

1. Introduction

Since the Global Financial Crisis (GFC), many jurisdictions have begun to conduct stress tests on a regular basis (BCBS 2107). In advanced economies, these tests are increasingly being used to inform macroprudential policy, like increasing the resilience of the financial system during expansions and better understanding the financial spillovers and amplification dynamics within the financial sector or between the real and financial sectors. In this chapter, we discuss several macroprudential elements that can be included in solvency stress tests to better capture spillovers

[*] This paper was prepared as a chapter for the Handbook of Financial Stress Testing, published by Cambridge University Press, forthcoming, and edited by J. Doyne Farmer, Alissa M. Kleinnijenhuis, Til Schuermann and Thom Wetzer. We thank Grace Brang and Candy Martinez for excellent research assistance and are grateful to David Arseneau, Ken Heinecke, Andreas Lehnert, Lisa Ryu, Jason Schmidt, Alex Vardoulakis, Cindy Vojtech, participants at the conference Rethinking Financial Stability: The FSAP at 20, the editors, and an anonymous referee for useful comments. All errors herein are ours. The views expressed in this paper are those of the authors and do not necessarily represent those of Federal Reserve Board of Governors or anyone in the Federal Reserve System.
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and the pros and cons of various modeling approaches. To provide a concrete example, we discuss the use of an add-on approach that incorporates reduced-form relationships between the cost of funding and the average capital ratio of the banking sector to simulate a funding shock that dynamically adjusts to changing vulnerabilities in the banking sector and the macroeconomic scenario.

For this chapter, we define a macroprudential policy as one that aims to reduce systemic risk—the risk of widespread disruption to the provision of financial services that can negatively impact the real economy (IMF-FSB-BIS 2016). This policy goal is then pursued through three distinct intermediate objectives: (1) increasing the resilience of the financial system to shocks; (2) leaning against the build-up of systemic vulnerabilities over the financial cycle; and (3) limiting structural vulnerabilities that arise from the interconnectedness of intermediaries or the critical role of individual intermediaries.

Not all regulatory stress tests explicitly consider the amplification of shocks from spillovers either within the financial sector or between the financial and real sectors, but most do contain elements that achieve important macroprudential policy goals.[1] Stress tests most clearly build resilience in the banking sector against the materialization of severe macroeconomic or financial shocks by prompting banks to limit capital distributions or raise more capital if the results show weaknesses. However, that resilience may be insufficient if the scope of the tests is too microprudential. Stress tests that include macroprudential elements may also be more effective in leaning against the buildup of systemic vulnerabilities over the financial cycle (Adrian, Covitz, and Liang 2014, Haldane, Radia, and Anderson 2020). The clearest example of

[1] One exemption is the Bank of England modeling of funding and fire sale spillovers. In addition, some academic papers have proposed frameworks that incorporate spillovers. For example, He and Krishnamurthy (2019) develop a model with financial spillovers that amplify the effect of initial shocks and can be used to compute the probability of reaching systemic risk state. We review other academic proposals to model fire sales in section 5.

such a leaning-against-the-wind policy would be taking steps to make the stress test more severe in the expansionary phase and less severe in the contractionary phase of the financial cycle.

Indeed, the considerable severity of the scenarios used in most jurisdictions' stress tests implicitly incorporates estimates of the damage to financial markets and the economy caused by a seizure of funding markets or distress of large financial institutions.[2] Nonetheless, given the potential for financial spillovers to disrupt the financial system, the macroprudential goals of stress tests could be significantly enhanced by incorporating elements that can explicitly project spillovers conditional on current vulnerabilities and a given scenario (Haldane 2009, BCBS 2009, IMF 2012, Baudino et al. 2018, Haldane, Radia and Anderson 2020). Endogenizing the reaction to the stress through reduced form or structural models also can enhance financial stability monitoring and risk identification by making stress tests a tool to analyze more-primitive shocks—like an energy price spike—and creating a better understanding of how those shocks amplify vulnerabilities and generate financial spillovers.

The important macroprudential objectives achieved by the aforementioned elements already in place raise the question of how to incorporate additional macroprudential goals in existing frameworks. Some macroprudential elements can be incorporated into existing stress test frameworks either as add-ons or by integrating them as part of the suite of scenario variables, with the associated losses projected using either reduced-form or structural models. However, other combinations of macroprudential elements and existing stress test frameworks would

[2] These mechanisms seem to have fueled, in large part, the sharp reduction in credit availability and the depth of the GFC (see, for example, Kashyap, Rajan and Stein 2008). In fact, theories of macroprudential regulation developed since the GFC have focused on the interactions within the financial system and the largest financial firms and the costs they impose on the broader economy and other financial institutions when those largest firms are distressed. (Brunnermeier et al. 2009, and Hanson, Kashyap and Stein 2011).

require supervisors to revisit existing assumptions, develop new frameworks, or collect additional data to incorporate models of financial spillovers.

We provide two examples of how to incorporate funding spillovers into stress tests through an add-on approach. The first example uses a simple exogenous shock to the cost and availability of short-term wholesale funding (STWF), which we call a "prudential shock." One feature of this add-on is that the funding stress impacts different banks than the macroeconomic stress considered in DFAST. The second example uses a reduced-form model of spillovers between the health of participating banks and the cost of STWF to create a dynamic shock that responds to the evolution of bank-capital and GDP growth over the projection horizon. Thus, funding stress is greater when the starting capital ratios are lower or losses from the macroeconomic shock are larger.

We further discuss other models of spillovers, like fire sales and the feedback between the macroeconomy and the financial system. Next, we discuss vulnerabilities where the use of a structural model or highly granular data seems to be necessary. For instance, reduced-form relationships are poor approximations of exposures arising from bilateral interactions, such as counterparty default.

Finally, we argue that the benefits of promoting new macroprudential goals needs to outweigh the costs of increased complexity or the potential to inhibit the goals that are promoted by existing macroprudential elements. Moreover, it is important to remember that neither reduced form nor structural models can accommodate all of the macroprudential elements discussed herein at the same time. For instance, a stress test that requires banks to meet a macroprudential goal of maintaining credit supply by growing the size of their balance sheet during the test would be inconsistent with one in which fire-sale dynamics also played an important role. Therefore, jurisdictions should remain flexible in their uses of macroprudential stress testing.

The rest of the chapter is organized as follows. In section 2, we review macroprudential elements currently in place in selected jurisdictions. In section 3, we discuss how funding stress can be incorporated into existing stress testing frameworks. In section 4, we describe our approach to incorporate macroprudential funding spillovers into existing frameworks. In section 5, we discuss how our approach relates to other proposals to incorporate other spillovers. Finally, section 6 provides some conclusions.

2. Macroprudential Elements Currently in Place

Current stress test frameworks incorporate several macroprudential elements that help to limit systemic risk through some of the three intermediate objectives of macroprudential policy previously mentioned.

First, stress tests have become an important input into prudential capital requirements in many jurisdictions, helping to build economy-wide resilience against the stresses considered in the test. For example, results from the European Banking Authority (EBA) stress tests are used by bank authorities in their Supervisory Review and Evaluation Process (SREP), which assesses capital among other risk dimensions (European Banking Authority, 2020). In 2014, the results of the EBA stress test required about twenty banks to issue new capital.[3] Likewise, the Federal Reserve has used the results from its Comprehensive Capital Analysis and Review (CCAR) to object to a firm's capital plan if a firm fails to demonstrate its ability to maintain required minimum capital ratios over the planning horizon or if it finds the bank's capital planning

[3] See https://www.eba.europa.eu/risk-analysis-and-data/eu-wide-stress-testing/2014/results.

processes to be unreliable.[4] An objection by the Federal Reserve usually has resulted in the bank being required to limit its dividends and share repurchases to no more than their previous year's capital distributions.[5]

In addition, some jurisdictions use stress test projections to calibrate macroprudential capital buffers. For example, the Bank of England and Swiss National Bank (SNB) use the projections from their stress tests as an input in their countercyclical capital buffer (CCyB) framework.[6] A different approach is to link stress-loss projections with capital conservation buffers (CCBs). For instance, the Federal Reserve has requested public comment on a rule that will make CCBs time-varying and risk-sensitive by conditioning them on individual bank losses in the test.[7]

Second, the use of common scenarios and the simultaneity of the exercise enable regulators to examine the resiliency of the system to certain shocks and to consider the appropriate policy response. For instance, the International Monetary Fund's (IMF) Financial System Assessment Program (FSAP) includes stress tests of banks representing 60 percent or more of total bank assets, and in some jurisdictions FSAPs have also considered stress tests of the insurance and pension funds sector (Jobst, Ong and Schmieder 2013, Adrian, Morsink and Schumacher 2020). Moreover, scenarios can also be tailored to examine the resilience of the

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[4] Board of Governors (2019). Additionally, even if the Federal Reserve does not object initially to firms' capital plans, firms generally have been required to request prior approval of a capital distribution if the dollar amount of the capital distribution will exceed the amount described in their capital plan.

[5] In its 2016 report, the U.S. Government Accountability Office stated that on a macroprudential level some firms felt "the stress tests have led to higher capital levels and improved risk management that have contributed to the stability of the financial system.", see GAO Report "Additional Actions Could Help Ensure the Achievements of Stress Test Goals," page 28, http://www.gao.gov/assets/690/681020.pdf.

[6] In the U.K. the CCyB is set by the Financial Policy Committee (Bank of England, 2015); in Switzerland it is set by the Federal Council on a proposal by the SNB after consultation with Financial Markets Supervisory Authority (IMF 2019).

[7] See proposal for the "stress capital buffer" https://www.federalreserve.gov/newsevents/pressreleases/bcreg20180410a.htm.

system to emerging vulnerabilities, such as the negative interest rates included in the severely adverse scenario of the 2016 DFAST exercise.

Third, increasing the severity of the hypothetical stress scenario when the economy is strong, together with the use of the results in setting prudential capital requirements, can lean-against the inherent procyclicality of the financial system (Haldane, Radia, and Anderson 2020).[8] In this way, when times are good, stress tests can induce banks to build up more capital than they otherwise would in order to increase resilience in a subsequent downturn. The US DFAST and CCAR do this in several ways, but most clearly through the calibration of the unemployment rate shock, which is described as typically rising 3 to 5 percentage points over the scenario horizon, to a minimum of 10 percent (12 CFR 252). Hence, with US unemployment falling below 4 percent, CCAR scenarios since 2018 have seen unemployment rise 6 percentage points or more, a full percentage point larger than the upper end of the typical range.[9] Similarly, the Bank of England calibrates the severity of the stress scenario to policymakers' assessment of the state of the financial cycle as well as the business cycle (Bank of England 2015).

Fourth, stress tests have been tailored to address the critical role and interconnectedness of the largest financial institutions. From a macroprudential perspective, the failure of a major financial institution has greater implications for financial stability than the failure of a smaller institution (see Lorenc and Zhang 2018). The size, interconnectedness and complexity of large

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[8] This inherent procyclicality manifests in the banking system in several ways. First, lending standards tend to loosen as the last crisis fades into history (Berger and Udell 2004). Second, investors' overreliance on models can lead to excessive risk taking in the run up to financial crises (Haldane 2009, Daniellson 2011, Haldane et al., 2020). Third, loss rates in US and EU stress tests have tended to decline as time has passed since the 2007-2009 financial crisis.

[9] However, such features will probably prove insufficient to achieve macroprudential goals, in part because larger increases in unemployment and steeper declines in asset prices become harder to justify as they move further outside the range of historical precedent. In addition, marginal changes in scenario variables (e.g., a 5-percentage-point increase in unemployment versus a 6-percentage-point increase) may not lead to proportional changes in loss estimates.

financial institutions make them sources of instability should an adverse situation in financial markets materialize. Thus, stress test scenarios can differentially address the risks posed by the largest institutions, which should help mitigate the additional and unique risks that these types of institutions pose to financial stability. For example, CCAR considers a market shock and the default of the largest counterparty to stress the trading activities and interconnectedness of the largest and most complex participating firms. We come back to the modeling of these financial spillovers in section 5.

Of course, the efficacy of the previous four elements, which aim at building resilience or leaning-against-the-wind, is limited by the scope of regulatory stress tests within the financial system.[10] This limitation is more important the larger the amount of credit intermediation and liquidity transformation that takes place in less regulated institutions and markets, the so-called shadow banking system. However, this limitation can be mitigated by regular surveillance of the entire financial system, which can be used to identify salient risks and spillovers from nonbank intermediaries to banks and the real economy and incorporated into the scenarios used in the bank stress tests.

Fifth, the extent of public disclosure of the results is an often-overlooked element of stress tests that provides macroprudential benefits. Indeed, the public disclosure of the results of the US stress test in 2009 contributed to restoring confidence in markets by providing much

[10] Supervisory stress tests tend to focus on the sector, but several jurisdictions have also stressed the activities of nonbanks intermediaries, like central clearing counterparties (CCPs), insurance companies, and asset managers. For example, the FSAP for Japan and Sweden in 2017 included the insurance sector (IMF 2017a, 2017b), and the FSAP for Belgium in 2018 included the insurance sector and financial conglomerates, comprising asset managers (IMF 2018). In the Belgium FSAP insurance companies and banks used the same scenarios, but in other cases the scenarios applied to different institutions can be different, limiting some macroprudential benefits of the exercise. Additional examples are supervisory stress tests where multiple CCPs are evaluated under common scenarios. For instance, stress tests on CCPs are conducted by the CFTC in the U.S. (https://www.cftc.gov/system/files?file=2019/05/02/cftcstresstest042019.pdf and by ESMA in Europe (https://www.esma.europa.eu/press-news/esma-news/esma-publishes-results-second-eu-wide-ccp-stress-test).

needed transparency during a period of financial uncertainty, and similar effects have been found for the European Comprehensive Assessment and Asset Quality Review (Georgescu et al. 2017). Although there is not consensus on the optimal level of information disclosure, there is consensus that publicly announcing stress test results can promote financial stability in turbulent times.[11] Some contend that the credibility of supervisory stress tests is undermined by the lack of market information in their design (Archarya, Engle and Pierret 2014, Sarin and Summers 2020). Yet, other observers have pointed to the credibility of US supervisory stress tests as one factor for the relatively strong market performance of US banks amid adverse market events early in 2016.[12] Aspects of tests that have been cited as contributing to market confidence are credible estimates of potential losses (such as through the use of independent supervisory models rather than banks' own estimates), transparency regarding individual institutions' projections, and a credible plan for dealing with institutions found to be undercapitalized or insolvent.

The development of independent models by supervisors to calculate each bank's projected losses enhances the efficacy of several of the aforementioned macroprudential elements. But, the development and credibility of these models to a large extent depends on the existence of robust data collection programs designed to support stress tests, such as the national credit registers maintained by many Basel member countries.[13] Likewise, the Federal Reserve has supported its post-crisis capital stress testing program by introducing the FR Y-14 data collection, which provides obligor level data for securities, business loans greater than $1

[11] See Faria-e-Castro, Martinez and Philippon (2017), Goldstein and Leitner (2018), and Goldstein and Leitner (2020).
[12] See http://www.reuters.com/article/us-britain-eu-usa-banks-idUSKCN0ZD0OP. Jobst, Ong and Schmieder (2013) argue that the credibility of the Supervisory Capital Assessment Program (SCAP) exercise in 2009 was useful to restore market confidence in the US financial system.
[13] It is worth pointing out that expanded data availability itself constitutes an element of the macroprudential policy toolkit. In fact, Bassett et al. (2011) have argued that lack of data contributed to the inability of regulators, particularly in US mortgage markets, to understand the buildup of vulnerabilities in the financial system between 2003 and 2008.

million, credit cards, and residential mortgages, as well as finely segmented data for other types of loans.

Nonetheless, blind spots, especially for publicly available data, continue to exist.[14] For instance, detailed and timely data on bank funding sources and relationships is available only for the small number of very large banks that are subject to the Liquidity Coverage Ratio and is confidential. In part, these blind spots remain in the US because of statutory requirements to balance reporting burden with potential benefits as well as firms' concerns about the potential inadvertent disclosure of proprietary information, such as trading strategies. One way to increase stability while reducing the burden of more-adequate reporting could be for banks to be incentivized to make larger investments in data infrastructure. In the following discussion, we also highlight some specific improvements in data collections that would facilitate the implementation macroprudential elements to capture funding stress.

3. Adding Funding Stress

Evidence from the GFC points to a credit squeeze in STWF markets and liquidity hoarding as key amplification mechanisms within the financial system. Strains in STWF markets intensified starting in the second half of 2007 (Gorton and Metrick 2012, Acharya, Schnabl and Suarez 2013). As uncertainty rose from mid-2007 through the early part of 2009, the cost of these funding instruments spiked and some markets previously thought to be very low risk, e.g., auction-rate securities, closed entirely (McConnell and Saretto 2010). While banks identified as financially weak faced acute funding constraints, even banks with strong financial positions saw their funding

[14] The absence of data on derivative counterparties led to the failure of regulators to appreciate the central role that AIG Financial Products Group was playing in the credit default swap market for subprime mortgage MBS in the run-up to the Financial Crisis (Kroszner and Strahan, 2011).

costs increase. The resulting widespread stress created negative spillovers, a generalized pull back by credit providers, and liquidity hoarding.[15]

These spillovers are interrelated and can cause negative feedback loops. The pull back by credit providers incentivizes banks to hoard liquidity and exacerbates the credit squeeze (Diamond and Rajan, 2005, Gale and Yorulmazer, 2013). This is especially the case for STWF, which reprices quickly because sophisticated and risk-averse wholesale credit providers respond swiftly to the first signs of distress. In response to the lessons of the financial crisis, many jurisdictions have adopted the Liquidity Coverage Ratio (LCR) and Net Stable Funding Ratio (NSFR), both of which are calibrated to a stress scenario common to all banks and designed to allow firms to self-insure against a loss of funding for up to 1 year. Some also have implemented liquidity stress tests, such as the Comprehensive Liquidity Assessment and Review (CLAR) in the United States. Therefore, adding funding stress to solvency stress tests may seem to be duplicative of enhanced liquidity regulation.

However, we argue that the addition of a funding shock to capital stress tests would be complementary, because the experience of 2007 and 2008 show that access to liquidity and capital adequacy are inherently linked. Although the LCR and NSFR account for the potential for short-term funding to run as banks experience losses that erode their capital position, they do not account for the impact that restricted access to such funding would have on funding costs and hence profitability of even healthy banks once markets are disrupted. Thus, unless the capital stress test captures these additional costs adequately, it will underestimate the capital shortfall associated with the supervisory scenario. In fact, several jurisdictions have included funding

[15] Ashcraft, McAndrews, and Skeie (2008) present evidence of liquidity hoarding in the US interbank market. Similarly, Heider, Hoerova, and Holthausen (2015) present evidence of liquidity hoarding in the euro area interbank market. Finally, Acharya and Merrouche (2013) present evidence of liquidity hoarding by large settlement banks in the U.K.

shocks as a driver of stress in solvency stress tests.[16] Moreover, explicitly modelling the negative spillovers and amplification dynamics under stress helps to build resilience against these higher round effects, improves risk identification, and leans against the buildup of financial vulnerabilities.

The relationship between system-wide capital and average costs of STWF is most clear during the previous financial crisis. To study the dynamics of these variables we use information from FR Y-9C regulatory reports for US bank holding companies (BHCs) that participated in DFAST 2018.[17] We summarize the system-wide capital ratios with the unweighted geometric mean of CET1 capital ratios for those banks. Using the geometric mean is motivated by the fact that extreme stress at a small number of institutions may precipitate widespread concern about the banking industry that results in contagion to otherwise healthy institutions.

For the cost of STWF we consider three different proxies, but focus primarily on the TED spread. The TED spread is the difference between the interest rate on 3-month US Treasuries and the interest rate on interbank loans, measured by the 3-month LIBOR based in US dollars.[18] LIBOR has been a widely used benchmark for funding costs over our sample period, so it is expected to be a reasonable gauge of banks' STWF costs. But, an important limitation of LIBOR is that it is based on bank surveys.[19] For robustness, we use the spread between 3-month

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[16] The IMF country FSAPs have included funding costs as a driver of losses under stress for France, Germany, Japan, New Zealand, Poland, U.K., and Sweden (Jobst, Ong and Schmieder 2013, Adrian, Morsink and Schumacher 2020). In addition, the Bank of England in its 2019 stress scenario considers an increase in the cost of wholesale funding implemented as an increase of 2 percentage points of the five-year senior unsecured bond spread.

[17] To be precise, we consider the 34 BHCs for which the Federal Reserve Board published the results of DFAST 2018 and which report non-negative CET1 ratios in FR Y-9C. For the list of DFAST 2018 banks see https://www.federalreserve.gov/newsevents/pressreleases/bcreg20180621a.htm, as opposed to the 38 BHCs that were initially subject to DFAST (https://www.federalreserve.gov/newsevents/pressreleases/bcreg20180201a.htm) before the Crapo Banking Bill became law in May, 2018 (https://www.banking.senate.gov/newsroom/majority/president-signs-crapo-banking-bill-into-law).

[18] We use the quarterly average of the daily TEDRATE, retrieved from FRED, Federal Reserve Bank of St. Louis; https://fred.stlouisfed.org/series/TEDRATE.

[19] LIBOR's reputation was undermined by accusations over rigging, and it is currently being phased out, see https://www.fsb.org/wp-content/uploads/P181219.pdf.

US Treasuries and the interest rate on 3-month commercial paper (CP) issued by financial firms with high credit ratings.[20] Relative to the TED spread, the CP spread offers the advantage that it is based on market data, but it only represents a single STWF source, as opposed to a broader measure of bank funding.

Finally, we compute a comprehensive cost of STWF using the FR Y-9C regulatory reports, following Bassett et al. (2020). STWF is defined as in the US implementation of the capital surcharge for globally systemically important banks (G-SIB rule), which includes: (1) secured funding transactions; (2) unsecured wholesale funding; (3) covered asset exchanges, (4) short positions, and (5) brokered deposits (Board of Governors of the Federal Reserve System, 2015). These categories are mapped as closely as possible to data on liability balances and interest expenses reported in FR Y-9C forms,[21] supplemented with CP rate information.[22]

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[20] In all our calculations, we use the 3-Month Treasury Constant Maturity Rate [DGS3MO], retrieved from FRED, Federal Reserve Bank of St. Louis; https://fred.stlouisfed.org/series/DGS3MO. We use the quarterly average of the 3-Month AA Financial Commercial Paper Rate [DCPF3M], retrieved from FRED, Federal Reserve Bank of St. Louis; https://fred.stlouisfed.org/series/DCPF3M. Both series are sourced from the Board of Governors of the Federal Reserve System (US).

[21] The exact liability items from FR Y-9C are (codes reported in parenthesis): federal funds and repos (HC-K.2), trading liabilities (HC-D.13.a-b), commercial paper (HC-M.14.a), other borrowed money with a remaining maturity of one year or less (HC-M.14.b), brokered deposits with a remaining maturity of one year or less (HC-E-M.1), uninsured time deposits with a remaining maturity of one year or less (HC-E-M.3), and foreign deposits with a remaining maturity of one year or less (HC-E-M.4). The exact interest expense and liability items used to compute cost rates are: foreign deposits (HI.2.a.(2) and HC-K.7); federal funds and repos (HI.2.b and HC-K.2); uninsured time deposits (HI.2.a.(1)(b) and HI.2.a.(1)(a) before 2016:Q4, and HC-E.1-2.e); brokered deposits (HI.2.a.(1)(a) and HI.2.a.(1)(b) before 2016:Q4, and HC-E.1-2.d); trading liabilities and other borrowed money (HI.2.c and HC.15-16). Note that interest expenses sometimes correspond to less granular categories than the categories identified as STWF components in the FR Y-9C.

[22] The CP rate corresponds to the average of short-term CP rates, weighted by quarterly issuance, where CP rates are calculated as the quarterly average of daily series. The series, from the Board of Governors of the Federal Reserve System (US) and sourced from FRED, Federal Reserve Bank of St. Louis, are: 1-Month AA Financial Commercial Paper Rate [DCPF1M], 2-Month AA Financial Commercial Paper Rate [DCPF2M], 3-Month AA Financial Commercial Paper Rate [DCPF3M]. The respective weights are: Total Value of Issues, with a Maturity Between 21 and 40 Days Used in Calculating the AA Financial Commercial Paper Rates [FIN2140AAAMT], Total Value of Issues, with a Maturity Between 41 and 80 Days Used in Calculating the AA Financial Commercial Paper Rates [FIN4180AAAMT], and Total Value of Issues, with a Maturity Greater than 80 Days Used in Calculating the AA Financial Commercial Paper Rates [FINGT80AAAMT].

The calculation proceeds as follows. For each bank participating in the 2018 DFAST, the weighted-average effective cost of each STWF source is calculated using the ratio of the relevant interest expense item to the average balance of the corresponding liability for each quarter in which those banks reported on the Y-9C. Second, for each STWF source in each quarter, the distribution of the estimated rates paid is trimmed at the 10th and 90th percentile. Then, the average rate for each source-quarter is computed using the trimmed cost rates, weighted by average liability balances. Finally, the time series of average rates for each source are averaged, weighted by liability balances, and expressed at an annual rate. Thus, this measure of STWF costs represents the weighted-average effective rate paid by a representative bank for wholesale funding in that quarter, and the spread is calculated relative to the 3-month Treasury. Relative to the other spreads measuring STWF costs, the aforementioned STWF spread has the advantage that it represents the actual average funding cost paid during the quarter, encompasses a broader set of STWF sources, and corresponds to the set of DFAST 2018 banks that we analyze. However, some of the liabilities that comprise the STWF spread reprice at frequencies lower than a quarter, so it reflects both current and past funding conditions.[23] Therefore, it fluctuates around the more market-sensitive spreads and takes negative values when market interest rates are rising, as was the case in 2006 and 2018.

The individual components of this comprehensive measure can be used to show the relationship between banks' financial health and the cost of STWF at the individual bank level for banks that approached failure and then entered into merger agreements under extreme distress. This was the case for two large banks before the height of the Financial Crisis: National City and Wachovia. Figure 1 presents the spread of the effective interest rate paid on a

[23] This issue is particularly problematic with FR Y-9C data as interest expenses are not reported for short-term maturities. Instead, cost rates for STWF sources are imputed from cost rates of similar liabilities for all maturities.

representative liability at these two banks for the nine quarters before their failure relative to the cost of that funding source at a sample of banks of similar size.[24] The figure shows that the spreads of their funding costs over those of similarly sized banks not (yet) experiencing acute stress increased steadily in the quarters ahead of their failure or merger. National City's spread on large time deposits (in red) peaked at about 250 basis points, whereas Wachovia's spread on federal funds and repo (in blue) peaked at about 150 basis points.

Figure 2 depicts the time series of average capital ratios and the three proxies for the cost of STWF. The figure shows spikes in the cost of STWF to more than 200 basis points across all three proxies in late 2008, when the financial crisis intensified and average capital ratios declined to their minimum levels. Thus, when markets were most disrupted, the TED spread and CP rates, which are more representative of banks marginal funding costs than the STWF spread, were also consistent with the more-comprehensive measure of banks' overall cost of funding. As governments introduced unprecedented support for the financial system and capital ratios started rising in 2009, overall STWF costs dropped back to about 100 basis points, but the TED spread and CP spread dropped further, to below 50 basis points. The close convergence of the three measures during the financial crisis and its immediate aftermath provides important validation for the choice of proxies. Therefore, the rest of this paper uses the TED spread as the baseline measure of STWF costs, reflecting the balance of representativeness and responsiveness in its crisis and post-crisis behavior.

Nonetheless, the limitations of each of the three proxies highlight that a jurisdiction implementing a funding shock would likely want to revisit their information collections to better

[24] For National City, which was acquired in October 2008 and had assets of $151 billion in 2008Q3, we considered banks with assets between $150 and $500 billion; for Wachovia, which stopped independent operations in September 2008 and had assets of $675 billion in 2008Q3, we considered banks with assets between $300 billion and $1 trillion.

capture the quantity and pricing of STWF in a systematic way over time. For instance, the FR Y-15 data that support the calculation of the G-SIB surcharge have a complete accounting of STWF, but that data is not fully granular and does not include the interest rates paid on those liabilities. The new FR 2052A data used for monitoring liquidity requirements has a granular breakdown of STWF instruments, but is only collected from the largest banks. The new FR 2420 data collects interest rates paid by banks on certain wholesale funding sources and is a somewhat larger panel. All three of these sources may become valuable for modeling purposes, but have only been available for a limited time.

Prudential Funding Shock

The most straightforward way to add a component to the stress test that simulates a funding shock is to impose a significant exogenous increase in banks' costs of funds over the projection horizon.[25] To illustrate, we follow Bassett et al. (2016) and consider a 100 basis point shock over the first four quarters of the stress scenario. That shock represents a generalized increase in the costs of all STWF (as defined above in calculating the comprehensive STWF spread) that hits all banks equally. Keeping with the current design of the DFAST and CCAR framework, we consider that banks do not change their mix of liabilities (between STWF and other sources) or shrink their balance sheets in response to the funding shock.[26]

This simple calibration helps to illustrate the effect of a funding shock and is within the range of the evidence described above. That is, if s_{wt} denotes the TED spread in basis points at

[25] This approach is consistent with rationing by price or by quantity. Regulators could achieve this spike in funding costs by specifying an exogenous increase in the interest rate for a specific liability or set of liabilities in the stress test scenarios, or by specifying the closure of a particular funding market that forces banks to obtain alternative funding at a higher cost, resulting in a 100 basis point increase in overall cost of STWF.

[26] In stress test models with a dynamic balance sheet, we expect funding costs to have two opposing effects on profitability. On the one hand, as banks de-lever they may avoid paying higher funding costs at the margin. On the other hand, credit balances may shrink, lowering interest income.

an annual rate, the increase in the cost of STWF Δs_{wt} equals 100 if $1 \leq t \leq 4$ and 0 if $t \geq 5$. Mechanically, an increase of 100 basis points in the cost of funds for a fraction of a bank's liabilities will have a commensurate effect on interest expenses, dampening projected net interest income.[27] The impact of the STWF-shock on post-stress minimum capital ratios then corresponds simply to the original projection of capital ratios minus the cumulative decline in net income as a fraction of risk weighted assets (RWA).

Table 1 presents estimates of the effect of this 100 basis point shock on bank minimum capital ratios for BHCs that participated in DFAST in 2018 based their on STWF balances in 2017:Q4. The estimated effect of this shock to STWF averages 35 basis points. That is, the 100 basis point increase in the cost of STWF over the first four quarters of the exercise reduces net income by 35 basis points of initial RWA. Compared with the average net interest income as a percent of RWA of about 360 basis points at large commercial banks in 2018, these additional losses are nontrivial. Further context for these projected losses can be obtained by comparing them with the 400 basis point decline in capital ratios experienced in the severely adverse macroeconomic scenario in DFAST 2018 presented in Table 1 and Figure 3.[28]

Figure 3 presents the history of the TED spread (solid blue line) and the historical geometric mean CET1 ratio for banks that participated in DFAST 2018 (solid red line). The dashed gray lines represent the projected path of these variables in the DFAST Supervisory

[27] This calculation abstracts from the impact of taxes that would somewhat reduce the magnitude of the findings. In this implementation, we also do not credit banks with additional interest income for their investments in floating-rate assets tied to the same short-term wholesale funding rates.

[28] Throughout this chapter, we consider the projected losses under the Dodd-Frank Act Stress Tests (DFAST). The later corresponds to the supervisory stress test required under the Dodd-Frank Wall Street Reform and Consumer Protection Act (12 U.S.C. 536(i); 12 CFR part 252) and is related but distinct from CCAR. In particular, DFAST projections assume constant dividends equal to the average of the 4-quarters prior to the beginning of the exercise and no buybacks, instead of the planned capital distributions considered in CCAR. Given that our simulations envision additional levels of stress, the generally much small distributions assumed in DFAST seem the more appropriate comparision.

Severely Adverse scenario for reference. The DFAST severely adverse macroeconomic scenario does not include the TED spread in its variable inventory; for simplicity, we assume projections consider a constant spread at its jump-off value. As we describe in the appendix, we use public disclosures of the starting and ending values of CET1 capital ratios and scenario variables to impute the path of CET1 capital over the stress horizon for each participating bank. The dashed red line in Figure 3 shows the small decrease in the geometric mean of the individual bank projections after accounting for the effect of the shock to the TED spread.

The estimated effect of the prudential STWF shock exhibits ample dispersion among banks, as evidenced by the large standard deviation relative to average losses shown in Table 1. In addition, for 10 percent of banks, this shock represents losses of no more than 7 basis points of RWA. By contrast, the 10 percent of firms with the largest losses from this shock experience declines of CET1 of at least 80 basis points of RWA. Thus, for some banks that had otherwise ended the test near the regulatory minimum, this additional decrease in capital buffers could have led to a reduction in their dividends or share repurchases.

Finally, the banks affected most by the funding cost shock are different from those affected most by the macroeconomic shock in the DFAST 2018 exercise. In fact, the correlation between losses from the shock to STWF and the decline in capital ratios from the macroeconomic shock is only 0.54. Figure 4 depicts a scatterplot of the decline in capital ratios under prudential funding stress and macroeconomic stress. The solid line depicts the best fitted linear relationship between these declines. The dispersion of points away from this line reveals the different distributional impact of the two shocks. Thus, a prudential funding shock seems to capture a missing risk dimension in stress tests rather than being duplicative of factors already included in the tests.

4. Adding Funding Spillovers

This section extends the analysis of a funding shock to model financial spillovers by creating a dynamic relationship between the assumed increase in funding costs and the deteriorating health of the banking sector and slowing economic activity.

As in the previous case, we consider a cost shock to all STWF sources and hold banks' balance sheets constant for the simulation. But, in contrast with the previous case, the magnitude of the STWF shock in each projection quarter depends on the projected health of all participating firms and the state of the economy.[29] From the perspective of each participating institution, this form of funding shock provides an incentive to tune its capital plan to the overall health of *all* participating firms.[30] For instance, when the average starting capital levels are high, firms will not necessarily need to account for industry health in their capital plan. In contrast, when overall starting capital levels are low, even firms that are themselves strongly capitalized will have incentives to reduce planned capital distributions. Moreover, this specification of a dynamic funding shock furthers the macroprudential benefit of the stress tests, as it explicitly models spillovers and amplification dynamics within the financial sector and between the real and financial sectors.

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[29] Of course, such estimates may underestimate the relationship because the unprecedented level of government support deployed during the financial crisis likely attenuated the rise in funding spreads and reduced the duration of the spikes. In addition, most developed country recessions have not had an associated financial crisis, but rather were associated with significant declines in short-term interest rates stemming from flight-to-quality flows and monetary policy accommodation. Therefore, parameter estimates that incorporate multiple benign business cycles and one crisis period may also generate smaller projected shocks.

[30] The 2017 Japan FSAP includes a stress-test scenario where projected funding costs are a function of an aggregate funding shock and idiosyncratic funding shocks that are a function of projected individual bank capital (IMF 2017a). When projected funding costs depend on the financial health of individual firms, the funding shock will incentivize firms to steer away from capital plans that scrape the minimum capital requirements during the scenario, because they would see their funding costs increase when that occurs.

Relationship between STWF Spreads and Banks' Capital

We postulate the following relationship between STWF costs, the health of participating banks, and the real economy

$$s_{w,t} = f(\bar{k}_t, GDP_t) \ , \qquad (1)$$

where $s_{w,t}$ denotes the STWF spread, $\bar{k}_t$ denotes the (geometric) average CET1 ratio for participating banks, and GDP_t denotes the annualized quarterly growth rate of nominal GDP.[31] A more general specification of this relationship could account for bank heterogeneity, as indicated by the experiences of National City and Wachovia presented above. However, the lack of reliable data on individual banks' marginal cost of STWF prevents us from being able to estimate a specification that accounts for this heterogeneity. In addition, STWF costs depend mechanically on past financial and economic conditions, as some liabilities have fixed interest rates and terms longer than a quarter. This approach could accommodate this dependence on past conditions if appropriate time series of STWF sources and prices were available, but it would complicate the simulation.

We estimate this empirical relationship between these variables by fitting GDP growth and a second-order polynomial of average CET1 ratios to the STWF spread, using the following regression:

$$s_{w,t} = \alpha + \beta_1 \bar{k}_t + \beta_2 \bar{k}_t^2 + \beta_3 GDP_t + \varepsilon_t \ , \qquad (2)$$

where α, β_1, β_2, and β_3 are coefficients to be estimated, ε_t are mean zero innovations, and $\bar{k}_t^2$ corresponds to (geometric) mean capital ratios squared.[32] From an econometric perspective, the

[31] GDP growth corresponds to U.S. Bureau of Economic Analysis, Gross Domestic Product [A191RP1Q027SBEA], retrieved from FRED, Federal Reserve Bank of St. Louis; https://fred.stlouisfed.org/series/A191RP1Q027SBEA.
[32] In unreported analysis we considered orthogonalized capital ratios, that is, the linear capital term is mapped to the interval $[-1,1]$, whereas the quadratic term equals $(3\bar{k}_t - 1)/2$. Results were qualitatively and quantitatively robust.

regressors in equation (2) are endogenous, so the estimated coefficients should not be interpreted as the causal effect of changes in bank capital and economic activity on spreads. Rather, equation (2) should be thought of as summarizing the relationship of these variables, which we will use to calibrate a STWF shock that is sensitive to the scenario and vulnerabilities in the banking sector. Moreover, from a model risk management perspective, relationship (2) offers the advantage of being both intuitive and "as simple as possible, but not simpler" (Canabarro 2020).

We expect the signs of the coefficients of equation (2) to represent a decreasing function of STWF costs on economic activity and bank capital over most of its range, i.e., $\beta_1 + 2\beta_2\bar{k}_t \leq 0$ and $\beta_3 \leq 0$. Moreover, structural models of credit default in the tradition of Merton (1974) imply a non-linear relationship between capital and funding spreads, motivating the inclusion of the second-order polynomial. In particular, funding costs are expected to be more sensitive to bank capital as capital becomes insufficient to protect bank creditors from credit losses (Aymanns et al. 2016, Schmitz, Sigmund and Valderrama 2017). This convexity in the relationship between funding costs and bank capital is then key to model the amplification from funding spillovers.

Table 2 presents the estimates of equation (2). The first column considers the full sample from 2001Q1 until 2019Q3. The estimated coefficients imply a decreasing relationship between the TED spread and GDP growth, which is significant at the 1 percent confidence level. For bank capital, we consider the joint magnitude and significance of the first- and second-order coefficients of CET1. These results show that funding costs are decreasing in the health of the banking sector over much of the observed range of CET1 capital ratios. However, the positive coefficient for the quadratic capital term indicates that the fitted relationship is convex. That is, as banks approach their minimum CET1 ratio the cost of funds becomes more sensitive to bank capital, as predicted by credit risk models. Conversely, the marginal benefit of capital on STWF costs declines as capital ratios reach very high levels. This equation achieves its inflection point when the CET1 ratio is above 10.1 percent, a value that is in the lower end of estimates of optimal bank capital ratios (Firestone, Lorenc, and Ranish, 2017).

Column 2 of Table 2 reports the results of regression (2) when the sample is split at the beginning of the GFC in 2007Q4. In the post-2007 period, the convex relation between bank health and STWF costs is similar to the full sample, though the statistical significance of GDP growth dissipates. The pre-2007 sample is too short to reliably estimate the relationship between STWF costs and capital and GDP growth.

The estimated relationship between these variables appears robust to the choice of capital ratio and a somewhat longer time horizon. In column 3 and 4 of Table 2, we proxy bank health by the geometric mean of tier 1 capital ratios that are available since 1996Q1. The results using this longer sample and the alternative measure of bank capital are quite similar to those in the primary regression specification (column 3). Namely, STWF costs depend negatively on economic activity and the relationship with tier 1 capital ratios is convex, with these relationships being statistically significant at the 1 percent confidence level. The inflection point for the tier 1 capital ratio in this regression is 11.7 percent, consistent with the result for CET1 capital. Using this longer sample we are also able to obtain qualitatively similar results for the pre-2007 period. However, the only statistically significant estimates are jointly the two terms associated to capital (column 4).

To further explore the robustness of the relationship between STWF costs, banks' health, and economic activity, Table 3 reports regression results for equation (2), for the two alternative proxies for STWF costs, previously described. To facilitate the comparison, column 1 of Table 3 presents our baseline results from Table 2. Column 2 considers the CP spread as a proxy for STWF costs. The results are very similar to our baseline, with a convex relationship between the CP spread and capital ratios that show an inflection point at 10 percent. The effect of GDP growth on the CP spread is negative but not statistically significant. Finally, column 3 presents the results when funding costs are measured by the STWF spread, computed as previously described. But, in this case the function that relates capital ratios to STWF costs, while statistically significant, is concave. This counterintuitive result seems to be associated with the additional persistence of the STWF spread, relative to the forward-looking spread measures, because adding lags of the dependent variable in equation (2) restores a convex relationship. Nevertheless, the ability to use a more parsimonious functional form for this relationship reinforces our choice of the TED spread as the primary variable for this exercise.

Figure 5 plots the combination of TED spreads, CET1 ratios, and the fitted values from model (2), holding GDP constant (0 percent growth). As noted, the estimated relationship, $\hat{f}\left(\bar{k}_t, GDP_t\right)$, implies that funding costs are higher when banks' capital increases above 10.1 percent. To avoid this counterintuitive prediction, we set funding costs equal to the prediction of the second-order polynomial when bank capital is below 10.1 percent and at the value corresponding to a capital ratio of 10.1 percent when bank capital is higher. That is,

$$s_{w,t} = \alpha + \beta_1 \min\{\bar{k}_t, \kappa\} + \beta_2 \left(\min\{\bar{k}_t, \kappa\}\right)^2 + \beta_3 GDP_t \ , \tag{3}$$

where $\kappa = -\beta_1/(2\beta_2)$ corresponds to the minimum of the second order polynomial on bank capital.

The dashed blue line in Figure 5 depicts this fitted relationship; the light blue bands correspond to the range of values that the spread can take in the simulation given the minimum and maximum projected GDP growth over the DFAST 2018 severely adverse scenario. The CET1 ratio was well below 10 percent for the entire pre-2007 period, but moved above 10 percent at the end of 2010 and has hovered around 12 percent since 2013. Therefore, this specification would appropriately conclude that funding cost shocks are less likely and less disruptive when banks enter a downturn with substantial capital buffers, as was the case in 2019, than if they were to enter a downturn already impaired. However, the average CET1 ratio falls well below 10 percent during the DFAST stress tests, providing variation in projected losses.

Macroprudential Funding Spillovers

The empirical specification for $f\left(\bar{k}_t, GDP_t\right)$ together with the estimates of the evolution of capital over the stress scenario, $\left\{\bar{k}_t\right\}_{t\in\{1,\ldots,9\}}$, and projected GDP growth under DFAST 2018 severely adverse scenario simulate the effect of a macroprudential funding shock. The cost of STWF over the stress scenario is assumed to be $s_{w,t} = \hat{f}\left(\bar{k}_{t-1}, GDP_t\right)$, where we use the lagged value of average capital ratios to project STWF costs. This timing assumption allows us to simulate the macroprudential funding shock without violating consistency requirements. The challenge with using an add-on considering the contemporaneous relationship is best illustrated with an example. Suppose in the first projection quarter of the test post-stress average CET1 is 8 percent. Then the estimated relationship between STWF funding costs and average capital implies that STWF costs will be higher, generating additional losses. We could stop there, but without an additional assumption that would generate a fixed point on a subsequent iteration, the updated path of capital will imply additional projected costs of STWF, which in turn imply lower projected capital, higher STWF costs, and so on.

The final trajectory of average CET1 ratios together with the estimated relationship between CET1 and funding costs imply STWF spreads, $s_{w,t}$, increase 25 basis points to 51 basis points in the second projection quarter and then decline to 23 basis points by the ninth projection quarter (dashed blue line in Figure 6). Specifically, this spread in 2017Q4 stood at 26 basis points and we denote it with $s_{w,0}$. Thus, the effective shock to STWF costs in quarter t is given by $s_{w,t} - s_{w,0} = \hat{\alpha} + \hat{\beta}_1 \min\{\bar{k}_{t-1}, \hat{\kappa}\} + \hat{\beta}_2 \left(\min\{\bar{k}_{t-1}, \hat{\kappa}\}\right)^2 + \hat{\beta}_3 GDP_t - s_{w,0}$. It follows that the macroprudential STWF shock increases to 25 basis points in the second quarter and then declines to -3 basis points by the ninth quarter.

Table 1 presents the projected effect of this funding shock on bank minimum capital ratios for DFAST 2018 banks. The estimated average effect on net income of the macroprudential shock to STWF averages 6 basis points of RWA. Although not close to the level of the prudential shock, the estimated effects of the macroprudential funding shock still exhibit some dispersion among banks, reflecting the substantial heterogeneity in banks' reliance on STWF. For 10 percent of banks the funding shock represents losses of no more than 1 basis point of RWA. By contrast, the 10 percent of firms with the largest losses from this shock experience declines of CET1 of at least 13 basis points of RWA.

Average projected losses and the dispersion of outcomes are much smaller than the prudential funding shock described above. This follows directly from the empirical relationships between the TED spread and bank capital. As depicted in Figure 5, the high starting values of bank capital in the 2018 exercise prevent material increases in funding costs unless the geometric average capital ratio for participating banks falls below 10.1 percent. Moreover, GDP growth recovers over the latter half of the projection horizon, which causes STWF spreads to decline and end marginally below their jump-off value (Figure 6). By contrast, the prudential shock of 100 basis points results in a STWF cost that jumps to 126 basis points over the first four projection quarters and then return to the jump-off value.

Macroprudential Funding Shock and Banks' Capital

To better highlight the nonlinear interaction between the severity of the projected funding shock and the financial health of participating firms at the beginning of the exercise, we consider a counterfactual exercise where DFAST 2018 firms are assumed to start the exercise with CET1 ratios that are 2 percentage points lower than their values at the test's jump-off point.[33] We assume that even with these lower starting capital levels banks experience the same losses as projected under DFAST, so the trajectory of CET1 ratios over the projected horizon shifts down by the same amount as the jump-off values.

With banks' financial health consistently worse over the projected horizon, our estimated relationship projects much larger STWF spreads. The 26 basis point jump-off spread is projected to increase between 4 and 113 basis points to between 30 and 139 basis points (Figure 7). Table 1 presents our estimates of the effect of this funding shock. The projected effects on net income of the counterfactual macroprudential STWF shock average 50 basis points of RWA, which is considerably larger than the average 6 basis points projected using the current CET1 ratios at the jump-off. It is instructive to note that the additional funding stress is concentrated among banks that rely more on STWF. In fact, for the 10 percent of banks with smaller losses,

[33] Indeed, several of the largest US banks have announced medium term targets for the CET1 ratios that are 1 percentage point or more lower than their current ratios. See the recent transcript of earning calls, from Bank of America, https://www.fool.com/earnings/call-transcripts/2020/01/15/bank-of-america-corp-bac-q4-2019-earnings-call-tra.aspx, Wells Fargo, https://www.fool.com/earnings/call-transcripts/2020/01/14/wells-fargo-co-wfc-q4-2019-earnings-call-transcrip.aspx, and Capital One, https://www.fool.com/earnings/call-transcripts/2020/01/21/capital-one-financial-corp-cof-q4-2019-earnings-ca.aspx.

those losses are smaller than 1 basis point, whereas for the 10 percent of firms with the largest losses, those losses reach at least 115 basis points of RWA (Table 1).

Thus, modeling the financial spillovers from funding shocks can significantly increase the severity of projected funding stress, but only when banks enter the test with somewhat weaker capital ratios than currently prevail. This feature improves the ability of the test to identify conditions that can put participating banks at risk and to build resilience against those shocks before economic conditions actually deteriorate. However, in stress tests where amplification of financial spillovers is explicitly modeled, the initial supervisory scenarios should be constructed so as to avoid double counting these effects.

In addition to illustrating the way that amplification dynamics are brought into the test through financial spillovers, our macroprudential funding simulations underscore the data and modeling requirements to incorporate financial spillovers as add-ons, using reduced-form relationships. In our simulation, ratios of capital and STWF to RWA represent the *bank variables* involved in the spillovers, and the spread of STWF represents the *market outcome* involved. Data collection programs are needed to measure accurately bank variables and market outcomes. In the case of our funding spillover we use FR Y-9C forms and the TED spread from FRED to approximate these variables. As previously noted, additional projection accuracy would be obtained if more granular data on STWF balances and costs were part of data collection programs.

There are two model requirements. One is a model that links bank variables with market outcomes, which we model using the reduced-form relationship between average CET1 ratios and the spread of STWF (equation (3)). The other is a model to update the projection of bank variables conditional on projected market outcomes. In our case, we use a bottom-up approach to approximate additional income losses based on the simulated spread of STWF and individual bank's ratio of STWF to RWA. Finally, we note that the development of supervisory models to update bank variables is required for practical considerations. The alternative would involve a sequence of bank submissions and updates to the test's scenario, which seems impractical.

5. Adding Other Financial Spillovers

Financial spillovers in periods of stress include other channels besides funding spillovers. In this section we review three of these channels: fire sales, macro-financial feedback loops, and network effects.

One important source of spillovers of financial distress is fire sales (see, among others, Shleifer and Vishny 2011 and Allen, Babus and Carletti 2012). In fact, theoretical analyses draw a link between fire sales, or market liquidity, and conditions in credit markets, or funding liquidity (e.g., Geanakoplos 2003, Brunnermeier and Pedersen 2009). For instance, a bank that suffers losses and experiences a decline in its CET1 capital ratio might adjust by selling assets to reduce its RWA and funding needs, rather than facing higher funding costs as assumed in the simulations in the previous sections. These asset sales under already stressed conditions create further stress in markets, especially for less-liquid assets. As a result, the prices received for those assets are depressed, which reduces the mark-to-market value of similar assets at other institutions and reduces the prices for other sellers.[34] By including potential fire sale losses in banks' capital buffers through stress testing, prudential authorities can hope to control vulnerabilities at the beginning of a downturn, rather than contributing to a downward spiral.

[34] Mark-to-market losses, under the Basel III implementations in most jurisdictions for advanced approaches banks, are included in accumulated other comprehensive income that affect the accretion of CET1.

Several frameworks exist to simulate the spillover effects of fire sales. Greenwood et al. (2015) develop a linear model of fire sale spillovers, under three key assumptions: (1) upon a negative shock, banks sell assets to return to their initial leverage ratio; (2) banks' asset sales are proportional to their initial holdings; and (3) the loss on fire-sold assets is proportional to aggregate quantities sold. The advantage of these stylized assumptions is that they yield simple linear expressions for the effect of an initial shock to banks' leverage, which are used to measure individual banks' contribution to systemic risk.

Subsequent authors adapted this approach to construct an index of aggregate vulnerabilities to fire-sale spillovers for euro area banks (Cappiello and Supera, 2014) and for large US banks (Duarte and Eisenbach, 2018; hereafter DE). DE relax the assumption that banks aim to restore their original leverage, and instead assume that banks have a latent target, where both the latent target and the speed of adjustment are time varying. The speed of adjustment and target leverage ratios are jointly estimated fitting a dynamic model of capital structure with partial adjustment toward a leverage target.

Cont and Schaanning (2017) use this framework to model fire sales in a macroprudential stress test of European banks. These authors assume that banks adjust their leverage ratios when they breach their regulatory constraints and target 105 percent of the minimum regulatory leverage ratio (other regulatory ratios for capital or liquidity may also be considered).[35] This adjustment rule implies that fire sales only occur when losses exceed bank-specific thresholds. Moreover, these authors discuss how price impact functions that are linear in the value of assets sold can be calibrated using market depth, which varies by asset class.

[35] Cont and Schaanning (2017) define the leverage ratio as the ratio of assets to equity and consider that banks target a 95 percent of the maximum regulatory asset-to-equity ratio.

The fire sale approach has the merit of modeling bank actions, closer to a structural approach, but each of the above frameworks could be implemented as an add-on. Nevertheless, there is little historical evidence to inform the modeling of banks' adjustment.[36] Moreover, a structural approach to model fire sales would necessarily need to consider nonbank intermediaries and nonbank liquidity providers that participate in these asset markets, especially in markets where those firms are not subject to prudential capital and liquidity regulation.[37]

Finally, note that allowing banks to adjust their balance sheet over the projected scenario represents a key methodological departure from assuming static balance sheets, as in the DFAST exercise (Baudino et al. 2018). Such a change would require that supervisors explicitly model balance sheet dynamics as an element of the framework. In addition, the assumption of a constant balance sheet has an important macroprudential impact; it prevents banks from meeting the requirements of the test by "shrinking to health," which somewhat reduces the likelihood of a credit supply shock that could exacerbate the downturn, if an adverse macroeconomic scenario were to materialize.

Another important source of amplification and spillovers of financial distress is the feedback loop between macroeconomic and financial conditions. Most of the current stress testing frameworks use a very severe macroeconomic and financial market scenario in order to embed likely spillovers and financial accelerator effects within the single round of stress testing.[38] However, at the end of such an exercise, banks are typically in significantly weaker

[36] Some authors even call into question whether banks delevered after the financial crisis for the purpose of adjusting to their desired leverage or capital ratios (Begenau, Biggio and Majerovitz 2018).
[37] For evidence on fire sales by nonbanks, see Khandani and Lo (2011), Manconi, Massa and Yasuda (2012), and Jotikasthira, Lundblad and Ramadorai (2012).
[38] For an example of a stress testing framework modeling macro-financial linkages see Andersen et al. (2019).

condition than they began the test, and policymakers would benefit from studying whether they would continue to be a drag on economic performance in that state.

Therefore, directly modeling the feedback loop between the financial system and the real economy could better advance the macroprudential goals of stress tests.[39] As banks' ex ante financial health improves, we expect that their supply of credit will be more resilient to the same real economic shocks. By contrast, as the share of poorly capitalized banks rises, a negative economic shock will limit the supply of credit and macro-financial spillovers will be stronger. Thus, supervisors may be able to glean important insights from studying the reaction of the economy and banking system to a smaller initial shock, and then accounting for the endogenous response of banks and the economy by iterating through higher-round effects. These spillovers require modeling macroeconomic and financial variables jointly, suggesting integrating these channels into the test design, rather than using an add-on as we do for funding spillovers. Though a reduced-form approach may be suitable in some instances, advances in modeling macro-financial feedback loops will likely require structural models with robust financial sectors.

Finally, we discuss some approaches to address counterparty defaults in a macroprudential framework. Counterparty defaults are an important source of amplification and spillovers of financial distress, with the spillovers from the default of a large financial institution being widespread. Stress tests in some jurisdictions require banks to contemplate the default of one of their major counterparties.[40] By contrast, a more macroprudential approach to model

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[39] In a macroprudential framework, one would prefer the modelling of the feedback between financial and macroeconomic variables be informed by both the health of participating banks and the projections for nonbank financial intermediaries. Information on the latter is intrinsically sparse, but reduced-form models can make use of simple statistics like the share of non-bank intermediated credit.

[40] For example, in the DFAST severely adverse scenario, credit default losses (CDL) are calculated using the following approach. The largest trading firms are required to rank their counterparty stressed losses and report the largest, excluding G-7 sovereigns and CCPs. These losses are calculated including securities financing and derivative exposures. See https://www.federalreserve.gov/supervisionreg/files/bcreg20180201a1.pdf.

default risk might consider the same scenario for all banks, i.e., the default of the same counterparties, and the second-round effects of spillovers from such defaults on the surviving counterparties. This is challenging to achieve without considering the structure of the network of individual counterparty relationships.

Some structural frameworks have been developed to incorporate financial spillovers from counterparty default into stress tests. For example, Eisenberg and Noe (2001) show how the payments after the default of counterparties are jointly determined by all the bilateral relationships and their relative priority in a network representing a single clearing mechanism. All of those factors also contribute to the repricing of non-defaulted derivative contracts, and larger margins from derivatives counterparties including CCPs.[41] This result underscores the necessity of the structural approach to model counterparty defaults.

In order for supervisors to conduct a macroprudential large counterparty default test, the quantity and quality of data collected will need to be improved. Improved data would aid in the development of structural loss models that would be used to project losses. The reporting of such highly confidential data would require an understanding among firms and regulators about the ways in which it would be protected and could be used. Another option would be to require banks to use their own models and data to project initial losses and then spillovers; though that may require multiple rounds of estimates as supervisors evaluate results across the system. A complication of the bank-run option is that the information that banks would need to run second-

[41] Understanding the role of CCPs is important given their increased prominence in handling counterparty risk within financial markets after the recent financial crisis and given recent large defaults that have tested these institutions. For instance, on September 17th, 2018, the default of two large traders depleted around two-thirds of Nasdaq's mutual default fund (see https://www.bloomberg.com/view/articles/2018-09-17/central-counterparties-mean-derivatives-risk-hasn-t-gone-away).

round effects could be used by banks to determine confidential counterparty exposures of their competitors.

6. Conclusions

In this chapter, we discuss several macroprudential elements that can be included in solvency stress tests to better capture spillovers and the pros and cons of various modeling approaches. We provide two examples that incorporate funding spillovers into solvency stress tests through an add-on approach. First, we consider a "prudential shock," where bank losses are a function of an exogenous shock to the cost and availability of short-term wholesale funding (STWF). Second, we use the relationship between the health of participating banks, economic growth, and the spread of STWF relative to short-term government securities to simulate spillovers from the financial health of banks to their costs of short-term wholesale funds. This reduced-form relationship can be combined with banks' current capital position and STWF intensity to project a dynmaic shock that is responsive to current, and projected, levels of bank-capital and GDP growth. This approach achieves an additional macroprudential goal, as the effective shock to the spread of STWF is negatively correlated with starting capital levels and the severity of the macroeconomic scenario.

We show how our approach to modeling funding spillovers relates to existing models of fire sales spillovers, many of which can also be implemented as reduced form add-ons to existing frameworks. We also discuss models of spillovers between the macroeconomy and the financial system; however, we conclude that those elements are more effective when integrated into a comprehensive framework, as opposed to incorporated as an add-on. Finally, we discuss the challenges faced by policymakers who desire to move beyond the add-on approach for modeling bilateral interactions in financial markets, like counterparty defaults. In order to incorporate second-round effects of counterparty defaults, stress test designers will need to choose between developing a structural model to project losses, which also requires enhanced data collection, or relying on bank-provided loss estimates. One limitation of the latter option is that it would require banks and regulators to iterate and might require regulators disclosing information that can then be used to back out confidential bilateral exposures.

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Appendix: Projected Trajectories of CET1 Ratios

The public disclosures of DFAST results do not include the full projected path of CET1 ratios, rather the disclosures provide the ending and minimum post-stress CET1 ratios as well as the jump-off CET1 ratio.[42] Using the publicly available information, we estimate the trajectory of CET1 ratios over the severely adverse scenario to simulate the macroprudential funding shock as follows.

First, we modify the approach of Durdu, Edge, Schwindt (2017) to calculate severity based on unemployment and house prices. In particular, we construct a severity index over the 9 projection quarters, as the average between the normalized severity score for the projected unemployment and house price paths. Formally, let u_t and HPI_t denote the projected paths for unemployment and house prices for quarter $t \in \{0, \dots, 9\}$, where 0 represents the jump-off point and the other 9 quarters represent the 9 projection quarters in the test. We calculate the severity index in projected quarter t as

$$severity_t = \frac{1}{2}\left[\frac{(u_t - u_0)}{\max\limits_{j \in \{1,\dots,9\}}(u_j - u_0)} + \frac{(\log HPI_0 - \log HPI_t)}{\max\limits_{j \in \{1,\dots,9\}}(\log HPI_0 - \mathrm{lo} \qquad {}_j)}\right]. \tag{3}$$

Second, we assume that the capital loss in percentage points of RWA during the projected scenario is proportional to the severity index. Using the minimum CET1 ratio for a given bank i, k_{i,t^*}, we can determine the constant of proportionality between projected CET1 ratios and the severity index, $\alpha_i = \left(k_{i,0} - k_{i,t^*}\right)/(severity_{t^*})$, where t^* denotes the quarter where the severity index peaks. Our assumptions imply than the projected path of capital reaches its minimum when severity peaks, and provide an estimated path for each bank's CET1 ratio, $k_{i,t} = k_{i,0} - \alpha_i\, severity_t$. Using individual bank's projected paths, we compute the geometric mean of CET1 ratios for participating firms in each quarter, $\bar{k}_t$.

[42] See https://www.federalreserve.gov/publications/files/2018-dfast-methodology-results-20180621.pdf

Tables and Figures

Table 1. Effect of Funding and Macroeconomic Shocks for DFAST 2018 Banks

Shock	Mean	Standard Deviation	10th Percentile	Median	90th Percentile
Prudential funding	35	33	7	27	80
Macroprudential funding	6	6	1	4	13
Macroprudential funding (2 percentage point lower initial CET1 ratios)	50	48	10	38	115
Severely Adverse DFAST 2018	402	187	183	390	657

Note: Funding shocks are decribed in the text. The severely adverse scenario in DFAST 2018 includes macroecnomic and global market shock.
Source: Own calculations based on Board of Governors of the Federal Reserve System (US), Federal Reserve Bank of St. Louis, FR Y-9C, and U.S. Bureau of Economic Analysis.

Table 2. STWF Spread, Bank Capital, and Economic Conditions

Dependent variable: TED spread

	(1)	(2)	(3)	(4)
CET1	-1.651***	-1.624***	-1.185***	-5.871
	(0.211)	(0.187)	(0.395)	(8.674)
CET1 Squared	0.082***	0.077***	0.050***	0.293
	(0.011)	(0.010)	(0.018)	(0.485)
GDP Growth	-0.045***	-0.018	-0.059***	0.032***
	(0.010)	(0.012)	(0.012)	(0.014)
Constant	8.512***	8.773***	7.517***	29.406***
	(0.965)	(0.863)	(2.128)	(38.766)
Sample period	2001Q1-2019Q3	2007Q4-2019Q3	1996Q1-2019Q3	1996Q1-2007Q3
Capital ratio	CET1	CET1	T1CE	T1CE
F-statistic ($\bar{k}_t = \bar{k}_t^2 = 0$)	43.21***	61.98***	20.14***	12.35***
Observations	75	48	95	47
Adjusted R^2	0.651	0.818	0.338	0.371

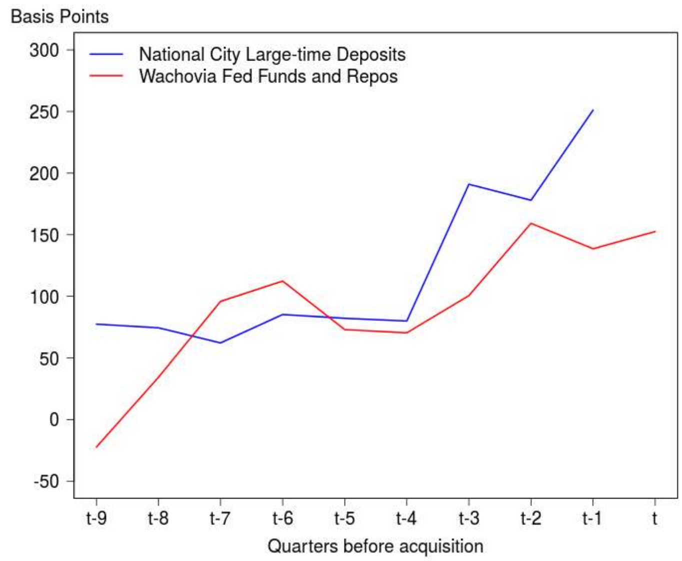
Notes: *** significant at 1 percent, ** significant at 5 percent , and * significant at 10 percent. CET1 common equity tier 1 capital CET1 common equity tier 1 capital, T1CE tier 1 common equity capital.
Source: Own calculations based on forms FR Y-9C, FRED, U.S. Bureau of Economic Analysis, and Board of Governors of the Federal Reserve System (US).

Table 3. Heterogeneous STWF Spreads, Bank Capital, and Economic Activity

	(1)	(2)	(3)
Dependent Variable:	TED spread	CP spread	STWF spread
CET1	-1.651***	-1.5000***	1.118***
	(0.211)	(0.210)	(0.418)
$CET1^2$	0.082***	0.075***	-0.058***
	(0.011)	(0.011)	(0.022)
GDP Growth	-0.045***	-0.040	-0.104***
	(0.010)	(0.010)	(0.020)
Constant	8.512***	7.582***	-4.102**
	(0.965)	(0.932)	(1.914)
Sample period	2001Q1-2019Q3	2001Q1-2019Q3	2001Q1-2019Q3
F-statistic ($\bar{k}_t = \bar{k}_t^2 = 0$)	43.21***	33.46***	3.63**
Observations	75	75	75
Adjusted R2	0.651	0.593	0.265

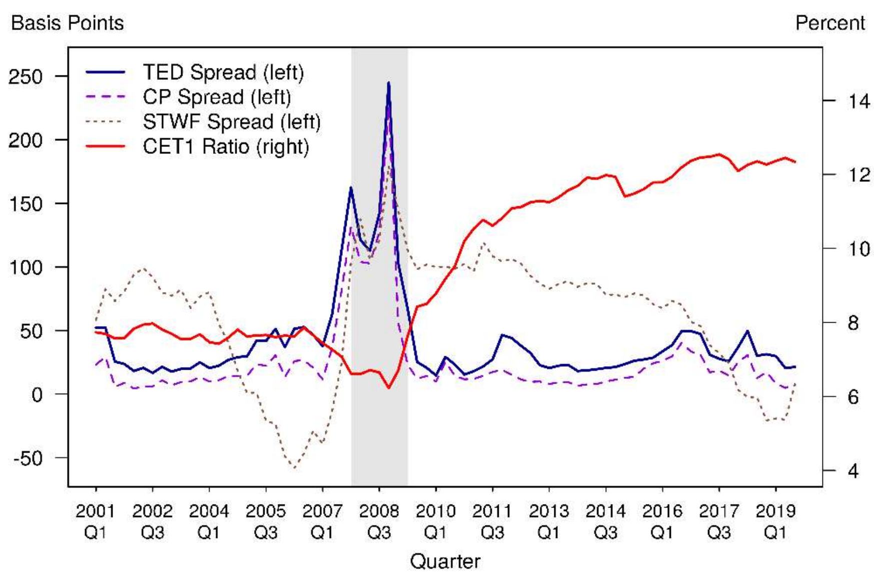
Notes: *** significant at 1 percent, ** significant at 5 percent , and * significant at 10 percent. CET1 common equity tier 1 capital.
Source: Own calculations based on Board of Governors of the Federal Reserve System (US), Federal Reserve Bank of St. Louis, FR Y-9C, and U.S. Bureau of Economic Analysis..

Figure 1. Spread of STWF for Banks with Idiosyncratic Stress



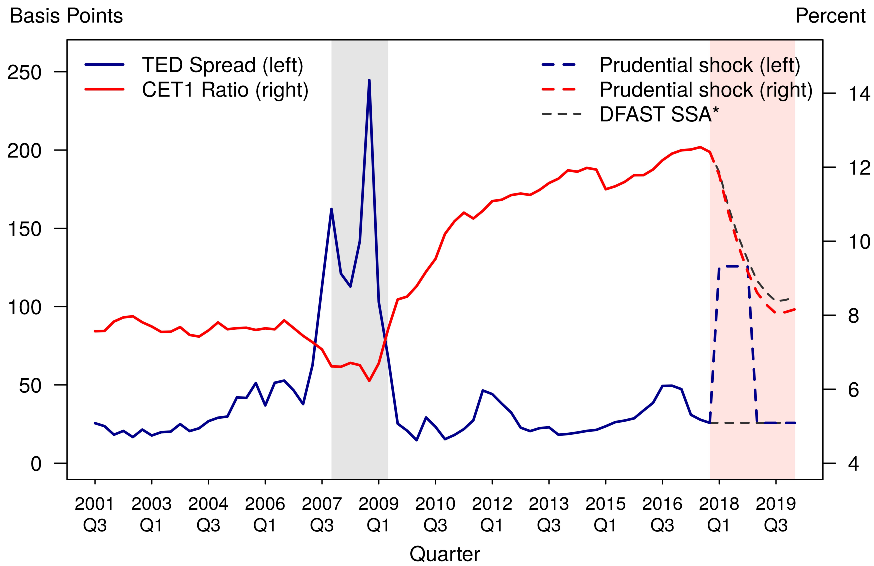
Note: Spread over a group of peer institutions that did not experience acute stress.
Source: Own calculations based on U.S. Call Reports.

Figure 2. DFAST 2018 Banks: Average Capital Ratios and STWF spreads



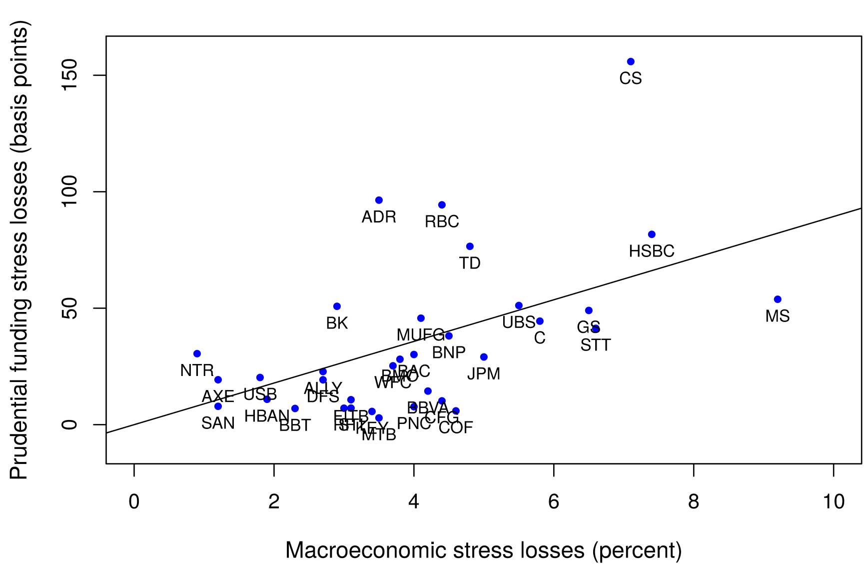
Notes: Average CET1 ratios corresponds to the geometric mean of CET1 ratios for DFAST 2018 banks. TED, CP, and STWF spreads are relative to 3-month US Treasury Bills. Shaded area denotes NBER recession quarters.
Source: Own calculations based on Board of Governors of the Federal Reserve System (US), Federal Reserve Bank of St. Louis, FR Y-9C, and U.S. Bureau of Economic Analysis.

Figure 3. DFAST 2018 Banks: Prudential Funding Shock



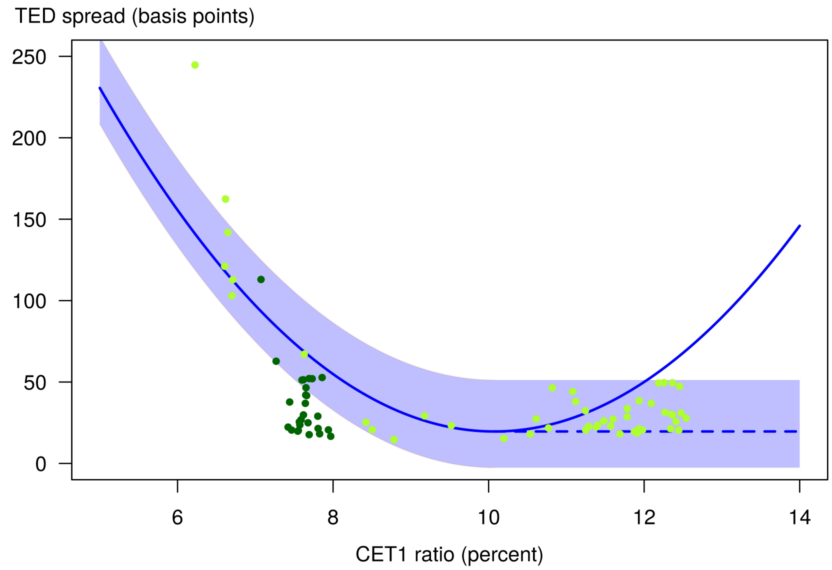
* DFAST SSA corresponds to the supervisory severey adverse scenario in DFAST 2018.
Source: Own calculations based on Board of Governors of the Federal Reserve System (US), Federal Reserve Bank of St. Louis, FR Y-9C, and U.S. Bureau of Economic Analysis.

Figure 4. DFAST 2018 Banks: Losses from Prudential Funding versus Macroeconomic Stress



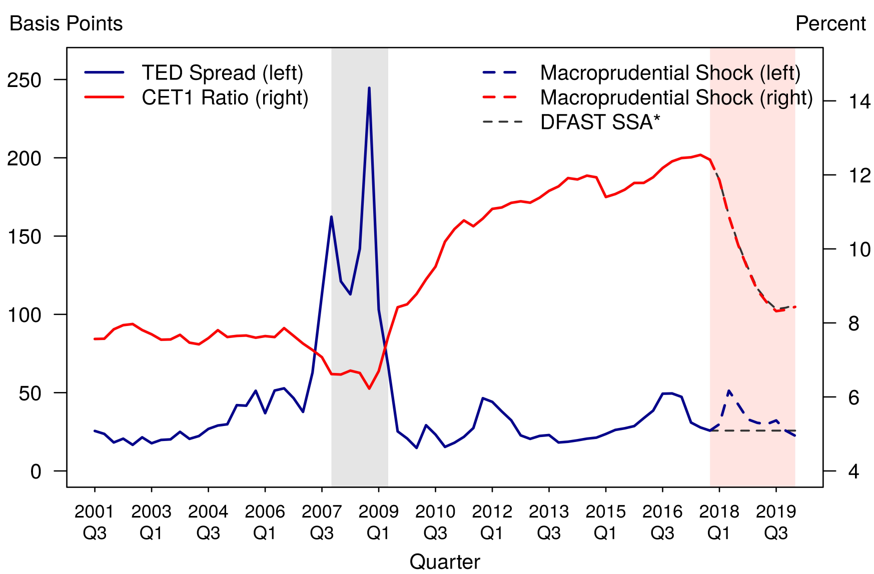
Notes: Losses expressed as a fraction of RWA. Losses from macroeconomic stress corresponds to the losses under the severely adverse scenario in DFAST 2018. Solid line corresponds to fitted linear model of prudential funding losses on macroeconomic losses ($\beta = 8.94$).
Source: Own calculations based on Board of Governors of the Federal Reserve System (US), Federal Reserve Bank of St. Louis, Nonconfidential FR Y-9C, and U.S. Bureau of Economic Analysis.

Figure 5. DFAST 2018 Banks: Average CET1 Ratio and TED Spread



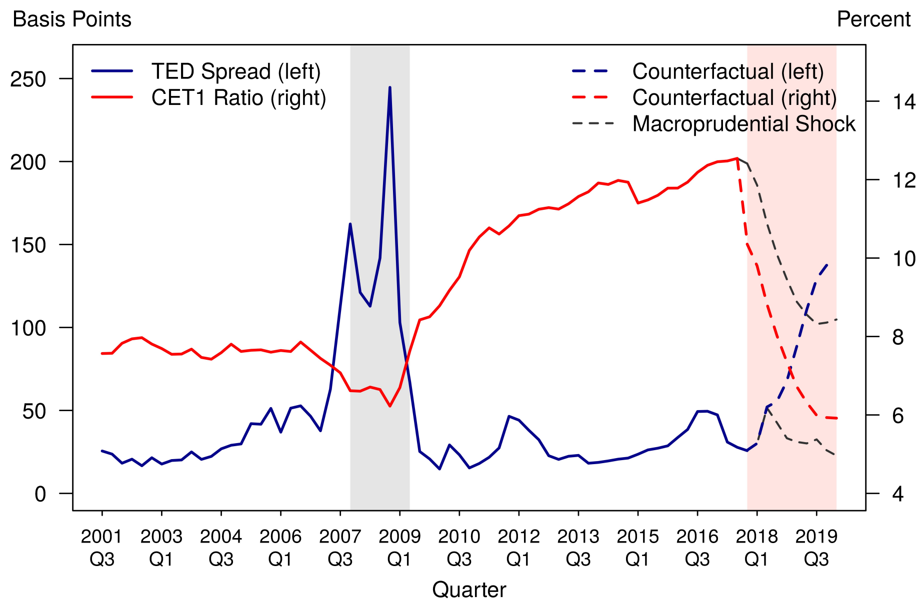
Notes: Post-2007 (light green dots) corresponds to the period from 2007Q4 to 2017Q4 and pre-2007 (dark green dots) to 2001Q1 to 2007Q3. The solid blue line is the projection of the TED Spread from the regression in column (1) of Table 2. The dashed line represents the transformed value when the CET1 ratio is greater than $\hat{\kappa} = 10.1$ percent based on equation (3).
Source: Own calculations based on Board of Governors of the Federal Reserve System (US), Federal Reserve Bank of St. Louis, FR Y-9C, and U.S. Bureau of Economic Analysis.

Figure 6. DFAST 2018 Banks: Macroprudential Funding Shock



* DFAST SSA corresponds to the supervisory severey adverse scenario in DFAST 2018.
Source: Own calculations based on Board of Governors of the Federal Reserve System (US), Federal Reserve Bank of St. Louis, FR Y-9C, and U.S. Bureau of Economic Analysis.

Figure 7. DFAST 2018 Banks: Leverage and Funding Spillovers



Source: Own calculations based on Board of Governors of the Federal Reserve System (US), Federal Reserve Bank of St. Louis, FR Y-9C, and U.S. Bureau of Economic Analysis.