



Environmental sustainability and financial stability: can macroprudential stress testing measure and mitigate climate-related systemic financial risk?

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Abstract

Despite widespread recognition among financial regulators and central banks that climate change may threaten financial stability, the causes and consequences of climate-related systemic financial risk remain underexplored. Stress testing has emerged as one of the most prevalent regulatory tools for addressing climate-related financial risks, and this article analyzes the role of stress testing in mitigating the effects of climate change on financial stability. Specifically, it synthesizes the multi-disciplinary literature on climate-related financial risk, financial stability, and stress testing to develop a framework for evaluating the capacity and effectiveness of stress tests for measuring and managing climate-related systemic financial risk. It then takes stock of climate stress testing proposals and early practices globally and applies the evaluative framework in comparative case studies of the Bank of England and US Federal Reserve. It concludes that stress testing can support the measurement and management of both microprudential and macroprudential climate-related financial risks, but the benefits of stress testing vis-à-vis climate change and financial stability are largely unrealized. Addressing the disconnect between climate stress testing policy motivation and implementation as well as the divergence between leading and lagging jurisdictions will require both interagency and international regulatory cooperation.

Keywords Climate-related financial risk · Systemic risk · Financial stability · Macroprudential regulation · Stress testing

Introduction

In 2015, Mark Carney referred to climate change as the “tragedy of the horizon,” remarking that because of the incongruous temporal scopes of financial stability policy and climate change consequences, “once climate change becomes a defining issue for financial stability, it may already be too late” [1 p.3]. There has since been a remarkable shift: a 2019 survey of financial regulators and central banks ($n = 33$) found that some 70% view climate change as a “major threat” to financial stability [2 p.7]. In some ways,

this shift is unsurprising given the increasingly widespread appreciation of the dire consequences of unmitigated climate change and interconnectedness of these consequences across sectors and geographies [3]. Yet, addressing the financial risks resulting from both the physical manifestations of, and societal responses to, climate change introduces a host of novel analytical and governance challenges for financial regulators and central banks [4]. Over the last several years, financial regulators around the globe have begun identifying, assessing, and, to a lesser extent, addressing climate-related financial risks. For example, a 2020 survey of Financial Stability Board members ($n = 33$)—comprising international and domestic banking, insurance, and investment regulators—found that nearly three-quarters (73%) consider, or plan to consider, climate-related financial risks in financial stability monitoring [5]. Another 2020 survey ($n = 27$) highlights the various activities that financial regulators and central banks are undertaking to better understand climate-related risks, including conducting research (89%), convening stakeholder conversations (92%), surveying firm

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practices (75%) and disclosures (87%), and issuing supervisory guidance (41%) [6].

Stress testing is among the most common regulatory tools for assessing and addressing climate-related financial risks. Myriad governmental, intergovernmental, and nongovernmental organizations have issued proposals calling for the institutionalization of climate stress testing [7–17]. Although a 2019 survey of financial regulators and central banks ($n=33$) found that only 15% of respondents include climate considerations in routine stress tests, some 79% reportedly planned to incorporate climate-related financial risks into future stress tests [2]. A 2021 survey of supervisors and regulators focused more broadly on the incorporation of environmental, social, and governance risks into stress tests ($n=14$) found similar results, with some 14% of respondents already integrating these risks into supervisory stress tests, 79% planning to do so in the next three years, and 7% engaging in related activities, such as voluntary exercises [18]. Despite this widespread interest among policymakers, climate stress testing practices are nascent [5, 6, 18–21]. Moreover, although financial regulators and central banks have framed climate change as a financial stability issue, there has been relatively little attention paid to the causes and consequences of climate-related systemic financial risk in extant policy discussions. The relationship between climate change, financial stability, and potential regulatory responses is similarly underexplored in the literature [22–24]. Recognizing that financial market policymakers and participants cannot manage what cannot be measured, and cannot measure what cannot be defined, this article provides a novel analysis of climate-related systemic financial risk and the role of stress testing in mitigating the effects of climate change on financial stability.

The article proceeds as follows: The “[Climate change and financial instability](#)” section defines and contextualizes the motivating problem—the potential effects of climate change on financial stability—through a discussion of the causes and consequences of climate-related systemic financial risk, integrating the multi-disciplinary literature on climate-related financial risk and financial stability. The “[Stress testing in theory and practice](#)” section reviews the literature on stress testing, with a focus on lessons learned in the post-global financial crisis implementation of microprudential and macroprudential stress tests. The “[Evaluative framework for climate stress testing](#)” section draws on the preceding sections to develop a framework for evaluating the capacity and effectiveness of stress tests for measuring and managing climate-related systemic financial risk. The “[Climate stress testing practices](#)” section takes stock of climate stress testing proposals and practices globally and applies the evaluative framework in comparative case studies of the Bank of

England (BOE) and Board of Governors of the US Federal Reserve System (FRB). The “[Conclusion](#)” section summarizes the article and describes areas for future research. To preview the key findings: stress testing can support the measurement and management of both microprudential and macroprudential climate-related financial risks, but the benefits of stress testing vis-à-vis climate change and financial stability are unrealized. Addressing the disconnect between climate stress testing policy motivation and implementation as well as the divergence between leading and lagging jurisdictions will require both interagency and international regulatory cooperation.

Climate change and financial instability

Assessing the effects of climate change on financial stability requires attentiveness to both the causes and consequences of climate-related systemic financial risk. While there has recently been considerable focus on climate-related financial risks and a recognition that such risks may be systemic, the underlying transmission channels and propagation pathways are underexplored in both the academic literature and extant policy discussions [5, 6, 20, 25–28]. Indeed, although there is a long standing literature on the macroeconomic impacts of climate change and an emerging literature on the relationship between certain climate-related risks and financial assets, the literature on both the transmission channels and consequences of climate-related risks for financial institutions and, particularly, systems is much less developed [20, 23, 24]. Synthesizing the climate-related financial risk and financial stability literatures, this section provides a high-level discussion of the environmental, economic, and financial risks resulting from climate change (light, medium, and dark blue boxes, respectively, in Fig. 1), their transmission channels, and the pathways by which climate-related financial risks may become systemic, thereby inhibiting financial stability (gray arrows in Fig. 1).

Climate-related physical and transition risks

Climate change creates and exacerbates natural hazards, which can be categorized as chronic or acute. Chronic natural hazards are persistent stressors (i.e., slow onset events) resulting from a warming climate, such as sea-level rise [12, 20, 29–31]. Acute natural hazards are episodic shocks (i.e., sudden onset events) driven by climate change, such as hurricanes [12, 20, 29–31]. As the climate warms more rapidly, the probability distributions of



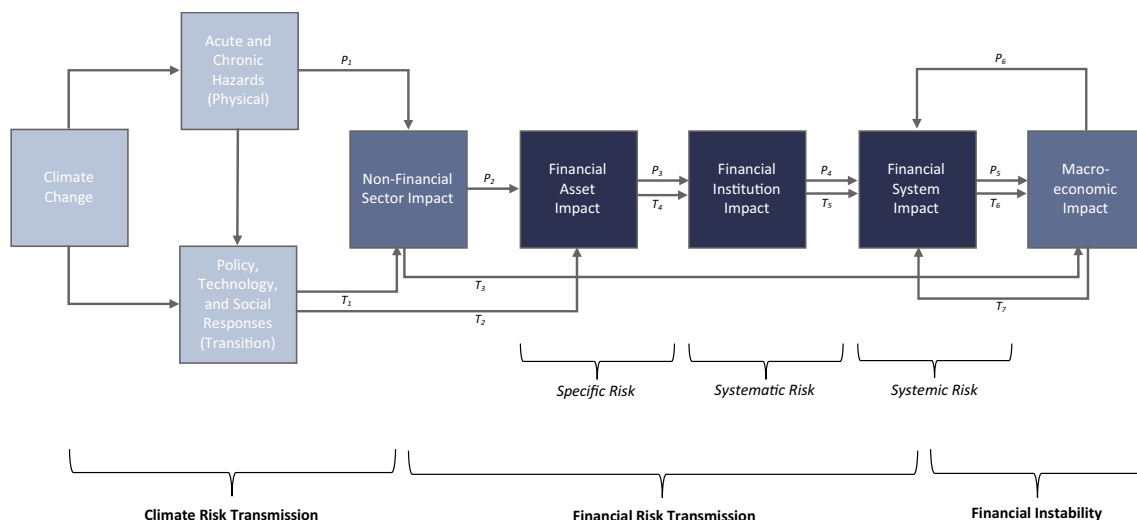


Fig. 1 Transmission of climate risk to financial markets and propagation of climate-related systemic financial risk

climate-driven natural hazards are shifting, resulting in an increased likelihood of catastrophic environmental consequences (i.e., fatter tails) [3].

The economic risks associated with climate change are categorized in the literature as physical and transition risks. Physical risk encompasses the economic consequences of an acute or chronic climate-driven natural disaster, such as the disruption, repair, and recovery costs a firm and its stakeholders incur as the result of inundation from a hurricane or extreme cold from a winter storm [12, 25].¹ Transition risk encompasses the economic consequences of policies (e.g., carbon tax), technological advancements (e.g., long-duration energy storage), or societal actions (e.g., shifting consumer or investor preferences) to mitigate or adapt to climate change [12, 25]. Extant discussions of transition risk often focus on the economic consequences of an abrupt transition to a lower-carbon economy, such as via rapid devaluation of carbon-intensive assets, but the transition to a sustainable economy should be defined more broadly. Specifically, as the Intergovernmental Panel on Climate Change's (IPCC) most recent report highlights, transitioning to a sustainable economy requires mitigation of all greenhouse gas emissions (i.e., carbon dioxide, methane, nitrous oxide, and fluorinated gases)—which involves not only a reduction in the production of greenhouse gas emissions but also the capture, use, and storage of emitted greenhouse

gases to reduce atmospheric concentrations—as well as adaptation to the existing irreversible effects of climate change [31–34]. Transition risk is distinct from physical risk in that it involves interaction among physical, political, social, and market dynamics, such that the adverse consequences may arise from both substantive changes as well as from uncertainty surrounding potential changes [25]. As such, the risks associated with the transition to a sustainable economy are often described as varying based on the extent to which the transition is “orderly” (i.e., immediate and measured) versus “disorderly” (i.e., sudden and unanticipated) [14].

Climate-related financial risks

Climate-related physical and transition risks affect both sectors in the real economy and the financial services sector. Climate-related financial risk can be quantified at the asset, institution, or system level. Climate change can affect financial assets by directly reducing the value or productivity of underlying real assets. For example, a natural disaster may destroy or rapidly depreciate the value of capital assets (i.e., property, plant, and equipment) while a carbon tax may increase operating costs for carbon-intensive activities, thereby reducing productivity of a given asset [35]. At the institution level, the effects of climate change may manifest in credit, market, liquidity, operational, or reputational risk. The materiality of these different risks will vary by institutional characteristics. An acute shock like a hurricane, for example, may increase a bank's credit risk (e.g., impairment of collateral assets), market risk (e.g., volatility in bonds and stocks for climate-exposed corporates), liquidity risk (e.g., fire sales for impacted assets), and operational

¹ Consistent with the literature, natural hazard is used to refer to the threat of a climate-driven natural phenomenon that will have a negative effect on humans, while the realization of that effect is referred to as a natural disaster.



Table 1 Examples of climate-related financial risk by transmission channel, risk type, and subsector

	Credit	Market	Liquidity	Operational	Reputational	
Physical	Banking	Loan defaults resulting from disruption costs for climate-exposed borrowers and impairment of collateral assets	Valuation uncertainty for climate-exposed assets	Interruption of electronic payment systems and associated demand for cash reserves	Business interruption or liability costs for climate-exposed locations or supply chains	Customer dissatisfaction with climate hazard mitigations
	Investment	Bond defaults resulting from disruption costs for climate-exposed issuers	Volatility in stocks, bonds, and derivatives for climate-exposed industries, regions, and underlying assets	Fire sales for climate-exposed assets	Business interruption or liability costs for climate-exposed locations or supply chains	Customer dissatisfaction with climate hazard mitigations
	Insurance	Large-scale correlated claims for climate-exposed property and casualty policyholders due to increasingly frequent and severe acute and chronic climate hazards			Risk transfers to reinsurers and government insurers of last resort for climate-exposed underwriting	Customer dissatisfaction with climate hazard mitigations
Transition	Banking	Loan defaults resulting from technology- or policy-driven transition costs for carbon-intensive borrowers	Valuation uncertainty for carbon-intensive (or transition-enabling) assets	Rapid draw down of deposits or credit lines for counterparties affected by climate change mitigation or adaptation policies	Legal and compliance costs associated with carbon-intensive lending portfolios	Decreased shareholder value due to deficiencies in climate risk management
	Investment	Bond defaults resulting from technology- or policy-driven transition costs for carbon-intensive issuers	Abrupt price corrections in stocks and bonds for carbon-intensive industries and economies	Fire sales for assets affected by climate change mitigation or adaptation policies	Legal and compliance costs associated with carbon-intensive investment portfolios	Decreased shareholder value due to deficiencies in climate risk management
	Insurance	Premia mispricing for carbon-intensive (or transition-enabling) policyholders given uncertainty around climate change mitigation and adaptation technologies			Risk transfers to reinsurers and government insurers of last resort for carbon-intensive underwriting	Decreased shareholder value due to deficiencies in climate risk management



risk (e.g., business interruption costs for locations or supply chains). Table 1 provides examples of climate-related financial risks by transmission channel (i.e., physical, transition), financial risk type (i.e., credit, market, liquidity, operational, reputational), and subsector (i.e., banking, insurance, investment); because large financial institutions often provide diversified financial services, climate-related financial risks for a given firm may span multiple subsectors.

Climate-related systemic financial risk

Climate change may threaten financial stability if climate-related financial risks are, or become, systemic. Despite widespread interest in the concept of systemic risk in the post-global financial crisis era, there is no widely accepted definition. Drawing on the existing literature, this article defines systemic risk as risk that propagates at the financial system level (i.e., financial shock amplification), impeding the functioning of the financial sector (i.e., financial system impairment), and creating spillovers into the real economy (i.e., financial externalities) [38]. Systemic risk should be distinguished from specific risk (i.e., idiosyncratic risk), which manifests at the asset and institution levels and can be managed at the portfolio level through diversification. Although often conflated, systemic risk should also be distinguished from systematic risk (i.e., market risk), which manifests at the sector or subsector level but does not have the potential to impede the operating of the entire financial system or create spillovers into the real economy [39]. While much of the discussion about systemic risk focuses on country-level macrofinancial linkages, a “system” can be defined at various scales ranging from local to global. Recognizing the regional dynamics of climate-related financial exposures—for example, regions susceptible to hurricanes and primarily served by small and community banks—the concept of “sub-systemic” risk has been articulated in recent regulatory discussions [10]. One conceptually useful way to understand systemic risk is vis-à-vis the potential of a risk to inhibit financial stability (i.e., the ability of the financial system to manage risks and absorb shocks in order to continually support economic processes) [40, 41].

Climate change may trigger both exogenous and endogenous sources of systemic risk. Unmitigated global warming may cause sufficiently widespread and consequential exogenous shocks to be destabilizing to the financial system and the real economy. However, systemic risk may also be endogenous, resulting from the amplification of an initial localized shock and ensuing system-wide propagation of risk [42]. Various system dynamics—including interconnectedness (e.g., tight coupling within and across banking, insurance, and investment services), complexity (e.g., multi-sector and multi-jurisdiction scope), brittleness (e.g., mispricing due to uncertainty), and procyclicality (e.g.,

excessive leverage)—can make a system more vulnerable to systemic risk amplification, including as a result of climate change [5]. Because anticipating and preventing exogenous shocks is exceedingly difficult, systemic risk management often focuses on identifying propagation pathways and addressing firm- and system-level vulnerabilities that enable risk magnification [42]. However, climate change is a known risk, and as such both the exogenous triggers and endogenous propagation of climate-related systemic financial risk can be analyzed.

As depicted by the feedback loops in Fig. 1, the propagation pathways for climate-related systemic risk are complex and interdependent. Indeed, the Bank for International Settlements (BIS) has described climate change as a “green swan,” because it is a source of systemic risk characterized by “interacting, nonlinear, fundamentally unpredictable, environmental, social, economic and geopolitical dynamics” [36 p. 1, 43]. Building greater understanding of these dynamics is an active area of research [5, 6, 25, 27], and the following hypothetical examples illustrate two potential climate-related systemic financial risk propagation pathways (depicted by the “P” and “T” arrows in Fig. 1).

The first example focuses on physical risk: a severe hurricane that negatively affects individuals and firms in the real economy (P_1). The resulting inundation of residential and commercial property leads to asset devaluation, such as loan collateral for mortgages (P_2). This specific risk becomes a systematic risk as the resulting devaluation leads to widespread losses among financial firms insuring, investing in, or lending against those assets via property insurance, mortgage-backed securities, or collateralized real estate loans (P_3). This systematic risk becomes a systemic risk as the mispricing of climate-related risk and interconnectedness amplify initial losses via fire sales and counterparty contagion, which in turn impedes the functioning of the financial system (P_4) and constrains lending to the real economy (P_5) [44, 45]. This credit supply shock contributes to macroeconomic contraction, which, when coupled with other direct effects of the precipitating risk (e.g., reduced gross regional product due to business disruptions) creates a negative feedback loop to financial system instability (P_6). This simplified example is most plausible when the system is defined relatively locally. However, these dynamics could also be observed at the regional or national level as climate-driven natural hazards become more frequent and severe, thereby increasing the probability of coinciding and compounding climate hazards (e.g., heatwaves and wildfires) within geographies and sectors [3].

The second example focuses on transition risk: a climate mitigation policy that internalizes emissions externalities, for which affected industries have not sufficiently prepared and thus results in a sudden increase in firm operating costs (T_1) and correction in asset pricing (T_2) [46]. This abrupt



transition affects short-term production as carbon-intensive industries adapt, thereby potentially contributing to a macroeconomic contraction (T_3). In parallel, it also creates “stranded assets” (i.e., assets such as fossil fuel reserves that are rapidly and substantially devalued) and this specific risk becomes a systematic risk because devaluation affects not only asset owners in the real economy, but also creditors, shareholders, and insurers that fail to properly price transition risks (T_4) [47, 48]. These widespread correlated exposures among financial institutions could result in systemic risk as uncertainty amplifies the initial price shock (T_5). The rapid deflation of a “carbon bubble” (i.e., the inflated valuation of carbon-intensive firms resulting from the substantial negative carbon emissions externality) could result in reinforcing negative feedback loops among the financial sector (T_6) and real economy (T_7), mirroring the asset bubbles that have preceded prior financial crises [1, 49].

Thus, evaluating the effects of climate change on financial stability requires identifying how the precipitating climate change risk is transmitted to the financial sector, how the resulting financial risks propagate across the financial system, and how macrofinancial linkages amplify or absorb these risks. Drawing on the discussion of physical and transition risks, climate-related financial risks, and the potential propagation of climate-related systemic risk in this section, the subsequent sections analyze whether and how stress testing can be used to operationalize these dynamics to mitigate the effects of climate change on financial stability.

Stress testing in theory and practice

To analyze whether and how stress testing can be used to measure and manage climate-related systemic risk, it is important to first reflect on the existing uses of stress testing in the financial sector, and the benefits and limitations of stress testing as a macroprudential tool. This section summarizes the emergence, current practice, and scholarly critiques of stress testing, which in turn informs the development of the evaluative framework for climate stress testing presented in the next section.

Stress testing is a form of scenario-based analysis used to evaluate the resilience of an institution or system to hypothetical stressors [50, 51]. Financial stress tests use scenarios to define exogenous shocks and adverse market conditions, and financial models to project how these stressors affect the exposures of financial firms or sectors and the implications for institutional or system resilience [52]. Financial firms have long used scenario-based analysis for internal risk management, and the implementation of bank stress tests was supported by international frameworks such as the Basel Committee for Banking Supervision’s 1996 Market Risk Amendment and 2004 Basel II framework [53, 54].

In addition to these firm-level stress tests, the International Monetary Fund (IMF) and World Bank established the Financial Sector Assessment Program in 1999, which includes macro stress tests of participating countries’ financial systems [54]. During the 2007–2009 global financial crisis, stress testing became an integral component of crisis management, particularly for the FRB and the Committee of European Banking Supervisors. Stress testing was systematically integrated into post-crisis microprudential and macroprudential regulatory and supervisory toolkits [54, 55].

As this brief history demonstrates, supervisory stress testing—i.e., stress tests designed, implemented (or overseen), and analyzed by regulatory agencies, central banks, or supervisory authorities—plays a distinctive role depending on when it is deployed. In “wartime,” stress testing supports crisis management [56]. For example, it can inform recapitalization strategies and restore market confidence by sending a signal about the resilience of financial firms and sectors amidst a crisis and concurrent policy responses. In “peacetime,” stress testing supports risk management [56]. For example, it can be used to monitor risks and inform regulation by providing a forward-looking assessment of institutional and system resilience to potential (severe but plausible) adverse scenarios.

Supervisory peacetime stress tests can be further categorized by their policy objectives [57]. Microprudential stress tests seek to inform firm-level actions, including setting microprudential standards and informing firm risk management practices. For example, solvency stress tests provide a forward-looking dynamic assessment of capital adequacy and are used to calibrate static backward-looking firm-level capital standards in many jurisdictions [54, 55, 58]. Macroprudential stress tests seek to inform system-level actions, including monitoring systemic risk and calibrating policies targeting financial stability. For example, some jurisdictions use stress tests to calibrate countercyclical capital buffers and sectoral capital requirements [59]. While some authorities, such as the European Central Bank (ECB), separate microprudential and macroprudential stress testing exercises, many jurisdictions implement stress tests that have both microprudential and macroprudential objectives [60].

A theme across the extant stress testing literature is that the design of stress tests should be aligned with underlying policy objectives [52, 56]. While this seems fairly intuitive, in practice policy objectives and stress test designs have diverged based on regulatory authorities and resources [57, 61]. A key design consideration is the level at which stress tests are implemented (i.e., firm vs. system), which should align with the risks that are being measured and the potential risk management actions that are being considered, and will determine the metrics, models, and data that are fit for purpose [61]. Firm-level stress tests measure the effects of a given scenario on a firm’s portfolio and generally employ



bottom-up models, in which the empirical relationship between the stressor and the outcome of interest is estimated at a high level of granularity using firm-specific data.² This modeling approach enables an assessment of financial institutions' idiosyncratic risks and as such is useful for informing firm-level risk management practices and calibrating microprudential regulatory requirements. In contrast, system-level stress tests seek to measure the effects of a given scenario at the sector or subsector (e.g., banking, insurance, investment) level, and are generally conducted by centralized regulatory authorities using top-down models, in which the empirical relationship between the stressor and the outcome of interest is estimated at a lower level of granularity using aggregate macroeconomic and regularly reported macrofinancial data [50–52]. This modeling approach enables an assessment of system-wide risk and as such may inform the calibration of macroprudential standards [43, 52]. In practice, stress tests with both microprudential and macroprudential objectives have combined top-down, bottom-up, and hybrid modeling approaches [57]. For example, the BOE and FRB both conduct stress tests with microprudential and macroprudential objectives but employ different modeling priorities with respect to granularity and severity. In the US, supervisors focus modeling efforts on “forming an independent view of bank level results at a fairly granular level,” often employing more plausible scenarios, while in the UK, supervisors focus modeling efforts on “understanding the system-wide effects involving spillovers into the rest of the financial system and the real economy,” often employing more severe scenarios [56 p.134]. Some scholars have argued that the former enables a more robust coupling of stress testing and microprudential regulation and partially addresses concerns about model instability in more top-down approaches [63]. However, others have argued that the latter plays to the comparative advantage of regulators in conducting peacetime macroprudential stress tests with more severe scenarios to explore emergent risks and system vulnerabilities, which in turn can be used to link stress testing to macroprudential regulation [64].

Notwithstanding the argument that firms have a comparative advantage in understanding institutional risks whereas regulators have a comparative advantage in understanding system-wide risks [56], another key theme in the literature is the analytical complexity associated with measuring and managing financial stability risks, including via macroprudential stress testing. In particular, the literature underscores

the challenges of modeling both exogenous and endogenous sources of systemic risk [43]. As discussed above, systemic risk may result from an exogenous shock that is sufficiently widespread and high consequence to be destabilizing. Thus, one concern raised in the literature is whether the shocks introduced in stress test scenarios are appropriately severe to represent potential threats to financial stability [55]. Indeed, scholars have argued that stress tests have performed poorly as early warning devices, calling into question the utility of stress tests in operationalizing inherently difficult to predict tail risks (i.e., low probability, high consequence) [52, 55]. However, systemic risk often results from the amplification of risk throughout the financial system, even if the precipitating shock is relatively localized. A second concern raised in the literature is how completely the propagation of systemic risk is analyzed. In general, microprudential stress tests model first-round effects—i.e., the direct and isolated impacts of a scenario on a firm's balance sheet—whereas macroprudential stress tests should include both first- and second-round effects—i.e., the indirect and interactive impacts of a scenario on a broad range of financial and non-financial sector agents [57]. To measure these indirect and interactive effects, stress tests need to model the propagation of risk throughout the system, including amplification among interconnected financial institutions and potential spillovers into the real economy [43, 51, 55]. Existing studies, and historical experience, suggest the magnitude of these second-round effects can be quite substantial [65, 66].

For jurisdictions that implement stress tests to fulfill both macroprudential and microprudential objectives, the direct effects captured in firm-level horizontal stress tests may provide the foundation for analysis of second-round effects at the system level [51]. Several authorities have made progress on developing modeling approaches for direct contagion channels (i.e., cross-holdings) and selected macrofinancial feedback loops within stress tests [43]. For example, the ECB's macroprudential exercise models feedback effects for individual banks and interbank contagion as well as selected macrofinancial linkages [57]. Another example is the IMF, which models amplification mechanisms resulting from interconnectedness and leverage in the interbank market as well as feedback loops between the financial sector and real economy within and across jurisdictions [67]. However, the literature identifies persistent analytical challenges associated with representing indirect contagion effects (i.e., interlinkages), such as fire sales, information asymmetry, strategic complementarities, and herding [43], as well as integrating the full set of potential interactions among the financial sector and real economy [55]. Moreover, existing approaches tend to focus on transmission channels for which models are well-established [57], resulting in incompleteness around novel sources of risk that do not propagate through standard macrofinancial channels. Various strategies

² There is variation in how the terms top-down and bottom-up are used in the context of stress testing. In Europe, they often refer to whether banks (i.e., bottom-up) or their supervisors (i.e., top-down) develop the models and scenarios and manage the implementation, whereas in the US they often refer to the level at which empirical relationships are estimated [52, 62].



to incorporate a broader range of transmission channels into stress tests have been proposed, such as integrating liquidity and solvency stress testing to capture liquidity-solvency interactions as a source of microprudential risk and potential systemic feedback loops (e.g., via fire sales), as well as layering network analysis and agent-based-modeling to analyze the propagation of macroprudential risk via contagion and dynamic firm behavior, respectively [65, 66].

A final theme in the literature is that stress tests should enable not only risk measurement but also risk management, albeit with robust debates about the efficacy of alternative mechanisms [61]. For example, the scope, timing, and granularity of stress test disclosure varies across jurisdictions [57], and while there is scholarly consensus that disclosure of firm-level results is essential for promoting market discipline [55], there are divergent perspectives on the consequences of disclosing models and methodologies (e.g., due to concerns about gaming and model monoculture) [68]. There is also variation in how stress test results are used and debates about the implications for effectively managing risks. Some have argued that for stress tests to be effective they must be tied to remedial actions, such as calibrating regulatory requirements or approving firm strategies [54, 55]. Indeed, one of the BIS' stress testing principles is that "stress testing should be used as a risk management tool and to inform business decisions," including "to quantify the capital needs at [a] systemic level during a time of crisis" and "to inform the calibration of macroprudential policies and instruments" [61 p.87]. Others have argued that the primary risk management benefit of stress testing is structuring thinking among various stakeholders, including firms and market regulators with more microprudential perspectives and central banks and financial stability regulators with more macroprudential perspectives [52, 69].

In summary, stress testing is an essential financial regulatory risk measurement and management tool. While the governance, implementation, and outcomes of stress testing have become more robust in the decade since the global financial crisis, the literature raises concerns about the alignment between stress testing objectives and design, the challenges associated with measuring systemic risk, and the ways in which stress testing can support not only risk measurement, but also more effective risk management.

Evaluative framework for climate stress testing

This section develops a framework for analyzing whether and how stress testing can be used to measure and manage climate-related systemic risk, and in turn, mitigate the effects of climate change on financial stability. Drawing on the climate-related financial risk, financial stability, and

stress testing literature discussed in the preceding sections, the framework is grounded in two principles.

First, the design and use of climate stress tests should be aligned with the underlying policy objective. Stress tests, including those incorporating climate change, may be used to address financial firm risks, financial system risks, macroeconomic risks, and, in some cases, a central bank's own balance sheet risks [15]. Given that financial regulators and central banks have largely mobilized around climate change as a potential threat to financial stability, climate stress tests should seek to inform the measurement and management of climate-related systemic risk. With respect to measurement, climate stress tests should provide legibility into the effects of climate change on financial institutions and the financial system in which they are embedded, with attentiveness to how climate-related financial risk can propagate through the financial system and create spillovers into the real economy. To mitigate the effects of climate change on financial stability, stress tests should enable more effective or efficient management of climate-related systemic risk by financial regulators, firms, and markets.

Second, the integration of climate risks into stress tests should be informed by institutional constraints, including the scope of financial stability regulatory authorities and design of existing stress testing regimes. This attentiveness to institutional design is critical to ensure that climate stress testing is feasible in the near-term and climate risk is systematically integrated into financial risk measurement and management practices rather than treated as an ancillary non-financial risk in the longer-term. Given existing policy debates about the utility of macroprudential stress testing, the framework is particularly focused on opportunities to address deficiencies identified in the literature and calibrate existing stress tests to better capture potential systemic risks, including those introduced by climate change. Recognizing the wide range of existing stress test designs and heterogeneity of climate exposures across firms, the framework focuses on how firm-level stress tests can inform system-level analysis as well as risk management actions by regulators, firms, and markets via a two-stage modeling approach, thereby incorporating both microprudential and macroprudential policy objectives.

The framework consists of seven criteria that can be used to evaluate whether and how stress tests are, or could be, used to support the measurement of climate-related systemic risk ("[Risk measurement](#)" section) and whether and how the outcomes of stress tests are, or could be, used to improve the management of such risks ("[Risk management](#)" section). This framework is applied to comparative case studies of effectiveness and capacity below ("[Framework application](#)" section).



Risk measurement

The first set of criteria analyzes the capacity or effectiveness of a given stress testing regime for measuring climate-related systemic financial risk. Notably, the goal of macroprudential climate stress testing should not be to precisely predict the causes and consequences of climate-related systemic financial risks, but rather to explore various transmission channels and propagation pathways within the financial system and identify firm- and system-level vulnerabilities that enable the magnification of these risks. As such, the four risk management criteria—scope, scenario design, metrics, and systems analysis—focus on the extent to which stress tests do, or could, support assessment of the potential effects of climate change on financial stability.

Scope: supervisory stress tests are applied to all systemically important and materially climate-exposed financial firms

The first risk measurement criterion relates to the applicability of scenarios, that is, which financial firms are subject to climate stress tests. Although all firms with material climate exposures should consider employing scenario analysis to measure the resilience of their business strategies to physical and transition risks, initial prioritization of supervisory stress tests should be guided by the regulatory principles of materiality and proportionality.

Regulators should prioritize stress testing firms with the greatest climate-related financial exposures—firms for which the realization of severe physical or transition risks could impair functioning—and firms of the greatest systemic importance—firms whose impairment would pose the greatest risk to financial stability. This dual focus on the materiality of climate exposure and proportionality of systemic importance underscores the criticality of centralizing climate stress testing with regulators empowered to address financial stability rather than those focusing on conduct within a particular subsector (e.g., banking, insurance, investment). A sectoral approach may lead to the systematic underestimation of the effects of climate change on particular types of financial products and firms and an incomplete representation of interactions and amplification mechanisms, thereby limiting the validity of any results vis-à-vis financial stability [57, 70]. There may be reasonable, albeit imperfect, proxies to guide selection; for example, size, interconnectedness, complexity, substitutability, and cross-jurisdiction activity are used as indicators of systemic importance and factors such as relative concentration of lending in climate-exposed regions, financed emissions, or carbon-intensity of investment portfolios may be used as partial indicators of climate-related financial exposures [18, 20, 71, 72].

Scenario design and modeling approach: input variables and models incorporate climate-related financial risks transmitted via physical and transition channels, with appropriate spatial and temporal resolution and robust representation of uncertainty and interdependencies

The second risk measurement criterion relates to the stressors—i.e., the exogenous shocks and adverse market conditions as represented by input variables—applied within a given test and the modeling approaches used to estimate the impacts of stressors on tested firms. In other words, as depicted in Fig. 1, climate stress test scenarios and models provide the translation from climate risk to macroeconomic (or sectoral) risk to financial (asset, firm, or system) risk.

With respect to input variables, stress tests generally include an underlying narrative, transmission channels, and specification of the scope and severity of stressors [57]. For climate stress tests, the underlying narrative should reflect the acute or chronic climate hazards and policy, technology, or social changes that result in physical and transition risk, respectively. For example, physical risk might be operationalized via temperature pathways and the frequency and severity of resulting extreme weather events, while transition risk might be operationalized via carbon prices, emissions, and energy mix [14, 72]. Scenario narratives are essential for both guiding modeling and articulating non-modellable underlying assumptions, which may be particularly relevant for climate risks (e.g., due to political and behavioral dynamics). The transmission channels should specify how the underlying climate risks or responses represented in the narrative cause an exogenous shock or adverse market conditions, and the resulting impacts on key macroeconomic and macrofinancial input variables. For example, macroeconomic variables might include changes in gross domestic product, unemployment, sector profitability, and property prices while macrofinancial variables might include corporate and government bond yields, equity indices, and exchange rates. While existing stress test scenarios are often threat agnostic (e.g., operationalizing recessionary conditions but not defining the causes of the recession [73]), specification of the underlying causes and causal paths informs risk management and enables more robust ex-post validation of scenario and model assumptions, which is particularly important for novel financial risks, including those resulting from climate change. Given the relationship between physical and transition risks—for example, the increasing severity and frequency of climate-driven natural hazards creates more pronounced physical risks, which may in turn increase the likelihood of mitigation policies, thereby producing transition risks and, over the longer-term, reducing physical risks—climate stress tests should address both. Including multiple risks and transmission channels in a single scenario



is more computationally intensive than developing parallel scenarios, but also enables more accurate representation of the interdependencies among climate-related risks and responses [36].

Scenarios should include robust representation of uncertainty with respect to the spatial and temporal scope and severity of climate risks and responses, as well as the resulting economic and financial consequences. Scenarios will necessarily have different scopes based on the underlying risk and transmission channel. For example, temperature-based scenarios tend to be longer than event-based scenarios, with policy-based scenarios varying based on a given temperature or emissions target [10]. Given that climate change will have both within- and cross-sector/-border impacts as well as near- and long-term impacts, integrating climate change into existing stress tests will almost certainly necessitate longer time horizons and broader scopes to fully capture risks and impacts. However, early progress on climate stress testing has demonstrated the ability to disaggregate nearer-term (i.e., within the current business cycle) and longer-term (i.e., outside of the current business cycle) assessments of climate risk and strategies to address the uncertainty associated with each [74]. Uncertainty about the magnitude of impacts can be partially captured through scenarios of varying severity, while uncertainty about the spatial or temporal scope of impacts can be partially captured by calibrating models to reflect near-term and localized extreme worst-case scenarios (i.e., tails of predicted climate risks to enable realization of macroeconomic and financial impacts within the scenario scope) [75]. Including at least one tail risk scenario is critical for representing the potential exogenous triggers of climate-related systemic financial risk. Given the probabilistic nature of climate risks and responses, uncertainty regarding the scope and severity of the resulting impacts, and the novelty of modeling these dynamics for financial regulators, early stress tests should account for some degree of model error and assumptions should be well documented and iteratively reviewed [63].

The second component of scenario design is the modeling approach, that is, the methodologies by which input variables are translated into impacts on financial assets, firms, and systems [43, 52]. As discussed in the previous section, stress tests may employ top-down, bottom-up, and hybrid estimation models, which vary in the scope of risks included and granularity of data required (e.g., level of sub-sectoral and regional decomposition). For example, transition risks may be more feasible to represent in top-down models because the hypothesized transmission pathways are operationalized at the macroeconomic and sectoral levels. Physical risks, on the other hand, may be more feasible to represent in hybrid or bottom-up models that

can account for regional economic impacts and heterogeneous portfolio-level interactions. The modeling approach will also affect the steps required to conduct systems analysis and translate results into firm- and system-level risk management strategies. To the extent possible, modeling approaches should seek to balance microprudential and macroprudential objectives.

Although developing climate stress tests requires novel data and modeling capabilities [4, 76], there are opportunities to leverage scenarios and methodologies developed by intergovernmental organizations. For example, the Network of Central Banks and Supervisors for Greening the Financial System (NGFS) and the UN Environment Programme's Finance Initiative have drawn on well-established general circulation models, natural hazard models, and integrated assessment models to develop reference scenarios for various physical and transition risks and, to some extent, translate these climate risks into macroeconomic and macrofinancial input variables [77, 78]. Discussed in more detail in the "Climate stress testing practices" section, leading jurisdictions have leveraged these reference scenarios and underlying climate-economy and macroeconomic models, commercially available scenario analysis tools, in-house financial models, and diverse data sources to implement climate scenario analyses and stress testing pilots [5, 21]. International cooperation among financial regulators on climate scenario design is particularly important because of the cross-border and multi-sector nature of climate-related financial risks and thus the need to compare and aggregate results across jurisdictions and sectors [18, 21]. Additionally, coordination among domestic and international financial and environmental authorities can ensure the accurate translation of climate and natural hazard models into scenarios appropriate for analyzing financial risks, which is essential given the heterogeneity of assumptions in underlying physical and social science climate models (e.g., regarding discount rates and climate sensitivity) [31, 79–81]. Finally, financial regulators and firms alike have flagged the importance of the development of a common set of scenarios and assumptions to provide the foundation for regulatory cooperation in the development of international standards for climate-related financial risk management [18].

Metrics: model output variables quantitatively and qualitatively measure how climate change affects the performance of tested firms and are translated into decision-relevant metrics

The third risk measurement criterion relates to what stress tests measure and whether output variables are relevant to firm or regulatory decision making. As described above, physical and transition channels may result in myriad types



of financial risks, including credit, market, liquidity, operational, and reputational risks. Some of these risks may be captured in standard stress test performance metrics, but probabilistic metrics that isolate the consequences of climate risks will enable more accurate performance targets as firms move from climate risk measurement to risk management.

The maturation of metrics for stress tests may be informed by, and may inform, the parallel development of green taxonomies, sustainable accounting methodologies, and climate risk disclosure frameworks, which in turn are driving advancements in climate risk analytics. Green taxonomies categorize sustainable and transition-enabling economic activities and assets and provide standardized definitions and a framework for categorizing contributions to climate change mitigation or adaptation [82]. Sustainable accounting methodologies provide a measurement approach for translating contributions to climate change or climate mitigation and adaptation efforts into financial metrics, which in turn can be integrated into both government reporting and private auditing standards [83–87]. For example, portfolio-level emissions can be used in various metrics that provide useful estimates of climate exposures, such as weighted average carbon intensity—which provides a measure of portfolio exposure to carbon-intensive companies weighted by company revenue—, carbon earnings at risk—the net present value of potential future earnings based on different carbon prices—, and portfolio alignment with various temperature targets. Other metrics focus on transition-enabling efforts, such as the dollar value of “green” transactions metrics. Moreover, academics are increasingly exploring how existing financial metrics can be adapted to better reflect climate risk, for example, scholars have proposed a climate value at risk assessment approach—which applies traditional value at risk methodologies to firms’ balance sheets but isolates the effects of climate risk scenarios of varying severity—as well as methodologies to extend solvency analysis to isolate the effects of climate risk proxies on capital adequacy [26]. Commercial service providers have incorporated approaches from the literature into scenario analysis frameworks, in part to meet the demand emerging from voluntary climate risk disclosure frameworks, such as the Task Force on Climate-related Financial Disclosures (TCFD) [12, 88, 89].

In addition to these quantitative performance metrics, stress tests should include qualitative assessments of firms’ climate risk management practices. A recent survey of central banks and regulators suggests that evaluations of governance practices and risk management frameworks are among the most common approaches for understanding how financial firms are addressing climate change risks [2]. Qualitative and quantitative metrics should be considered in combination to provide a holistic picture of exposures to physical and transition risks and the extent to which firms’ potential responses exacerbate or mitigate these risks. A key

benefit of regulatory cooperation in the development of climate stress testing—as with the post-global financial crisis development of solvency stress testing—will be establishing a more complete, consistent, and comparable set of metrics in an increasingly crowded and incompatible voluntary standards space.

Systems analysis: firm-level stress tests enable system-level analysis of the effects of climate change on financial stability, including correlated exposures, counterparty contagion, and the propagation of risks across the financial sector and real economy

The fourth risk measurement criterion relates to the extension of firm-level stress tests to measure the effects of climate change on the financial system and its stability via system-level analysis. As noted in the preceding section, a key tradeoff in the design of stress tests is the level of analysis, which should be driven by the underlying policy objectives and potential policy responses [52, 56]. Because climate-related financial risk may manifest and be managed at both the firm and system levels, climate stress tests should seek to combine microprudential and macroprudential objectives, using horizontal stress tests to measure firms’ idiosyncratic climate risks and systems analysis to understand how such risks aggregate and interact at the financial sector level.

As described above, climate change may trigger both exogenous and endogenous sources of systemic risk, which should be represented in systems analysis. To address the potential for a climate-driven shock that is sufficiently widespread to impede the functioning of the financial system, systems analysis should evaluate potential correlated exposures resulting from the inclusion of such a shock in the firm-level analysis. To address the potential amplification of climate-related financial risk, systems analysis should evaluate counterparty contagion and the propagation of risks within the financial system and across the financial sector and real economy. At the simplest level, systems analysis could consist of integration of firm-level results into aggregate metrics, such as total losses from a given climate change risk for a given set of firms. For example, scholars have recently proposed a systemic climate risk metric, “CRISK,” which is the country-level aggregate expected capital shortfall of banks resulting from climate transition risk scenarios [26]. As described above, it is common for regulators to use horizontal stress testing data and results for systems modeling, and aggregating firm-level results is necessary for understanding total direct effects and may be sufficient if the primary concern is widespread correlated exposures [26]. However, for many of the climate change dynamics that are hypothesized to have systemic implications, the concern is about not only the magnitude of direct effects, but also the potential for propagation throughout the system via



contagion and other amplification factors [21–23]. Horizontal firm-level stress testing that incorporates counterparty analyses may account for channels of direct contagion but is insufficient to capture sources of indirect contagion (e.g., fire sales, feedback effects). System-level analysis should therefore seek to model second-round effects, which would reflect the indirect and interactive impacts of scenarios on a range of financial, and potentially non-financial, sector agents [21]. These interactions can be modeled at the financial subsector level (e.g., among banks), financial sector level (e.g., among banks, insurers, and reinsurers), and at the multi-sector level (i.e., among the financial system and sectors in the real economy) [43, 51, 55, 67].

As previously noted, systemic risk modeling is an active area of research and capabilities may need to be developed iteratively depending on the scope and level of sophistication of an implementing authority's existing stress tests. For example, while many jurisdictions have developed strategies to quantify direct contagion and selected macrofinancial linkages, modeling of indirect contagion and non-traditional macrofinancial linkages is more limited. Developing a system-wide view of climate-related correlated exposures and potential counterparty contagion are critical first steps, and there are several opportunities for incremental expansion. For example, because the effects of climate change are heterogeneous across sectors and geographies, improving understanding of macrofinancial linkages among the financial sector and those sectors or regions most exposed to climate-related physical or transition risks is a critical first step [67, 75]. There are also opportunities for learning among leading jurisdictions. As discussed above, the ECB and IMF have developed advanced the modeling of second-round effects in routine stress tests that may be relevant to climate stress testing, and international coordination among early adopters of climate stress testing may enable a more holistic assessment of cross-border effects [5, 90]. Finally, there are emergent methodologies in the literature that may inform practice, for example researchers have begun exploring how complex systems modeling approaches (e.g., network analysis) can be used to better account for direct and indirect climate exposures among financial institutions and the systemic implications [25]. Forward-looking jurisdictions should approach the development of climate stress tests as an opportunity to improve the modeling of second-round effects (i.e., the endogenous drivers of financial instability), which together with the introduction of shocks that better represent tail risks (i.e., the exogenous drivers of financial instability) would considerably advance the quality of systemic risk stress testing more broadly, particularly with respect to representing underlying volatility, uncertainty, complexity, and ambiguity.

Risk management

Effective risk measurement is necessary but insufficient for mitigating the effects of climate change on financial stability. The second set of criteria analyzes the capacity or effectiveness of a given stress testing regime for informing the management of climate-related systemic risk via market discipline, risk mitigation evaluation, and evidence-based regulation. The role and limitations of stress testing as part of a broader climate risk management toolkit are discussed in the conclusion.

Market discipline: stress testing is sufficiently credible and transparent to promote market discipline by enabling more accurate pricing of climate risks and incentivizing improvements in tested firms' climate risk management practices

The first risk management criterion relates to whether the practice of stress testing and associated disclosures lead to improved climate risk management via market discipline. A key benefit of stress testing is that it enables market participants to better assess firms' risks and risk management approaches, which in turn incentivizes tested firms to improve performance and processes [55, 69]. For firms subject to climate stress tests, preparing for and participating in stress testing—which requires management articulation of and firmwide visibility into climate risks—may enhance board and management understanding of and accountability for climate risks, particularly when there is an expectation that results will be disclosed. With respect to markets, the disclosure of stress testing results can provide greater transparency around participating firms'—and potentially their major counterparties'—exposures to physical and transition risks and the efficacy of their risk management approaches. If this disclosure facilitates more accurate market pricing of climate risks, it may mitigate the adverse effects of a sudden policy-based price correction and the resulting financial stability consequences of a disorderly transition [24]. Similarly, the disclosure of stress test results may drive shareholder actions to enhance participating firms' climate risk management practices.

There is a longstanding literature on the role of stress testing results disclosure on market behavior across institutional contexts [91], and more recent empirical work highlights the power of climate disclosures to shape market behavior [92]. However, these market disciplining effects will only be observed if stress tests are credible and transparent, and the resulting disclosures are decision-relevant. Prior analyses suggest that disclosures of climate-related financial risks are “incomplete, inconsistent, and insufficient,” contributing to the dual market failures—emissions externalities and information asymmetries—driving the mispricing of climate risk



[86, 93, 94]. Disclosure of stress test results may promote market discipline if it enables more complete, consistent, and comparable accounting of climate-related financial risk. Moreover, while advocating for systems analysis to measure climate-related systemic financial risk, disclosure of such risks must necessarily occur at a more granular level to catalyze stakeholder actions. For example, firm-level reporting may enable market assessments of institutional resilience to climate change whereas reporting at a more granular level would be necessary to drive repricing of climate risks for financial assets [64].

Mitigation evaluation: stress testing enables tested firms to articulate and assess the effectiveness of alternative strategies to increase resilience to climate-related risks

The second risk management criterion relates to the extent to which stress testing enables tested firms to develop more effective and efficient climate risk management strategies. As described above, stress testing may incentivize firms to improve risk management—because participating firms gain a better understanding of their risks and anticipate market responses to the disclosure of results—but it may also enable participating firms to assess the effectiveness of alternative climate risk mitigation strategies. Such analysis may occur as part of routine stress testing via dynamic balance sheets or may be captured through a second-round or parallel analysis of risk management responses.

A wide range of climate-related financial risk management strategies are emerging, and stress testing can serve as a tool to quantitatively and qualitatively evaluate the effectiveness of alternative approaches. Articulating mitigation strategies—ranging from analyzing and pricing exposures (e.g., climate risk premia) to redirecting capital (e.g., divestment) to hedging (e.g., insurance) to capacity building—within the context of a stress test may enable both evaluation and demonstration of the resilience of selected strategies to physical and transition risks. For example, scenarios could be rerun with mitigations to identify their cost effectiveness relative to predetermined performance objectives or to evaluate the costs and benefits associated with a given mitigation [96]. A recent survey ($n = 71$) suggests that while myriad financial services firms are beginning to incorporate climate change into firm-run scenario analyses, such assessments are seldom used to inform risk management strategies [97]. This finding suggests an unrealized opportunity for firms to use climate stress testing to inform integrated strategies to mitigate their own climate-related financial risks as well as opportunities related to broader climate mitigation, adaptation, and monitoring efforts (e.g., investing in transition-enabling technologies, disclosing climate risk analyses). It should be noted that optimal climate risk management for individual firms may not be optimal for financial

stability and thus regulators should evaluate potential mitigations with respect to impacts on both firm and system resilience. For example, recent studies highlight the potential for protection gaps as EU insurers improve climate risk measurement capabilities and climate-related risk transfers in US mortgage markets [98, 99], this shifting of liabilities to households or taxpayers via government insurers of last resort could have systemic implications in a future with increasingly severe and widespread climate shocks. Thus, while financial firms can leverage climate stress testing to develop innovative strategies to manage their own climate-related risks, firm action alone does not enable complete understanding of system-level impacts or identification of socially optimal risk mitigation strategies.

Evidence-based regulation: stress testing provides evidence to regulators that informs the design and implementation of microprudential and macroprudential regulation to better manage the accumulation and propagation of climate-related systemic risk

The third risk management criterion relates to the role of stress testing in the design and implementation of evidence-based regulatory policy. As with stress testing more broadly, climate stress testing can inform risk management by enabling the calibration and enforcement of microprudential and macroprudential standards and supporting monitoring of the accumulation and propagation of climate-related risk throughout the financial system. While the literature suggests that linking stress tests to remedial actions is critical to promoting their effectiveness [55], doing so requires a relatively high degree of confidence in the risk measurement strategy. A debate in the literature is emerging regarding the comparative merits of building precise measurement strategies versus taking a more precautionary approach given the radical uncertainty associated with climate-related financial risk [100, 101].

Various microprudential and macroprudential tools to address climate risks have been suggested, including green-supporting or sectoral risk weights for capital requirements, concentration limits, carbon-countercyclical capital buffers, green supporting margin requirements, and enhanced climate risk disclosure [4, 49, 103, 104]. However, regulators are in the early stages of considering these measures; for example, a 2020 survey of central banks ($n = 27$) found that the majority had not yet considered including climate-related financial risks in prudential capital frameworks [6]. As microprudential and macroprudential regulations to bolster financial firm and sector resilience to climate change mature, stress testing may both inform design and enable implementation [14]. For example, the ECB has recently noted that while its climate stress test will not have a capital hurdle rate, it may inform the supervisory process by



which it sets banks' capital add-ons pursuant to Basel's Pillar II [106, 107]. Similarly, the BOE is using the results of its climate stress test to assess alignment with climate risk management supervisory expectations and is also exploring how underlying capabilities and data might be matured to support ongoing work on capital frameworks for climate risks [108].

In addition to informing microprudential and macroprudential regulation, stress testing may facilitate better understanding of the accumulation and propagation of climate-related risk throughout the financial system. Indeed, by incorporating tail risk scenarios, modeling endogenous drivers of financial instability, and exploring strategies to bolster system resilience, macroprudential climate stress testing could support a precautionary approach to climate risk. As described above, stress testing can help structure thinking among various stakeholders, including integrating the more microprudential risk management perspectives of firms and market regulators with the more macroprudential perspectives of central banks and financial stability regulators. The process of developing stress tests—particularly with coordination across financial regulators—could provide legibility into the pathways by which climate-related financial risk becomes systemic, and thus may enable broader macroprudential strategies by elucidating systemically important institutions and activities.

Climate stress testing practices

Stress testing has emerged as one of the most prevalent regulatory tools for addressing climate-related financial risks [6]. As noted in the introduction, myriad governmental and inter-governmental organizations have called for the institutionalization of climate stress tests and a 2019 survey of central banks and regulators ($n=33$) found that 84% had already incorporated or planned to incorporate climate change into stress tests within the next three years [2]. In the years since, notwithstanding the pandemic and attendant economic and health crises, regulators have continued to advance climate stress testing efforts [2, 5, 72]. This section takes stock of cross-national policy proposals and early practices and provides a preliminary application of the evaluative framework for climate stress testing in comparative case studies of effectiveness—for a leading jurisdiction, the UK—and capacity—for a lagging jurisdiction, the US.

Climate stress testing proposals and early practices

Central banks and regulators globally are developing scenario analyses and stress tests that incorporate climate-related financial risks [2, 5, 72]. Table 2 provides a summary of progress among these leading authorities, organized

by jurisdiction, entity, year of (proposed) exercise, scope of climate risks and financial institutions covered, and exercise type.³ Discussed in more detail below, despite widespread interest in stress testing, progress to date has been uneven across jurisdictions, and even among leading jurisdictions, existing stress testing practices are insufficient to measure and manage the effects of climate change on financial stability. In particular, the institutionalization of systematic stress testing practices is nascent as is the operationalization of systemic risk within climate stress tests.

As Table 2 depicts, a growing number of central banks and regulators are conducting climate-related scenario analyses—which consist of a centralized exercise designed and conducted by a regulatory authority without direct participation by firms or results linked to remedial actions [20, 50]. Scenario analyses thus far have tended to focus on financial sector exposures to specific physical risks or financial sector sensitivity to transition risks within a given jurisdiction. For example, Denmark's central bank conducted a study of mortgage lending risks resulting from projected sea-level rise in 2019 and a scenario analysis of the sensitivity of banks' capital positions to an abrupt transition, characterized by a substantial impairment charge over a short time-frame, in 2020 [129, 130]. Similarly, the central bank of the Netherlands was an early leader in climate scenario analyses, assessing weather-related physical risks and disorderly energy transition risks via policy and technology shocks for banks, insurers, and pension funds in 2017 and 2018, respectively [127, 128]. Scenario analyses have leveraged diverse data sources (e.g., historical natural disaster data, routine supervisory data, bespoke surveys) to provide a high-level assessment of physical and transition risks [5, 21]. Scenario analyses can complement other climate risk research efforts and serve as a foundation for stress tests; however, tradeoffs in scope and granularity combined with the relatively static nature of these analyses suggest that they are insufficient to measure or manage climate-related financial risk.

Climate stress testing practices—which involve the application of supervisory scenario analysis to test the resilience of firms or sectors, generally with direct participation by tested entities to enable sufficient granularity and confidence to inform institution- or system-level responses or remedial actions [5, 21]—are less developed. Thus far, climate stress tests have consisted of exploratory or pilot exercises, often

³ A range of other entities are also conducting climate scenario analyses, such as the IMF via its Financial Sector Assessment Program, and climate scenario analyses are reportedly forthcoming in an even broader range of jurisdictions, including Austria, Brazil, Hungary, Italy, Japan, Korea, Malta, New Zealand, and Poland [19]. Table 2 is limited to stress testing practices implemented by financial regulators and central banks, and for which publications from the issuing authority were publicly available at the time of writing.



Table 2 Selected climate stress testing practices and proposals

Jurisdiction (authority)	Climate-related financial risk scenario analyses and stress tests
United Kingdom (Bank of England/Prudential Regulation Authority)	2017 scenario analysis of transition risk for UK financial markets [109] 2019 pilot stress test to assess physical and transition risks for UK insurers [110, 111] 2021 systematic climate stress test to assess physical and transition risks for large UK banks and insurers [108, 112, 113]
European Union (European Central Bank/European Systemic Risk Board/European Banking Authority/European Insurance and Occupational Pensions Authority/European Securities and Markets Authority)	2020 ESMA scenario analysis of transition risk for EU investors [115] 2021 ECB economy-wide scenario analysis of physical and transition risks for EU banks, insurers, and investors [98, 116] 2021 ESRB/ECB parallel scenario analyses of physical and transition risks for large EU banks and investors [94, 95] 2022 ECB systematic climate stress test to assess physical and transition risks for large EU banks [106, 107, 117, 118]
France (Banque de France/Autorité de Contrôle Prudentiel et de Résolution)	2020 voluntary pilot stress test to assess transition risk for large FR banks and physical and transition risks for large FR insurers [119, 120]
Canada (Bank of Canada/ Office of the Superintendent of Financial Institutions)	2020 economy-wide scenario analysis of physical and transition risks for CA financial markets [121] 2021 voluntary pilot stress test to assess physical and transition risks for selected CA banks and insurers [122]
Australia (Australian Prudential Regulatory Authority/Council of Financial Regulators)	2021 pilot stress test to assess physical and transition risks for large AU banks [123–125]
The Netherlands (De Nederlandsche Bank)	2017 scenario analysis of physical risk for NL banks, insurers, and investors [126] 2018 scenario analysis of transition risk for NL banks, insurers, and investors [127, 128]
Denmark (Danmarks Nationalbank)	2019 scenario analysis of physical risk for DK banks [129] 2020 scenario analysis of transition risk for DK banks [130]
Germany (Deutsche Bundesbank)	2020 scenario analysis of transition risk for DE banks, insurers, and investors [131] 2023 scenario analysis of physical and transition risks for DE banks, insurers, and investors announced [132]
Singapore (Monetary Authority of Singapore)	2018 industry-wide stress test included physical risk for SG insurers [133] 2022 stress test for SG financial firms announced [133]
Hong Kong (Hong Kong Monetary Authority)	2021 voluntary pilot stress test to assess physical and transition risks for large HK banks [134]
China (People's Bank of China)	2021 pilot stress tests to assess transition risk for CN development and commercial banks [135]
Switzerland (Swiss Federal Office for the Environment/State Secretariat for International Finance)	2017 and 2020 scenario analyses of physical and transition risks for CH banks, insurers, and investors, conducted by external consultant [136]
United States (Federal Reserve)	2023 pilot scenario analysis for large US banks announced [137]

with voluntary firm participation, although more systematic stress tests are emerging in leading jurisdictions. The design of extant stress tests varies with respect to the physical and transition channels, financial risks, and institutions included. For example, France's prudential regulator and central bank conducted a voluntary stress test pilot to assess the impacts of physical and transition risks for large French insurers and the impact of transition risk for large French banks in 2020 [119, 120, 140]. Like other climate stress tests, this pilot leveraged external scenarios (from the NGFS and IPCC)

as well as prior central bank-led efforts, including a 2019 survey-based analysis of climate-related physical, transition, and liability risks for French banks and insurers [141–143]. The BOE was the first authority to conduct a compulsory climate stress test (discussed in more detail below) and the ECB recently published results from a systematic climate stress test [108, 118]. As with scenario analyses, stress tests have used external reference scenarios and coupled external integrated assessment and macroeconomic models with in-house financial models, but are differentiated by



the translation from aggregate financial (sub)sector risk to firm-specific risk via a combination of both supervisory and firm-level modeling, which in several cases accounts for firm behavior (via a dynamic balance sheet) and cross-sector interactions. This combined approach enables these stress tests to provide a more granular and dynamic assessment of climate risk, firm behavior, and potential system implications than climate scenario analyses.

Several gaps emerge from this stocktake of climate stress test proposals and early practices. First, with respect to scope, most exercises have focused on a relatively narrow subset of climate-related financial risks—largely credit and, to a lesser extent, market risks for loan and investment portfolios, respectively—and affected firms—mostly banks, with some insurers and relatively few investment firms. While many exercises have included both physical and transition risks, analysis of risk interactions and interdependencies is limited. Moreover, although voluntary initiatives are critical for capacity building among both authorities and participating firms, there may be an adverse selection problem that limits the generalizability of results and validity of inferences about systemic risk and resilience. Second, with respect to coordination, while many exercises have leveraged common scenarios, the design of exercises has varied considerably across jurisdictions; heterogeneity in the design of stress testing pilots might enable learning across jurisdictions about the different types of climate-related financial risks, but lack of harmonization may also inhibit integration of cross-border impacts and coordination of financial regulatory responses. Third, with respect to financial stability, although many exercises have macroprudential objectives, the operationalization of systemic risk is limited to aggregating (partial) exposures, with inattention to second-round effects. There has been some qualitative assessment of tested firms and large counterparties' potential mitigations and interactions—including the possibility of insurance protection gaps [112]—but modeling of risk amplification and financial stability implications is nascent [20, 21]. Fourth, exercises to date have largely focused on risk measurement, with most seeking to identify climate risks and assess the nature and magnitude of exposures for firms and sectors, rather than informing regulatory or firm risk management strategies.

Early progress suggests that institutionalizing climate stress testing is an iterative process. Jurisdictions leading the development and preliminary implementation of more systematic climate stress tests have experience conducting climate-related risk research, stakeholder engagement, scenario analyses, and stress test pilots, as well as issuing complementary supervisory guidance. For example, in advance of the Climate Biennial Exploratory Scenario (CBES), the BOE produced extensive research on climate-related financial risks [109, 144–147], conducted a survey of industry

climate risk practices [148], issued a supervisory statement on climate risk [149], and launched a pilot climate stress test for the insurance sector [110, 111]. Similarly, in advance of the implementation of climate stress tests [117], European authorities partnered to conduct climate scenario analyses [94, 95, 98], publish supervisory guidance for climate risk analysis and disclosure [150], and review bank-led climate stress testing practices as part of alignment with supervisory expectations [74]. This iterative progress is promising given that many jurisdictions are reportedly engaging in these activities [2, 5]. For example, in addition to the jurisdictions depicted in Table 2, several other central banks are conducting research, collecting data, and engaging regulated entities and commercial service providers to assess climate risks (e.g., Norway [151, 152], Mexico [153], Italy [154–156], Spain [157], Japan [158]). However, it also underscores the importance of distinguishing capacity building exercises from systematic stress tests when evaluating the potential benefits vis-à-vis climate change and financial stability.

In summary, although there have been many stress testing policy proposals and increased use of scenario analyses among leading jurisdictions, the limited stress testing practices to date are insufficient to measure and manage climate-related systemic financial risk. Iterative progress is promising, however, inattention to systemic risk across existing analyses suggests a disconnect between policy motivation and implementation. While some tailoring by jurisdiction is necessary, greater coordination in stress testing design and implementation methodologies would enable a more holistic assessment of climate risks, including spillovers across jurisdictions, as well as coherence in regulatory strategies to address these risks. The detailed comparative case studies presented in the next section explore these themes in greater detail.

Framework application: comparative case studies of effectiveness and capacity

The BOE and FRB serve as illustrative comparative cases because of their similar institutional designs and divergent approaches to climate risk. As central banks of large economies with major financial centers, both the BOE and FRB have financial stability mandates that include regulating systemically important financial institutions. Both central banks conduct annual solvency stress tests for these institutions—which include multiple scenarios, countercyclical elements, and added shocks for particular firms—and use the results of these stress tests to calibrate capital requirements and monitor systemic risk. The scenarios designed by the BOE and FRB are also used in other supervisory and firm-run stress tests. While both stress testing regimes combine microprudential and macroprudential objectives, the BOE's stress tests reflect a somewhat greater macroprudential focus: it



uses stress tests to calibrate macroprudential policy (e.g., countercyclical capital buffer), runs a biennial exploratory scenario to evaluate novel risks, and has developed workstreams on system-wide amplification and feedback [43, 51]. It should also be noted that pursuant to US legislative and regulatory reforms, the design and scope of BOE and FRB stress tests have diverged more in recent years.

This section applies the evaluative framework for climate stress testing developed in the preceding section to the BOE and FRB. To preview the findings, which are also summarized in Table 3, the BOE is a leader in the implementation of climate stress testing and the design of its first climate stress test enables partial measurement of climate-related financial risks and financial stability implications. Noting that measurement is a necessary condition for effective and efficient risk management, this section identifies opportunities for the BOE to improve the measurement and expand to management of climate-related systemic risk. Notwithstanding its central role in global financial markets and advanced prudential regulatory regime, the US lags its international counterparts in confronting climate-related financial risks, including via the development of climate stress tests. However, the FRB has both the authority and the capacity to incorporate climate risks into its existing stress testing regime, and this section identifies potential strategies to do so.

Bank of England

The BOE began concurrent solvency stress testing in 2014 and conducts annual stress tests of the largest UK banks and building societies to assess the resilience of these financial institutions and the financial system. The BOE's stress tests inform both firm and system-wide capital buffers. Via the Prudential Regulatory Authority, the BOE also conducts periodic solvency stress tests for selected insurance firms [51]. Beginning in 2017, it also began conducting a biennial exploratory exercise to evaluate novel risks, particularly those that may be decoupled from the normal financial cycle. The 2021 exploratory exercise, the CBES, focused on climate risk and represents the first systematic climate stress test.⁴ The stated purpose of the CBES was to “test the resilience of the current business models of the largest banks, insurers and the financial system to the physical and transition risks from climate change” [112 p.1]. Specifically, it was designed to provide an assessment of the magnitude of climate-related financial risks for large UK banks and insurers, the climate-related risk management and governance strategies of these firms, and the implications of climate

change and financial sector responses for financial stability. This section assesses the CBES based on the criteria articulated in the evaluative framework for climate stress testing.

The CBES was applied to the UK's largest banks and building societies as well as large general and life insurers. Participating banks covered 70% of UK residential and commercial lending, life insurers covered 65% of the UK market by asset size (with various business models), general insurers covered 60% of the UK market by premium size, and selected syndicates covered 40% of the Society of Lloyd's property and liability insurance market by premium size [108]. The BOE integrated the bank and insurance stress tests to provide a more complete assessment of climate-related financial risks for the entire financial system, including potential interdependencies and risk-transfers (e.g., effects of changes in insurance provision on banks' credit risks). Discussed in more detail below, the structure of the counterparty analysis also necessitated an assessment of climate exposures for many large non-financial UK companies [160].

The CBES included three scenarios with physical and transition risks for all participants, as well a separate analysis of liability risks for general insurers based on seven hypothetical legal cases [108]. The three primary CBES scenarios expanded on NGFS scenarios via the BOE's work with climate scientists and other subject matter experts, and represented an early and orderly transition with limited physical risks (“early action”), a late and disorderly transition with limited physical risks (“late action”), and severe physical risks in the absence of a transition (“no additional action”). The magnitude of physical and transition risks within these scenarios was driven by the timing and stringency of climate policies, as described by scenario narratives that included temperature, emissions, and mitigation pathways, and resulting physical and transition risks. Physical risks were operationalized as changes in the frequency and severity of chronic and acute climate-driven natural hazards, based on global and regional temperature pathways, with sufficient granularity to represent geographic variation in these risks. Transition risks were operationalized as different combinations of climate policies, technological developments, and consumer preferences, with an emphasis on the effects of carbon pricing. These physical and transition risks were translated into macroeconomic and macrofinancial variables such as gross domestic product, unemployment, bond yields, and equity indices. The scenarios did not include a macroeconomic shock beyond those resulting from physical and transition risks [112]. The CBES employed a 30-year modeling horizon and reporting at five-year intervals, with the impact of climate risks based on comparisons to static 2020 balance sheets. Uncertainty with respect to the timing and severity of impacts was represented within and across scenarios, and via an additional sensitivity analysis in the

⁴ The first round of the CBES began in June 2021, the second round began in February 2022, and the results were published in May 2022.



Table 3 Climate stress testing effectiveness and capacity

	Criteria	Bank of England	US Federal Reserve
Scope	Systemically important and materially climate-exposed financial institutions	Large UK banks, building societies, and general and life insurers	Largest and most complex US banks; scope could be expanded via FSOE designation and scenarios could inform broader US stress testing regime
Scenario Design and Modeling Approach	Physical and transition risks with appropriate spatial and temporal resolution and robust representation of uncertainty and interdependencies	Three scenarios combining physical and transition risks over a 30-year time horizon with 5-year reporting intervals and a static baseline balance sheet; separate analysis of litigation risks for general insurers	Climate scenarios could be implemented as part of the comprehensive macro scenario or as an added component; necessitates the development of threat-specific narratives for climate risks and transmission pathways
Metrics	Performance-based and decision-relevant metrics derived from quantitative and qualitative outputs	Quantitative metrics include changes in banking book assets for banks and liabilities and assets for insurers; qualitative metrics include climate risk measurement and management assumptions and approaches for participants and selected counterparties	Existing capital-based metrics could be used to assess performance, but disaggregated balance sheet impacts and broader risk management processes may be more informative; additional metrics should be considered as climate risk data, methodologies, and frameworks advance
Systems Analysis	Firm-level analysis enables system-level modeling of the effects of climate change on financial stability via risk aggregation and amplification	Facilitated by concurrent application and detailed reporting for banks and insurers, as well as follow-on data collection to assess system-wide interactions, inconsistencies, and financial stability implications	Requires expansion, but the scope and concurrent application could facilitate analysis of second-round effects and the counterparty analysis could be expanded to improve the measurement of system-wide interactions and financial stability implications
Market Discipline	Incentivizes improved risk management practices and enables price corrections via disclosure	Increased climate risk awareness among participating firms via individual feedback and integration into supervisory assessment; potential for price corrections limited by aggregate disclosure	Granular disclosure could facilitate market discipline among participating firms and their stakeholders
Mitigation Evaluation	Firms articulate and assess the effectiveness of alternative strategies to increase resilience to climate risks	Static balance sheet in the first round, but articulation of potential management actions in the second round and documentation of assumptions about counterparties' actions	Mitigations could be represented in capital planning via dynamic balance sheets, as well as in expanded use of the qualitative assessment to include climate risk management processes
Evidence-Based Regulation	Supports the monitoring of climate-related systemic risk accumulation and propagation and informs the design and implementation of microprudential and macroprudential standards	Monitoring the accumulation and propagation of climate-related systemic risk is an explicit purpose; not used for calibrating firm- or system-level capital standards (routine stress tests are used to calibrate these requirements), but will inform interagency and international cooperation on climate-related financial risk regulation	Monitoring the accumulation and propagation of systemic risk is an explicit purpose (but routine stress tests are not used to calibrate macroprudential requirements); could be used to calibrate microprudential capital standards with sufficiently robust measurement approaches



second round. Although the scenarios were not predictive—but rather represented the potential macroeconomic and macrofinancial risks associated with alternative climate scenarios—the BOE reportedly plans to work with climate scientists to provide probabilities for the realizations of impacts aligned with each scenario and also asked tested firms to provide expectations around the likelihood of alternative scenarios. Moreover, for physical risks, firms were asked to model both the mean and tail of climate risk distributions, and the “no additional action” scenario was calibrated to reflect within-scenario realization of the more material risks anticipated outside of the scenario timeframe (i.e., risks anticipated in the period from 2050 to 2080 occurred by 2050 within the scenario) [112].

The CBES had both microprudential and macroprudential goals, and the scenario design and modeling approach balanced the level of granularity needed to enable firms to meaningfully assess their idiosyncratic climate risks with the level of consistency needed to enable comparability and aggregation to assess system-level climate risk. To achieve this balance, the scenarios were applied concurrently and consistently across participants, with variables focused on the UK and key economies and operationalized at the regional and sectoral levels, and participants expanded the analysis via the inclusion of other economies and more granular counterparty impacts. Participants modeled the impacts of each scenario on their corporate, household, and government exposures. For corporate exposures, participants were also required to engage with counterparties and use publicly available data, such as TCFD disclosures, to analyze how a given scenario would affect the counterparty, the counterparty’s vulnerability (inclusive of any planned mitigations), and the resulting financial impacts; counterparty impacts were compared to scenario averages to ensure coherence or explore divergence. This more detailed counterparty analysis was originally proposed for 80% of nominal exposures to corporates with climate-exposed assets, but was subsequently revised to cover at least the top 100 non-financial corporate exposures, the three largest companies in the sectors most impacted by the scenarios (if not in top 100), and the five largest exposures [161]. A less granular approach was permitted for the remaining counterparties, such as extrapolation from sectoral indicators.

The CBES included quantitative metrics to evaluate the impact of climate scenarios on participants’ balance sheets and business models—accounting for the “direct and indirect impacts of climate-related financial risks, as well as the mitigation and adaptation plans of counterparties” [112 p.9]—and a qualitative questionnaire to assess participants’ climate risk modeling and management approaches. The quantitative metrics used in the CBES are similar to those employed in the BOE’s insurance and banking stress tests—insurers were asked to report on both liabilities and assets

(with an emphasis on the value of invested assets and insurance claims), while banks were asked to report on assets (with an emphasis on detailed credit risk analysis for large corporate counterparties) but were not required to provide detailed modeling of liabilities or income statements. In the initial proposal, banks were required to report on assets for both their banking books—via annual and cumulative impairment charges—and their trading books—via the change in fair value of assets—however, the BOE decided to exclude the trading book in light of feedback about the dynamic nature of these risks [160, 161]. While the standard balance sheet metrics are not climate-specific, the comparison to the 2020 baseline, absence of additional macroeconomic shocks, and detailed reporting requirements enable at least partial isolation of climate impacts. For example, exposures in key regions were reported at the sub-national level and sectors with the greatest vulnerability were also reported at more granular levels. Insurers were instructed to disaggregate the values of assets and liabilities by natural hazard and territory within each scenario. For the top 50 counterparties, participants also provided a detailed breakdown of modeling approaches and assumptions, including assumptions about counterparties’ mitigation and adaptation strategies. The original proposal also included an assessment of the temperature alignment of participants’ portfolios based on an aggregation of counterparty assessments, for example, by estimating global temperature increases given the emissions intensity and technology pathways of counterparty activities, however, the revised proposal excluded the temperature alignment assessment in response to concerns about data availability [112, 161]. While the initial analysis quantified results based on static balance sheets, participants also identified how and when they would modify business models in response to each scenario, leveraging a provided menu of management actions to address climate-related risks (e.g., pricing exposures) and opportunities (e.g., redirecting capital). Finally, participants also conducted a qualitative assessment of risks not captured elsewhere, including climate-related operational, reputational, and litigation risks, as well as risks arising from bank-insurer interactions [112].

Following the firm-level exercise, the BOE conducted an analysis of “system-wide impacts and inconsistencies,” which included a second-round data collection. This systems analysis was enabled by the design of the firm-level stress test, including the detailed information collected on participants’ modeling approaches, data, and assumptions about climate risks and resilience [112]. The CBES proposal outlined how the systems analysis would explore climate-related systemic risk and the implications for financial stability via an assessment of the system-level impact of bank and insurer behaviors and interactions as well as an analysis of the plausibility and potential consequences of participants’ mitigation actions, both individually and



in aggregate. The CBES proposal stated that this analysis would consider the potential for “spillovers across sectors, for behaviours to amplify the impact of the underlying climate shocks, and for material disruption to the provision of financial services to UK households and businesses” [112 p.9], leveraging firm responses on when, why, and how they would react to scenarios. Although detailed results of this analysis were not published, the CBES proposal outlined four key areas it would explore: changes in the provision/pricing of services to the real economy, inconsistencies in assumptions, fire sales, and capacity to support the transition [112]. The second-round data collection was designed to address inconsistencies identified in the first-round submission and provide participants with the opportunity to “respond to the aggregated results from the first round, and potentially revise parts of their submissions in response to Bank feedback” [112 p.25]. The results indicate that this data collection included firm responses on transition opportunities in various competitive landscapes, the impact and management responses if losses were double the initial projections, the methodologies for assessing the credibility of counterparties’ transition plans, and the envisaged role of public sector support for climate-vulnerable entities [108].

With respect to risk measurement, the results provide some insight into climate-related financial risks for large UK banks and insurers and the potential implications for financial sector stability, but interpretation is limited by the exercise design, modeling challenges, and data gaps. The results of the first-round analysis suggest that climate loss projections would be equivalent to a 10–15% drag on profits annually, but there is substantial uncertainty around the magnitude of these risks due to the limited scope of the exercise and “immaturity of firms’ approaches and the complexity of modelling the impact of these risks” [108 p.12]. For example, BOE staff analysis found that losses could be four times higher than UK insurers’ submitted estimates [108]. A close read of the results also highlights sectoral, geographic, and temporal concentrations that may be troubling from a financial stability perspective and are obscured by the cumulative average loss projections [108]. For example, carbon-intensive sectors account for a third of credit loss provisions in transition scenarios despite representing only 15% of banks’ corporate exposures, mortgage impairments are highly concentrated in regions prone to flooding, and 40% of losses occurred in the first five years of the transition in the late action scenario [108]. The results of the second-round analysis also highlight potential system-wide consequences, including the macroeconomic consequences of fire sales and credit supply shocks associated with a disorderly transition. The BOE appropriately cautioned that the validity of results is limited by the design of the exercise (e.g., exclusion of banks’ trading losses and life insurers’ mortality risks), the immaturity of climate financial risk modeling

(e.g., uncertainty around climate loss projections and reliance on external providers), and data gaps (e.g., reliance on counterparties’ transition plans and lack of standardized information on corporate asset locations and value chain emissions) [108].

While the purpose of the CBES is risk measurement, there are several aspects of the exercise design that support risk management. With respect to market discipline, the BOE did not publish stress test results for individual firms, but participants received feedback on the strengths and weaknesses of submissions and the BOE used findings on climate risk management to assess alignment with climate risk supervisory expectations [108, 112, 149]. Thus, while the lack of firm-level disclosure limits the market disciplining effects of the CBES, the results state that it has driven improvements in firms’ risk management approaches by exposing data and modeling gaps [108]. With respect to informing firm risk management strategy, the articulation and analysis of potential mitigations—including management actions provided by the BOE, embedded in participants’ transition plans, and resulting from counterparty assessments—may contribute to better understanding of climate risks and potential responses. With respect to informing regulatory responses to climate risk, the results outline several ways in which the CBES and underlying capabilities will support work on microprudential and macroprudential tools to address climate risks at the national and international levels [108]. For example, the BOE is exploring the role of regulatory capital frameworks in bolstering firm and system resilience to the financial consequences of climate change, and has noted that stress testing could in principle inform the calibration of capital requirements for climate risk, but will require better data and more sophisticated models [102]. The results also describe how the CBES findings will inform ongoing work on climate-related financial stability policy issues (e.g., financial system resilience and real economy spillovers) [108]. Finally, the BOE plans to identify best practices and disseminate lessons learned within the UK government and across international peers to improve cross-sectoral modeling and reduce regulatory fragmentation, respectively [108].

Thus, the CBES is the first systematic climate stress test and represents important progress in the assessment of climate-related financial risk, however, given the identified limitations, BOE’s regulatory authority, and rapidly maturing analytical capabilities, there are opportunities to improve the measurement and expand to management of the effects of climate change on financial stability. The scope of the CBES was fairly broad, covering a substantial portion of financial activity in the banking and insurance sectors; however, the exclusion of investment firms and banks’ trading books is an impediment to assessing market risks [161]. The scenarios integrated physical and transition



risks, were attentive to the distinctive temporal and spatial dynamics of climate risk and the attendant uncertainties, included at least some tail risks, and balanced the need for comparability at the system-level and decision-relevance at the firm-level. The included metrics provide a useful, albeit partial, assessment of climate-related financial risk for participants and their major counterparties. The proposed initial framework—which included a more complete accounting of banks' climate risk (via change in fair value of trading assets) and transition readiness (via temperature-based portfolio alignment)—would have provided a more holistic assessment of participating firms' resilience to physical and transition risks. As data concerns are addressed, alignment of stress testing metrics with current and emergent climate disclosure frameworks and capital requirements could maximize the utility of the exercise for both the BOE and participating firms [12, 108, 162–164]. The design of the CBES incorporates microprudential and macroprudential elements, using horizontal stress tests to size the climate exposures of banks and insurers and systems analysis to explore how such risks aggregate and interact, including risks resulting from bank-insurer interdependencies and herding in management responses. While a detailed description of the methodology and results of the systems analysis was not published, there are opportunities to leverage the systemic risk amplification modeling approaches in existing stress tests and ongoing development of analytical approaches for quantifying second-round effects and financial sector-real economy spillovers [43, 51]. Finally, as the BOE moves from risk measurement to risk management, stress testing may play a role in calibrating firm- and system-level capital buffers, but could also inform the broader implementation of the UK climate-finance agenda, such as mandatory TCFD-aligned climate risk disclosures [164, 165].

US Federal Reserve

In the US, stress tests were used to restore market confidence during the 2007–2009 global financial crisis and post-crisis legislation institutionalized peacetime stress tests [166]. The Dodd–Frank Wall Street Reform and Consumer Protection Act of 2010 includes stress testing authority as part of the FRB's enhanced prudential supervision of certain banks and non-bank systemically important financial institutions as designated by the Financial Stability Oversight Council (FSOC) [167]. Legislative and regulatory reforms in recent years have reduced the frequency, scope, and stringency of stress tests, while changes to the FSOC's designation processes have limited the applicability of enhanced prudential supervision for non-bank financial institutions [168, 169, 193]. Although other US financial regulators engage in stress testing, stress testing to support financial stability is uniquely within the purview of the FRB, as such, the focus of this

analysis is on the design and implementation of supervisory stress tests within the Federal Reserve System.

The US lags its international counterparts in confronting climate-driven financial risks, although the regulatory landscape as it relates to these risks is rapidly evolving [9, 170–173]. The FRB has acknowledged climate change as a potential threat to the financial system in the past [174, 175], and more recently has connected climate change to its microprudential and macroprudential mandates in official publications [176–178], joined some 100 other central banks as members of the NGFS [179], formed working groups on supervisory and financial stability climate risk issues [180], and signaled its intention to conduct a pilot scenario analysis exercise for climate risk [180–137].⁵ This section considers whether and how climate-related systemic risk could be incorporated into the FRB's stress testing regime, given the FRB's financial stability regulatory authority and the design of existing stress tests.

The FRB has the authority to vary the scope and frequency of stress tests based on firm size and institutional characteristics, however, only the largest and most complex banks are currently subject to the FRB's annual (or periodic) supervisory stress tests. While these banks represent a substantial share of the US financial sector, there may be other bank and non-bank financial firms that meet the criteria of material climate exposures and systemic importance [9, 182, 183]. Although these firms may perform company-run stress tests or undergo stress testing under the supervision of other regulatory authorities, their exclusion from the FRB's stress testing regime means that their potential contributions to financial (in)stability, including vis-à-vis climate-related systemic risk, may be omitted from systems analysis. Notably, FSOC has the authority to designate non-bank financial institutions as systemically important, which brings these firms under the authority of the FRB's enhanced prudential supervision, including stress testing. Moreover, the FRB has authority over financial market utilities, for which some have suggested climate stress testing, potentially building on derivative markets regulators' reverse and liquidity stress testing for centralized clearing parties [10, 159, 184].

The FRB's stress tests evaluate firm- and system-level resilience, with a focus on the capital adequacy of participating firms. The FRB develops scenarios of varying severity for each cycle, which are used in both supervisory and company-run stress tests and represent the effects of hypothetical adverse macroeconomic conditions via input variables

⁵ US state-level insurance regulators have also used scenario analysis to explore climate risks—in 2018 and 2021, the California State Insurance Commission and New York Department of Financial Services, respectively, worked with an external consultant to conduct scenario analyses of transition risk for insurers within their states [138, 139].



related to domestic and international economic activity, asset prices, and interest rates. For the largest and most complex firms, two additional components are incorporated into the most severe scenarios: a global market shock—which simulates deteriorations in global markets that result in “general market distress and heightened uncertainty”—and a counterparty default—which simulates the effects of an “instantaneous and unexpected default” of the tested firm’s largest counterparty [187 p.7]. Existing scenarios are effectively threat agnostic, they reflect how adverse macroeconomic conditions stemming from some unspecified threat would affect key variables, however, the FRB has conducted threat-specific sensitivity analyses in response to COVID-19 [188]. Thus, given the design of current stress tests, climate risks could be incorporated via the comprehensive scenario, the global market shock or counterparty default additional components, or a new additional component. In the comprehensive scenario, the macroeconomic and macrofinancial impacts of climate change could be reflected via the existing input variables—for example, physical and transition risks could be represented by changes in commodity prices for climate-exposed and carbon-intensive sectors, respectively. Although the additional components are similarly threat-agnostic, they could be used to provide more specificity about transmission channels—for example, the global market shock component could be used to assess transition risk resulting from heterogeneity in cross-national climate mitigation policies, while the counterparty default component could be used to operationalize physical risk for counterparties that have the greatest climate exposures. The FRB also has the authority to require covered firms to include added components in stress tests based on “the company’s financial condition, size, complexity, risk profile, scope of operations, or activities, or risks to the US economy” [167]. As such, the FRB could develop a new additional component reflecting specific climate risks and transmission channels. Finally, although outside the scope of this analysis, climate risk might be considered in the context of the comprehensive liquidity assessment review; as noted above, the integration of solvency and liquidity stress testing is an active area of systemic risk research and policy discussion [43].

The FRB’s stress tests include a range of metrics to evaluate how each scenario affects firms’ balance sheets and capital positions over a nine-quarter planning horizon, with capital-based solvency metrics, such as the common equity tier 1 ratio, reported as the primary performance outcomes [73, 186, 187]. As part of stress tests, the FRB previously conducted a qualitative assessment of selected firms’ capital planning practices, which covered “governance, risk management, internal controls, capital policies, incorporating stressful conditions and events, and estimating impact on capital positions,” however, this assessment is now part of the standard confidential supervisory process [73 p.17].

Existing capital adequacy metrics could be used to gauge firm-level resilience to climate risks but would necessitate careful causal attribution to disaggregate the effects of physical and transition risks, as well as a taxonomy to guide the incorporation of climate change into asset risk weightings. A more incremental approach might entail first seeking to measure the impact of scenarios on assets and liabilities and then identifying the appropriate performance metrics to represent climate risks and guide risk management decisions. Prior analyses have noted that the statutory linking of stress testing and capital planning authorities means that any expansion of stress testing to address climate risks would necessarily need to preserve the focus on capital [159]. However, there are a broad range of firm risk management actions that stress tests might inform, only some of which would be captured by capital planning processes. Moreover, to maximize utility for both regulators and regulated entities, the quantitative metrics employed in stress testing could seek to align with those being developed in sustainable accounting methodologies and disclosure frameworks, including potential changes to mandatory disclosure frameworks at the US state and federal levels [12, 189, 190]. Finally, the qualitative assessment previously implemented in stress tests could potentially be expanded to incorporate not only the efficacy of capital planning but also of climate risk planning processes—including firms’ strategies for measuring and managing climate-related credit, market, liquidity, operational, and reputational risks.

Although the FRB’s stress tests are firm-level exercises, the FRB notes three related “macroprudential elements” that facilitate system-level analysis of financial stability issues [40 p.67]. First, the scope and severity of stress tests, which enables “examination of the loss-absorbing capacity of institutions under a common macroeconomic scenario that has features similar to the strains experienced in a severe recession” and reflects “salient risks” [40 p.67]. Second, the horizontal application of stress tests to the largest banks—representing some 80% of banking sector assets—which enables assessment of potential correlated exposures [40, 57]. Third, the inclusion of counterparty shocks, which enables evaluation of the effects of counterparty distress for the largest and most interconnected firms [40]. As such, embedding a sufficiently severe climate scenario in the FRB’s horizontal stress tests could enable analysis of climate-related systemic risk arising from banking sector correlated exposures and selected systemic risk amplification channels. The scope and design of the FRB’s stress tests facilitate estimation of the magnitude of direct effects for the banking subsector, but these aggregate estimates omit correlated exposures among other financial services subsectors. The counterparty default may enable assessment of systemic risk amplification resulting from counterparty contagion, but the scope of the added



component is insufficient to fully represent second-round effects [57].

While it is premature to evaluate whether the inclusion of climate risk in the FRB's stress tests would lead to improved management of those risks, it is possible to assess how existing stress tests may inform firm, regulatory, and market actions. With respect to market discipline, there is evidence that financial markets are responsive to stress test disclosures [4, 91], and the granularity of disclosures under existing stress tests could facilitate greater US market-based transparency about climate risks. However, the extent to which disclosures would promote market discipline depends on the design and credibility of stress tests and whether results transparency addresses deficiencies in existing voluntary climate risk disclosures. With respect to informing firm strategy, given the design of current stress tests, firms' actions in anticipation of, or in response to, physical or transition risks could be represented in dynamic balance sheets and capital plans, although potential mitigation strategies may go beyond capital planning processes. Aligning stress testing requirements with current and emergent disclosure frameworks could also create incentives for firms to use the underlying scenario analysis to evaluate, and demonstrate, the resilience of their business strategies to climate risks, a key component of TCFD's framework—of which most large US banks are supporters and for which compliance is “significantly lower” than any of the other recommended disclosures [191 p.4, 192]. With respect to informing regulatory responses, the FRB uses stress tests to calibrate capital requirements via the stress capital buffer (previously, capital distributions could be restricted based on the inadequacy of capital positions or planning processes [193]). As such, following the validation of its measurement strategy, the FRB could potentially use the results of climate stress tests to calibrate microprudential capital standards and to analyze the accumulation and propagation of climate-related systemic risk, which in turn might inform macroprudential responses. Additionally, FSOC, which currently employs an activities-based approach to analyze sources of financial instability, could use information from these stress tests to identify activities that increase climate-related financial risk or system vulnerability to risk amplification. Independent of these regulatory responses, climate stress testing could incentivize and inform more effective firm risk management strategies via market discipline and mitigation evaluation, respectively.

Thus, although the US lags its international counterparts in confronting climate-driven financial risks and developing climate stress tests, US financial regulators have the authority and the capacity to incorporate climate change into the existing stress testing regime. While the scope of current stress tests may be insufficient to fully capture the effects of climate change on financial stability, the FRB could incorporate climate change into stress testing for the largest

and most complex banks, which are by definition systemically important. Additionally, the realization of proposals calling for FSOC's incorporation of climate change into systemic risk monitoring and designation authority could expand the scope of the FRB's stress tests [185]. Moreover, the FRB's development of climate scenarios would facilitate the inclusion of climate-related financial risk in other financial regulator- and firm-run stress tests, with potential for coordination via the Federal Financial Institutions Examination Council (FFIEC) and Federal Insurance Office (FIO) [10, 169]. The FRB has several options for incorporating climate risk into existing scenarios, and there are opportunities for incremental progress and learning via interagency and international regulatory coordination. For example, the FRB could partner with other governmental and nongovernmental entities to leverage existing climate, natural hazard, and climate-economic modeling expertise to produce estimates of the effects of climate change on the macroeconomic variables routinely included in stress tests or to develop an additional component focused on climate risk (e.g., leveraging FSOC's Climate Data and Analytics Hub [194]). Similarly, FRB research on climate change and financial stability and engagement in international regulatory fora—such as the NGFS, Basel Committee on Banking Supervision's Task Force on Climate-Related Financial Risks, Financial Stability Board, G20 Sustainable Finance Study Group, and Central Banks' and Supervisors' Climate Training Alliance—could support the development of climate stress test scenarios. Metrics should be reassessed as US climate risk disclosure frameworks mature, but estimating the effects of climate change on assets and liabilities and incorporating climate risk management into a more holistic qualitative assessment are important first steps. Moreover, the FRB is reportedly collecting supervisory data on firm approaches to evaluating climate exposures, which may inform the development of metrics and scenarios; to maximize utility for macroprudential climate risk measurement, the FRB's efforts around climate change should be coordinated with FFIEC and FIO to ensure banks and insurance companies regulated and supervised by other state and federal agencies and their specific regional risks are represented in ongoing data collection and analysis [9, 171]. The FRB's existing approach to systems analysis could enable partial assessment of climate-related systemic risk, but systematic modeling of indirect effects arising from interactions among financial services subsectors and macrofinancial linkages are key gaps. The FRB has undertaken efforts to better represent systemic risks in stress tests—including exploring the incorporation of direct or system-wide liquidity shocks to understand liquidity-solvency interactions—and has developed sophisticated financial stability models for other institutional functions [43, 176, 177]. Moreover, there are opportunities to leverage these existing modeling



efforts, as well as international progress and emergent academic research, as discussed above, to improve analyses of financial sector interactions and cross-sector interconnections [25, 90]. Thus, while developing and implementing climate stress testing is a substantial undertaking, this section identifies concrete steps the FRB could take to begin to assess microprudential and macroprudential climate-related financial risks and explores how a sufficiently rigorous risk measurement approach could enable US financial markets, firms, and regulators to improve climate risk management.

Conclusion

Despite widespread recognition among financial regulators and central banks that climate change may threaten financial stability, the causes and consequences of climate-related systemic financial risk remain underexplored. Stress testing has emerged as one of the most prevalent regulatory tools for addressing climate-related financial risks, and this article analyzes the role of stress testing in mitigating the effects of climate change on financial stability.

Stress testing can support the measurement and management of both microprudential and macroprudential climate-related financial risks. Drawing on the climate-related financial risk, financial stability, and stress testing literature, this article argues that stress testing is an essential tool for addressing financial risks, including potential systemic risks resulting from climate change. It identifies how the design of stress tests—including scope, scenarios, metrics, and systems analysis—could support the measurement of climate-related systemic financial risk. Noting that measurement is a necessary condition for effective and efficient risk management, this article also discusses how financial firms, regulators, and market participants could use stress tests to mitigate the effects of climate change on financial stability—via market discipline, mitigation evaluation, and evidence-based regulation. Moreover, by incorporating tail risk scenarios, modeling endogenous drivers of financial instability, and exploring strategies to bolster system resilience, macroprudential climate stress testing could also support a precautionary approach to climate risk. While the framework proposed in this article is necessarily ambitious, iterative approaches to climate stress testing can enable (at least partial) assessment of firm- and system-level climate exposures, provide insight into the propagation pathways and system characteristics that could result in the amplification of climate-related systemic risk, and structure thinking about potential responses among financial policymakers and market participants.

However, the benefits of stress testing vis-à-vis climate change and financial stability are unrealized. Notwithstanding sustained interest in stress testing among policymakers, progress to date has been uneven across jurisdictions, and even among leading jurisdictions, climate stress testing

practices are insufficient to mitigate the effects of climate change on financial stability. In particular, the institutionalization of systematic stress testing practices is nascent, with leading authorities conducting one-off scenario analyses and largely voluntary pilot stress tests. The operationalization of systemic risk within existing climate stress tests is also limited, with most exercises focusing on a relatively narrow subset of microprudential risks and financial institutions, suggesting a disconnect between policy motivation and implementation. While the design of financial stability regulatory authorities and existing stress testing regimes shapes approaches to climate stress testing, institutional design alone does not explain the divergence between leading and lagging jurisdictions, as exemplified by the comparative case studies of the BOE and FRB.

Stress testing is an essential tool for better understanding, and potentially mitigating, the effects of climate change on financial stability, but it is not a panacea [57]. The literature highlights that although stress testing practices have become more robust in the decade following the global financial crisis, there continues to be room for improvement in the modeling of systemic risk and the linking of results to macroprudential policies; such challenges will persist with climate stress testing, which will also bring novel challenges. Forward-looking jurisdictions should approach the development of climate stress tests as an opportunity to improve the quality of systemic risk stress testing more broadly, including by evolving exogenous shocks to better reflect tail risks and by improving modeling of second-round effects to better reflect endogenous drivers of financial instability. Moreover, climate stress testing should be considered within the context of a broader regulatory strategy for addressing climate-related financial risks, which might also include other types of climate-related financial risk assessments, supervisory expectations for climate risk management, standardization of climate risk disclosure requirements, and capital frameworks for climate resilience. Together, these policies can mitigate the financial consequences of climate change, but they are not a substitute for macroeconomic and financial policies to address the causes of climate change [34, 102, 195].

Regulatory cooperation—within and across jurisdictions—is needed to advance climate stress testing and climate-related financial risk regulation more broadly. Interagency cooperation can support scenario development by leveraging and enabling translation across government-wide climate, natural hazard, macroeconomic, and financial modeling expertise. Such coordination is particularly important in light of recent research highlighting the misuse and misinterpretation of climate models for financial risk analyses [79]. Moreover, as governments take increasingly holistic approaches to climate policy, there may be opportunities to learn from financial sector experience. For example, stress testing might be extended to non-financial firms with



substantial climate-related exposures to assess resilience to, and inform disclosures of, physical and transition risks [96, 196]. International regulatory cooperation will ensure coherence across microprudential and macroprudential responses to climate change, including stress testing [197]. The next phase of this research will explore how interagency coordination could inform the development of stress testing methodologies as well as opportunities for two-way learning as policymakers across all levels of government and sectors prioritize resilience to climate change. Future research will also include an expanded cross-national evaluation of climate stress testing practices and identification of international regulatory cooperation strategies to overcome market failures inherent to the provision of global public goods like environmental sustainability and financial stability.

Declaration

Conflict of interest The author states that there is no conflict of interest.

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