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Climate-related Financial Stability Risks for the United States: Methods and Applications

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[1] The views expressed here are solely the responsibility of the author and should not be interpreted as reflecting the view of the Board of Governors of the Federal Reserve System or of any other person associated with the Federal Reserve System.
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Executive Summary

This paper has two objectives:

1. Review the available literature on Climate-Related Financial Stability Risks (CRFSRs) as it pertains to the United States. Specifically, the literature review considers several modeling approaches and aims to
    1.1 Identify financial market vulnerabilities (e.g., bank leverage),
    1.2 Provide an assessment of those vulnerabilities (high/medium/low) as identified by the current literature, and
    1.3 Evaluate the uncertainty surrounding these assessments based on interpretation of the findings and coverage of existing literature (high/low).
2. Identify methodologies to link climate risks to financial stability and possible research paths to assess U.S. CRFSRs.

The paper is structured in three parts. First, it characterizes the potential financial system vulnerabilities of climate change. Second, it describes the major methodologies adopted in studying the implications of climate change and provides an assessment of financial system vulnerabilities identified by the current literature. Third, it discusses how different methodologies can be further developed or combined to assess U.S. CRFSRs.

The paper contains four key findings:

First, modelling and assessing CRFSRs present several challenges, and no single methodology can address all of them: (1) accounting for uncertainty, (2) adapting to long time horizons, (3) embedding heterogeneity, (4) incorporating technological change, and (5) modeling damage functions to measure the economic impacts of climate change. The paper highlights the limitations of the methodologies considered and the need for further research (see Table 1).

Second, the literature on U.S. CRFSRs is thin and identifies only a few U.S. financial system vulnerabilities (see Table 2).

Third, currently available results should be interpreted with caution. The paper considers the number of studies available for the assessment, the modelling assumptions behind those studies, and the overall qualitative evaluation of the results, and concludes that any assessment based on the extant literature is characterized by a large degree of uncertainty (see Table 2).

Fourth, no methodology can be used in isolation to fully assess U.S. CRFSRs; several methodologies need to be combined for a more complete understanding. For example, the reduced form outputs from micro- and macro-econometric statistical methods can be used to inform the main parameters and assumptions in computable general equilibrium and dynamic stochastic general equilibrium models, as well as the distributions of different random variables in agent-based models. In turn, equilibrium models and agent-based models can be used to design scenarios that feed into scenario analysis, sensitivity analysis, stress testing, and other practitioner approaches (see Figure 2).

1. Introduction

There has been increased interest in assessing the preparedness and resilience of the financial sector due to concerns about the economic impacts and financial risks associated with climate change. This paper specifically reviews the current literature on climate-related financial stability risks (CRFSRs): risks that may result from climate change that could potentially impact the safety and soundness of the U.S. financial system. This literature is limited and there are many opportunities for theoretical and empirical advancements. We note that such work faces significant challenges. Many of the standard assumptions that underlie existing methodologies may not be well-suited to analyze the financial stability implications of climate change. Nonetheless, work in this area has begun, with some lines of inquiry analyzing these implications from a micro-level approach – for example, reviewing the value-at-risk of specific portfolios due to climate change effects – while others use a macro-level approach – for example, linking potential carbon emission pathways to productivity effects over decades. The literature review is organized around the different existing methodologies and focuses primarily on studies conducted for the U.S. financial sector. When applicable, we note opportunities to strengthen climate-related stability financial research.

2. Climate-Related Risks and Financial System Vulnerabilities

Climate-related risk is typically divided into "physical risk" (*i.e.*, damages to facilities, operations, and assets caused by climate change-induced hazards and conditions) and "transition risk" (*i.e.*, losses resulting from a transition of production and consumption towards methods and products that are compatible with a net-zero economy).[2, 3]

Physical risk can be divided into two categories. "Chronic physical risk" is caused by steadily deteriorating conditions over time; examples include sea level rise and slow increases in mean temperatures. "Acute physical risk" is caused by damages from severe hazards, either due to an increase in the probability or severity of the event; examples include hurricanes, floods, and wildfires. Physical risk can affect asset values and credit availability, and force relocation of businesses and households with potential financial stability consequences.

Transition risk is typically divided into three categories. "Policy risk" refers to the risk that policies associated with the transition to a lower- emissions economy may raise costs to some firms and households, induce shifts in the location and nature of economic activity, and impose restrictions that affect the viability or profitability of certain industries. "Technological risk" is the risk that certain assets may suffer a devaluation caused by climate change-induced innovation and become "stranded".[4] Finally, "preference risk" refers to risks arising from shifts in investor and consumer preferences away from carbon-intensive products toward greener ones.

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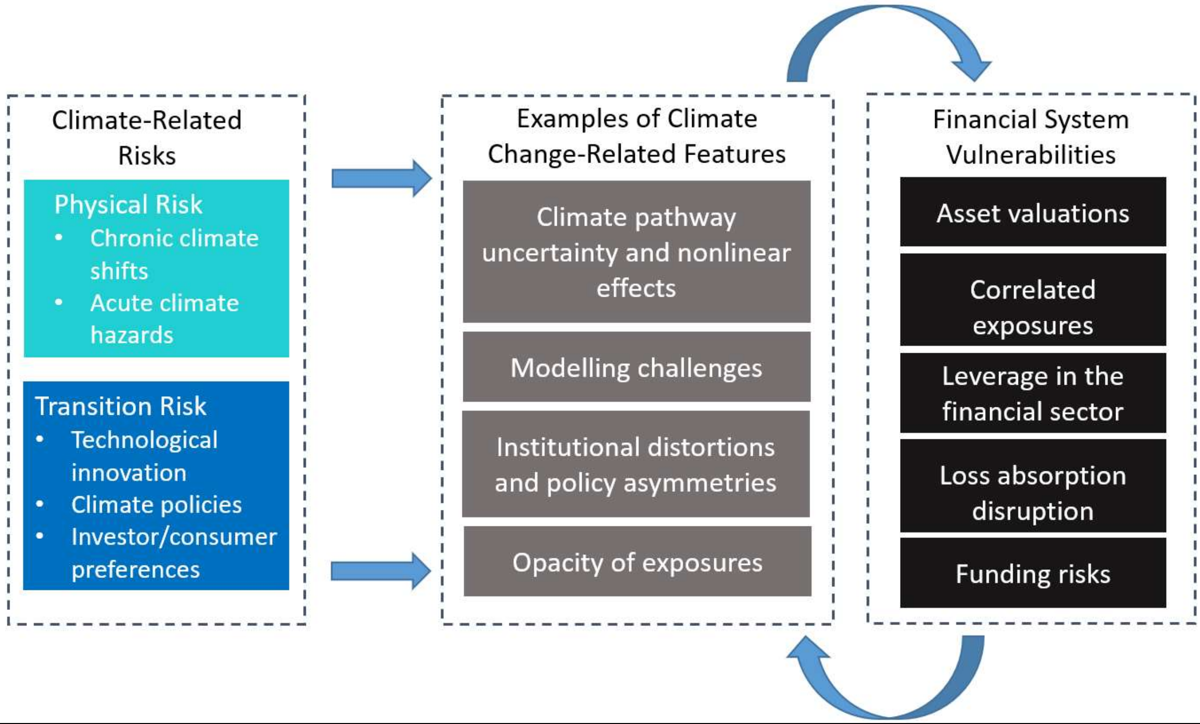
[2] See Brunetti, Dennis, Gates, Hancock, Ignell, Kiser, Kotta, Kovner, Rosen and Tabor (2021).

[3] A third category, known as "litigation risks," covers the potential for impacts from a wide variety of legal proceedings around climate, risks that are highly uncertain and challenging to analyze.

[4] According to Lloyds of London, "Stranded assets are defined as assets that have suffered from unanticipated or premature write-downs, devaluation or conversion to liabilities. In recent years, the issue

Figure 1:

Possible Transmission from Climate-related Risks to Financial System Vulnerabilities



As climate-related risks evolve, climate change-related features are likely to become more salient and amplify financial system vulnerabilities. These financial system vulnerabilities also have the potential to interact with climate change-related features and be further amplified through feedback loops, as shown by the blue curved arrows.

Figure 1 depicts possible transmission channels from climate-related risks to financial system vulnerabilities.[5] As these risks evolve, climate change-related features are likely to become more salient and possibly amplify financial system vulnerabilities. For example, climate-related risks may increase the correlation of shocks – and therefore the aggregate exposures of financial institutions – in ways that are challenging to model. In the context of physical risks, the

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of stranded assets caused by environmental factors, such as climate change and society's attitudes towards it, has become increasingly high profile. Changes to the physical environment driven by climate change, and society's response to these changes, could potentially strand entire regions and global industries within short timeframe, leading to direct and indirect impacts on investment strategies and liabilities." See: https://www.lloyds.com/strandedassets

Carbon Tracker defines stranded assets as those that "at some time prior to the end of their economic life are no longer able to earn an economic return, as a result of changes associated with the transition to a low-carbon economy" and "turn out to be worth less than expected as a result of changes associated with the energy transition". They discussed this concept in their 2011 "Unburnable Carbon" report. See: https://carbontracker.org/resources/terms-list/#unburnable-carbon

[5] This figure builds on previous work conducted by Brunetti *et al*. (2021) and relates to the financial stability monitoring framework described in the Federal Reserve's Financial Stability Reports, see Board of Governors (2020).

simultaneous occurrence of hazards such as hugely damaging hurricanes, inland rain bombs, and wildfires across the continent may become more frequent than historical data would suggest and significantly impact financial institutions operating and holding assets in vulnerable locations. In the context of transition risk, the introduction of new technologies or policies will inevitably lead to creative destruction within and across firms. While the rise and fall of products or firms is a standard feature of the modern economy, transition risk is suggestive that the scope and rapidity of economic shifts could exceed the historical pace of change that the financial sector is accustomed to.[6] In addition, even if macroeconomically the growth in green sectors offsets the decline in emissions-intensive sectors, negative effects may be concentrated by region and sector.

Given that historical data may have limited relevance for predicting future climate states, financial institutions have little historical guidance on which to base projections, suggesting that existing risk management models and frameworks may leave them inadequately prepared for climate-related risks. Nonlinear effects may further complicate efforts to mitigate and model climate-related risks, as tipping points are difficult to predict.[7] Additional challenges remain. First, many financial market participants may lack the ability or incentive to invest in better understanding their exposures, many of which are opaque.[8] Second, some factors, such as the impact of emerging disruptive technologies, are intrinsically unpredictable. Third, institutional distortions and policy asymmetries may increase financial system vulnerabilities. For instance, studies by Ouazad and Kahn (2021) and Keenan and Bradt (2020) document how U.S. banks, benefitting from asymmetric information on climate-related risks, may have been able to shift risk to other entities (for example, the purchasers of mortgage securities). While this type of risk shifting, in addition to insurance, may protect certain entities from the impacts of climate-related risks in the short-term, it may not be a sustainable mitigant and may inadvertently lead to a buildup of risks in other counterparties with potentially significant financial stability consequences.

As with any shock, climate-related risk is absorbed by institutional "layers", beginning with insurers, passing through households and non-financial firms, and ending with banks, pensions, securities holders, and ultimately the government. Financial stability requires that these loss-absorbing layers continue to function reliably in the presence of climate shocks; this can be broadly termed a "flow-of-risk" analysis.[9] Due to the climate change-related features shown in Figure 1, financial institutions may underestimate the magnitude of climate-related risks and increase (or fail to decrease) leverage where appropriate. If insurers, for instance, lever up, they may be unable

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[6] The Glasgow Financial Alliance for Net Zero suggests that $32 trillion of global investment will be needed between 2021-2030. More information can be found here: https://www.gfanzero.com/netzerofinancing

[7] A 2018 Intergovernmental Panel on Climate Change special report defines tipping points in the global climate system as "large-scale singular events" and "critical thresholds that, when exceeded, can lead to a significant change in the state of the system, often with an understanding that the change is irreversible". Examples of such tipping points could include loss of Arctic Sea ice and widespread permafrost thawing. These events can be difficult to predict due to the high degree of uncertainty surrounding the climate system itself. See: https://www.ipcc.ch/sr15/chapter/chapter-3/

[8] See, e.g., Brunetti *et al*. (2021).

[9] The financial literature has sometimes characterized analysis of loss-absorption layers as analysis of the waterfall of losses. Waterfall analysis has historically been used to analyze liquidity risks to asset managers, see, e.g., Cetorelli, Duarte and Eisenbach (2016) and Bouveret (2017).

to provide coverage when correlated climate-related shocks occur, possibly limiting their ability to absorb losses. This may then affect banks' abilities to lend if they held assets that were impacted by the shock.[10] Due to the climate change-related features shown in Figure 1, it may be challenging for banks themselves to adequately account for funding disruptions. The disruption of loss absorption capacity, beginning with insurers and passing through to banks, has the potential to cause sudden changes in asset valuations and financial instability, and these effects could be especially acute if insurers decide to curtail policy coverage for climate-vulnerable assets.

These financial system vulnerabilities also have the potential to interact with climate change-related features and become amplified through feedback loops, as shown by the blue curved arrows in Figure 1. For example, high leverage may inadvertently provide too much funding to non-green institutions. In turn, continued emissions by those companies may further increase uncertainty about future climate pathways, since each additional ton of CO_2 emitted into the atmosphere further warms the planet and alters the climate. The feedback loops shown in the figure also account for the possible interactions between the real economy and the financial sector. Residential real estate construction along the U.S. coast has been a fundamental driver of growth for many communities, but it also has increased the exposure of lenders, guarantors, and purchasers of securitized mortgages to physical risk. Should banks and other mortgage providers curb lending for home construction in these areas, the impact on local economic growth, employment, and tax revenue could be severe. These decreases would in turn imperil the ability of local households and firms to repay existing (non-mortgage) debts, a clear instance of heightened credit risk. In turn, if banks' abilities to lend to households and businesses are curtailed, there may be reduced economic activity and associated financial stability implications.

More generally, the features illustrated in Figure 1 can be expressed as direct and indirect effects. Direct effects are captured as the flow of losses through the financial system. Indirect effects are captured as changes in liquidity, demand for credit, and other spillovers. Batten, Sowerbutts and Tanaka (2016) itemize indirect effects, including *inter alia*: (i) increased uncertainty for investors and loss of market confidence, (ii) damage to banking and payment service facilities (in the case of acute physical risk), (iii) a reduction in insurance in affected areas, (iv) reputational risks, (v) limited financial resources available for reconstruction from physical damage due to weakening of household & corporate balance sheets and fall in output in affected area (in the case of acute physical risk), (vi) a decrease in collateral values, (vii) asset fire sales leading to decreases in asset prices, (viii) and a reduction of lending in unaffected areas/sectors as well as affected areas/sectors due to bank losses in affected areas/sectors.

While climate-related risks have not yet led to financial instability – in which large scale losses reverberate through the financial system and impair financial institutions or the functioning of key liquidity or credit markets – the consequences of possible interactions and feedback loops between financial system vulnerabilities and climate change-related features highlight the need for further analysis. Specifically, increased monitoring of vulnerabilities, improved modelling techniques,

[10] In this example, banks would rely on insurers to backstop losses associated with the climate shock. As another example of a financial stability vulnerability, unforeseen counterparty or market risk could emerge if all participants pursue identical risk mitigation strategies, such as insurance.

appropriate disclosure, and well-designed transition policies are important for maintaining financial stability.

3. Candidate Methodologies

The assessment of CRFSRs may follow processes similar to those used for managing any significant risk; however, CRFSRs have unique properties that challenge traditional risk approaches. While estimation of CRFSRs has been, and continues to be, extensively discussed, work is still in its early stages and there is no consensus on preferred modelling approaches.

Modelling and assessing CRFSRs present several challenges relating to: (1) uncertainty, (2) long time horizons, (3) heterogeneity, (4) technological change, and (5) damage functions for measuring the economic impact of climate change.[11]

Uncertainty in measuring CRFSRs may significantly undermine the validity of risk estimates. The climate system is a complex structure composed by five major components (and the interactions between them): the atmosphere, the oceans, the cryosphere (snow and ice), the land surface, the biosphere, and the interactions between them. There is a large degree of uncertainty about the magnitude and feedback mechanisms of the climate system, as well as how the system affects and interacts with economic and financial variables. All modeling approaches are based on strong assumptions about the future behavior of economic agents, the future of technological innovation, future emissions pathways, the impact of emissions on climate, and the economic and financial consequences of climate change. Moreover, non-linearities related to climate tipping points and the interconnectedness of natural, financial, and economic systems are additional sources of model uncertainty that will inevitably affect the validity of risk estimates.

The **long time horizon** surrounding CRFSRs further challenges estimating risks. Traditional methodologies usually forecast risks within a 5-year horizon, at most. This is not sufficient for fully estimating CRFSRs, as impacts are expected to manifest over longer time horizons. As a result, estimating CRFSRs requires additional assumptions about the evolution of balance sheets, physical systems, and discount factors.

Heterogeneities in financial markets and institutions' exposures also complicate climate-related risk modeling. Heterogeneity refers to the differences in portfolio composition of market participants, the geographical location of counterparties and collateral, and sectoral classifications (firms belonging to the same sector have correlated exposures). Heterogeneities may also result from the fragmented U.S. regulatory landscape.

Technological change may have two differing impacts. On the one hand, it is important for mitigating and adapting to the effects of climate change. On the other hand, climate change-induced innovation may cause certain assets to suffer a devaluation and become stranded. Thus, understanding how innovation evolves is a crucial part of assessing CRFSRs. Many methodologies

[11] The assessment of CRFSRs requires new, unique, and granular data. These data are, at best, only partially available. Moreover, data linking past climate change events to financial stability risks may not be representative of future pathways. Appendix 6.1 contains a brief description of data needs for the methodologies discussed in section 3.

either do not consider innovations or make simple assumptions about them. Given the magnitude of technological and infrastructural changes we have experienced in the last few decades, it is important to consider them when assessing vulnerabilities related to climate change. Moreover, considering both climate adaptation and mitigation in response functions should be central in modeling CRFSRs.

Damage functions map climate-related risks to economic and household welfare outcomes. They are important for determining the social costs of climate change and, hence, the optimal policy response. Damages, among other things, include net negative effects on the labor market, capital stock, and natural capital. Tangible and non-tangible impacts of climate change are difficult to estimate, which may lead to limited damage functions and imprecise ("noisy") estimates of economic damages.

The remainder of this section catalogues the range of methodologies that have been used to study climate-related risks and could be employed to estimate U.S. CRFSRS, while focusing on their ability to address the five challenges discussed above. We describe each methodology briefly and then discuss key empirical findings. When meaningful, we distinguish between transition and physical risks and whether a methodology is suitable for forward- and/or backward-looking analyses. When available, we report financial system vulnerabilities and an assessment of those vulnerabilities (high/medium/low) based on the literature we review. It is important to note that vulnerabilities and their assessments are based on the literature we analyze and are, by definition, incomplete. For each assessment, we also indicate the uncertainty (high/low) surrounding that assessment. To do so, we look at the number of studies available for the assessment, the modelling assumptions behind those studies, and the overall qualitative evaluation of the results. We begin our discussion with methodologies that have historically been more prevalent.[12]

3.1 Integrated Assessment Models

Integrated assessment models (IAMs) combine economic and climate models to analyze the relationships between emissions, climate change, and economic growth. The goal of an IAM is either to (1) conduct a highly aggregated cost-benefit analysis of climate change mitigation, or (2) analyze the cost-effectiveness of climate policies and their resulting emissions pathways. IAMs are widely used for developing climate scenarios.[13] IAMs (together with equilibrium models, discussed in Section 3.2) have long been used to study broad economic climate-change implications, and only recently have been used to assess CRFSRs.

[12] Section 6.2 in the Appendix contains a schematic comparison of methodologies across different dimensions.

[13] IAMs are featured prominently in reports from the Intergovernmental Panel on Climate Change, and they are used by government agencies to calculate the economic damage from a marginal unit of greenhouse gas emissions, or the "social cost of greenhouse gases" (Interagency Working Group on Social Cost of Greenhouse Gases, 2021).

At a basic level, IAMs consist of two interlinked "modules."[14] The first is an economic module, which models production, consumption, and investment. This is typically an aggregated representative agent model where the agent solves an intertemporal optimization problem. The second module is a climate module, which models greenhouse gas emissions and the carbon cycle. The climate module estimates the changes to incremental geophysical factors such as global mean temperature.

Despite their wide usage, IAMs have significant shortcomings, as shown in Table 1.[15] Like other models, IAMs are limited by the inherent difficulties of modeling climate change, especially because most IAMs do not model tipping points or feedback loops in the climate system. Additionally, the outputs of IAMs are typically highly aggregated, and IAMs generally do not account for heterogeneity, instead relying on a representative agent approach and using aggregated damage functions.[16, 17] Moreover, most IAMs do not model financial intermediation, and they typically do not account for long-term technological advancements or damages from disorderly transitions away from fossil fuels. Finally, IAMs rely on arbitrary social discount rates, which raise technical and ethical concerns.[18]

Given their lack of a financial component, researchers do not use IAMs in isolation to estimate financial stability risks. Instead, some researchers use IAMs to build integrated economic and climate scenarios. They then use these scenarios as an input to a second methodology, such as a stress test.[19]

3.2 Equilibrium Models

General equilibrium models solve for a complex system of endogenous responses of economic agents, interlinkages, and systemic interactions between various agents and sectors in the economy. As such, these models can help with studying economic and financial implications of climate change, going beyond reduced-form or statistical methods. In Sections 3.2.1 and 3.2.2, we concentrate on the two main methodologies used to assess CRFSRs in an equilibrium setting.

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[14] A subset of IAMs, called policy optimization models (POMs), include a third module for the economic damages of climate change (IPCC, 2001). In this module, the "damage function" calculates economic damages based on inputs from the economic and climate modules.

[15] For an extended discussion of the shortcomings of IAMs, see Farmer, Hepburn, Mealy, and Teytelboym (2015).

[16] IAMs can be complex and produce disaggregated intermediate outputs. However, because IAMs typically rely on simplified economic and climate modules with many assumptions, researchers tend to use only the final aggregated model outputs.

[17] These functions are central to cost-benefit analysis using IAMs, but they have been criticized by researchers for their lack of calibration data and use of scalar functions of temperature (see Farmer *et al.*, 2015).

[18] The social discount rate heavily influences the economic damages and emissions pathways of IAMs, often to the point of dominating other model inputs (*e.g.*, see Emmerling Drouet, van der Wijst, van Vuuren, Bosetti, and Tavoni, 2019). The discount rate is also widely acknowledged as raising ethical concerns over inter-generational equity, as higher discount rates place a lower value on the social welfare of future generations, allowing for less aggressive climate policies (see Beckerman and Hepurn, 2007).

[19] Several studies discussed in Section 3.7 rely on a set of scenarios constructed using IAMs.

3.2.1 Computable General Equilibrium Models

The Computable General Equilibrium (CGE) approach is one of the most popular ways to model and solve for general equilibrium, in a theoretically consistent fashion. It computationally solves for key economic equilibrium outcomes, including resource allocation and income distribution. Such economic outcomes and welfare effects under different climate scenarios, and the ensuing disruptions of economic activity, can be used for comparative statics analysis of climate-related risks.

The CGE approach has strengths and weaknesses, as shown in Table 1. On one hand, it allows measurement of climate-related economic outcomes and welfare costs over a long horizon that easily extends beyond the short-term horizon of 3 to 5 years. CGE models can also be flexibly adjusted to multi-sector, multi-country, or global set-ups, each of which is suitable for assessing policies covering different levels of jurisdictions. The approach is often criticized for relying on strong assumptions, particularly on perfect information, exogenous technology, a lack of adjustment costs and frictions in production, and an inelastic supply of labor. These assumptions do not allow the model to speak to uncertainty, endogenous responses in technology, or input substitution. However, CGE models can incorporate heterogeneous exposure of economic agents to climate-related risks and, to some extent, damage functions. Lastly, the so-called "black box" aspect – complex and often custom-written models with a large number of variables – makes it hard to decompose the mechanism and trace the effects of policies to particular features or parameters in the model.

Despite their wide popularity in climate studies, CGE models have not been sufficiently altered to incorporate aspects that can address financial stability implications of climate-related risks. Instead, these models have been mostly used to assess economic impacts of climate-related outcomes in the U.S., as well as in many other countries.[20] Similar to IAMs, the CGE models have also been used to develop climate scenarios that can feed into other approaches including stress tests.

3.2.2 Dynamic Stochastic General Equilibrium Models

Similar to the CGE models, Dynamic Stochastic General Equilibrium (DSGE) models constitute another type of micro-founded general equilibrium models, which can incorporate behavioral changes and systemic interactions among agents and sectors in the economy over a short- to long-term time horizon. As shown in Table 1, DSGE models improve on the CGE models by incorporating uncertainty and endogenous changes in technological innovation in response to climate events and policies. In addition, DSGE models allow one to more clearly identify the transmission mechanism of different types of uncertainty (technological, monetary, etc.), to compare different policy interventions, and to prescribe a time-optimal path for the best policy instrument. However, such improvements come at the expense of computational burden which

[20] CGE models in climate studies have examined backward- as well as forward-looking economic impacts of both physical and transition risks in the U.S. Some studies include Babiker *et al*. (2000), Fan and Davlasheridze (2019), Hazilla and Kopp (1990), Jorgenson and Wilcoxen (1993), and Rose and Liao (2005).

tends to limit the size of a typical DSGE model, including the degree of details (for instance, sectoral disaggregation, heterogenous climate exposures by different economic agents, and damage functions) that the model can handle. Assumptions on rational expectations and stationarity of fundamentals are other commonly criticized features of the DSGE. In particular, the nature of climate uncertainty makes it hard to assess optimal climate policy predictions based on DSGE models. For instance, when DSGE models are used to examine real business cycle effects, the underlying stationarity of the fundamentals imply that errors will ultimately be corrected. This is not the case for climate change, where errors are likely to compound over time. [21]

Similar to IAMs and CGE models, DSGE models have mostly focused on assessing the economic impacts of climate-related risks in the U.S., rather than studying financial stability implications.[22] These models are also being used by central bankers and industry practitioners to develop climate scenarios that serve as inputs for other analyses such as stress tests and other practitioner approaches. However, the literature on Environmental DSGE ("E-DSGE") models has been growing. Among the few recent studies that have begun to specifically examine the financial impacts of climate-related risks is Carattini, Heutel, and Melkadze (2021). [23] They model the banking sector within a DSGE framework and examine the implications of financial frictions (*i.e.*, the moral hazard problem between depositors and banks) on transition risk in response to, specifically, a carbon tax. Calibrating on U.S. data, their simulation results over a five-year horizon show that an abrupt transition can induce banking sector volatility by immediately dropping the banking sector capital by around 10 percent through bank exposures to non-green firms' assets, only to fully recover over the next five years.

Findings from E-DSGE models with financial systems provide preliminary assessments of the U.S. CRFSRs. For instance, the findings by Carattini *et al*. (2021) claim that U.S. financial stability implications of **forward-looking** transition risk may be low, because current bank capital buffers can easily absorb a 10 percent loss in equity—see Table 2.[24] Nevertheless, at the current stage,

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[21] Heutel (2012) uses an Environmental DSGE ("E-DSGE") model to run simulations over 25 years to show that procyclicality in carbon emissions is optimal. Golosov, Hassler, Krusell, and Tsyvinski (2014) uses a DSGE to claim that the optimal carbon tax is slightly higher than median estimates from the literature. Other applications include Annicchiarico and Di Dio (2015), and Dissou and Karnizova (2016).

[22] DSGE models in climate studies have examined forward-looking economic impacts of both physical and transition risks in the U.S., *e.g.,* Fischer and Springborn (2011) and Keen and Pakko (2007). More recently, E-DGSE models have become one of the most popular approaches in the climate literature to gauge economic impacts on transition risks and, in particular, inform the optimal climate policy – see Annicchiarico and Di Dio (2015), Dissou and Karnizova (2016), Golosov *et al*. (2014), and Heutel (2012).

[23] However, most such extensions of E-DSGE remain in nascent stages, incorporating financial modeling within the E-DSGE but not necessarily modeling financial stability risks. An example of such research is Punzi (2018). This paper shows that the E-DSGE model can be extended to incorporate bank lending and examine the capital requirements to promote production by the green (non-polluting) sector. The paper finds that positive financial shocks (*e.g.*, easier access to credit) to green firms and macroprudential policies like differentiated capital requirements can have lasting positive impacts on the output increase by green firms.

[24] Other findings include the drop in equity capital leading to a general reduction in bank lending to all sectors including both green (non-polluting) and non-green during the transition process, thereby

such assessment should be carefully considered for any practical use and several important caveats should be considered. First, such assessment is based on an exceptionally thin literature, and hence, the uncertainty surrounding the assessment is unusually large. Second, the findings will vary greatly depending on modelling assumptions, including the type, nature, and severity of financial market frictions, potential departures from the representative agent and single sector framework, and calibration of certain parameters including substitutability.[25] Lastly, the assessment does not address forward-looking transition risk to financial stability overall. It only reflects one type of vulnerability, namely aggregate bank leverage, and does not speak to other types of vulnerabilities, such as asset valuation or leverage in other parts of the financial sector.

3.3 Overlapping Generation Models

In contrast to the infinitely-lived agents in models discussed in Sections 3.1 and 3.2, overlapping generation (OLG), or life-cycle, models are populated by finite-lived cohorts of agents that coexist for some time. These models' intergenerational aspect, with "young" and "old," makes them particularly instructive in the context of climate change because the costs and benefits of climate change and mitigation policies fall unevenly on different generations. They are also useful for studying the fiscal implications and distributional effects of carbon taxes and other mitigation policies for different generations, as indicated in Table 1.

An early contribution by Howarth (1998) calibrates an OLG model of climate change and the world economy to study optimal abatement policies under alternative social welfare functions. Absent intergenerational transfers, efficient abatement implies a mean global temperature increase of 7.4°C relative to the pre-industrial norm. A utilitarian optimum (where current and future generations are equally weighted) features much more aggressive abatement and a long-run temperature increase of 3.4°C.[26] More recently, Rausch and Yonezawa (2018), and Williams,

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lengthening the duration of the overall economic recession. Macroprudential policy that shifts bank exposure from non-green to green firm assets can mitigate such transition risk.

[25] The authors recognize some of these shortcomings.

[26] Leach (2009), Rausch (2013), Carbone, Morgenstern, Williams, and Burtraw (2013), and Fried (2018) show that current and future generations will have conflicting preferences on how carbon taxes revenues are "recycled." Sachs (2014) suggests funding mitigation efforts with public debt (rather than taxes) in order to shift mitigation costs to later generations that benefit from mitigation. Rasmussen (2003) simulates a multi-sector model of the U.S. to reckon the distributional effects of a carbon tax. He finds that generations a century out incur substantially higher costs than current generations and the current old generation may gain. Karp and Rezaei (2014) study the distributional aspect of a carbon tax and the associated political economy. They show (theoretically) that because asset prices capitalize future environmental benefits, carbon taxes benefit the current old generation (that owns the assets) and harms the current young one by decreasing real wages. Transfer from the old to young generation can improve the distributional effects, and, under certain political/demographic circumstances, such transfers are politically implementable. In an early application, John and Pecchinino (1994) study the tradeoff between growth and the environment in an OLG model where people care about both. In equilibrium, environmental quality fits the well-documented, environmental "Kuznets curve" – lower quality in middle-income countries. Even though the environment is a public good, overinvesting in environmental quality can occur (a dynamic inefficiency typical in OLG models). Kotlikoff, Polbin, and Zubarev (2016) argue using an OLG model that gradual abatement strategies such as the 2015 Paris Accord create a "use it or lose it" that may accelerate fossil fuel

Gordon, Burtraw, Carbone, and Morgenstern (2014) use an OLG framework to analyze the distributional effects of carbon taxes.

OLG models can also capture related externalities and dynamic inefficiencies because current generations may not consider how their decisions affect future ones. While useful in those regards, the OLG framework as applied in the climate context tends to be theoretical (or, occasionally, simulated), so it may be less useful than other methodologies for calibrating financial stability risks. Because the analysis tends to be theoretical, it is also more forward-looking. None of the OLG literature to date considers the financial stability implications of climate change for the U.S., as demonstrated by the NAs in Table 2.

3.4 Statistical Methods

Statistical methods complement analyses based on equilibrium and integrated assessment models. The methods described in the previous sections are well-suited to capture interactions between agents but rely on statistical methods to accurately measure correlations in the data that, in turn, are used as building blocks for equilibrium models. Macro- and micro-econometric statistical methods have been used in asset pricing and corporate finance, two subfields of the broader finance academic literature, to identify and measure U.S. CRFSRs. As reviewed below, the asset pricing literature has analyzed whether physical and transition risks are incorporated in prices of financial assets, including equity, fixed income, and real estate. The corporate finance literature has analyzed the extent to which firms, and the productive sector at large, are exposed to physical and transition risks. These two types of analyses are informative for U.S. CRFSRs to the extent that the financial sector (e.g., banks, pension funds, insurance companies, hedge funds, mutual funds) is highly exposed to (i) swings in asset prices related to a sudden reassessment of physical and transition risks or (ii) direct and indirect losses following extreme climate change-related events.

While widely used in the literature, statistical methods have some limitations, as shown in Table 1. On the one hand, they are intuitive, simple to estimate, and able to capture the important role of heterogeneities (*e.g.,* geographical, sectoral, regulatory differences) for assessing CRFSRs. On the other hand, they rely on partial equilibrium models estimated on past or current information and, therefore, ignore equilibrium considerations, particularly important given the long time horizon of climate change and the role of technological changes. While well-suited to estimate direct damages, the reduced form nature of these models does not allow a precise estimation of the indirect costs such as social costs. Moreover, statistical methods do not necessarily capture the inherent uncertainty of climate change but are helpful to document non-linearities of physical and transition risks. It should also be noted that statistical methods, like DSGE models, CGE models, and IAMs, can be used to develop climate scenarios which serve as inputs for other approaches, which we discuss in Sections 3.7 and 3.8. They can also be used to calibrate parameters and inform assumptions of agent-based models, as discussed in Section 3.6.

Physical risk, backward-looking. The backward-looking statistical methods literature mainly provides evidence of changes in firm behavior and asset prices in response to physical risks of

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use and thus raise global temperatures. The paper uses a simple OLG model to illustrate this long-noted Green Paradox. They show immediate policy action can raise welfare for all generations.

climate change. Brown, Gustafson, and Ivanov (2021) show that firms respond to winter weather by drawing down and increasing the size of their credit lines with banks. The banks charge borrowers for this liquidity via increased interest rates and less borrower-friendly loan provisions. Ivanov, Macchiavelli, and Santos (forthcoming) also show that banks help firms hit by disasters but reduce their credit supply to distant regions that are not affected by disasters. Correa, He, Herpfer, and Lel (2020) show that, following disasters, banks also increase rates charged to at-risk but unaffected firms. Barth, Sun, and Zhang (2019) document that bank income increases after natural disasters and confirm that banks play a key role in supporting the economy following natural disasters. Blickle, Hamerling and Morgan (2021) also find increased bank income and lending after weather disasters with only insignificant or small effects on loan losses and default risk. Both studies suggest that physical risks to banks are modest. By contrast, Noth and Schuewer (2018) find that extreme weather events increase the likelihood of banks' default and foreclosure ratios. Affected firms rely on banks for emergency liquidity, provided at higher rates and less favorable terms precisely when these firms need liquidity the most. Banks, in addition to potential direct damages from extreme climate events, might also face sudden large drawdowns from existing credit lines as firms tap banks' liquidity to navigate climate shocks increasing, in turn, banks' incomes.

The statistical methods literature also speaks to the effect of physical risks on asset prices. Baldauf, Garlappi, and Yannelis (2020) find that houses projected to be underwater in neighborhoods where households believe in climate change sell at a discount compared to neighborhoods where households do not believe in climate change.[27] Bernstein, Gustafson, and Lewis (2019) find that homes exposed to sea level rise sell for approximately 7 percent less than observably equivalent unexposed properties equidistant from the beach. The authors also show that this discount has grown over time and is driven by sophisticated buyers and communities worried about global warming. These price differences are likely reflected in the value of assets held by financial institutions, such as mortgages, mortgage-backed securities, and other related products.

Huynh and Xia (2021) find that prices of corporate bonds incorporate climate-related risks. Bonds with a higher climate change news beta earn lower future returns, as investors increase their demand for bonds that can be used to hedge against climate-related risks. Goldsmith-Pinkham, Gustafson, Lewis, and Schwert (2021) and Schwert (2017) show that municipal bond prices also incorporate climate-related risks. Changes in climate-related risks might therefore affect corporate bond holders, such as insurance companies and pension funds. Finally, Braun, Braun, and Weigert (2021) find a "hurricane premium" – stocks with a low sensitivity to U.S. hurricane losses outperform those with a high sensitivity by 8.9 percent per annum, suggesting that climate-related risks may have a nontrivial impact on asset pricing.

Combined, the backward-looking statistical methods literature suggests that both housing and securities markets are vulnerable to the physical risks of flood exposure and changes in individual

[27] The authors obtain beliefs about climate change at the county level from the Yale Climate Opinion Maps 2016.

beliefs in climate change. As seen in Table 2, the overall assessment of financial vulnerabilities linked to backward-looking physical risk is likely medium, driven ultimately by the degree of lenders' diversification, the extent to which asset prices already incorporate climate-related risks, and the severity of future climate shocks.

Physical risk, forward-looking. The forward-looking statistical methods literature on financial stability and climate change highlights both the effect of physical risk and potential ways to incorporate this risk into asset pricing. Lemoine (2021) estimates that an additional 2°C of global warming would eliminate profits from the average acre of current farmland in the eastern U.S. The physical risks posed by climate change are particularly important for the real estate market. Rao (2017) shows that if sea levels rise in line with scientists' predictions by 2100, almost 300 U.S. cities would lose at least half of their residential real estate, and 36 U.S. cities would be completely lost. Florida is particularly affected as one out of eight homes in Florida would be under water.
Hauer, Evans, and Mishra (2016) also analyze physical risk in the U.S. real estate market and find that a 2100 sea level rise of 0.9m places a land area projected to house 4.2 million people at risk of inundation, whereas 1.8m sea level rise affects 13.1 million people. Ouazad and Kahn (2021) show that lenders are more likely to approve mortgages that can be securitized, thereby transferring climate-related risk, in the aftermath of natural disasters. Engle, Giglio, Kelly, Lee, and Stroebel (2020) present a methodology, based on option pricing, for constructing climate-related risk hedge portfolios using publicly traded assets. Perez-Gonzalez and Yun (2013) study the introduction of weather derivatives and find that weather-sensitive firms disproportionally benefit from this innovation. The use of weather derivatives leads to higher valuations, investments, and leverage.

Effectively pricing climate-related risk is an adaptation strategy to mitigate the losses that can potentially take place within the century. The overall assessment of vulnerabilities linked to forward-looking physical risk is likely high, mostly driven by commercial and residential real estate, through direct holdings and securitization activity.

Transition risk, backward-looking. Backward-looking statistical models provide an understanding of how firms' and investors' risk-taking behaviors respond to transition risks. Hsu, Li, and Tsou (2020) document a large pollution premium, namely substantially higher returns generated by high toxic emission intensity firms compared with low toxic emission intensity firms. The authors attribute the pollution premium to environmental policy uncertainty, which they interpret as a source of systematic risk. Furthermore, firms' preferences for climate-aware assets and investor demands from climate-negligent firms indicate the inclusion of transition risks into risk-taking behavior. These premia might represent a vulnerability, to the extent that investors will require even lower returns to hold climate-aware assets in the future, in turn, affecting the prices of assets held by financial institutions. Baker, Bergstresser, Serafeim, and Wurgler (2020) show that investors sacrifice returns to hold green bonds. Municipal green bonds are issued at a premium and their ownership is more concentrated, with a small subset of investors over-weighing these bonds in their portfolio. Chava (2014) finds that investors demand significantly higher expected returns on stocks excluded by environmental screens compared with firms without such environmental concerns. The author also shows that lenders charge a higher interest rate on loans issued to firms with these environmental concerns. These higher borrowing costs might cause weak firms to struggle making interest payments, pushing them closer to financial distress. Seltzer, Starks, and Zhu (2021) also document that firms' bond financing costs reflect their carbon footprints, particularly when the issuer is located in a state with stricter regulatory enforcement. Ivanov, Kruttli, and Watulaga (2021) show that high-emission firms face shorter loan maturities, higher interest rates, and lower access to permanent forms of bank financing compared to low-emission firms. This evidence suggests an overall assessment of vulnerabilities linked to backward-looking physical risk as medium, as shown in Table 2.

Transition risk, forward-looking. The forward-looking transition risk literature emphasizes balance sheet and asset pricing behavior in response to the discontinued use of environmentally harmful resources. Bolton and Kacperczyk (2021) analyze firms' exposures to carbon-transition risk. They document a widespread carbon premium, higher stock returns for companies with higher levels of carbon emissions, in all sectors over Asia, Europe, and North America. Morris, Kaufman, and Doshi (2021) document that the transition from carbon will likely hit the public finances of coal-dependent communities. As seen in Table 2, the overall assessment of vulnerabilities linked to forward-looking transition risk is likely medium, mostly driven by potential swings in asset prices following changes in transition risks.

While the literature on statistical methods in assessing U.S. CRFSRs is relatively abundant, there is substantial uncertainty about its findings, as highlighted in Table 2. Given their partial equilibrium and inherently backward-looking nature, these models can be used to measure correlations in past data and discipline equilibrium models. However, the estimated coefficients typically depend on the empirical setting, such as a specific natural event. In addition, even holding the event constant, the estimated coefficients in a particular geographical region in a year might differ from those estimated in another area or year. In sum, the magnitudes obtained with statistical methods might not generalize outside the empirical context where the methods were applied, in turn, generating substantial uncertainty about the use of the estimates to guide policy.

3.5 Input-output Models

Input–output (IO) models are quantitative economic models that represent the interdependencies between different sectors of an economy.[28] They present the domestic supply and use of commodities by industry and show how the output from one industrial sector may become an input to another sector. Thus, the models help to identify not only industries that produce carbon-intensive assets, but also the ones using such assets as inputs. Because indirect losses from a

[28] Both IO models and integrated assessment models (IAMs) bring together and summarize relationships from different parts of the economy to assess climate risks. However, IO models specifically consider the interlinkages between various industries through their production and usage of carbon intensive assets, whereas IAMs consider different parts of the economy including demographic, political, and economic variables that affect climate risks.

climate event may surpass direct losses in a developed, highly interconnected economy, IO models have gained interest, especially in disaster evaluation.[29]

The main strength of environmentally-extended input-output (EEIO) models lies in their ability to provide a simple and robust method for evaluating the linkages between economic consumption activities and their environmental impacts. Because they are using input-output data to estimate the linkages among different sectors in the economy, they do not require strict assumptions, they are helpful for addressing some of the uncertainty inherent to modelling climate change, and are less complex than many alternatives, such as CGE models. Hence, by construction, IO models incorporate heterogeneous agents in the economy, at least at the sectoral level and might be useful in identifying potentially vulnerable geographies and sectors to transition policies. Finally, IO models are useful for producing estimates of climate change-related damages by incorporating linkages among different sectors. However, such data reliance brings the biggest caveat of IO models: They are mostly backward-looking and require extrapolation from past trends, as they are based on historical input-output tables. Thus, the models cannot capture significant technological advances. Second, given this lack of adaptation to technological change, IO models are more relevant for short- to medium-term horizon implications, which can be challenging since climate-related risks are better captured over a longer-term time horizon. Finally, IO models mainly focus on supply chain disruptions (rather than general equilibrium effects) and thus are arguably incomplete. These benefits and drawbacks of IO models are summarized in Table 1.

Though IO models are mostly retrospective, they are used to quantify both backward-looking physical risk and forward-looking transition risk. A few papers employ IO models to study the effects of transition risk on financial stability at an international level (see Vermeulen, Schets, Lohuis, Kolbl, Jansen, and Heeringa, 2018 for an application for Netherlands, and Mainar-Causapé, Barrera-Lozano, and Fuentes-Saguar, 2020 for various European Union states). A number of studies, including Mathur and Morris (2014) and Marron and Toder (2015), have examined the distributional effects of a carbon tax across income classes and/or regions in the United States. A few studies also use IO models to assess the *economic* impact of climate disasters in the United States (see Hallegatte, 2008, and Kunz, Mühr, Kunz-Plapp, Daniell, Khazai, Wenzel, Vannieuwenhuyse, Comes, Elmer, Schröter, Fohringer, Münzberg, Lucas, and Zschau, 2013, who study the costs of Hurricane Katrina and Hurricane Sandy, respectively). However, there is no study in the extant literature that employs IO models to assess U.S. CRFSRs, as noted by the NAs in Table 2.

[29] One application of the IO model on the climate universe is developed by the U.S. Environmental Protection Agency. The technical details of the U.S. Environmentally-Extended Input-Output (USEEIO) model can be found in Yang, Ingwersen, Hawkins, Srocka, and Meyer (2017). In a nutshell, USEEIO uses the Bureau of Economic Analysis IO tables and pairs them with environmental data on resource use and releases of pollutants from various public sources. Thus, the model outcome can be used to quantify environmental impact of all commodities and industries in the U.S. See: https://www.epa.gov/land-research/us-environmentally-extended-input-output-useeio-technical-content

3.6 Agent-based Models

Agent-based models (ABMs) are simulation-based models that capture complex interactions and feedback mechanisms between heterogenous agents and the financial and real economies. In the simulations, agents can be households, firms, banks, and the government, amongst other entities, and these agents are programmed to operate based on certain rules and assumptions. Thus, these models can provide granular, forward-looking insight into how climate-related risks can affect different economic and financial actors.

A key advantage of ABMs is that they are flexible enough to incorporate heterogenous agent assumptions, which allow for a more realistic representation of socioeconomic systems. This is especially relevant for U.S. climate change analysis, as different regions of varying incomes are likely to experience heterogenous effects from climate change (see Hsiang, Kopp, Jina, Rising, Delgado, Mohan, Rasmussen, Muir-Wood, Wilson, Oppenheimer, Larsen, Houser, 2017). ABMs are also flexible enough to incorporate empirical evidence since they are not equilibrium constrained, meaning that ABMs can use more realistic estimates of climate change-related damages and have more flexible damage functions, as noted in Table 1. Another advantage is that ABMs can incorporate uncertainty in agents' decision-making and capture endogenous changes that arise due to agent interactions – such as technology adoption or formation of market structures – which is helpful for addressing some of the uncertainty inherent to modelling climate change. Climate nonlinearities and tipping points also pose additional uncertainties as they are tail-risks; ABMs can somewhat address this challenge, as they inherently run repeated simulations for events associated with different probability distributions. Since ABMs are simulation-based, it is possible to forecast the longer-term, which is helpful given that climate-related risks are better captured over a longer-term time horizon. Finally, ABMs are particularly applicable to financial stability questions, as they can closely model economic and financial systems and provide systemic risk assessments by incorporating specific agent and network effects.

Despite these merits, two key challenges remain. First, ABMs are very computationally intensive and require detailed data to build agents' behavioral rules (see Farmer, Hepburn, Mealy and Teytelboym, 2015 and Patt and Siebenhüner, 2005). As computing power increases and socioeconomic and climate datasets expand, this challenge may be less relevant. Second, agents' behaviors may not be rational and representative with respect to climate-related risks (see Farmer *et al*., 2015). Thus, results are still subject to uncertainty and do not necessarily fully reflect the costs and risks of climate change.

In connection with methodologies above, it should be noted that the outputs of statistical methods can be used to inform parameters and assumptions in ABMs. Furthermore, modelling capabilities are improving and expanding in the direction of agent-based integrated assessment models (see Farmer *et al*., 2015). That said, there are not yet studies in the literature that use ABMs to examine the potential impacts of U.S. CRFSRs, as shown by the NAs in Table 2.

3.7 Scenario Analysis, Stress Testing, and Sensitivity Analysis

Scenario analysis considers the outcomes of plausible climate scenarios, sometimes over long time horizons, to estimate CRFSRs. This approach takes climate and economic projections as inputs, links their parameters to financial risks, and outputs costs and exposures to risk. Though quite similar to scenario analysis, sensitivity analysis and stress tests differ in construction and applicability. In a sensitivity analysis one parameter is changed between two scenarios to analyze its specific effect, or "sensitivity", on results. For instance, given a carbon tax scenario, a sensitivity analysis might change the parameter for the cost of renewable energy technologies to better understand how sensitive the effects of a carbon tax policy are to the price of renewable alternatives. In a climate stress test, a modeler uses granular balance sheet data to predict the impact of a sudden climate-related shock on a large financial institution's portfolio (microprudential) or the financial system as a whole (macroprudential). Stress tests analyze tail events and can be used in conjunction with scenario analysis for supervisory assessments. Scenario analyses do not necessarily consider tail events and can be used by both financial institutions and supervisors. These methodologies share many similarities and are thus discussed together in this section.

These three methodologies typically take climate scenarios as an input to model the impact of the scenarios on a range of economic and financial outcomes, such as real estate prices or sovereign credit ratings. The scenarios differ in their projected levels of emissions, the extent of climate change, climate policies, technological changes, and damages to the global economy. The scenarios can be modeled using IAMs, CGEs, DSGEs, statistical methods, and other climate and economic modeling tools. There are also "off-the-shelf" scenarios developed by economists and climate scientists for the public research community.[30]

A key benefit of these methodologies is that they can address some of the uncertainties inherent to climate-related risks by considering a wide range of possible future pathways, instead of attempting to predict an exact future outcome. Additionally, these methods are applicable to many institutions, such as banks, governments, insurers, and central banks, for purposes such as risk management, strategic decision making, investment in adaptation, and resource allocation. This wide-ranging applicability can shed light on heterogeneities in climate-related risks. While these methodologies are being increasingly used and provide beneficial risk assessments, their results are still subject to uncertainty and hampered by data gaps. For example, historical records may be incomplete or of little use for predicting the severity and frequency of future climate disasters; this is challenging for financial markets, institutions, and regulators, who typically rely on historical

[30] Frequently used scenarios are:

- Representative Concentration Pathways (RCPs), developed by the IPCC. There are several RCPs and each reflects a possible trajectory for global emissions, differing in their particle concentrations and radiative forcing. See Pachauri *et al*. (2014).
- NGFS climate scenarios, developed by the Network for Greening the Financial System. The scenarios reflect low and high levels of physical and transition risk, ranging from "orderly" to "too little, too late". See NGFS (2021).
- World Energy Outlook scenarios, published by the International Energy Agency (IEA). The WEO scenarios are based on the World Energy Model, a large-scale energy market simulation. See IEA (2021).

It is important to note that these scenarios have limitations, and some institutions regularly update the assumptions used in their construction.

data to inform their understanding of potential future risks. The strengths and challenges of these methodologies are noted in Table 1.

Scenario analysis, stress testing, and sensitivity analysis can be applied to estimate vulnerability to **physical risk**, both chronic and acute. For chronic risks, these methodologies will typically use a scenario projecting incremental changes in long-term climate patterns such as temperature, precipitation, or sea level, and model how an incrementally harsher climate could lead to a build-up of vulnerabilities. For example, UBS conducted a sensitivity analysis as part of the UN Environment Finance Initiative (UNEP FI) Pilot to estimate the exposure of its utility company loans to the incremental physical damages of climate change.[31] Comparing 2°C and 4°C scenarios with a baseline, UBS estimated productive capacity losses of the firms in its portfolio and translated the losses into increased probabilities of default.

For acute **physical risk**, these methodologies are used to estimate the impact of extreme events on firm operations and financial health. This can be done either by simulating the impact of a single, very extreme event, such as a powerful hurricane, or by estimating the impact of changes to the underlying distribution of weather events, whereby severe weather events such as wildfires become longer, more frequent, and more severe. For example, Citi recently conducted a scenario analysis to assess the operational resiliency of their New York City and Tampa facilities in the face of severe thunderstorms and tropical storms and found that remote work strategies can help maintain business continuity.[32] A McKinsey case study examines the impacts of storm surges on residential real estate in Florida using a Representative Concentration Pathways (RCP) 8.5 scenario; they project that losses from tail events are likely to increase from about $35 billion today to $50 billion by 2050.[33] The study also highlights that the federal government serves as a final backstop for coverage of disaster-related losses. The Congressional Budget Office (CBO) notes that damages from hurricane winds, storm surges, and heavy rain may impact the federal budget in two ways: (i) increased spending for repairs and assistance, and (ii) an increase in net federal outlays.[34] They also find that expected annual economic losses from damages caused by hurricane winds and storm-related flooding are about $34 billion to the residential sector, $9 billion to commercial businesses, and $12 billion to the public sector. Thus, the overall assessment of vulnerabilities linked to forward-looking physical risk is likely high with a high level of uncertainty (see Table 2).

These methods have also been used to understand the potential for **transition risk** to financial institutions. Practitioners will typically study either the impact of a sudden change in climate-related policies and regulations or the long-term impact of changes in production and consumption related to the transition away from carbon-intensive activities, including the impacts of stranded

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[31] UNEP (2018).
[32] Citigroup (2020).
[33] For these statistics, the study defines a "tail event" as an event with a current one percent annual probability. The authors note that "Damages with current annual exceedance probability of 1% are projected to become more likely; by 2050 they are expected to have an exceedance probability of ~2%" and that "Damages [are] based on constant exposure, i.e., increase in potential damages to 2030 or 2050 is due to change in expected hazards." See: McKinsey Global Institute (2020).
[34] Congressional Budget Office (2019).

assets. For example, Jung, Engle, and Burner (2021) apply a stress testing framework to estimate the time-varying exposure of large, advanced economy banks to a sudden collapse of returns on fossil fuel assets. The authors calculate a "climate beta", or the correlation between returns on bank stocks and a stranded asset portfolio that takes a long position in fossil fuels and a short position in the S&P 500. They then estimate "CRISK", which is each financial institution's capital shortfall given a collapse in returns on fossil fuel stocks. The authors find that while some large U.S. banks were not significantly exposed to a collapse in fossil fuel returns, several banks that lend to fossil fuel firms could see large capital shortfalls. This paper applies statistical methods, stress testing, and other practitioner approaches (discussed in Section 3.8), highlighting the benefits of using multiple methodologies to assess CRFSRs.

Relatedly, the California Department of Insurance partnered with 2° Investing Initiative (2DII) to analyze the exposure of Californian insurance companies to a low-carbon economy transition.[35] They also examined alignment with the goal of limiting global warming to 2°C and expected exposure to high- and low-carbon activities in the future. The assessment, which used IEA scenarios, was conducted for all insurers operating in the state with more than $100 million in premiums and impacts were assessed at the insurer- and system-level. The report finds that insurers' assets remain exposed to transition risks and that fossil fuel investments may become stranded assets. The report also explores how physical risks could pose additional challenges, finding that insurers' investments in coal-powered utilities are highly exposed to wildfires and that their assets may be negatively affected by water scarcity. More recently, 2DII has also worked with the New York Department of Financial Services to study insurers' exposures to transition risk using a scenario analysis.[36] The study reveals that most firms' forward-looking five-year plans did not align with the Paris Agreement and highlights within-industry exposure differences to carbon intensive sectors.[37]

While the previous studies indicate that insurance companies and banks[38] may still have significant exposures to carbon-intensive assets that do not align with the Paris Agreement, the transition to a net-zero economy is likely to be announced in advance and implemented over time, thus the overall assessment of financial stability risk linked to forward-looking transition risk is likely medium with a high level of uncertainty (see Table 2).

There is a small, growing literature primarily developed by practitioners that uses scenario analysis, sensitivity analysis, and stress testing to analyze some financial stability vulnerabilities from climate-related risks. However, this literature is not comprehensive across industries, asset classes, or time horizons, and it is especially thin for U.S.-specific risks. Additionally, these methods are constrained by limited data, their outputs depend on the assumptions and scenarios

[35] California Department of Insurance and 2DII (2018).
[36] The scenarios used in this study are based on 2DII's Paris Agreement Capital Transition Assessment (PACTA) model. The PACTA tool is designed for financial entities to measure their portfolio's alignment with climate scenarios that adhere to the Paris Agreement and can be accessed here: https://www.transitionmonitor.com
[37] New York Department of Financial Services and 2DII (2021).
[38] This is intended to capture a possible two-fold effect since banks may hold carbon-intensive assets and rely on insurers, who may also hold carbon-intensive assets, to backstop their losses.

used, and they have only been applied to certain institutions within the U.S. financial system, not the system itself. Moreover, the path of climate change is highly uncertain and subject to nonlinearities and tipping points. Therefore, while the existing literature suggests that U.S. vulnerabilities to real estate prices due to physical risk are likely "high," it should be noted that this reflects an early stage of analysis. Likewise, while the literature suggests that vulnerabilities from transition risk due to exposure to carbon-intensive assets is likely "medium", this assessment is similarly uncertain (see Table 2).

3.8 Other Practitioner Approaches

Similar to methodologies discussed in Section 3.7, **climate risk scores** and **ratings**, **climate Value at Risk** (VaR) metrics, and **natural capital analyses** are intended to be simpler than traditional modelling methods to increase applicability and usability for practitioners. They offer insights into exposures at varying levels of granularity, from portfolio- to system-level. Like methodologies discussed in Section 3.7, their assumptions and parameters can be informed by IAMs, CGEs, DSGEs, and statistical methods. They are also applicable to many stakeholders for risk management and strategic planning purposes, highlighting their ability to somewhat account for heterogeneity as noted in Table 1.

Climate risk scores and ratings evaluate exposure to climate-related risks at the asset, portfolio, institution, and regional levels for future conditions and policies based on current operations. Multiple private and public entities offer these assessments at the firm- and sovereign-level, and these metrics can be helpful for aligning longer-term goals with climate targets. That said, each provider may use a different methodology, which can make it difficult to compare different outcomes especially since methodologies are not typically disclosed. For example, Environmental, Social, and Governance (ESG) scores are often created by private companies that use different underlying methodologies and data, making comparison across scores challenging. Without comparison capabilities and methodology disclosures, it can also be challenging to interpret these scores and ratings. For instance, ESG scores may correlate in unexpected ways, as noted by Boffo, Marshall, and Patalano (2020), who find that high "E" scores positively correlate with high carbon emissions. This can undermine the reliability of ESG scores and incentivize greenwashing. Elmalt, Igan, and Kirti (2021) also find "at best a weak relationship" between high ESG scoring and low emissions growth. Firms with better ESG scores seem to have somewhat slower emissions growth, but this relationship is quite weak and not statistically significant when examining within-country or within-firm variation. Rzeznik, Hanley, and Pelizzon (2021) find that disparate ESG rating scales may lead investors to buy (sell) stocks they incorrectly perceive as having been recently upgraded (downgraded), which may have asset pricing and financial stability impacts. Aware of these ESG scoring issues, Berg, Kolbel, Pavlova, and Rigobon (2021), develop a noise-correction procedure to better understand how ESG performance affects stock returns; they find that stocks with higher ESG performance have higher expected returns. Given the issues surrounding the transparency, quality, reliability, and comparability of climate risk scores and ratings, further research is needed in this space.

Climate Value at Risk (VaR) analyses apply the traditional value-at-risk framework to assess the future impacts of climate change on the financial system. Using this methodology, modelers can estimate the value of financial assets at risk at a given probability over a particular time horizon for various climate scenarios, which can be derived from IAMs, CGEs, DSGEs, and statistical methods. Climate VaR analyses shed light on how costly a range of possible outcomes, particularly tail-risk events, could be and provide a baseline estimate for damages to the financial system. These metrics quantify the extent of exposure, but it may be challenging to translate results into meaningful actions and avoid myopia since most climate-related risk is concentrated in the tail.

Natural capital analysis measures firms' exposure to natural degradation, such as water stress, habitat destruction, and land erosion from excess use. This method applies a framework that positions natural sources – such as water, forests, and clean air – as a limited capital stock and assesses future impacts of its depletion. In this analysis, practitioners identify natural dependencies, identify risks to those natural resources, and examine impacts on operations and supply chains. Rather than examining how institutions may damage natural resources, this methodology instead examines how institutions' business models may be affected by natural capital degradation.

Climate risk scores and ratings usually do not analyze physical and transition risk separately; these metrics quantify exposure to both types of risks in a single measure. That said, Bank of America recently conducted a pilot project to estimate how exposed a sample portfolio of their U.S. residential mortgages might be to acute physical risk.[39] They assigned each property a score between zero and five based on how severely it may be impacted by 12 types of hazards. Based on where outstanding mortgage balances were, these risk scores were used to create heatmaps for visualization of potential risk exposure across the U.S.

The climate VaR literature and data examining physical and transition risks are sparse but slowly expanding. Dietz, Bowen, Dixon, and Gradwell (2016) have estimated the value of global assets at risk (this is discussed further in Section 4). As for U.S.-specific analyses, Ceres recently published a report examining U.S. banks' exposures to physical risk.[40] They find that the annual climate VaR of major U.S. banks' syndicated loan portfolios could be about 10 percent in the worst-case scenario, amounting to roughly $250 billion of a portfolio worth $2.2 trillion. Their analysis relies on RCP and Shared Socioeconomic Pathways (SSP) scenarios and they include costs of direct and indirect effects, using a CGE model to estimate indirect effects. Ceres also conducted a similar exercise to assess U.S. banks' direct and indirect exposures to transition risk,[41] and applied climate VaR and stress test techniques. They find that over half of major U.S. banks' syndicated loan portfolios are exposed, since many have clients in various sectors that are not aligned with the Paris Agreement. Thus, the overall assessments of financial stability risk linked to forward-looking physical and transition risks are likely medium (see Table 2).

Modelling capabilities are also starting to expand amongst private and public providers. For example, MSCI offers clients portfolio-level climate VaR metrics[42] and the NYU Stern Volatility

[39] Bank of America (2021).
[40] Ceres (2021).
[41] Ceres (2020).
[42] More information can be found on MSCI's product website: https://www.msci.com/our-solutions/esg-investing/climate-solutions/climate-data-metrics

Laboratory has created an interactive risk estimation tool[43] to quantify how climate may impact the performance of financial assets; within the tool, users can select different securities categories, time horizons, and performance metrics. Data in this space is also improving, as providers are beginning to consider how higher carbon intensities may affect the profitability of financial and non-financial firms. For example, S&P Trucost provides a "Carbon Earnings at Risk" dataset for users to analyze company-level exposure to future carbon pricing policies based on their current emissions.[44]

Though there have not yet been natural capital analyses assessing U.S. **physical risks**, the Natural Capital Finance Alliance (NCFA) partnered with UBS, Citi, and others to launch the Exploring Natural Capital Opportunities, Risks and Exposure (ENCORE) tool[45] in 2018, which has sector- and sub-industry- level assessments designed to help banks, investors, and insurance companies globally better understand their natural capital dependencies and potential impacts of its degradation. Additionally, the NCFA has conducted exploratory natural capital analysis case studies for banks located abroad.[46] In the U.S., a hypothetical study could examine how poor air quality from more frequent and severe wildfires affects the profitability of businesses that rely on clean air. The study could also assess if effects are large enough to induce a business contraction or otherwise impact national macroeconomic statistics, a concern for financial institutions and central banks.

Natural capital analysis is better suited for analyzing physical risk than transition risk since it focuses on how natural degradation from physical risks impacts business activity. It is less applicable for evaluating the impacts of climate-related policies, technologies, and preferences. Accordingly, there are no natural capital analyses examining the impacts of transition risk in the U.S.

[43] More information can be found on the NYU Stern Volatility and Risk Institute's climate website: https://vlab.stern.nyu.edu/welcome/climate
[44] More information can be found on S&P's product website: https://www.marketplace.spglobal.com/en/datasets/trucost-carbon-earnings-at-risk-(184)
[45] More information can be found on NCFA's ENCORE website here: https://encore.naturalcapital.finance/en
[46] NCFA and PricewaterhouseCoopers (PwC). (2018).

3.9 Key Takeaways

In Table 1, we summarize the results of the literature review on the ability of the methodologies described in the previous subsections to potentially address the challenges for modelling and assessing CRFSRs. The main conclusion is that no single methodology can address all challenges, which highlights the limitations of the methodologies considered and the need for further analysis.

Table 1: Challenges of Quantifying U.S. CRFSRs

Methodology	*Potential for addressing modeling challenges*				
	Uncertainty	**Long time Horizon**	**Heterogeneities**	**Technological Change**	**Damage Function**
Integrated Assessment Models	No	Yes	No	Somewhat	Somewhat
Equilibrium Models (CGE & DSGE)	Yes (DSGE)	Yes	Yes (CGE)	Yes (DSGE)	Yes
Overlapping Generation Models	Somewhat	Yes	Yes	Somewhat	Yes
Statistical Methods	Somewhat	No	Yes	No	No
Input-output Models	Somewhat	No	Yes	No	Yes
Agent-based Models	Somewhat	Yes	Yes	Somewhat	Yes
Scenario Analysis, Stress Testing, Sensitivity Analysis	Somewhat	Yes	Yes	Somewhat	Yes
Other Practitioner Approaches	Somewhat	Somewhat	Somewhat	No	Somewhat

Uncertainty: There is a large degree of uncertainty about the magnitude and feedback mechanisms of the climate system, as well as how the system affects and interacts with economic and financial variables. **Long time horizons**: Climate change impacts are expected to manifest over longer time horizons. **Heterogeneities**: Financial markets and institutions are exposed to climate-related risks in different ways. **Technological change**: Understanding how innovation evolves is a crucial part of assessing CRFSRs. **Damage functions:** Damages, among other things, include effects on the labor market, capital stock, and natural capital.
Yes/Somewhat/No refer to whether a methodology can *potentially* address the challenges in measuring CRFSRs.

In Table 2, we present whether a listed methodology is used to quantify U.S. CRFSRs in the extant literature, the corresponding assessment of the risk based on the literature we analyze, and the level of confidence on the assessed risk. Two main results emerge, represented in Table 2. First, there is little information available on U.S. CRFSRs. The number of "NA" (for "not applicable") items in Table 1 indicates how little is known about the financial stability implications of climate-related risks for the U.S. Second, even what is known is characterized by a large degree of uncertainty, suggesting that results should be interpreted with caution.

Table 2
U.S. Financial Stability Implications of Climate-Related Risks: Vulnerabilities/Assessment/Uncertainty of the Assessment

Model Type / Horizon / Risk Type	**Backward-looking Horizon**		**Forward-looking Horizon**	
	Physical Risk	*Transition Risk*	*Physical Risk*	*Transition Risk*
Integrated Assessment Models	NA	NA	NA	NA
Equilibrium Models	NA	NA	NA	Bank leverage/ Low vulnerability/ High uncertainty
Overlapping Generation Models	NA	NA	NA	NA
Statistical Methods	Borrowing costs and direct and indirect losses/ Medium vulnerability/ High uncertainty	Borrowing costs and direct and indirect losses/ Medium vulnerability/ High uncertainty	Real estate prices/ High vulnerability/ High uncertainty	Corp. debt and equity prices/ Medium vulnerability/ High uncertainty
Input-output Models	NA	NA	NA	NA
Agent-based Models	NA	NA	NA	NA
Scenario Analysis, Stress Testing, Sensitivity Analysis	NA	NA	Real estate prices/ High vulnerability/ High uncertainty	Insurers' and banks' portfolios/ Medium vulnerability/ High uncertainty
Other Practitioner Approaches	NA	NA	Banks' syndicated loan portfolios/ Medium vulnerability/ High uncertainty	Banks' syndicated loan portfolios/ Medium vulnerability/ High uncertainty

In each cell, we report vulnerability/assessment/uncertainty of the listed methodology used to quantify U.S. CRFSRs in the extant literature. "Vulnerability" lists the metric considered in the literature, such as bank leverage. "Assessment" summarizes the literature's assessment of the risk as high, medium, or low. "Uncertainty" (high or low) surrounding the assessment is based on the number of studies available for the assessment, the modelling assumptions behind those studies, and the overall qualitative evaluation of the results. If there is no study in the extant literature employing the listed methodology to study U.S. CRFSRs, we report NA.

4. Financial Stability Applications

4.1 Recommendations for Research on U.S. CRFSRs

The previous section discusses the challenges in measuring climate-related risks and how different methodologies are able (or unable) to address them. This section presents our considerations, including some recommendations, for a possible way forward in assessing U.S. CRFSRs. Specifically, we highlight a subset of methodologies introduced in Section 3, which we gauge as more relevant to quantify the implications of climate-related risks for U.S. financial stability. Nevertheless, a key takeaway is that no single approach can accomplish this goal. Several methodologies must be combined to provide a clear understanding of the full financial implications of CRFSRs.

The way forward necessarily entails combining agent-based models, general equilibrium models, and statistical methods. This effort will help shed light on vulnerabilities that may affect U.S. financial stability. Each methodology also needs to be further improved to overcome current limitations. As computational power and solution techniques evolve, researchers will be able to build and solve more comprehensive dynamic equilibrium models. As data quality and availability improve, statistical methods will be able to estimate new parameters and potentially unveil new correlations and heterogeneities.

Another important consideration is that most methodologies assume stationarity of underlying dynamic processes or the existence of well-behaved statistical moments. Those assumptions may not be well suited to analyze the impact of climate change. New methodologies may need to be developed to address this issue. We leave this consideration to future research.

4.1.1 Equilibrium Models

The general equilibrium framework provides a useful benchmark for how the real sector is likely to change over time in response to changing prices.[47] Two of the most popular general equilibrium models, CGE and DSGE, generate internally-consistent economic outcomes that incorporate the crucial role of prices and markets, based on the non-linear setup that closely resembles the real world more than other models: firms will engage in input substitution, households will move away from floodplains, and policymakers will respond by imposing taxes or providing subsidies. These new equilibrium outcomes will entail changes in the value of assets and the flow of financing, with implications for the stability of the financial system.

In terms of empirical application, there is an important modeling tradeoff that distinguishes these two models. By sacrificing uncertainty, CGE models eliminate the accompanying computational challenges and become more amenable to higher degrees of cross-sectional heterogeneity. CGE models are hence useful in producing quantitative magnitudes of regional, national, and sectorial

[47] See, for example, Chen and Rose (2018), and Hazilla and Kopp (1990).

economic impacts arising from extreme weather events.[48] Therefore, these models could be best used when addressing U.S. CRFSRs arising from physical risk. By contrast, the computational challenges of integrating uncertainty limit the DSGE models' scope of disaggregation over sectors and jurisdictions and thus the heterogeneous exposures of economic agents and sectors. Instead, DSGE models allow for a clearer understanding of the channels of transmission between climate shocks and economic outcomes over time, under the assumption of various types of uncertainties including, in particular, policy uncertainty. Forward-looking analysis by DSGE models therefore allows a deeper focus on U.S. CRFSRs stemming from transition risk.

While there is no prior work that explicitly incorporates the modeling of U.S. CRFSRs within a CGE framework, there are two promising possibilities. First, the existing CGE models of climate analysis and those of the banking or financial sectors (for instance, Diaz-Gimenez, Prescott, Fitzgerald, and Alvarez, 1992) could be combined to produce a CGE model that encompasses climate-related risks and the financial sector. Second, CGE models can help extend conventional macro-financial models to cover financial markets and institutions by integrating illustrative scenarios on the timing and magnitudes of economic impacts from climate-related transition and physical risks (see Network for Greening the Financial System, 2020). Adding climate scenarios to traditional macro-financial models, stress test models, scenario analysis, sensitivity analysis and other practitioner approaches could allow assessment of leverage and funding risk and other financial stability vulnerabilities.[49]

One of the main outlets for DSGE has been policy analysis and forecasting by central banks in macro-financial and macroprudential analyses, with model expansions to encompass financial intermediation and to examine dynamic relationships and interactions between households, firms, financial institutions, and the government including the central bank.[50] As such, similar to IAMs and CGEs, one possible approach to examine U.S. CRFSRs is to use DSGE models as an input to scenario analysis, stress testing, sensitivity analysis, and other practitioner approaches.

A particularly promising possibility for DSGE lies in E-DSGE models that explicitly incorporate CRFSRs to examine transition risks, as seen in Carattini *et al*. (2021) in Section 3.2.2. Combinations of E-DSGE and financial linkages and intermediation might be able to address U.S. CRFSRs, which can in turn contribute to assessing a wide range of vulnerabilities that include asset valuation, leverage, funding risk, and interconnectedness. This latter characteristic highlights the ability of these models to capture indirect effects.

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[48]In the United States, there are several examples of CGE models for climate analysis. See, the Emissions Prediction and Policy Analysis (EPPA) by MIT, the G-Cubed model, the Global Trade Analysis Project (GTAP), and Intertemporal General Equilibrium Model (IGEM) – see Chen, Paltsev, Reilly, Morris and Babiker (2015); Corong, Hertel, McDougall, Tsigas, and van der Mensbrugghe (2017); Jorgenson, Goettle, Wilcoxen, Ho, Jin, and Schoennagel (2008); and McKibbin and Wilcoxen (1999). These models can incorporate rich datasets derived from National Income and Product Accounts (NIPA), input-output tables, and aggregate national employment of inputs (labor, capital, energy sources).

[49] One recent example is a work by the Bank of Canada where a CGE model was used to produce illustrative scenarios on the timing and magnitudes of economic impacts from climate-related transition and physical risks – see Ens and Johnston (2020).

[50] See IMF (2021), and Lipinsky and Miescu (2019).

4.1.2 Statistical Methods

Statistical methods are well-suited to quantify parameters of models that can be used to assess U.S. CRFSRs. Building on the evidence from past extreme weather events, statistical methods can capture the direct effects of climate change. These methods can also be used to estimate the direct effects of transition risk. These methodologies allow a precise estimation of a well-defined correlation, holding other quantities and prices constant. For example, statistical methods are well-suited to measure the losses incurred by banks exposed, through their residential mortgage business, to communities hit by a flood. As per the indirect effects, statistical methods can be used to analyze changes in liquidity and in credit provision by financial institutions following extreme weather events.

These methodologies are particularly important because they complement general equilibrium frameworks in two ways. First, they allow researchers to quantify parameters used in CGE, DSGE, and agent-based models. Second, they discipline models by documenting correlations that these models need to generate. In sum, statistical methods are a promising tool to assess climate change-related financial stability risk in the U.S., especially as part of a comprehensive toolkit of models.

One important caveat to the use of statistical methods is the need for detailed and granular data. The application of these approaches often requires access to confidential information, which is difficult to aggregate given the fragmented U.S. regulatory landscape. The lack of consistent, comprehensive datasets poses an additional challenge when using statistical methods.

4.1.3 ABMs

ABM models are theoretically well-suited to capture both direct and indirect financial stability risks on the financial sector and real economy. Since ABMs are agent-level, results can be highly granular and aggregated as needed. This granularity allows modelers to simulate financial market structures closely, by programming agents to operate in networks and interact with each other. These agent-level specifications and interactions can help identify which agents are more vulnerable to climate-related risks (e.g., low- and moderate-income communities), how significantly agents are exposed, what risk amplification mechanisms exist, and to what extent some agents can offset risks that other agents face. For instance, a modeler could measure how a sudden carbon tax policy may lead to defaults among agents with carbon-intensive assets and estimate the effects on other agents exposed to those defaulting. ABMs can capture fire sales and sudden asset value depreciations, which may affect the financial positions of agents holding overlapping portfolios as well as the financial stability of the system.

Botte, Ciarli, Foxon, Jackson, Jackson, and Valente (2021) construct an agent-based, stock-flow-consistent model (TRansit) and consider a reference scenario and a “fast transition” scenario, in which an economy transitions to net-zero in about six and a half years. They study the impacts of the transition on banks, households, government, and firms, and consider economic, social, and financial stability impacts. They find that the government in particular plays an important stabilizing role during a transition. While ABM models have theoretical advantages in integrating a financial sector, most climate models are still at a proof-of-concept level and we are not aware of any ABM models on U.S. CRFSRs.

4.1.4 Scenario Analysis, Stress Testing, Sensitivity Analysis

These methodologies can be applied by firms or by regulators. We focus on the latter, since it is more useful in assessing U.S. CRFSRs.[51]

Supervisory authorities may use these methodologies to conduct microprudential and macroprudential assessments to better understand the effects of CRFSRs. From a macroprudential perspective, regulators can use these methods to analyze the resilience (or lack thereof) of the financial system through direct and indirect financial stability effects. From a microprudential perspective, these methodologies can shed light on which institutions in the system are more vulnerable. Some central banks are in early stages of using these methodologies to analyze the impacts of climate-related risks.

The European Central Bank (ECB) and European Systemic Risk Board (ESRB) used long-term scenario analysis to identify climate-related financial stability vulnerabilities and physical and transition risks at the country, sector, and firm level in the European Union. The findings show uneven and significant impacts of climate-related risks for the European financial sector if mitigation efforts are insufficient or ineffective, highlighting the need for robust climate policies and smooth net-zero transitions. The report identifies potential amplification channels, such as fire sales, and includes a box outlining how climate-related risks may be amplified in an interconnected financial system, but it does not explicitly account for these indirect effects and thus notes that estimates likely represent the lower-bound.

In September 2021, the ECB released the results of its economy-wide climate stress test. The exercise assesses the resilience of over four million non-financial corporates and 1,600 Euro Area banks to both physical and transition risks under three different NGFS scenarios in a 30-year forecast period. To conduct this analysis, the ECB constructed an extensive dataset by merging firm-level financial data, firms' climate-related risk data, including physical risk scores and carbon emissions data, and data on Euro Area banks' exposures to these firms through loan and corporate bond holdings. These granular data allowed the ECB to map physical and transition risks at the sector, bank, and country level and compute firms' and banks' loan portfolio default probabilities.[52] The key takeaways are 1) early adaptation costs are significantly lower than the medium- and long-term costs of inaction, 2) physical risks increase non-linearly over time and are expected to become very significant, and 3) costs stemming from climate-related risks are moderate for the average firm and bank. However, if climate change is not mitigated, large and significant institutions, select geographic locations (such as southern Europe), and certain industries would bear significant costs, possibly leading to systemic events. The results and methodology will inform the ECB's 2022 supervisory climate stress tests for banks.

[51] These methodologies are useful for financial institutions to assess which assets are more vulnerable to physical and transition risks and to better understand their operational resilience. Overall, however, they do not provide assessments of U.S. CRFSRs since they tend to only examine portfolio-level effects.

[52] Firm-level probabilities of default (PDs) are translated to banks' loan book PDs by using the exposure-weighted average of corporate-level PDs.

In 2018, the De Nederlandsche Bank (DNB) conducted an energy transition risk stress test on the Netherlands' financial system. Recognizing that alignment with the Paris Agreement would require a significant emissions reduction, the DNB conducted this stress test to better understand potential financial stability implications of a disorderly transition. They use four severe but possible energy transition scenarios in a five-year forecast period to ensure financial institutions have relevant, short- to medium-term stress test results. In this analysis, the DNB used detailed securities holdings data to determine most of the equity and bond exposures of banks, insurers, and pension funds. Key conclusions are: 1) individual institutions may face sizeable, but manageable, risks, 2) policymakers can mitigate losses by introducing timely and effective climate policies, and 3) individual institutions that integrate transition risks in their frameworks can mitigate potential portfolio risks. Finally, they note that stress tests are especially helpful for understanding climate-related risks given high levels of uncertainty.

In June 2021, the Bank of England (BoE) launched its climate stress test exercise to assess the risks that climate change poses to the largest United Kingdom (U.K.) banks and insurers.[53] They are looking to understand specific business model constraints that institutions may face, improve risk management and strategic reviews, and quantify financial exposures based on end-2020 balance sheets. The BoE expects to publish their results in May 2022.

In France, the Autorité de Contrôle Prudentiel et de Résolution (ACPR) and the Banque de France (BdF) published the results of their 2020 pilot climate stress test.[54] The French regulators assessed the implications of physical and transition risks on credit risk, market risk, and sovereign risk for nine banks and 15 insurance institutions using NGFS scenarios. The exercise introduced important methodological innovations, such as dynamic balance sheet assumptions and investment in and out of sectors based on climate-related risk-reward considerations by financial institutions. The results show an overall moderate exposure of French banks and insurers to climate-related risks.

While these methodologies are highly applicable, there are limitations in their capabilities to assess U.S. CRFSRs. First, these methodologies may not fully capture second-round effects or financial system interconnectedness. In Section 4.2, we suggest one approach for potentially overcoming this limitation. Second, though not unique to these methodologies, detailed financial and climate data are lacking. For example, it is challenging to aggregate institution-level data on firms' Scope 1, 2, and 3 emissions[55] in a straightforward way since data collection is often sparse and incomplete. Standardizing global climate disclosures may help address some of these data challenges.

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[53] Bank of England. (2019).
[54] ACPR and BdF (2021).
[55] More information on how Scope 1, 2, and 3 emissions are defined can be found here: https://www.epa.gov/greeningepa/greenhouse-gases-epa

4.1.5 Other Practitioner Approaches[56]

Climate VaR assessments have been applied to measure financial stability risk at the global level. Dietz *et al*. (2016) find the expected climate VaR of global financial assets to be 1.8 percent (about $2.5 trillion) along a business-as-usual emissions pathway, with most risk concentrated in the tail; the 99th percentile climate VaR is 16.9 percent (about $24.2 trillion). Under a no-more-than-2-degree-warming emissions pathway, the authors find that the climate VaR reduces by 0.6 percentage points (pp) and the 99th percentile reduces by 7.7 pp. In that pathway, after accounting for mitigation costs, the present value of global financial assets is expected to be 0.2 percent higher and the 99th percentile is 9.1 percent higher than the business-as-usual emissions pathway.

The Carbon Disclosure Project also tabulates similar measures and reports[57] that 215 of the world's largest companies with a market capitalization of $17 trillion expect $1 trillion to be at risk from climate change, with many of those losses expected to be realized within the next five years. In general, climate VaR analysis is conducted at a portfolio-level for individual institutions, meaning that it often only captures direct risks to portfolio valuations and cash flows without considering broader systemic effects.

Natural capital analysis is generally conducted at the firm-level to help institutions identify their natural resource dependencies and assess impacts of its potential degradation. This exercise is valuable for institutions to identify their vulnerabilities, which may eventually help mitigate systemic losses and financial instabilities. For example, the NCFA performed a natural capital analysis on five participating banks in Colombia, Peru, and South Africa, focusing on the impacts of natural capital damages such as habitat degradation, ocean pollution, and water stress on banks' portfolios, both qualitatively and quantitatively.[58] Natural capital analyses hold promise for measuring U.S. CRFSRs if conducted in an aggregated manner for financial institutions. As an example, Calice, Diaz Kalan and Miguel (2021) find that Brazilian banks are materially exposed to biodiversity loss through their domestic non-financial corporate loan portfolios[59] and highlight this as a financial risk for those banks, as well as the Banco Central do Brasil. Broadly, interest in the links between biodiversity losses and financial stability risks is growing, with opportunities for further research. [60]

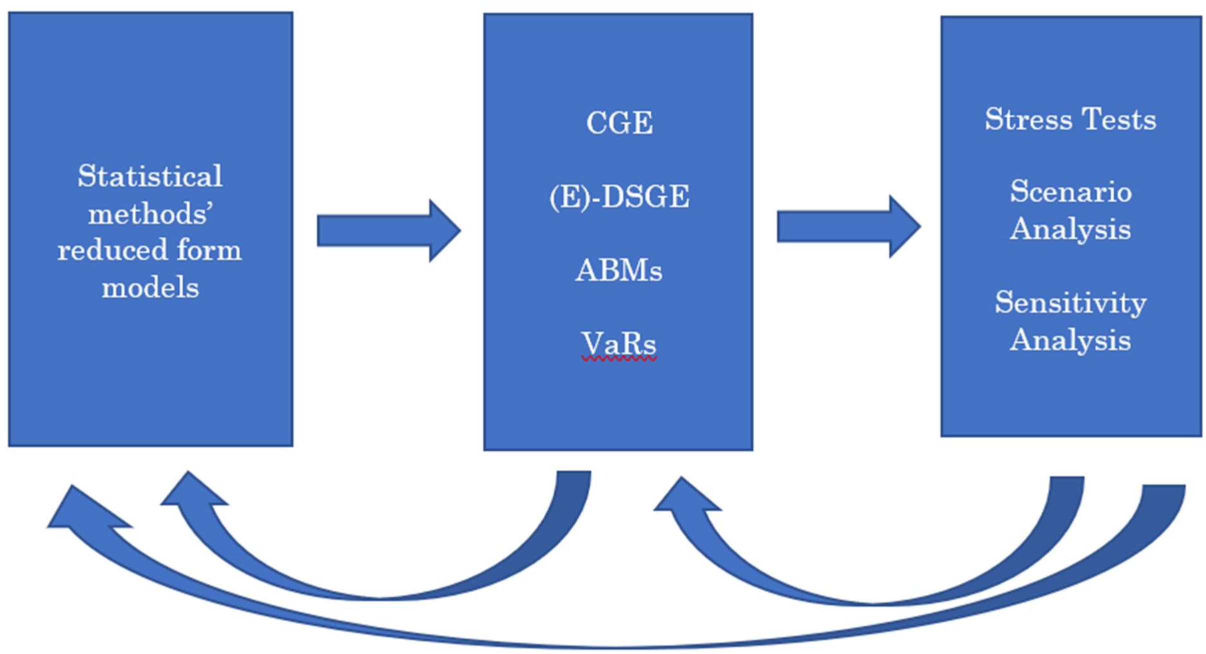
4.2 Key Takeaway

A key takeaway is that no methodology can be used in isolation to assess the financial stability implications of climate change; several methodologies need to be combined for a more complete

[56] Climate risk scores and ratings are produced by a variety of firms using differing and opaque methodologies. This makes it challenging to compare and interpret scores. This is a major shortcoming and must be taken into account when using them to identify and evaluate U.S. CRFSRs. Therefore, we concentrate only on VaR and natural capital analyses in this section.
[57] Carbon Disclosure Project (2019).
[58] NCFA and PwC (2018).
[59] They find that forty six percent of Brazilian banks' corporate loan portfolio and twenty percent of their total credit portfolio are concentrated in sectors that are very dependent on one or more ecosystem services.
[60] The NGFS recently formed a group to study these links and share insights with the larger research community. See NGFS (2021).

understanding of U.S. CRFSRs. For example, the reduced form outputs from micro- and macro-econometric statistical methods can be used to inform the main parameters and assumptions in CGEs, DSGEs, and ABMs, as well as the distributions of different random variables in ABMs. They can also be used to design the scenarios that feed into stress testing, sensitivity analysis, and other practitioner approaches. Similarly, outputs from CGEs, and DSGEs can be used to inform pathways used in scenario analysis, stress testing, sensitivity analysis, and other practitioner approaches. These connections between the inputs and outputs of these different methodologies highlight their complementary nature and emphasize the benefits of applying multiple methodologies to assess the financial stability implications of climate change, as each one adds further depth to the analysis. Importantly, there is an information feedback loop: results along the methodology chain refine and improve the inputs and results of different methodologies—see Figure 2.

Figure 2
Methodology Chain



Reduced form outputs from micro- and macro-econometric statistical methods can inform the main parameters, fundamental assumptions, and probability distributions of key random variables in CGE, DSGE, ABMs, and VaRs. This information could be useful for designing and conducting scenario analysis, sensitivity analysis, and stress tests. Methodologies are linked in a feedback loop where results along the methodology chain refine and improve the inputs and outputs of different methodologies.

5. Conclusions

A key message of this paper is that we are closer to the beginning than the end of integrating climate-related risks and financial system vulnerabilities in modelling. Anticipating the effects of climate-related risks requires accounting for fundamental uncertainty, complexity, and deviations from standard assumptions. Moreover, the direct and indirect effects of the transition to a low-carbon economy are substantially different from the direct and indirect effects of physical risks. An important role of the financial sector is to efficiently allocate capital. A potentially disorderly reallocation from a non-green to a green economy might, in turn, weaken the balance sheet of financial institutions with potentially large economic and financial effects. Tracing these effects through the economy and financial system in a way that allows for aggregation and assessment of systemic failures is difficult, and the challenge is compounded by a lack of granular and consistent data, agreement on asset classifications (*e.g.,* what it means to be a "green" or "non-green" asset), and cross-jurisdictional transparency.

These concerns might be sidestepped by taking a macroprudential approach that looks at the upper envelope of climate losses to be absorbed by the financial system. Indeed, most of the models described here focus on the extent of economic harms under different climate scenarios. IAMs provide a shorthand approach for connecting climate harms to economic damages. CGE and DSGE models add richness to this exercise, in some cases directly introducing a financial sector. However, the standard assumptions used to make agent behavior tractable may be ill-suited to assessing climate change-related financial system vulnerabilities. Empirical studies have shown a significant indifference to climate-related risks on the part of coastal homeowners, for example.[61] Moreover, incentives may differ so widely across a given class of agents that the representative agent assumption adopted by many methodologies is particularly strained. Perhaps most difficult to address is the incompatibility between a traditional normal distribution of outcomes with known statistical moments and the skewed distribution of climate-related risks with uncertain statistical moments. Most of the behavioral frameworks for rational risk management assume the former, and the macro-empirical work on climate risks is difficult to interpret outside of the assumption of stationarity implied by a normal distribution of outcomes. ABMs offer the potential to relax these assumptions and the computational power needed to implement ABMs is increasingly within reach. While some models are beginning to apply more realistic assumptions and distributions, there is a large gulf between the promise and the current state of these models.

Sizing the total amount of harm is surely informative about the load-bearing capacity of the financial system. However, financial crises are just as apt to emerge from an untenable distribution of these losses across financial sectors and institutions. For the U.S., there is very little work on the systemwide distribution of climate-related risks across counterparties, although the importance of the insurance sector for banking sector vulnerability to physical risks is well known. VaR models, scenario analysis, and stress testing represent a micro-level approach to complement the macro-level approach of the general equilibrium models. In general, the ability of a micro-level approach to address counterparty risk has yet to be realized, again due to lack of disclosures and adequate data. Moreover, climate-related risk metrics that would apply to financial institutions, especially non-banks, are non-existent. This leaves macroprudential climate analysis a wide-open topic for interested researchers.

[61] See Bernstein, Gustafson, and Lewis (2019), Filippova, Nguyen, Noy, and Rehm (2020), and Hino and Burke (2020), amongst others.

6. Appendices

6.1 Data Requirements

We outline data requirements for each of the methodologies described in Section 3. It should be noted, however, that these assessments are incomplete, and the full scope of climate data gaps and challenges are outside of the scope of this paper. The NGFS Workstream "Bridging the Data Gaps"[62] provides more information on this topic, in addition to initiatives led by the Basel Committee on Banking Supervision and the Financial Stability Board.

IAM: Detailed climate and economic data are required to construct the interlinked modules that comprise IAMs. Climate data needs often include projections for geophysical factors, such as global mean temperatures and solar radiation, as well as possible pathways for greenhouse gas emissions, energy and land use, technological advancements, and social and governance changes. These are in addition to economic data needed for large-scale, economy-wide cost-benefit and cost-effectiveness analyses, such as the projected pathways of macroeconomic indicators.

CGE: Data needed for model calibration include Social Accounting Matrices (SAMs), which are derived from National Income and Product Accounts (NIPA); input-output tables; quantities and prices of inputs such as labor, capital, and energy sources; and financial variables. Data gaps exist in calibrating key supply and demand parameters, including the elasticity of substitution and production cost functions, often resulting in an ad-hoc selection of values based on best judgment. This may lead to uncertainty in the accuracy of the new equilibrium under perturbation of climate-related parameters.

DSGE: Studies using DSGE models both calibrate – using commonly adopted values in the literature, surveys, or meta-studies – and estimate structural parameters using historical data. Data requirements are similar to CGEs, and as with CGEs, data gaps are particularly severe in determining certain parameters, including substitutability and discount rates. Thus, results may be sensitive to assumptions for these parameters.

OLG: OLG models are primarily theoretical and do not require much data.

Statistical Methods: Statistical methods require detailed and granular data. In particular, the analysis of the effects of extreme climate events on financial institutions requires (i) loan-level data at a monthly or quarterly frequency for various asset classes such as corporate credit to firms and commercial and residential mortgages, among others, and (ii) security-level holdings data. These data sets are commercially available for a subset of non-bank financial institutions and collected, for banks only, by the Federal Reserve to assess bank capital adequacy and to support stress testing. However, the Federal Reserve collects this data only for very large banks. Hence, there is a considerable data gap for smaller banks and other types of financial institutions such as insurance companies, pension funds, and investment managers.

IO: The application of IO models to assess the U.S. CRFSRs requires at least three sets of industry-level data: (i) the domestic supply and use of commodities, (ii) environmental data on resource

[62] See NGFS (2021) and more information can be found here: https://www.ngfs.net/en/about-us/governance/workstream-bridging-data-gaps

use, and (iii) financial data, such as U.S. banks and/or non-bank financials exposures by industry. Additionally, as climate-related risks can affect U.S. financial institutions through both their domestic and foreign exposures, linkages with the foreign industries might need to be considered.

ABM: These models require detailed data to develop agents' behavioral rules, program networks, and capture agent-interaction effects, reflecting the computationally intensive nature of this methodology. Information about agents (firms, households, businesses, government, etc.), their relationships to each other, and the environment they operate in are required. It is up to the modeler to determine how granular these data on agents and their environment should be, but the level of specification of input data will determine the level of detail of output data.

Scenario analysis, stress testing, sensitivity analysis: Since these methods are often applied at the asset- and portfolio-level and require that level of granularity for an institution- or system-level assessment, they require detailed climate, economic, and financial data. Data requirements can include geolocations of assets and operations at a granular level, as the same region may face different levels of risks (if there are, for example, vulnerable coastal locations near less exposed mountainous regions). Additional data requirements include credit ratings, asset valuations, portfolio exposures, firms' Scope 1, 2, and 3 emissions, supply chain pathways and dependencies, and projected climate and macroeconomic pathways. More broadly, consistent climate data disclosures from financial institutions would be necessary for conducting standardized risk assessments at a system-level.

Other Practitioner Approaches

Climate risk scores and ratings: These metrics are primarily created by private data providers that do not disclose their methodologies. Without source methodologies, it is difficult to pinpoint exact data items used to develop these scores and ratings. Nonetheless, since these metrics are generally conducted at the asset, portfolio, and institution level to assess climate-related risks, they are likely to require granular balance sheet data, geolocations of assets and operations, and information on firms' Scope 1, 2, and 3 emissions, in combination with data describing future climate and economic pathways, often derived from scenarios.

Natural Capital Analysis: Instead of requiring firm-level balance sheet and operational data to measure institutions' effects with respect to nature and the climate, this type of risk assessment requires data on a firm's natural capital dependencies to assess balance sheet and operational impacts. Thus, practitioners will need to identify an institution's natural capital dependencies and use projected climate pathways data to identify when and the extent to which physical risks may degrade those dependencies. Finally, they will need to integrate this information with data on institutions' operations, supply chain pathways, and balance sheets to assess impacts of natural capital degradation on firms' financial and operational health.

VaR: This methodology requires detailed, firm-level balance sheet data to measure what percentage of a portfolio may devalue due to climate-related risks under different scenarios. These scenarios apply detailed projected climate pathways data to simulate financial impacts under different climate outcomes. For a system-level analysis, individual institutions' balance sheet data can be aggregated to shed light on the magnitude of U.S. CRFSRs.

6.2 Methodologies Comparison

Comparing methodologies across different dimensions						
Methodology	Strengths	Weaknesses	Time Horizon	Applicability *versus* Complexity	Key assumptions	Applicability to modelling U.S. CRFSRs
Integrated Assessment Models (IAM)	Integrates climate and economic projections Projections are internally consistent Allows for cost-benefit analysis of climate mitigation	Most IAMs do not model money, finance, or banking Highly aggregated Typically relies on a smooth scalar damage function of chronic physical risk Lacks resiliency to imperfect information and unforeseen endogenous events, such as technology or policy change Black box effect	Short to long term	Highly applicable	Highly aggregated, general equilibrium theory, simplified climate models	Useful for generating scenarios for other methodologies
Computable General Equilibrium (CGE) Models	Quantifies general equilibrium effects by accounting for interlinkages across many economic sectors and agents Can be flexibly adjusted to multi-sector, multi-country or global set-ups	Strong assumptions including perfect information The "black box" aspect	Short to long term	Somewhat applicable	Perfect information, exogenous technology, no adjustment costs in production, and inelastic supply of labor	Economic outcomes from the model can be fed into a macro-financial analysis to assess CRFSRs
Dynamic Stochastic General Equilibrium (DSGE) Models	Incorporates uncertainty in agent-decision making and endogenous changes in innovation technology In extensive use by central banks for policy analysis	Trade-off of computational intensity and the degree of details that the model can handle Assumption of rational expectations	Short to long term	Somewhat applicable, with certain limits on model size	Rational expectations	Highly applicable. It can be combined with other methodologies
Overlapping Generation Models	Highlights intergenerational redistribution Incorporates life-cycle investment decisions	Closed economy model Does not consider endogenous systemic risks (climate change or transition)	Long term	Complex Marginally applicable	Usually assume perfect foresight about future prices and	Could be useful for studying asset price implications and policy conflicts across generations
Statistical Methods	Intuitive and relatively easy to estimate and interpret	Rely on partial equilibrium view of the world Mostly focused on past data and, thus, inherently backward looking	Short to long term	Highly applicable	These methods tend to ignore equilibrium considerations	Highly applicable. It can be combined with other methodologies

Input-output Models	Details environmental impacts at an industry level Can capture impacts of demand for goods and services on energy and resources Computationally simple and requires less assumptions	Cannot capture big technological advances as they are based on historical input-output tables Mainly focus on supply chain disruptions Requires industry level environmental and linkages data	Short to medium term	Highly applicable	Assumes that the history is a good representative of future trends	Marginally applicable. It can be combined with other methodologies
Agent-based Models	Captures interactions and feedback mechanisms between agents and the financial and real economy Incorporates heterogenous agent assumptions Accommodates network effects	Requires detailed data to build agents' behavioral rules Agents' behavior may not be rational and representative	Short to long term	Complex	Rational expectations and perfect information	Highly applicable. It accounts of network effects and risk amplification mechanisms
Scenario Analysis, Stress Testing, Sensitivity Analysis	Examines multiple future pathways and outcomes Helpful for risk management and strategic decision-making Applicable to many stakeholders Does not require extensive modelling capacity	Limited climate and financial data available Can be challenging to translate longer-term results into meaningful action	Short to long term	Highly applicable	Detailed financial and climate data	Forward-looking nature helpful for risk management and quantification Can conduct microprudential and macroprudential assessments
Other Practitioner Approaches: climate risk scores and ratings, climate VaR, natural capital analysis	Simpler than traditional modelling methods Applicable to many stakeholders	Scores and ratings have different methodologies, making comparison and interpretation difficult Most risk for climate VaRs is concentrated in the tail; may inadvertently enable myopia	Short to long term	Highly applicable	Detailed financial and climate data	Climate VaR helpful for quantifying extent of systemic exposure Natural capital analysis is somewhat applicable for risk management

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