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Understanding the Systemic Implications of Climate Transition Risk: Applying a Framework Using Canadian Financial System Data

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Abstract

Our study aims to gain insight on financial stability and climate transition risk. We develop a methodological framework that captures the direct effects of a stressful climate transition shock as well as the indirect—or systemic—implications of these direct effects. We apply this framework using data from the Canadian financial system. To capture the direct effects, we leverage the climate transition scenarios and financial risk assessment methods developed for the Bank of Canada and the Office of the Superintendent of Financial Institutions climate scenario analysis pilot project. We examine the direct effects—in the form of credit, market and liquidity risks—of the climate transition shock on financial system entities within the scope of our study. Specifically, we look at the public and private assets and derivatives portfolios of deposit-taking institutions, life insurance companies, pension funds and investment funds. To assess the indirect effects from the potential spread of the climate transition shock across an interconnected financial system, we extend an agent-based model to explore shock transmission channels such as cross-holding positions, business similarities, common exposures and fire sales. This model considers behavioural assumptions and rules, allowing us to understand the interconnectedness of the financial system. This work strengthens our understanding of how distinct entities within the financial system could be impacted by and respond to climate transition risks and opportunities, and of the potential channels through which those risks and opportunities may spread. More generally, this work contributes to building standardized systemic risk assessment and monitoring tools.

Topics: Climate change; Financial stability; Financial institutions; Financial markets; Economic models
JEL codes: Q54, C63, G01, G10, G20

Résumé

Dans cette étude, nous cherchons à en apprendre davantage sur la stabilité financière et le risque lié à la transition climatique. Nous créons un cadre méthodologique qui prend en compte les effets directs d'un choc perturbateur lié à la transition climatique ainsi que les répercussions indirectes – ou systémiques – de ces effets directs. Nous appliquons ce cadre en nous servant des données issues du système financier canadien. Pour intégrer les effets directs, nous recourons aux scénarios de transition climatique et aux méthodes d'évaluation des risques financiers élaborés pour le projet pilote d'analyse de scénarios climatiques de la Banque du Canada et du Bureau du surintendant des institutions financières. Nous examinons les effets directs – sous la forme de risques de crédit, de marché et de liquidité – du choc lié à la transition climatique sur les entités du système financier visées par notre étude. Nous nous penchons plus précisément sur les portefeuilles d'actifs et de dérivés publics et privés d'institutions de dépôt, de compagnies d'assurance vie, de fonds de pension et de fonds de placement. Pour évaluer les effets indirects de la possible propagation du choc lié à la transition climatique sur un système financier interconnecté, nous étendons un modèle multi-agents afin d'explorer les canaux de transmission des chocs (positions de participation croisée, modèles d'affaires similaires, expositions communes et liquidations). Ce modèle prend en considération des règles et hypothèses comportementales, ce qui nous permet de comprendre les interconnexions au sein du système financier. Cette étude renforce notre compréhension de la manière dont des entités distinctes du système financier pourraient être touchées par les risques et les possibilités liés à la transition climatique et y réagir, ainsi que des canaux par lesquels ceux-ci pourraient se propager. De façon plus générale, elle contribue à l'élaboration d'outils standardisés pour l'évaluation et la surveillance des risques systémiques.

Sujets : Changements climatiques; Stabilité financière; Institutions financières; Marchés financiers; Modèles économiques
Codes JEL : Q54, C63, G01, G10, G20

1. Introduction

The transition to a low-carbon economy could have negative financial consequences for some economic sectors (e.g., fossil fuels) and positive outcomes for others (e.g., renewable electricity generation). This is because of changes in global and domestic climate policy action, technology and consumer preferences. These changes, in turn, could lead to a sudden reassessment of asset prices and credit ratings, which could trigger losses and defaults. For instance, changes in anticipated revenues and expenses in many economic sectors affected by climate transition shocks could affect the debt servicing capacity and collateral value of borrowers, increasing credit risk for banks and other entities in the financial system. A rapid revaluation of equity in climate-relevant sectors due to, for example, changes in investors' expectations, could also expose financial institutions to market losses and gains.

Moreover, climate transition shocks could spread through several channels, potentially causing contagion across the financial system and posing challenges for financial stability. For instance, a shock could trigger fire sales of assets to meet liquidity needs, resulting in losses for the entities holding those assets. These losses could be larger, for example, if financial entities have common exposures and cross-holding positions.

The Bank of Canada and the Office of the Superintendent of Financial Institutions (OSFI) led a pilot project using climate scenario analysis.[1] Conducted in collaboration with six Canadian federally regulated financial institutions, the project had three objectives. One of these objectives was to contribute to the understanding of the potential exposure of financial institutions to climate transition risk. This pilot project is a foundational step in building the capacity to understand and assess how climate transition risk affects the Canadian financial system. This capacity is needed to further understand the associated financial stability risk.

In this paper, to strengthen our insight on how financial stability can be affected by climate transition risk, we extend the Bank's work along three dimensions:

- We broaden the number and types of financial system entities examined to include a representative set of deposit-taking institutions, life insurance companies, pension funds and investment funds.
- We widen the scope of asset types by considering a larger range of financial instruments and assets.
- We develop a methodological framework to examine systemic risk implications.

The objectives of this study are to:

- enhance financial authorities' and institutions' understanding of and capacity to identify, measure and manage climate transition risks and opportunities

[1] See Bank of Canada and OSFI (2022).

- examine how particular financial system entities could be impacted by and respond to climate-related risks and opportunities
- create systemic risk assessment and monitoring tools to assess how linkages and interactions among financial entities can affect financial stability

This paper presents a methodological framework that combines two analytical tools. We rely on scenario analysis to examine the direct effects—in the form of credit, market and liquidity risks—of a climate transition shock on the loans, securities and derivatives portfolios of the financial system entities within the scope of our study. To do this, we leverage the climate transition scenarios and financial risk assessment methods developed for the Bank of Canada–OSFI climate scenario analysis pilot project described earlier. We also extend an agent-based model (Hałaj 2018, 2020) to capture the indirect—or systemic—effects of these direct impacts, particularly how they may spread across the financial system and through which transmission channels (e.g., cross-holding positions, fire sales). This extended model adopts behavioural assumptions and rules along with balance sheet and portfolio information to capture the potential interconnectedness across financial system entities. To illustrate the types of metrics the framework generates, we apply it to Canadian financial system data.

Our analysis provides several insights on financial stability. We observe that entities' climate-related exposures, risk-taking behaviour, size, investment horizon and business models, as well as whether they are active in public or private markets, are factors that explain how distinct entity types may respond to climate transition shocks. We find that these responses can result in losses to the financial system that are larger than the initial direct effects. This is largely due to channels such as cross-holding positions and fire sales. Moreover, depending on the type of financial system entity, we find that some entities may be more prone to act as propagators of transition shocks in the financial system (i.e., investment funds), while others are more likely to act as shock absorbers (i.e., long-term investors such as pension funds).

This study should be interpreted with some important caveats in mind. Data challenges are a primary limitation, including those posed by working with non-harmonized datasets from many different sources. We exclude other types of risks and shocks that could occur concurrently with or compound the climate transition shock (e.g., climate-related physical risk, and transition-related implications on inflation risk, interest rate risk and real economy feedback loops). Also, although this analysis includes a broader range of assets that are sensitive to transition shocks, we do not consider other types of assets (e.g., commercial and residential mortgages, sovereign bonds, commodities) and economic sectors (e.g., mining sectors other than coal) that could be sensitive to a climate transition shock. Finally, we do not include the liability side of balance sheets and portfolios for most of the financial entities, and we assume that the balance sheet is static.

The remainder of the paper is organized as follows. Section 2 presents the methodological framework. Section 3 applies the framework using data from the Canadian financial system to illustrate the types of metrics that may be generated. Section 4 provides key insights about financial stability. And section 5 offers some concluding remarks and suggests areas for future work.

2. Framework for understanding systemic implications of climate transition risk

The methodological framework we develop combines two analytical methods. We use scenario analysis to capture the direct effects of climate transition shocks on individual financial entities, and we use agent-based modelling to examine the indirect, or systemic, effects of these shocks. We describe both of these methods below.

2.1. Examining direct effects on financial system entities through scenario analysis

Because of its forward-looking nature and inherent uncertainty about future events, climate transition risk is difficult to assess using standard methodologies that rely on historical data. This difficulty is compounded by further uncertainty about how policy, technology and socio-economic factors might evolve. In this context, scenario analysis serves as a flexible "what if" tool that is useful for exploring potential risks and opportunities under various possible futures. The scenarios are neither forecasts nor intended to be comprehensive but instead serve as plausible pathways designed to achieve specific climate targets.[2]

2.1.1 Leveraging the Bank of Canada's climate transition scenarios

Figure 1 shows the steps taken to capture the direct effects of a climate transition shock on distinct types of financial system entities through scenario analysis.

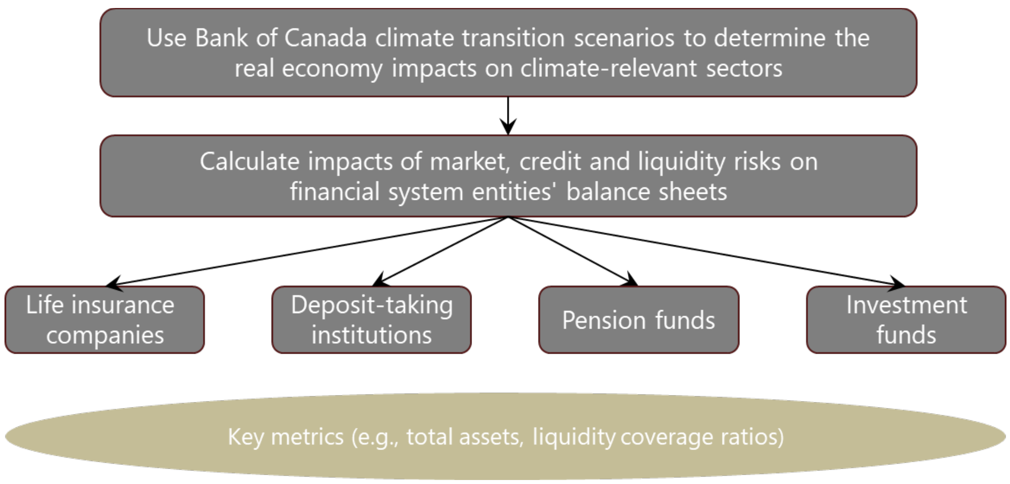
We leverage the set of global climate transition scenarios developed for the Bank of Canada and OSFI climate scenario analysis pilot project discussed earlier. The scenarios cover many geographical regions of the world.[3] The scenarios were intentionally designed to be adverse but plausible, capturing situations that have the potential to be stressful to the Canadian economy and the financial system. The four climate transition scenarios are the following:[4]

- **baseline (2019 policies)**—a baseline scenario consistent with global climate policies in place at the end of 2019

[2] Many financial authorities around the world have adopted scenario analysis to support their analysis of the macroeconomic and financial impacts of climate change. See Network for Greening the Financial System (2021).
[3] See Appendix A for a list of regions covered.
[4] For more information on the Bank of Canada climate transition scenarios, see Bank of Canada and OSFI (2022) and Chen et al. (2022).

- **below 2°C immediate**—an immediate policy action toward limiting average global warming to below 2°C
- **below 2°C delayed**—a delayed policy action toward limiting average global warming to below 2°C
- **net-zero 2050 (1.5°C)**—a more ambitious immediate policy action scenario to limit average global warming to 1.5°C that includes current net-zero commitments of some countries

Figure 1: **Translating scenario analysis outputs into financial risk metrics**



We also adopt the pilot project's climate-relevant sectors. These are sectors that are likely to be most affected, either negatively or positively, by the transition pathways. Some broad sectors, such as oil and gas, electricity, energy-intensive industries, and commercial transportation, were broken down into smaller groups because the transition may play out differently for those sub-sectors.[5] This provided sectoral groupings that are largely homogeneous in terms of climate transition exposures.

The scenarios were then used to define **sectoral risk factor pathways (RFPs)**, reflecting changes in four components affecting a sector's net income that may be impacted by the transition: direct emissions costs, indirect costs, capital expenditures and revenues.[6] The cumulative effect of changes in these different components illustrates how a sector can be affected by the transition, including the financial distress that it may encounter.

[5] See Appendix B for a list of climate-relevant sectors and a mapping to the most widely used industrial classification.
[6] For example, direct emissions costs for a sector may increase due to the sector's efforts to reduce greenhouse gas emissions. Indirect costs faced by a sector are those that are passed on from other sectors upstream. Capital expenditures, in turn, may rise with investment in new technologies. And the climate transition could lead to changes in consumer preferences, which may result in decreased demand and lower revenues for some firms.

2.1.2 Translating scenario outputs into financial risk metrics

We also leverage the pilot project's risk assessment methods to translate the scenario outputs into measures of credit and market risk. In the pilot project, the **credit risk assessment method** combined top-down and bottom-up assessments. A borrower-level impact assessment exercise using the scenarios' sectoral financial impacts (the RFPs discussed above) was conducted in the pilot project's bottom-up assessment. In the top-down assessment, the impacts from the bottom-up assessment were extrapolated to portfolio segments with similar transition risk exposures. Leveraging these assessments, the pilot project estimated a climate transition–credit risk relationship using a Merton-style model. For each sector-region pair, the model mapped scenario RFPs and heat map sensitivities into changes in probability of default. Then a Frye–Jacobs relationship was used to assess loss given default based on the probabilities of default. Finally, the credit risk was assessed through expected credit losses, which was based on projected probabilities of default, loss given default and exposures at default.[7]

The **market risk assessment method** used a top-down approach. Climate transition scenario impacts on equity valuations for each sector-region pair were determined based on a discounted dividend model.[8] Sectoral dividends were calculated from projected income along the transition paths, considering a given capital share of value added and a dividend rate. Also, for tractability, global climate policy commitments were assumed to be upheld and incorporated into equity valuations immediately at the time of the policy announcement, implying a discrete change in valuations at the time of the policy change. Economic agents were assumed to have foresight over a 10-year rolling window of climate policy, with the policy remaining constant from that point on. This implies a gradual adjustment in equity valuations following the discrete jump driven by the change in global policy climate pathways.[9]

In the context of the Bank–OSFI pilot project, the credit and market risk assessments focused on Canada and the United States since these two countries accounted for most of the assets of the pilot participants. Considering the larger scope of financial institutions in our study, we extend these risk assessments to all regions covered by the climate transition scenarios.[10]

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[7] The credit risk assessment method follows the methodology described in United Nations Environment Programme Finance Initiative (UNEP-FI), Oliver Wyman and Mercer, "Extending Our Horizons—Assessing credit risk and opportunity in a changing climate: Outputs of a working group of 16 banks piloting the TCFD Recommendations," (April 2018). In the pilot project, participating financial institutions were asked to select a minimum of five representative borrowers per sector in their portfolios. This choice balanced the benefits of higher precision in the estimated climate transition–credit risk relationship and the cost of the assessments for the financial institutions. For more details on the methodological steps taken in the pilot's credit risk assessment, see Hosseini et al. (2022) and Bank of Canada and OSFI (2022).

[8] Region-sector equity index values were estimated by discounting computed annual dividend flows within a 50-year, forward-looking window for each of the three climate transition scenarios from 2020 to 2100.

[9] Dividends were discounted using Morgan Stanley Capital International's average historical returns. See Hosseini et al. (2022) and Bank of Canada and OSFI (2022) for more details on the market risk assessment approach.

[10] This extension required the need to standardize the RFPs across regions. See section D.1 in Appendix D for details.

Including liquidity risk is key in understanding systemic risk. The **liquidity risk assessment method** is another extension of the pilot project's methods. Consistent with the goals of this study, the inclusion of a liquidity risk channel can inform us of the difficulties entities may face in meeting their short-term financial obligations. This could be due to an inability to convert their assets into cash without incurring a substantial loss. Specifically, we examine the liquidity held by financial system entities before the climate transition shock and their liquidity needs after the shock.

The liquidity held by a given entity is determined by weighting its asset positions by a Basel III-based liquidity factor.[11] We calculate liquidity measures for deposit-taking institutions, open-ended mutual funds (for investment fund entities) and pension funds. We assume that the cash flow on the liquidity coverage ratio framework for deposit-taking institutions follows the run-off rate from OSFI and the Autorité des marchés financiers (AMF) net cumulative cash flow returns. For open-ended mutual funds, we use historical data to estimate the expected cash outflows through redemptions. Finally, while pension funds have predictable outflows to pay their beneficiaries, they face relatively less-predictable liquidity constraints from their derivative positions.[12] Because of this, increased liquidity needs for derivatives positions are captured by a volatility-based measure (Standard Portfolio Analysis of Risk, or SPAN) for equity-related derivatives and a Monte Carlo simulation for debt-related derivatives.[13]

2.2. Examining systemic effects using agent-based modelling

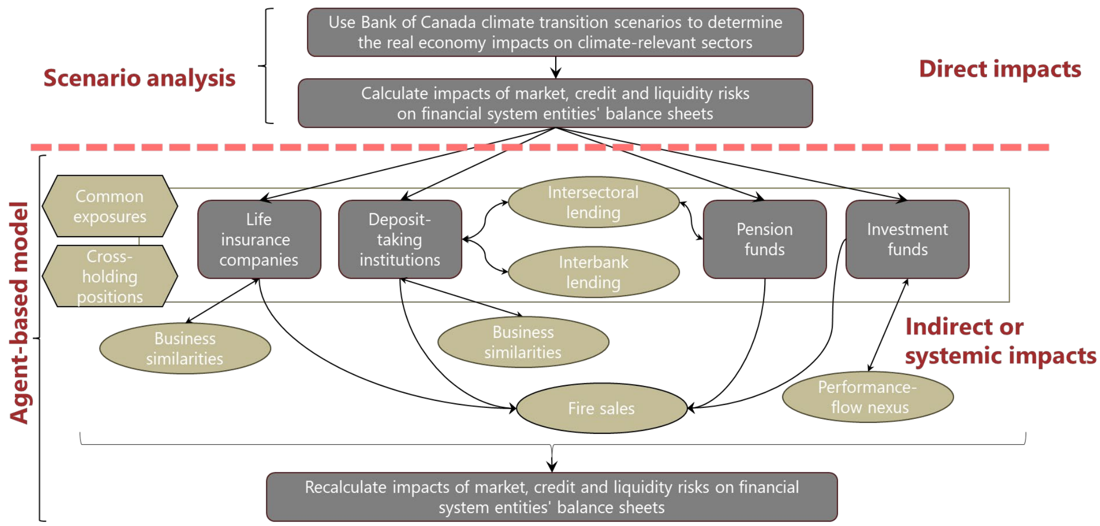
To understand how the systemic implications of climate transition shocks may spread across the financial system, we rely on agent-based modelling. Such a tool can distill the shock propagation effects through various transmission channels (e.g., fire sales, cross-holding positions, lending linkages). Further, it assumes behavioural and other types of rules are enacted by distinct financial entities to discipline the shock transmission process. Before describing how agent-based modelling is used in this study, we provide an overview of the transmission channels we consider.[14]

2.2.1 Transmission and amplification channels

Figure 2 presents an overview of the transmission channels considered in our study.

[11] See Bank for International Settlements (2013).
[12] See Bédard-Pagé et al. (2021).
[13] See Appendix D for more details.
[14] Such channels have been widely studied in the literature and by financial authorities (Dubiel-Teleszynski et al. 2022; ECB 2022; Gourdel and Sydow 2022; Roncoroni et al. 2021; and Sydow et al. 2021).

Figure 2: **Systemic effects—and their transmission channels—following climate transition shock**



Common exposures and fire sales

Common exposures in assets are indirect connections among financial institutions through their investment in similar asset holdings. In this study, entities share a common exposure when they invest in the same asset class issued from the same economic sector and region. We define common exposures using the climate-relevant public assets (equity or debt) held by the financial entities within the scope of our study. We focus on publicly traded assets because they are priced by the market, which allows entities to gain liquidity by selling them but might also expose entities to mark-to-market losses due to fire sales.[15] The greater the overlapping exposures to a given set of assets, the more vulnerable an entity may be to a given shock affecting those assets.

Common exposures can lead to systemic losses when an asset price decreases sharply, either because of a shock to that asset or because of selling pressure in secondary markets, such as in a fire sale. Fire sales could lead to securities being sold at large discounts due to a liquidity shortage. This situation can create opportunities for value investors willing to buy undervalued assets with recovery potential. However, fire sales pose challenges for investors because of increased mark-to-market losses and herd behaviour, potentially leading to larger losses.[16]

[15] In contrast, private assets are illiquid and priced at book value.

[16] Common exposures can have positive effects in normal times, such as diversification benefits and risk sharing. But they can also have negative effects in downturns through the amplification of losses and contagion. These effects can have adverse consequences for the real economy by reducing credit availability, investment opportunities and consumer confidence. See, for example, Acemoglu, Ozdaglar and Tahbaz-Salehi (2015) and Abad et al. (2022).

Business similarities
When the asset allocation among financial institutions for a given type of financial entity (e.g., banking sector) is similar, this could indicate potential exposure to similar risks. If an entity faces solvency issues after a shock (such as a climate transition shock), this could be informative about the solvency positions of similar entities, leading to an increase in funding costs.[17]

In our framework application, we consider how information contagion between entities with similar business models could imply higher funding costs when one entity is facing solvency issues after a climate transition shock.

Cross-holding positions
Cross-holding positions refer to entities owning investment (e.g., through shares) in other financial entities. This exposure implies that the financial performance of an entity directly influences its investor, thus potentially amplifying losses in the financial system.

Interbank and intersectoral lending
Lending channels between banks (i.e., interbank lending) or between banks and pension funds (i.e., intersectoral lending) keep liquidity flowing in the financial system. If a lender faces liquidity constraints, this could curtail the lending facilities to other counterparties. The borrower would carry a cost of replacement of the discontinued funding sources.

Performance-flow nexus
The performance-flow nexus is an amplification channel specific to open-ended mutual funds.[18] Large redemptions, triggered by the poor performance of funds, may drive fund managers to sell assets at lower prices to cover withdrawals, burdening remaining investors. This creates a "first-mover advantage" and triggers herding behaviour, which makes it difficult for fund managers to meet all redemption requests. Thus, losses can lead to redemptions, which in turn result in further losses. The role of this channel is illustrated in **Figure 3**.

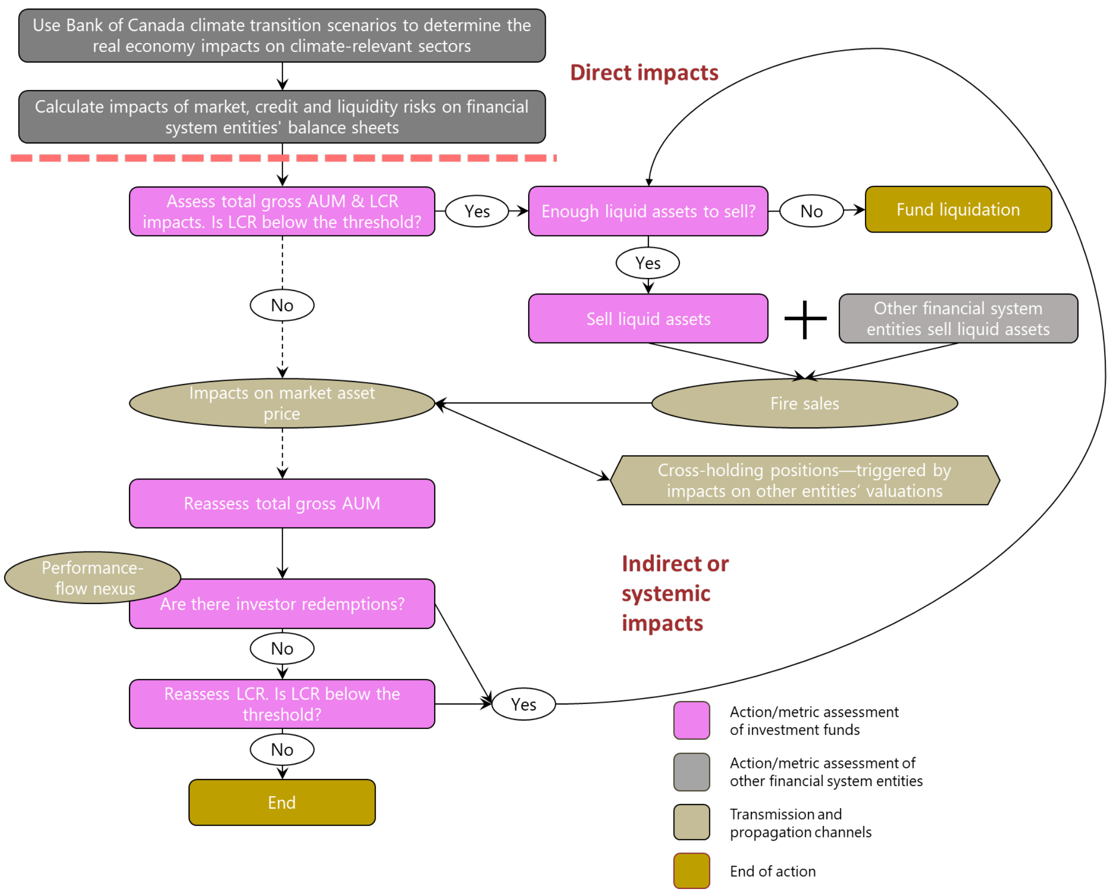
2.2.2 Extending Hałaj's (2018) agent-based model

Agent-based modelling is a computational approach in which heterogeneous agents interact in accordance with given decision rules (e.g., behavioural, regulatory) and where the spread of the shock depends on the linkages across the agents in the system. Agent-based models (ABMs) can thereby provide rich analytical insights about the systemic implications of a given

[17] Borrower default risk can also inform lender solvency risks (see Ahnert and Georg [2018]) and other lenders' solvency situations if a common systematic factor is shared (see Acharya and Yorulmazer [2008]). See Wang, van Lelyveld and Schaumburg (2019) for a discussion of information contagion through business model similarities.
[18] This channel has been observed in corporate bond funds (Goldstein, Jiang and Ng 2017; Dötz and Weth 2019) and equity funds (Chen, Goldstein and Jiang 2010). The performance-flow nexus has been introduced in several resilience exercises for mutual funds (Arora and Ouellet Leblanc 2018; ESMA 2019; Gourdel and Sydow 2022; Ojea-Ferreiro 2020; Fricke and Fricke 2021).

shock. Indeed, both entity-specific details (like risk profiles and portfolio characteristics) and commonalities and financial linkages across entities are core features of the financial system that can be modelled through an ABM. Notably, this approach is useful to model adverse conditions, such as in the case of a sharp adjustment of asset valuations due to a stressful climate transition shock.[19] **Figure 3** illustrates a decision tree for investment funds following a climate transition shock.

Figure 3: Decision tree for investment funds in our agent-based model



Note: AUM are assets under management; LCR is liquidity coverage ratio.

The ABM we develop in this study is based on Hałaj's (2018, 2020), which explores how liquidity shocks can spread and amplify in the financial system through direct and indirect channels. Hałaj's (2018) model captures the interactions between banks and asset managers,

[19] ABMs are well suited to capture stylized facts of the financial system, including periods of turmoil (e.g., out-of-equilibrium behaviours, multiple decision rules, heterogeneous and disaggregated balance sheets, and non-linear dynamics and spillovers). But it is worth noting a few of the drawbacks of ABMs. One drawback relates to parameter calibrations, where historical data may not be accurate depictions of actual values, which might not yet be observed. Another drawback is the stability of the model, which is highly dependent on the parameter selection. For more details on ABMs, see Lux and Zwinkels (2018).

accounting for feedback effects between liquidity and solvency, as well as the market impact of asset liquidation. Hałaj (2020) calibrates the model using Canadian banking data and simulates various scenarios of funding stress.

In our study, we extend Hałaj's (2018) ABM to include the other financial system entities within the scope of our study—namely, life insurance companies and pension funds. Further, we fine-tune the calibration of the fire sales parameter to adjust to different financial system entities based on their market liquidity, and we allow different degrees of sensitivity based on a quantile regression estimation.[20] We also add a buying behaviour rule for entities with a longer-term investment horizon. These entities would buy assets sold by other entities in the context of a fire sale. And entities would be interested in assets that could transition and become less carbon-intensive or greener (known as climate-transitioning assets). This would imply a positive return in the medium to long run but an initial investment in the short term.

These extensions allow us to explore alternative selling cases to discover insights from different types of market reactions, capturing the stochastic nature of distressed financial periods. The alternative fires sales cases are as follows:

- **Base case**—baseline parametrization for fire sales in our agent-based model.
- **Pension funds actively buy assets—**pension funds are assumed to actively buy climate-transitioning assets (i.e., those that may help with the climate transition) sold by entities with liquidity needs (investment funds in our framework application). Such assets originate from firms that are not currently benefiting from the transition scenarios but that could benefit over the longer run if a credible transition plan is implemented (i.e., environmental, social and governance [ESG] improvers). The motivation for this case is to reflect the opportunities created by climate-transitioning assets. Pension funds might monitor features related to the fundamental value of firms as well as the credibility of their transition plans. Such "bargain" investments could outperform the market benchmark (i.e., capturing alpha).[21]
- **Amplified fire sales**—asset sales, driven by investment funds in our framework application, have a larger effect on falling asset prices, reflecting the non-linearities in the relationship between selling volumes and price changes.[22] This could result from, for instance, self-fulfilling panics among investors and precautionary hoarding of liquidity by potential buyers.

[20] This follows Fukker et al. (2022).
[21] We reflect this investment possibility for pension funds to capture the effects of such an investment strategy, which may smooth out the burden related to the market stress faced by the financial system. See Appendix E for more details.
[22] See Fukker et al. (2022).

3. Applying the framework using Canadian financial system data

We use Canadian financial system data to apply the methodological framework presented in section 2. This application reveals the types of metrics the framework can generate. These metrics range from initial exposures to more complex financial risk and sectoral interconnectedness measures, both before and after the climate transition shock occurs.

For this application, we focus on impacts in the year 2050 for the delayed scenario described in section 2, which is, on average, the most financially stressful. Impacts in 2050 are compared with the baseline scenario.

3.1. Data, assumptions and limitations

3.1.1 Data sources

We rely on a variety of data sources to capture representative datasets of four major types of financial entities: deposit-taking institutions, life insurance companies, pension funds and investment funds.

The data collection process is multifaceted, involving reliance on various sources and arrangements.

- We use regulatory returns from OSFI for federally regulated deposit-taking institutions and life insurance companies; data for these entities regulated in the province of Quebec are obtained through a data sharing agreement with the AMF.
- Collaboration with several Canadian pension funds and asset managers of pension funds allows us to acquire detailed data on their exposures to climate-relevant sectors, covering both long and short positions in their portfolios of public and private assets and derivatives.[23]
- For investment funds, we use data from a third-party provider, Lipper, a Refinitiv Company. These data include information on approximately 2,000 open-ended mutual funds and exchange-traded funds (ETFs) in Canada.

All entities and funds we consider are based in Canada, though as previously mentioned, the analysis includes a worldwide coverage of their assets.[24] **Table 1** presents the data sources used in the scenario analysis to examine the direct effects of climate transition risk on distinct

[23] Box 1 presents highlights from this collaboration.
[24] Our study presents results for Canadian-domiciled open-ended mutual funds and ETFs. The mutual funds and ETFs are limited to equities, bonds, mixed assets, and others (including alternatives, money markets). Funds with asset compositions like real estate and commodities are outside the scope of our study. The ABM model includes investment funds domiciled in Canada, the United States or abroad that received investment from a Canadian financial entity. The inclusion of foreign entities intensifies market selling pressure, amplifying the fire sale effects.

financial entities. The ABM model was calibrated using some of the data sources described above as well as others. **Table 2** provides further details.

Table 1: Data sources for direct effects

Financial system entity or type of assets	Loans or private debt	Bonds*	Public equities*	Private equities	All other assets and metrics	Derivatives
Deposit-taking institutions	OSFI (A2, RAPID2 BF), AMF	OSFI (B2), AMF		—	OSFI (M4, NCCF, LCR, BCAR), AMF	—
Life insurance companies	OSFI (IPMT), AMF			—	OSFI (IPMT, LICAT), AMF	—
Pension funds	Voluntarily provided by participating pension funds					
Investment funds	—	Lipper, a Refinitiv Company		—	Lipper, a Refinitiv Company	—

*Where relevant, Eikon, a Refinitiv Company is used to complete public securities information.
Note: OSFI is the Office of the Superintendent of Financial Institutions; AMF is the Autorité des marchés financiers; A2 is OSFI's Non-Mortgage Loans return; B2 is OSFI's Securities return; M4 is OSFI's Balance Sheet return; LCR is OSFI's Liquidity Coverage Ratio Reporting Form; NCCF is OSFI's Net Cumulative Cash Flow Reporting Form; RAPID2 BF is OSFI's Wholesale Transaction return; BCAR is OSFI's Basel Capital Adequacy Reporting return; IPMT is OSFI's Investment Portfolio Monitoring Template; LICAT is OSFI's Life Insurance Capital Adequacy Test return.

Table 2: Data sources for systemic (or indirect) effects

Financial system entity or transmission channel	Common exposures	Cross-holding positions	Interbank lending	Intersectoral lending	Business similarities	Fire sales
Deposit-taking institutions	OSFI (B2, NCCF), AMF	OSFI (EB/ET-2A)	OSFI (EB/ET-2L)		OSFI (NCCF), AMF	Eikon, a Refinitiv Company
Life insurance companies	OSFI (IPMT), AMF		n/a	—	OSFI (LICAT, LIFE), AMF	
Pension funds	Voluntarily provided by participating pension funds**		n/a	OSFI (EB/ET-2A)*	n/a	
Investment funds	Lipper, a Refinitiv Company		n/a	—	—	

*90% of the intersectoral lending positions reported by banks to pension funds are assumed to be short-term.
**Cross-holding positions for pension funds cover only investment funds.
Note: Where data are unavailable, calibrations from other research are used. For example, Fukker et al. (2022) is used for debt price sensitivities to selling pressures and Hałaj (2020) for funding shocks due to decreasing solvencies. OSFI is the Office of the Superintendent of Financial Institutions; AMF is the Autorité des marchés financiers; B2 is OSFI's Securities return; EB/ET-2A and 2L are OSFI's Interbank and Major Exposures returns; NCCF is OSFI's Net Cumulative Cash Flow Reporting form; LICAT is OSFI's Life Insurance Capital Adequacy Test return; IPMT is OSFI's Investment Portfolio Monitoring Template; LIFE is OSFI's harmonized quarterly and annual supplement return on life insurance.

3.1.2 Key assumptions and limitations

To support the interpretation of the findings generated from our application of the framework, we note key data constraints and other analytical limitations. Our suite-of-model data requirements and our efforts to secure a representative sample of financial entities within the scope of our study encountered some challenges, including data quality, granularity and availability. Therefore, several assumptions were needed to apply the methodological framework.

Notably, our analysis lacks detailed asset-level information, especially for identifying assets impacted by climate-relevant sectors of the Canadian economy. This is particularly evident for federally regulated deposit-taking institutions and life insurance companies. For deposit-taking institutions, some regulatory return categories do not align well with our classification of climate-relevant sectors.[25] For life insurance companies, data on private equities are available but not usable in our framework because the classification system used in the returns cannot be leveraged for climate analysis. In contrast, our data partnerships with the AMF and Canadian pension funds provide detailed asset-level information on climate-relevant sectors. However, these partnerships are time-limited.

Beyond the data challenges, the application of the framework faces several analytical limitations.[26] The analysis focuses only on climate transition risk, excluding other concurrent shocks related to physical impacts of climate change.[27] Our study also excludes other transition-related implications on inflation, interest rates and real economy feedback loops. It focuses on the asset side of the balance sheet, not the liability side, which can also be affected by climate transition. Moreover, while we do include a wide range of assets, not all assets and sectors potentially impacted by climate transition are considered, such as infrastructure, real estate and sovereign bonds. Furthermore, while market intelligence gathering with financial system entities and authorities allows us to include some behavioural rules in the ABM, the main sources of reaction and decision are the key metrics (e.g., total assets, liquidity coverage ratios).[28] Lastly, a static balance sheet is assumed for analytical tractability, limiting portfolio adjustments in response to changing conditions. The static

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[25] For instance, the OSFI B2 return includes security holdings in the entire manufacturing sector, which comprises both climate-relevant and non-climate relevant sectors. To estimate holdings in each subsector, we assume that the securities' share aligns with the subsector's securities share in the overall non-financial corporate securities market.

[26] On climate data gaps, more broadly, as part of its work on climate, OSFI issued its draft "Climate Risk Returns for Federally Regulated Financial Institutions (FRFIs)" for industry consultation in June 2023. Once finalized, the returns will collect climate-related data elements directly from FRFIs, representing an important milestone for the quantification of potential exposures. The draft was designed in partnership with the Bank of Canada and the Canada Deposit Insurance Corporation. A report on the consultations, which closed on September 30, 2023, will be published in early 2024.

[27] For recent Bank staff work on physical-related climate risk, see Johnston et al. (2023).

[28] Further, consistent with the objectives of this study, we assume a horizontal slicing approach in the selling strategy, because this approach generates larger losses from the fire sales. More information about selling strategies is provided in Arora and Ouellet Leblanc (2018).

balance sheet assumption serves as a reasonable approximation of an entity's response in the short term, though it can misrepresent an entity's planning around the climate transition to mitigate potential losses.

3.2. Illustration

The following charts and tables illustrate the potential climate-relevant exposures, vulnerabilities and risks to the distinct financial system entity types as well as to the financial system as a whole. We explore these features before and after the materialization of the climate transition shock.

3.2.1 Before climate transition shock

Total financial system climate-relevant exposures

Panels a to d in **Chart 1** show the initial exposures of climate-relevant assets for the financial system entities within the scope of our study, which collectively manage a substantial portion of the Canadian financial system (total assets approximately $14.5 trillion). These climate-relevant exposures include assets of the following types:

- loans or private debt
- bonds
- public equity
- private equity (for pension funds only)

The financial system's overall climate-relevant exposures within the scope of our study constitute about 8% of total assets. However, exposures vary across the different types of entities. For instance, deposit-taking institutions have under 4% exposure to climate-relevant assets, while life insurance companies have about 19%.

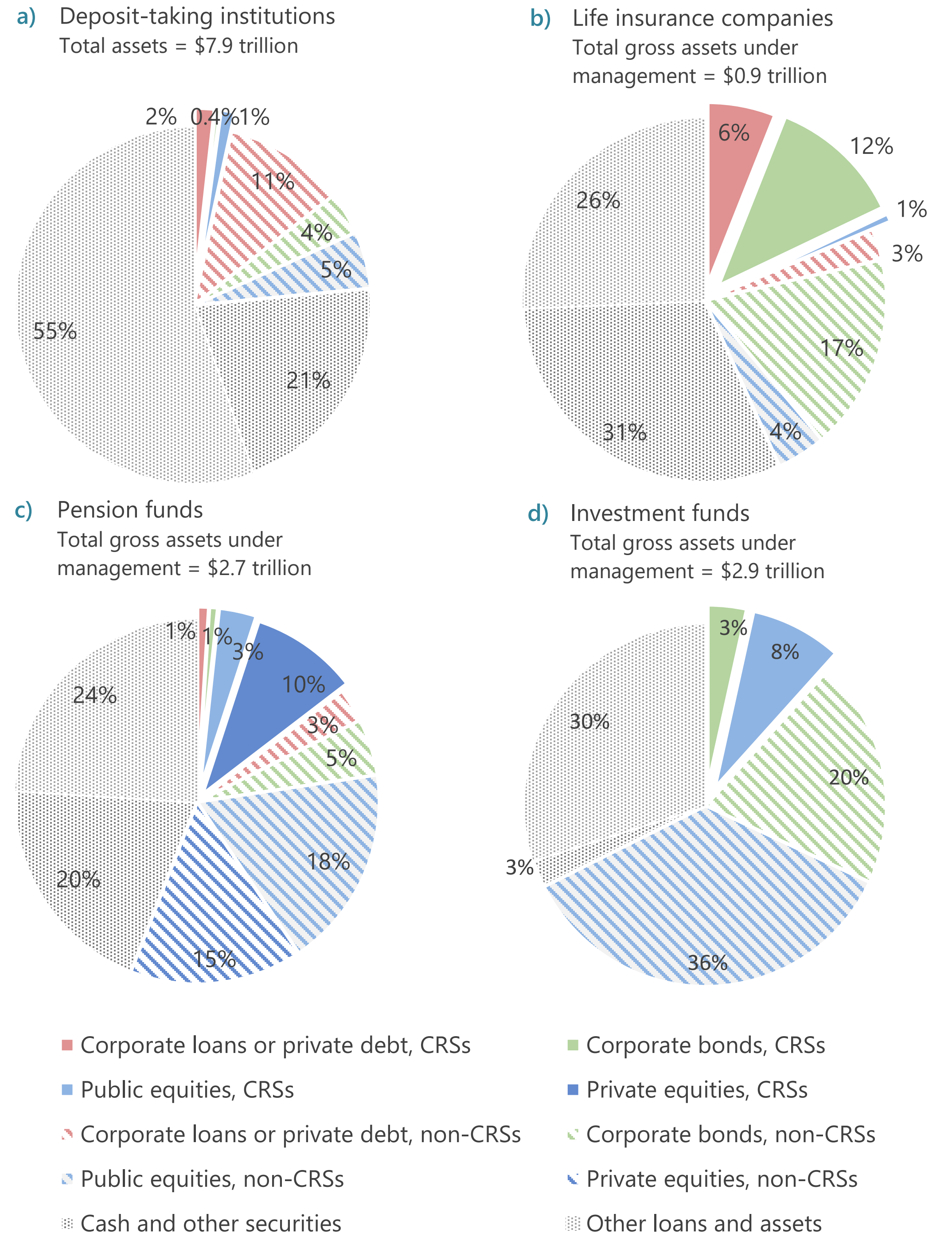
Exposures also vary across different types of entities in terms of their asset allocations. While life insurance companies tend to have a higher allocation in climate-relevant bonds and loans, pension funds' and investment funds' portfolios contain more climate-relevant equities, with pension funds holding a significant amount of climate-relevant private equities.

Common exposures to climate-relevant assets

Understanding how these exposures are shared within the financial system may also provide insight around potential climate-related systemic vulnerabilities. **Chart 2** shows how Canadian financial system entities are linked through their common exposures in climate-relevant assets (when they hold public assets in the same climate-relevant sector and region). The chart helps give a sense of the financial system's climate interconnectedness.[29] We focus on publicly traded assets due to their expected liquidity and potential to trigger contagion via

[29] We follow the approach of Pool, Stoffman and Yonker (2015) to define the portfolio overlap measure.

Chart 1: Climate-relevant asset exposures for financial system entities in scope of our study



Note: CRS is climate-relevant sector. Components in grey are assets outside of the study's scope (e.g., residential and commercial mortgages, sovereign bonds).

Sources: Office of the Superintendent of Financial Institutions; Autorité des marchés financiers; proprietary data from Canadian pension funds; Lipper, a Refinitiv Company; Eikon, a Refinitiv Company and Bank of Canada calculations
Last observations: deposit-taking institutions, life insurance companies, investment funds and most pension funds, December 2021; remaining pension funds, March 2022

fire sales. For example, despite pension funds holding approximately 15% of their assets in climate-relevant sectors, most of these assets are not publicly traded (**Chart 1**, panel c), limiting their exposure to contagion and fire sales.

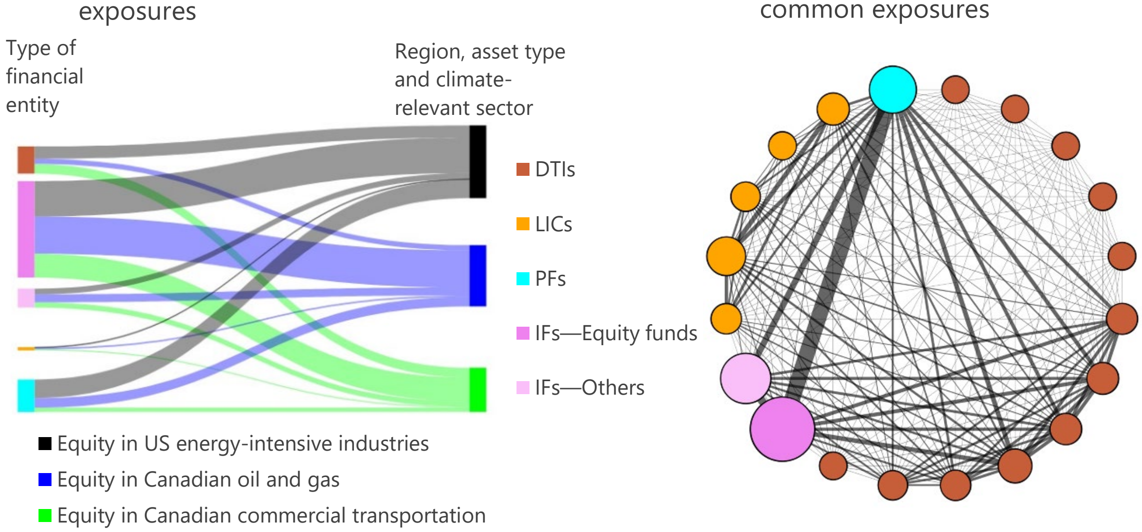
The three largest common exposures are held primarily by deposit-taking institutions, pension funds and investment funds (mainly equity funds), mostly through their equity positions in both energy-intensive industries in the United States and in oil and gas and commercial transportation in Canada (**Chart 2**, panel a). **Chart 2**, panel b shows the aggregation of linkages for all financial system entities across all public asset types, climate-relevant sectors, and regions. The larger the node, the more an institution is exposed through climate-relevant assets. The thicker the line, the larger the common exposure among entities. Large common positions among different financial entities represent stronger connections, which in turn potentially play a role in shock transmission and spread. Pension funds, the six largest deposit-taking institutions, and investment funds have the strongest common exposure connections. **Chart 2**, panel b also highlights the potential role of investment funds, especially equity funds, in acting as climate transition shock propagators in the Canadian financial system.

Chart 2: Climate-relevant common exposures across the Canadian financial system

Public assets only, by region, asset type and climate-relevant sector

a) Three largest climate-relevant exposures

b) Aggregated climate-relevant common exposures



Note: DTIs are deposit-taking institutions; LICs are life insurance companies; PFs are pension funds; IFs are investment funds.

Sources: Office of the Superintendent of Financial Institutions; Autorité des marchés financiers; proprietary data from Canadian pension funds; Lipper, a Refinitiv Company; Eikon, a Refinitiv Company; and Bank of Canada calculations
Last observations: DTIs, LICs, IFs and most PFs, December 2021; remaining PFs, March 2022

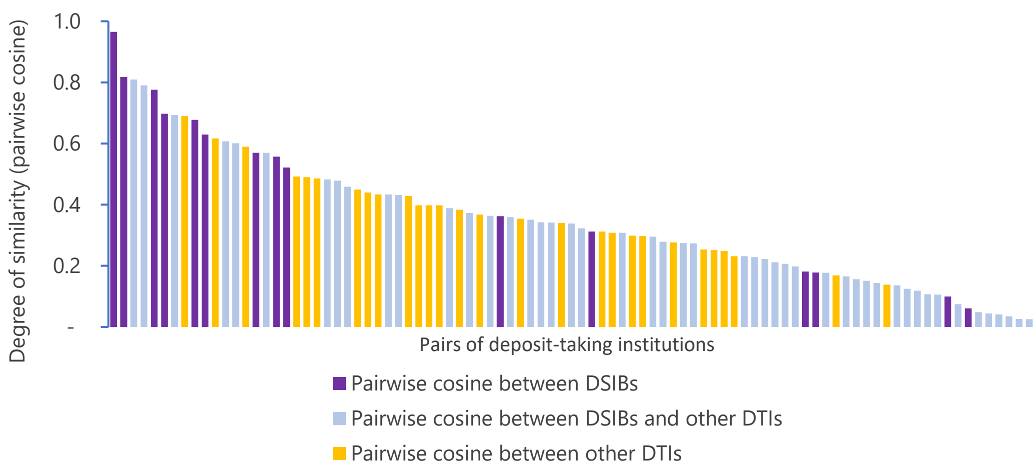
The following three charts shed light on some of the transmission and propagation channels discussed in section 2—namely business similarities, cross-holding positions and interbank and intersectoral lending. As discussed in section 2, these channels help inform our understanding of the financial system's connectivity as well as how a shock, such as a climate transition shock, may spread among entities.

Business similarities

We use cosine similarity to assess business similarities. **Chart 3** shows the pairwise cosine measures for the balance sheet items (e.g., equities) of the deposit-taking institutions in our study. Most pairwise cosine measures between each of the six largest Canadian banks (known as domestic systemically important banks, or DSIBs) and the other deposit-taking institutions are below 0.4, suggesting mild business similarities.[30] However, the situation is different among the six largest Canadian banks themselves. The average cosine measure is about 0.5, and nine pairwise measures exceed this average, suggesting strong business similarities among the six DSIBs. Because of this, if any of these entities were to experience financial distress due to a climate transition shock, they would likely face higher funding costs given their perceived similar risk exposure. For life insurance companies (not shown in Chart 3), we find strong business similarities among them, with all cosine measures exceeding 0.95. This implies that they would also experience potential increases in funding costs should one of them face solvency issues.

Chart 3: Business similarities across deposit-taking institutions

Pairwise cosine measures between deposit-taking institutions, ordered from largest to smallest



Note: DSIBs are domestic systemically important banks; DTIs are deposit-taking institutions.

Sources: Office of the Superintendent of Financial Institutions, Autorité des marchés financiers; and Bank of Canada calculations
Last observation: December 2021

[30] Values range from 0 to 1, where 1 indicates identical allocation of balance sheet items and 0 indicates completely different allocations. Details of the construction of this measure are provided in Hałaj (2018).

Cross-holding positions

Table 3 shows the level of cross-holding positions among different types of financial entities of the Canadian financial system. It shows that investment funds invest heavily in each other—up to 30% of their portfolios are composed of shares of other investment funds. Should these funds be impacted by a climate transition shock, they could act as a potential source of transmission and amplification. **Table 3** also highlights several data gaps that hinder our ability to obtain a complete picture of the cross-holding positions within the Canadian financial system.

Table 3: Level of cross-holding positions among financial system entities

Percentage of total assets, by type of asset and holding entity

		Type of entity—issuer				
Type of asset	**Type of entity—holder**	**Deposit-taking institutions**	**Life insurance companies**	**Pension funds***	**Investment funds**	**Total**
Debt	DSIBs**	0.11	0.01	0.11	0.01	0.23
	Life insurance companies	0.62	0.04	0.03	—	0.69
	Pension funds*	—	—	—	—	—
	Investment funds	2.12	0.24	0.08	—	2.44
Shares	DSIBs**	0.34	0.03	n/a	0.03	0.40
	Life insurance companies	0.50	0.07	n/a	0.04	0.61
	Pension funds	—	—	n/a	0.98	0.98
	Investment funds***	3.18	0.53	n/a	30.32	34.03

* Debt issued by pension funds is not presented due to study's exclusion of liability data.
** Data on cross-holding positions are available only for domestic systemically important banks (DSIBs).
*** Investment funds as a type of holder are restricted to open-ended mutual funds and exchange-traded funds domiciled in Canada. Depending on the data source used, investment funds as a type of issuer may include real estate funds or other funds.

Sources: Office of the Superintendent of Financial Institutions; Autorité des marchés financiers; proprietary data from Canadian pension funds; Lipper, a Refinitiv Company; Eikon, a Refinitiv Company; and Bank of Canada calculations
Last observations: deposit-taking institutions, life insurance companies, investment funds and most pension funds, December 2021; remaining pension funds, March 2022

Interbank and intersectoral lending

The level of interbank and intersectoral lending among DSIBs, and between DSIBs and pension funds, is shown in **Table 4**. We shed light on these types of entities because of their important role in the lending space of the Canadian financial system. Our analysis suggests that this is not an important potential propagation channel, as represented by their relatively low shares of total expected liquidity outflows of DSIBs and pension funds. Of note, the fact that our shock affects the asset side only may also explain the low relevance of this channel.

Table 4: **Interbank and intersectoral lending**

Percentage of total expected liquidity outflows of the borrower, by type of entity

	Type of entity—lender	
Type of entity—borrower	**DSIBs***	**Pension funds**
DSIBs*	1.01	1.71
Pension funds	6.93	—

*DSIBs are domestic systemically important banks. Non-DSIBs were not considered due to a lack of data on their intersectoral lending or borrowing counterparties.

Sources: Office of the Superintendent of Financial Institutions, proprietary data from Canadian pension funds; and Bank of Canada calculations
Last observations: DSIBs and most pension funds, December 2021; remaining pension funds, March 2022

3.2.2 After climate transition shock (framework application)

The charts in this section show the results from applying our methodological framework. These charts illustrate findings on both the direct effects (through scenario analysis) and systemic effects (through agent-based modelling) after the climate transition shock has occurred. Recall that the shock used in this study originated from the most stressful climate transition scenario—the **below 2°C delayed** scenario. The shock's impacts shown in the charts in this section are relative to the baseline scenario (2019 policies).

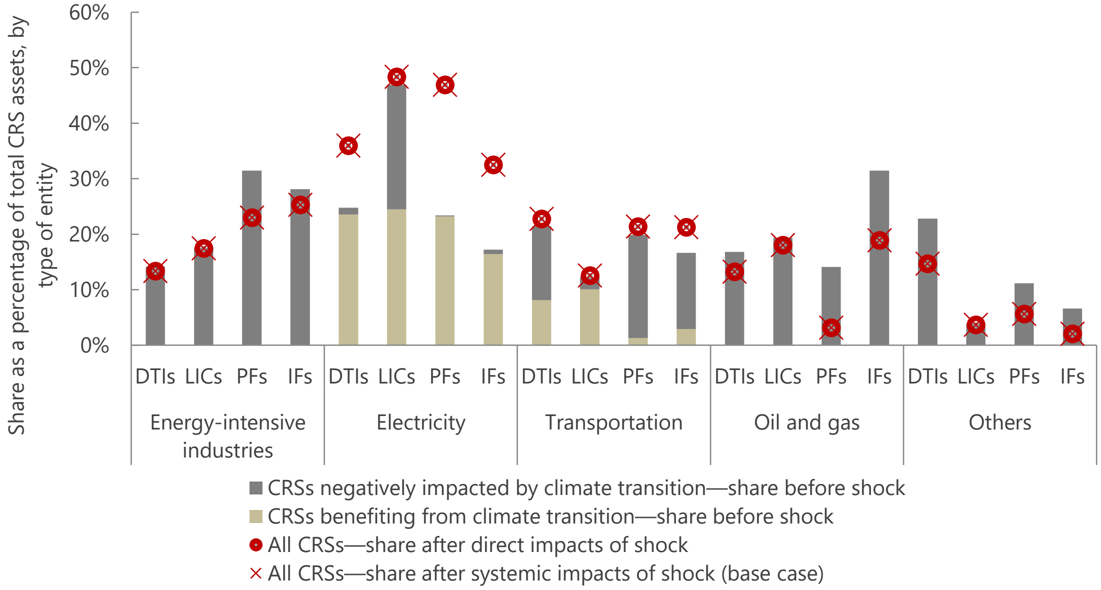
Investment allocation across climate-relevant sectors

Chart 4 presents the asset allocations across climate-relevant sectors for each type of financial entity. The grey and tan bars show the initial share of climate-relevant sector assets before the climate transition shock. Deposit-taking institutions, life insurance companies and pension funds exhibit similar asset allocations in sectors that benefit from our transition scenarios, with about one-third of their climate-relevant assets invested in these sectors. In contrast, investment funds have the smallest stake in these sectors, with less than one-fifth of their climate-related assets allocated in these sectors.

Chart 4 also shows how both the direct effects (red circles) and systemic effects (red Xs) of the climate transition shock can change the weighting of climate-relevant sectors relative to the total climate-related holdings of different financial entity types. Because we assume static balance sheets, changes to asset valuations in each sector after the shock change the relative weight of that sector in the entities' portfolios. As asset valuations fluctuate because of the shock, the shares of exposures to sectors that benefit from the transition scenarios increase. This is the case for deposit-taking institutions, life insurance companies and pension funds in the electricity sector. However, despite their important exposure to this sector, life insurance companies' shares increase less than those of pension funds, given that life insurance companies invest more heavily in bonds. Bonds generally fluctuate less in our transition scenarios compared with equities, which are more sensitive to changes in expected future cash flows and discount rates (shown later in **Chart 7**, panel b).

Chart 4: Share of exposures by type of climate-relevant sector

Each type of entity sums to 100%, impacts are percentage-point change, relative to baseline



Note: CRS is climate-relevant sector; DTIs are deposit-taking institutions; LICs are life insurance companies; PFs are pension funds; IFs are investment funds.

Sources: Office of the Superintendent of Financial Institutions; Autorité des marchés financiers; proprietary data from Canadian pension funds; Lipper, a Refinitiv Company; Eikon, a Refinitiv Company; and Bank of Canada calculations
Last observations: DTIs, LICs, IFs and most PFs, December 2021; remaining PFs, March 2022

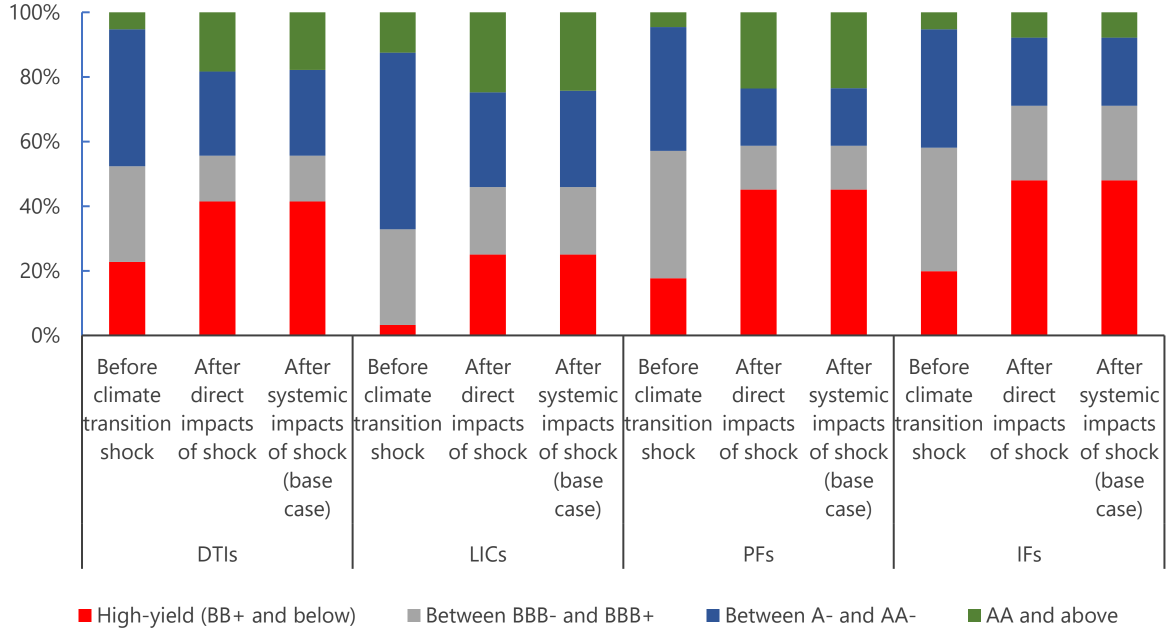
Allocation of debt holdings by credit rating

Financial entities' risk-taking behaviour concerning their climate-relevant assets also sheds light on the potential effects of a climate transition shock.[31] **Chart 5** and **Chart 6** illustrate the role of this informative dimension for climate-relevant bonds as well as climate-relevant loans and private debt. Life insurance companies hold 95% of their pre-shock climate-relevant bonds and loans allocation in the investment-grade space. Pension funds, meanwhile, exhibit a riskier pre-shock investment profile, with a significant portion of their climate-relevant private debt falling into the high-yield space.[32] Investment funds also hold a notable percentage of their climate-relevant corporate bond portfolio in high-yield securities.

[31] In this study, the riskiness of an asset is based on its credit rating. Higher credit ratings indicate lower risk and higher credit quality, while lower credit ratings indicate higher risk and lower credit quality.
[32] This corroborates a trend that indicates pension funds are taking more risk in private markets. However, through the negotiation of covenants, pension funds have a tighter hold on the terms of private debt contracts. For example, contract terms may incorporate details around a firm's climate transition plans, serving to mitigate climate-related risk.

Chart 5: Share of climate-relevant bond exposures, by bond credit rating

Percentage of total climate-relevant corporate bonds, weighted average for each type of entity, impacts are percentage-point change, relative to baseline



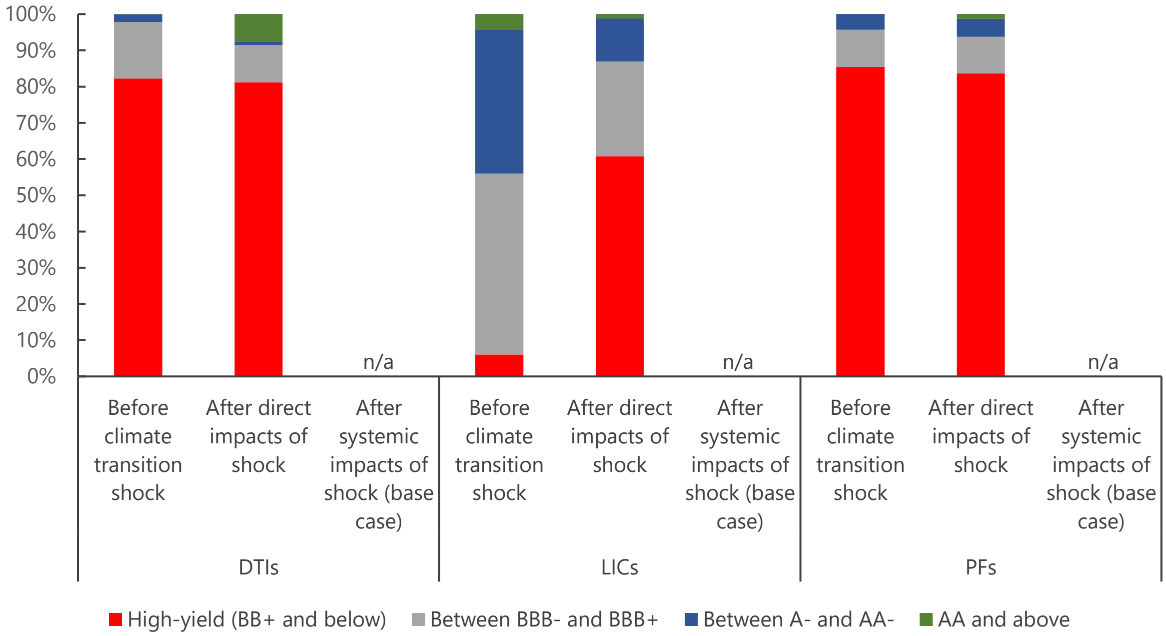
Note: DTIs are deposit-taking institutions; LICs are life insurance companies; PFs are pension funds; IFs are investment funds.

Sources: Office of the Superintendent of Financial Institutions; Autorité des marchés financiers; proprietary data from Canadian pension funds; Lipper, a Refinitiv Company; Eikon, a Refinitiv Company; and Bank of Canada calculations
Last observations: DTIs, LICs, IFs and most PFs, December 2021; remaining PFs, March 2022

Charts 5 and 6 also show that the allocation of credit risk becomes riskier as the climate-relevant bonds and loans are negatively impacted by the climate transition shock, migrating from investment-grade to the high-yield credit rating (shown in the charts by the increasing length of the red bars after the climate shock). This is particularly evident in the average risk profile of climate-relevant bond portfolios of pension funds and investment funds. Conversely, the credit ratings of climate-relevant assets in those sectors that stand to benefit from the transition see an improvement following the direct impacts (shown by the increasing length of the green and blue bars in **Chart 5** and **Chart 6**). This is particularly noteworthy for all entity types except investment funds, given their exposure to sectors that benefit from the transition.

Chart 6: Share of climate-relevant loan and private debt exposures, by loan or private debt credit rating

Percentage of total climate-relevant corporate loans and private debt, weighted average for each type of entity, impacts are percentage-point change, relative to baseline



Note: No systemic impacts occur for loans and private debt because of the absence of trade in secondary markets. DTIs are deposit-taking institutions; LICs are life insurance companies; PFs are pension funds; IFs are investment funds.

Sources: Office of the Superintendent of Financial Institutions; Autorité des marchés financiers; proprietary data from Canadian pension funds; and Bank of Canada calculations
Last observations: DTIs, LICs, IFs and most PFs, December 2021; remaining PFs, March 2022

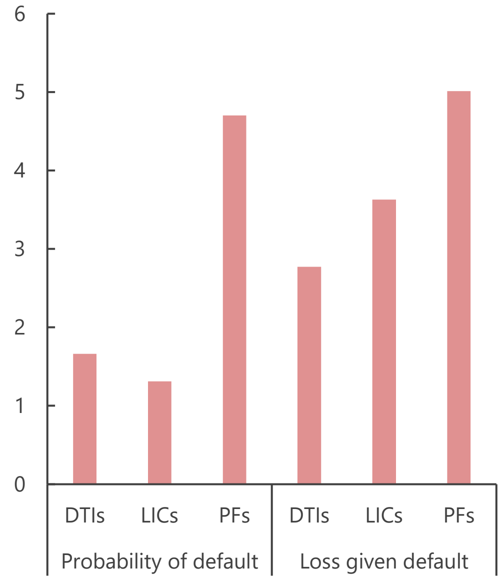
Credit, market and liquidity risk impacts

Chart 7 shows the direct effects on credit and market risks for the portfolios held by financial system entities after the climate transition shock. Deposit-taking institutions face a notable increase in credit risk in their climate-relevant loans portfolio (**Chart 7**, panel a). Their climate-relevant equities also experience significant market valuation impacts, while the effects on bonds are relatively minor (**Chart 7**, panel b). However, as we show later, the valuation of total assets in deposit-taking institutions' portfolios are not materially affected due to their relatively low initial exposure to climate-relevant assets.

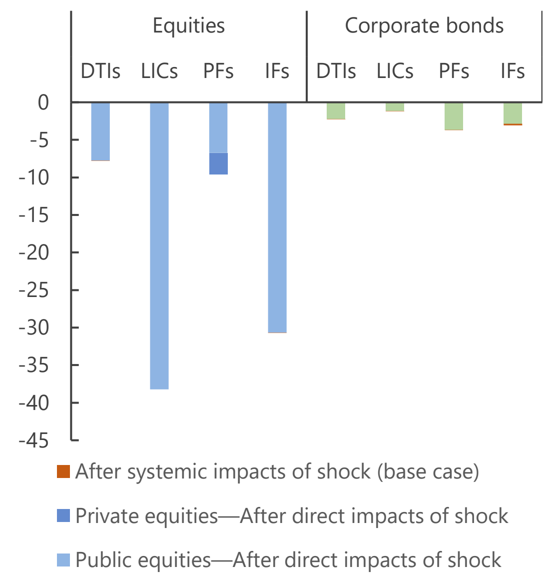
Life insurance companies experience lower credit risk impacts than deposit-taking institutions, which is consistent with their allocation of climate-relevant assets and risk-taking behaviour. Moreover, despite a considerable decrease in equity valuations, the overall impact is small due to life insurance companies' limited investment in climate-relevant equities. Pension funds' riskier investment profile contributes to the potential for greater losses, with a substantial increase in the average probability of default on their climate-relevant private debt portfolio. However, they face a relatively smaller decline in their average climate-relevant equity valuations, primarily from their public equity portfolio. Like other entities, investment funds show moderate credit risk impacts but face significant decline in their equity valuations.

Chart 7: Direct and systemic credit and market risk impacts on climate-relevant assets
Percentage-point change, relative to baseline, weighted average of climate-relevant assets, by type of entity

a) Probability of default and loss given default, climate-relevant corporate loans and private debt



b) Market valuations, climate-relevant corporate bonds and equities



Note: No systemic impacts occur for loans and private debt because of the absence of trade in secondary markets. DTIs are deposit-taking institutions; LICs are life insurance companies; PFs are pension funds; IFs are investment funds.

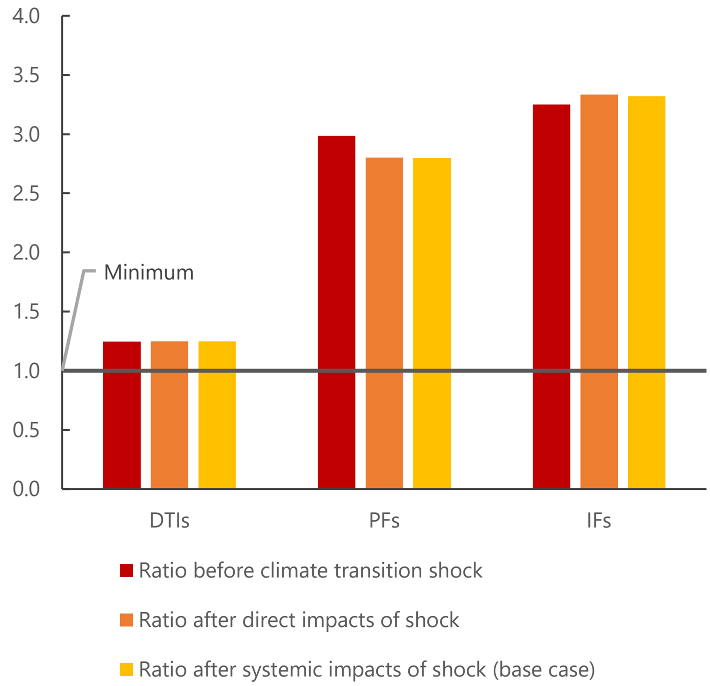
Sources: Office of the Superintendent of Financial Institutions; Autorité des marchés financiers; proprietary data from Canadian pension funds; Lipper, a Refinitiv Company; Eikon, a Refinitiv Company; and Bank of Canada calculations
Last observations: DTIs, LICs, IFs and most PFs, December 2021; remaining PFs, March 2022

A financial system's vulnerability to a climate transition shock may also be informed by impacts on the liquidity ratios of the different entities. **Chart 8** assesses how the liquidity ratio is impacted by the revaluation of assets, and in the specific case of pension funds, by the losses and margin calls from their derivatives exposures. It shows that liquidity ratios for all types of financial entities remain, on average, well above the threshold for the liquidity coverage ratio for deposit-taking institutions or expected outflows for pension funds and investment funds. This suggests that the financial entities have adequate liquidity to meet their obligations and cope with potential shocks.[33]

[33] See Appendix D for technical details about the liquidity risk methodology used in this study.

Chart 8: Direct and systemic impacts on liquidity ratios

Liquidity coverage ratios, by type of entity



Note: DTIs are deposit-taking institutions; LICs are life insurance companies; PFs are pension funds; IFs are investment funds.

Sources: Office of the Superintendent of Financial Institutions; Autorité des marchés financiers; proprietary data from Canadian pension funds; Lipper, a Refinitiv Company; Eikon, a Refinitiv Company; and Bank of Canada calculations
Last observations: DTIs, LICs, IFs and most PFs, December 2021; remaining PFs, March 2022

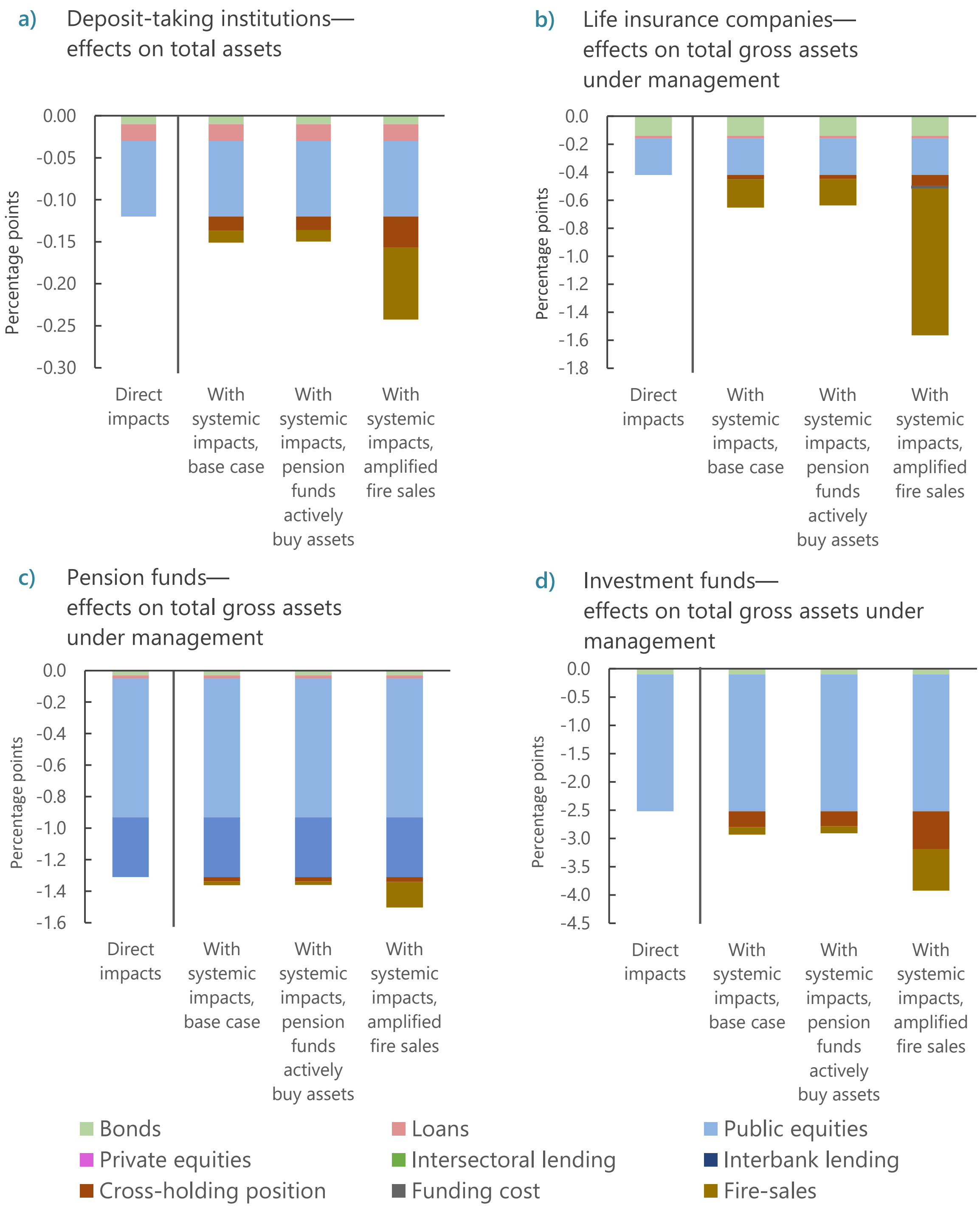
Asset valuation impacts by transmission channel

The panels in **Chart 9** show the changes in total asset valuations for different financial entities' portfolios. For deposit-taking institutions, life insurance companies and pension funds, the total asset valuations experience a minor to milder decline after the direct effects of the climate transition shock (first column in all panels). The deposit-taking institutions' relatively low initial exposure to climate-relevant assets, and life insurance companies' and pension funds' diversified portfolios, help mitigate direct impacts. Investment funds, in contrast, face greater direct effects, with a notable decline in their total gross assets under management, especially for equity funds.[34]

[34] Additional findings for investment funds, including the larger decline for equity funds, are shown in Appendix C.

Chart 9: Direct and systemic effects on total assets

Percentage-point change, relative to baseline



Sources: Office of the Superintendent of Financial Institutions; Autorité des marchés financiers; proprietary data from Canadian pension funds; Lipper, a Refinitiv Company; Eikon, a Refinitiv Company; and Bank of Canada calculations
Last observations: deposit-taking institutions, life insurance companies, investment funds and most pension funds, December 2021; remaining pension funds, March 2022

Though we observe mild direct effects of the climate transition shock, systemic effects may amplify these initial losses. To provide insights around this finding, the panels in **Chart 9** also present the transmission channels under the three alternative fire sale cases discussed in section 2:

- **base case**—baseline parametrization for fire sales in our agent-based model
- **pension funds actively buy assets**—pension funds actively buy climate-transitioning assets (i.e., assets that may help with the climate transition) sold by investment funds facing liquidity needs
- **amplified fire sales**—asset sales (mainly by investment funds) have a bigger effect on the falling asset prices, reflecting the non-linearities between selling volumes and price changes

Our analysis shows that even in the base case, mild direct effects—mostly triggered by fire sales—can increase significantly when accounting for these channels. While pension funds can lessen systemic effects through their active buying, the purchases are not large enough to absorb all undervalued assets. Finally, in the amplified fire sales case, the fallout from fire sales is significantly larger, triggering an increase in funding costs for life insurance companies and doubling the impact on investment funds' cross-holding positions.

Tracing back systemic effects by type of financial system entity

Chart 10 presents a breakdown of systemic effects of the climate transition shock by type of financial system entity. It traces these effects back to the type of entity that caused them. For example, in our fire sales base case, approximately 20% of investment funds' losses caused by systemic channels are attributable to the role of deposit-taking institutions.

In our fire sales base case, the climate transition shock prompts only investment funds to conduct fire sales. This sudden sell-off of assets leads to a decrease in asset prices, causing a devaluation of similar assets held by other financial system entities, thereby spreading the impacts across the financial system. **Chart 10**, panel a shows that most systemic effects in our framework application can be traced back to investment funds, with the effects for life insurance companies and pension funds primarily attributable to investment funds.

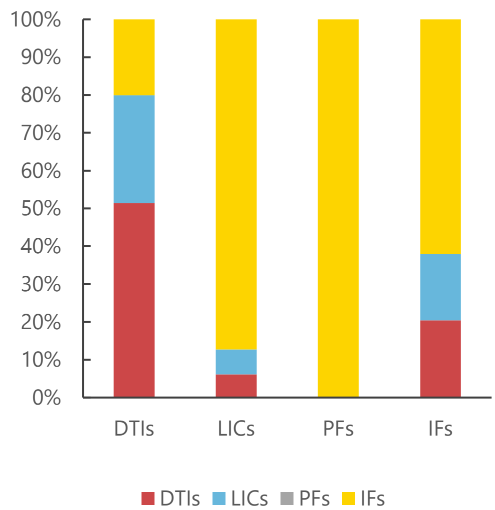
Chart 10, panel b shows the financial system's vulnerabilities related to its network connections following the climate transition shock. The node size represents the systemic impact on each entity, standardized by the entity's total assets.[35]

[35] The standardization prevents the bias toward the largest institutions. Notably, a large institution could suffer a higher impact in absolute terms, though proportionally, the hit might be less material than the one suffered by other smaller institutions.

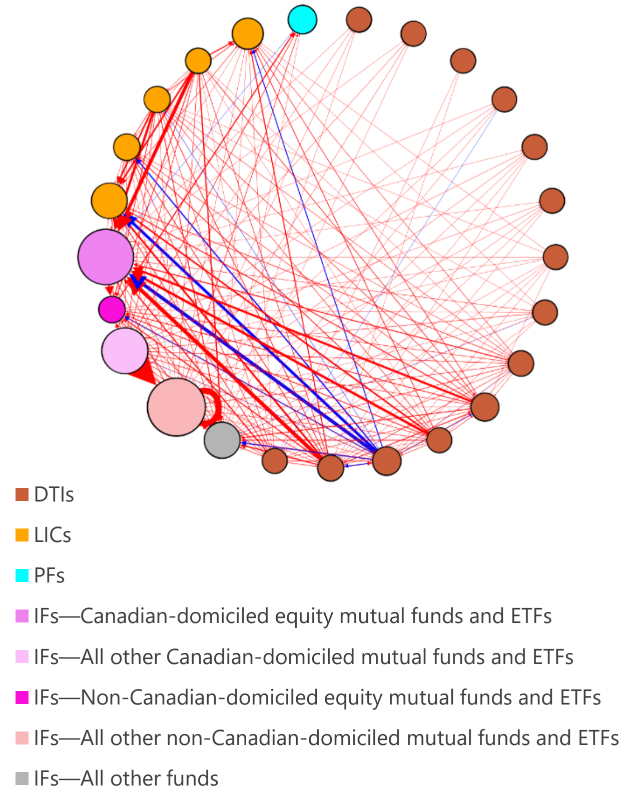
The chart also delineates the pathways of both direct and systemic impacts, tracing them back to their originating institutions. Blue lines indicate increases in total asset valuations. For example, deposit-taking institutions (DTIs) that benefit from the transition will contribute to increases in the asset valuations of investment funds and life insurance companies that hold shares in the DTIs. Conversely, red lines indicate losses, including those stemming from the systemic effects from cross-holding positions or fire sales.

Chart 10: Origination of systemic effects by entity type

a) Aggregated origination of systemic effects (base case) by entity type



b) Directional origination of systemic effects (base case) by entity type



Note: DTIs are deposit-taking institutions; LICs are life insurance companies; PFs are pension funds; IFs are investment funds.

Sources: Office of the Superintendent of Financial Institutions; Autorité des marchés financiers; proprietary data from Canadian pension funds; Lipper, a Refinitiv Company; Eikon, a Refinitiv Company; and Bank of Canada calculations
Last observations: DTIs, LICs, IFs and most PFs, December 2021; remaining PFs, March 2022

Additionally, the investment funds are broken down into five distinct fund types, differentiating between equity mutual funds/exchange-traded funds (ETFs) and non-equity mutual funds/ETFs, such as mixed assets, bonds and alternatives. This categorization helps assess how these funds' investment strategies may affect shock propagation. We also separate Canadian from foreign investment funds. **Chart 10**, panel b reveals that Canadian equity mutual funds/ETFs exhibit greater vulnerability than their foreign counterparts, as indicated by the larger node sizes. In contrast, non-equity funds demonstrate comparable levels of vulnerability both domestically and internationally.

Foreign investment funds are shown to play a significant role in transmitting systemic impacts, evidenced by the numerous arrows emanating from these nodes. For instance, the most substantial line connecting to the pension fund node originates from foreign equity funds. Notably, investment funds act as conduits for shock transmission across financial institutions, linking entities without direct cross-holding relationships. This is exemplified by the profits (**Chart 10**, panel b, blue arrows) flowing from the banking sector to Canadian equity funds, which hold shares in the DTIs. A thinner blue line from the Canadian equity funds to the pension fund node illustrates the interconnection between the banking sector and pension funds, mediated by the pension funds' stakes in investment funds, which in turn possess shares of the banking sector.

4. Financial stability insights

Against the backdrop of our application of the framework, this section presents our insights into financial stability and climate transition risk along two dimensions: distinct features of the financial system entities, and climate-related interconnectedness.

4.1 Insights on the distinct features of the financial system entities

Our application shows that although systemic factors may spread and amplify the direct effects of a climate transition shock, assessing the initial exposures of climate-related sectors provides insight into the risks that financial entities face. Evaluating portfolio allocations by sector and asset type reveals how entities' exposures to sectors that benefit from the transition may make some entities less susceptible to transition shocks.

The size of the financial system entity also plays an important role in its ability to understand and adapt to transition shocks. Larger entities often have more diversified portfolios and further developed capacities to assess climate risk, making them better equipped to navigate the challenges posed by transition shocks. Other factors, such as the entity's risk management strategies, sectoral focus and regulatory environment, also play a role.

Investment horizons are another factor in understanding transition risk. Entities with long investment horizons like pension funds and life insurance companies may act as dampeners within the financial system during a transition shock. Their long-term focus, evidenced by the longer average maturity of their assets relative to other entities, may lead them to seek bargains in sectors negatively impacted by the transition shock, thereby acting as a stabilizing force. In contrast, deposit-taking institutions, and particularly investment funds, may have the opposite effect. Shorter investment horizons, and dependence on more fragile funding sources for investment funds, lead these entities to become procyclical and increase volatility in fire-sale environments.

Our application sheds light on the risk-taking behaviour of different entity types. Pension funds and investment funds—in contrast to life insurance companies—invest a significant portion of assets in high-yield loans in climate-related sectors. The fact that these entities take more risk in private markets is useful in helping us understand the spread of a climate transition shock. Notably, privately held assets are not susceptible to the fire sales that can occur in public markets. Examining these varying risk-taking behaviours in combination with differing investment horizons provides a picture of the role played by different entity types during a climate transition shock.

Box 1

Highlights from our collaboration with Canadian pension funds

Our study benefited from rich collaboration with several Canadian pension funds and asset managers of pension funds. This partnership enabled us to access pension fund data relevant to the study. It also offered the opportunity for staff to engage in discussions with pension fund experts. Some highlights from this collaboration are presented below.

Strong and diversified engagement

We saw a high level of engagement and interest across multiple pension fund departments, including total fund risk, sustainable investment, and investment risk, among others. Engagement was sustained across all phases of the study—from development of the data template to methodological adjustments relevant for pension funds to market intelligence discussions.

Opportunity to discover, compare and validate

The study provided an opportunity for pension funds to compare themselves with the broader pension fund sector and other sectors of the financial system, and to gain additional perspectives on climate interconnectedness in the Canadian financial system. Participants generally found that the tools developed for the study served to validate or complement their own internal work and organizational thinking. In some cases, the study also provided the opportunity to compare findings and insights with pension funds' in-house analyses. The differences in methods and assumptions across institutions strengthened our understanding of transition risks and related analytical limitations.

Securing long-term investment perspectives

Working with pension funds helped us capture long-term investor perspectives. The pension funds provided a range of insights that we incorporated into this study, including:

- how they assess and manage climate transition risk
- how they seize opportunities through a variety of investment strategies and risk management practices
- how they address high levels of uncertainty about possible climate transition pathways

Challenges with the study's assumptions and approaches

Pension funds found some of the study's assumptions and methods to be challenging, including the static balance sheet assumption, the exclusion of macrofinancial feedback loops, and the different degrees of sectoral granularity across asset types. We also heard that the absence of analysis around the impacts of climate transition risk on inflation, interest rates and exchange rates created an incomplete picture. These challenges underscore the dynamic nature of the financial system and the need for more flexible and comprehensive modelling approaches. The distinct and complex regulatory and institutional environment in which Canadian pension funds and asset managers of pension funds operate limited our ability to conduct a more detailed analysis and derive deeper insights. Despite these limitations, our collaboration yielded valuable lessons and deepened our understanding of the impacts of climate transition risk within the Canadian financial system.

4.2 Insights on climate-related system interconnectedness

One insight from our analysis is that despite modest direct effects from climate transition shocks, the systemic effects highlight the financial system's interconnectedness, including that related to climate. Notably, our measures of common exposures across a mix of publicly traded assets point to climate-related system interconnectedness. This is particularly noticeable among the six largest Canadian banks (DSIBs) and among DSIBs, pension funds and investment funds. If a transition shock were to materialize or if financial entities were to take pre-emptive action on their transition plans, this could trigger movements in market valuations of assets traded in public markets due to climate-related interconnectedness.

Another insight pertains to investment funds. Because they are more procyclical and susceptible to redemption shocks than other types of financial entities, they can trigger and promote the spread of a stressful climate transition shock. Our analysis shows that, once the climate transition shock materializes, investment funds may require additional liquidity, leading to asset price pressures should a fire sale occur. This finding is further corroborated by our results for the selling case with amplified fire sales, where investors had a higher sensitivity to price volatility. Our study further shows that foreign investment funds can impact Canadian entities, pointing to the importance of cross-border transmission channels.

Finally, it is worth considering the potential role of entities that could be buyers for the undervalued assets, including from the fire sales case examined in this study, where pension funds actively buy climate-transitioning assets. In such scenarios, pension funds could play a role. Given their size, long-term investment horizons, stable contributor base and diverse investment strategies, pension funds might be interested in capitalizing on these undervalued assets as potential future opportunities.[36]

5. Concluding remarks

We develop a methodological framework to inform the understanding of the implications of climate transition risk across the financial system. This framework integrates scenario analysis with an agent-based model, allowing us to gain insights into the direct effects and systemic implications of climate transition shocks. We apply the framework to Canadian financial system data to help draw financial stability insights after a climate transition shock.

The application of the framework deepens our understanding of how climate transition risk may directly impact distinct financial system entities. We explore factors such as the entities' exposures to climate-relevant assets, risk-taking behaviour, size and investment horizon, business models and asset mixes (e.g., whether the entities are active in public or private markets). This gives us greater insight into how distinct financial entity types are impacted by and may respond to climate transition risk.

In addition, our analysis sheds light on how climate transition shocks may spread across entity types and potentially create systemic implications. Notably, common exposures help to identify the degree of climate-related interconnectedness in the financial system. Further, despite low initial direct exposures and financial impacts on financial system entities, some transmission channels such as cross-holding positions and fire sales may amplify direct effects. In addition, depending on the type of financial system entity, we find that some are more prone to act as a propagator of a transition shock in the financial system (i.e., investment funds) rather than a shock absorber (i.e., pension funds).

Our study also highlights several analytical challenges and limitations. Data challenges were a primary limitation in this study. The analysis excludes other types of risks that could occur concurrently with or compound the climate transition risk (e.g., climate-related physical risk, and transition-related inflation risk, interest rate risk, and real economy feedback loops). It also does not include some types of assets and economic sectors that could be sensitive to climate transition shocks (e.g., residential and commercial real estate, sovereign bonds, commodities, and mining sectors others than coal). Further, we do not include the liability side of balance sheets/portfolios for most of the financial institutions (partly due to data limitations) and assume a static balance sheet.

[36] This aligns with the findings of Bedard-Pagé et al. (2016), who suggest that pension funds act as a stabilizing force within the financial system.

Our insights and limitations underscore the need for further analytical efforts that encompass a broader range of asset types and sectors. This can help provide a more comprehensive understanding of the impact of transition risks across the financial landscape. This work does strengthen our knowledge of how distinct financial system entities may be impacted by and respond to climate transition risks and opportunities, and of the potential channels through which those risks and opportunities may spread across the financial system. More generally, our work contributes to building standardized systemic risk assessment and monitoring tools.

Appendices

Appendix A: Regional coverage

Table A-1 shows the regional and country-level coverage for our climate transition scenarios.

Table A-1: Regional coverage and mapping of regions to countries

Region	Countries
Canada	CA
United States	US
Mexico	MX
Brazil	BR
Other Latin America	AI, AG, AR, AW, BS, BB, BZ, BM, BO, KY, CL, CO, CR, CU, DM, DO, SV, EC, FK, GF, GL, GD, GP, GT, GY, HT, HN, JM, MQ, MS, AN, NI, PA, PY, PE, PR, KN, LC, PM, VC, SR, TT, TC, UY, VE, VG, VI
Europe (EU+)	AT, BE, BG, CY, CZ, DK, EE, FI, FR, DE, GR, HU, IS, IE, IT, LV, LI, LT, LU, MT, NL, NO, PL, PT, RO, SK, SI, ES, SE, CH, GB
Rest of Europe	AL, AD, AM, AZ, BY, BA, HR, FO, GE, GI, KZ, KG, MK, MD, MC, SM, RS, TJ, TR, TM, UA, UZ
Russian Federation	RU
China	CN, HK
India	IN
Japan	JP
Korea	KR
Indonesia	ID
Dynamic Asia	MY, PH, SG, TW, TH
Rest of East Asia	AF, BD, BT, BN, KH, KP, LA, MO, MV, MN, MM, NP, PK, LK, TL, VN
Australia and New Zealand	AS, AU, CK, FJ, PF, GU, KI, MH, FM, NR, NC, NZ, NU, NF, MP, PG, WS, SB, TK, TO, TV, VU, WF
Africa	DZ, AO, BJ, BW, BF, BI, CM, CV, CF, TD, CI, KM, CG, CD, DJ, EG, GQ, ER, ET, GA, GM, GH, GN, GW, KE, LS, LR, LY, MG, MW, ML, MR, MU, YT, MA, MZ, NA, NE, NG, RE, RW, SH, ST, SN, SC, SL, SO, ZA, SD, SZ, TZ, TG, TN, UG, ZM, ZW
Middle East	BH, IR, IQ, IL, JO, KW, LB, OM, PS, QA, SA, SY, AE, YE

Note: The table uses codes from the ISO 3166-1 alpha-2 classification system. See IBAN (2023) for mapping between codes and countries.

Appendix B: Sectoral coverage

Table B-1 presents our breakdown of the climate-relevant sectors and sub-sectors, which are related industries and activities that might be similarly impacted by the transition scenarios. We map climate-relevant sectors into the three most common industrial classification systems: the North American Industry Classification System (NAICS), the Global Industry Classification Standard (GICS) and the Bloomberg Industry Classification Standard (BICS). This allows us to classify assets from non-financial corporate sectors into climate-relevant sectors and sub-sectors as well as non-climate-relevant sectors. In the table, the sub-sectors in bold font are those benefiting from our transition scenarios.

Table B-1: Mapping climate-relevant sectors to industrial classifications

Sector	Sub-sector	NAICS	GICS	BICS
Crops	Crop production	111	30202010	1210101013
Livestock	Animal production and aquaculture	112	30202010	121010101110, 121010101111, 121010101112, 121010101210
Forestry	Forestry and logging	113	15105010	18101310
Coal	Coal mining, Contract drilling (except oil and gas), Other support activities for mining	2121, 213117, 213119	10102050, 15104020	18101514, 18101515
Oil and gas	Oil and gas extraction (except oil sands)	211110,	10102020, 10101010, 10102010	131010111010, 131010111012 131010111013
	Oil sands extraction	21114	10102020, 10101010	131010111011
	Crude petroleum from oil shale	211120	10102020, 10101010, 10102010	131010111010
	Services to oil and gas extraction and contract drilling	213111, 213118	10101020, 10101010	13101110, 1310111110, 1310111111
	Natural gas distribution	2212	551020, 551030, 10102040, 10102010	201011101111
Electricity	Fossil-fuel electric power generation	221112	55101010, 55105010, 551030	2010101110
	Hydro and nuclear	221111 221113	55105020, 55101010	201010111213, 2010101111
	Other renewables	221119	55105020	201010111210, 201010111211, 201010111212, 201010111214, 201010111215
	Electric power transmission, control and distribution	22112	551010	20101012

Refined oil	Petroleum and coal products manufacturing	324	10102050, 15101020, 10102040, 10102030, 10102010, 15101050	1310101310, 1810111011, 181010121811
Energy-intensive industries	Paper manufacturing, Printing and related support activities	322, 323	15105020, 20201010, 15103020, 50201040	18101311, 17111112
	Chemical manufacturing, Plastics and rubber products manufacturing	325, 326	352010, 352020, 151010, 25302020, 252020, 25201050, 25201040, 25201030, 30301010, 30302010, 25101020, 20102010	18101010, 18101011, 18101012, 17101511
	Non-metallic mineral product manufacturing	327	15102010, 20105010, 15103010	1810111110, 1110111112, 1810111112, 1810121010, 191010141112, 18101110
	Primary metal manufacturing, Fabricated metal product manufacturing	331, 332	151020, 201020, 201030, 20106020, 15103010, 15104025, 15104030, 15104045, 15104050, 20201060, 20105010, 15104010, 201030, 201020, 151020, 201010, 50202020, 15104040, 15104020	1710151011, 18101410, 1810151110, 181015111211
Commercial transportation	Air transportation	481	203010, 203020	17111210, 17111211
	Rail transportation	482	20304010	17111214, 1711121610
	Water transportation	483	20305030, 25301020, 20303010	17111213, 1711121613
	Pipeline transportation	486	10102040, 55102010, 55103010	131010121010, 13101012101112, 1310101211
	Other transportation	484, 485, 487, 488, 492, 493	25301020, 20201070, 20304020, 20305020	17111215, 1711121611, 1711121612, 1711121811, 17111212, 1711121713
Non-climate-relevant sectors	All other sectors		All other codes	

Note: NAICS is the North American Industry Classification System; GICS is the Global Industry Classification Standard; BICS is the Bloomberg Industry Classification Standard.

Source: The climate-relevant sectors are based on the Bank of Canada–Office of the Superintendent of Financial Institutions pilot project using scenario analysis to assess climate transition risk (Bank of Canada and OSFI 2022).

Appendix C: Additional findings for investment funds after climate transition shock

Chart C-1: Direct impacts on valuation of investment funds' total gross assets under management

Percentage-point change, relative to baseline

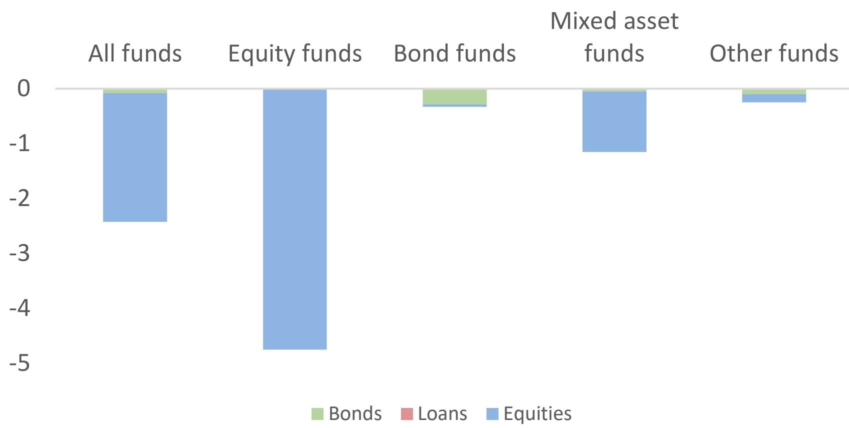


Table C-1: Investment funds taking direct market value hit of 10% or more on their gross assets under management

Share of total gross assets under management (AUM) by type of fund

Type of fund	Share of AUM with market value decline greater than 10%
All types of funds	12%
Equity funds	21%
Bond funds	0%
Mixed asset funds	1%
Other types of funds	4%

Appendix D: Extensions to scenario analysis

This appendix provides an overview of the extensions to the scenario analysis.

D.1 Standardization of risk factor pathways

We extend the credit and market risk models from the pilot project to other regions beyond Canada and the United States. To do this, we first map the model parameters from Canadian and US models to other regions based on the similarity of their net income pathways, measured using root mean squared error.

After mapping, we apply the Canadian or US models to other regions by transforming their risk factor pathways (RFPs) into the vector space of Canada or the United States. We use a standardization equation that aligns the mean and standard deviations of a region's RFPs with those of the benchmark region:

$$\widetilde{ni}_{r,s,t} = \frac{ni_{r,s,t} - \mu_{ni_{r,s}}}{\sigma_{ni_{r,s}}} * \sigma_{ni_{*,s}} + \mu_{ni_{*,s}},$$

where $ni_{r,s,t}$ is the RFPs at time *t* for region *r* and sector *s*, and $\mu_{ni_{r,s}}$ and $\sigma_{ni_{r,s}}$ are its mean and standard deviations, respectively. The mean and standard deviations of the benchmark region (i.e., either Canada or the United States) for region *r* and sector *s* are $\mu_{ni_{*,s}}$ and $\sigma_{ni_{*,s}}$, respectively. This standardization is applied only to the commercial transportation, coal, forestry, and livestock sectors because other sectors are already standardized.

D.2 Credit risk assessment in climate-relevant sector bond portfolios

We assess credit risk for climate-relevant sector (CRS) bonds based on the fair valuation of the portfolio given by:

$$V_0(p) = \sum_{t=1}^{T-1} \delta^t \left((1-p_t)^t + Rp(1-p_t)^{t-1}\right)y + \delta^T (1-p_T)^T (y+1),$$

where p_t is the probability of default at time *t* of the scenario, δ is the discount factor, *y* is the yield to maturity, *R* is the recovery rate (i.e., inverse of loss given default), and *T* is the maturity of bonds. Entities are assumed to have 10-year foresight. After this period, they anticipate constant transition risk impacts until the bond matures. After 2050, a constant net income pathway is assumed.

The valuation impact of the climate change scenario on bond portfolios is calculated by combining the theoretical valuation of the bonds under the baseline scenario (p^B) and the adverse climate transition risk scenario (p^C):

$$\Delta V = \frac{V_0(p^C) - V_0(p^B)}{V_0(p^B)}.$$

D.3 Liquidity risk analysis

Liquidity metrics are calculated for deposit-taking institutions (DTIs), pension funds and open-ended mutual funds.

- For **DTIs**: liquidity metrics are based on liquidity coverage ratio (LCR) inflows and outflows from Office of the Superintendent of Financial Institutions and Autorité des marchés financiers regulatory returns.
- For **pension funds**: liquidity metrics are based on the expected outflows provided by pension funds, assuming a 10% cash outflow of total net assets for outliers and accounting for liquidity needs from derivative exposures (see section D.3.3).
- For **open-ended mutual funds**: liquidity metrics are based on the estimation of the highest monthly outflow over five years from historical data, adjusting for a floor outflow based on average historical data and assuming an initial LCR of a least one (see section D.3.2).

Assets of pension funds and open-ended mutual funds are converted into high-quality liquid assets (HQLAs) using a liquidity factor (see section D.3.1).

D.3.1 High-quality liquid assets

HQLAs in the LCR are long-position assets expected to provide reliable collateral or cash during market stress. Liquidity weights are applied to each asset class and credit quality as per Basel III bank regulations (BIS 2013). HQLAs are generated by summing the liquidity-weighted shares of different asset classes:

$$HQLA_i = \sum_{q=1}^{N} \omega_{i,q} \, k_q,$$

where $\omega_{i,q}$ represents the proportion of an asset class q in asset i and k_q is the liquidity weight (see **Table D-1**).[37]

Table D-1: Liquidity weights for different asset types, by credit rating

Type of asset	CQS1	CQS2	CQS3
Cash	100%	100%	100%
Sovereign debt	100%	85%	50%
Corporate debt	85%	50%	50%
Equity	50%	50%	50%
Fund	Based on the underlying assets		

Note: CQS1 is credit quality step 1 and refers to AAA to AA ratings; CQS2 is credit quality step 2 and refers to A ratings; CQS3 is credit quality step 3 and refers to BBB ratings. Weights are from European Securities and Markets Authority (ESMA), "Stress simulation for investment funds," ESMA Economic Report (September 2019) and Bank for International Settlements, "Basel III: The Liquidity Coverage Ratio and liquidity risk monitoring tools," Basel Committee on Banking Supervision (January 2013).

[37] More details about the use of HQLA in the investment fund universe can be found in ESMA (2015).

D.3.2 Redemption flow in open-ended mutual funds

Data from Lipper, a Refinitiv Company, on investment fund flows are used to estimate a fund's liquidity transformation[38] and predict investor redemption responses to the fund's performance.[39] Liquidity transformation is the holdings' shift toward liquid stocks when high market volatility is anticipated due to potential investor redemptions.

The liquidity needs are defined as $\min\left(HQLA_i, max\left(f_{floor}, VaR_{1.7\%}(f_i)\right)\right)$, where $HQLA_i$ is the high-quality liquid asset (see section D.3.1) for fund i. The liquidity needs are the maximum between a floor f_{floor} and a quantile $VaR_{1.7\%}(f_i)$ of the historical flow (standardized by total net assets) for each fund i, which is used to predict potential redemptions.[40] We impose the initial LCR to be at least equal to one, to isolate liquidity needs stemming from climate transition risk only.

D.3.3 Derivate-related liquidity needs (for pension funds only)

We use two industry-standard methodologies to evaluate the impact of the climate transition shock on the liquidity needs stemming from equity and debt-related derivatives:

- For equity derivatives, we use the Standard Portfolio Analysis of Risk (SPAN) methodology to determine the initial margin required for a derivative contract.
- For debt-related derivatives, we use Monte Carlo simulations based on the Vasicek (2002) model to calculate the loss of a debt portfolio on which a derivative is built.

Positions provided by pension funds are adjusted using the derivative's delta to equate to a futures position.[41]

Equity underlying

The liquidity needs from equity derivatives arise from (i) increased initial margin requirements and (ii) mark-to-market losses, both increasing the denominator of the pension fund's LCR.

We use the SPAN method to determine the initial margin requirements for equity derivatives. The SPAN method defines the margin interval—that is, the maximum price fluctuation in percent that the derivative contract is expected to have over the predetermined liquidation horizon with the desired level of confidence. For the liquidation horizon and confidence level, we follow common industry calibrations and take the type of derivative—exchange-traded (ET) or over-the-counter (OTC)—into account. Specifically, we set the confidence level to

[38] See Chernenko and Sunderam (2016) and Huang (2020).

[39] See Goldstein, Jiang and Ng (2017).

[40] Historical flows reveal an average maximum outflow of 5% to 20%, varying by investment strategy. For each fund, we calculate the highest historical monthly outflow with a 98.3% probability, equivalent to the highest outflow seen every five years (1/(12 × 5) × 100 = 1.7%). We apply a floor to the outflows to account for limitations in historical data for newly established and small funds, similar to ESMA (2021).

[41] Further adjustments considering the derivative's convexity (gamma) are omitted for simplification.

99.87%, and together with the normal distribution assumption this corresponds to the margin interval being $MI = 3\sqrt{n}\,\sigma_{260d}$, where the liquidation horizon n = 2 for ET or 5 for OTC derivatives.[42]

The estimate for the volatility of the derivative contract's returns, σ_{260d}, is obtained from an exponentially weighted moving average model:

$$\sigma_{260d} = \sqrt{\frac{(1-\lambda)\sum_{i=1}^{260}\lambda^{i-1}(R_{t-i}-\bar{R})^2}{(1-\lambda^{260})}},$$

where λ = 0.99, balancing time-varying market risk without triggering procyclicality issues.[43]

We employ a time series of returns for a CRS index from Canadian, US and European equity data from Eikon, a Refinitiv Company. We start at the beginning of the COVID-19 crisis to simulate a period of high market volatility. We adjust daily returns based on the climate shock for a sector and a region on top of the price evolution of the COVID-19 crisis.

The initial margin requirement in dollars is the product of the exposure and the margin interval. The increase in initial margin requirement from one day to the next indicates the additional liquidity needed to keep the derivative position open. Finally, as is standard in the industry for equity derivatives, we assume daily settling of gains and losses due to market value changes.

Debt underlying

Derivative debt positions are aggregated by sector and region, and the Vasicek (2002) model is used to generate the Monte Carlo simulations to evaluate the maximum credit loss at a 99.7% confidence level over a five-day liquidation period. The change in maximum credit loss when the probability of default (PD) changes from the initial value to a value under a certain transition scenario (PD_S) is scaled to a five-day loss, aligned with the liquidation period, as:

$$MC = \sqrt{\frac{5}{250}}\,[VaR_{99.7\%}(PD_S) - VaR_{99.7\%}(PD)]$$

where $P\big(CreditLoss(PD) < VaR_{99.7\%}(PD)\big) = 0.997.$[44]

[42] For similar parameter calibrations used by central counterparties (CCPs) in Canada and Europe, see Odabasioglu (forthcoming) and Boudiaf, Scheicher and Vacirca (2023), respectively.
[43] See, for instance, Brunnermeier and Pedersen (2009) for more information about potential procyclicality issues in the derivatives. See Odabasioglu (forthcoming) for further details on the SPAN methodology, as well as how the calibration of parameters impacts the initial margin requirements.
[44] We use variance reduction techniques to increase the precision of the estimates obtained from the simulation.

Appendix E: Extensions of Hałaj's (2018) agent-based model

We extend Hałaj's (2018) agent-based model (ABM) for each type of entity in scope of this study. We present key design features for two of these extensions: fire sales and the transitioning of assets from being less carbon-intensive or greener (i.e., climate-transitioning assets).

E.1 Extension for fire sales

An exponential price impact function (Schnabel and Shin 2002; Cifuentes, Feruci and Shin 2005; Cont and Schaanning 2017; Hałaj 2018, 2020; Fukker et al. 2022) is used to capture the effect of selling pressure on asset price changes:

$$\Psi_{\phi}(V) = (1 - \exp(-V\alpha)),$$

where V is the amount of assets sold by market participants and α is the sensitivity of the price to a certain sold amount. Hałaj (2018, 2020) estimates α = 0.0005 and 0.002 respectively, corresponding to price impacts in basis points for each billion in liquidation in Canadian dollars.

The function's output is highly sensitive to α's value. We use α = 0.002 (Hałaj 2020) for non-climate-relevant sector (CRS) equities. In contrast, for CRS equities, we use data from Eikon, a Refinitiv Company, to estimate the relationship using ordinary least squares estimation and a quantile regression to generate stress in the market. For bond sensitivity, we used Fukker et al.'s (2022) values to rescale the equity price sensitivity and infer the bond price sensitivity for both CRS and non-CRS bonds (i.e., both non-CRS corporate and sovereign bonds). The amplified fire sales case corresponds to the estimate of the fifth percentile.

E.2 Extension for climate-transitioning assets

Our scenario analysis provides a useful perspective but does not reflect the opportunities that climate-transitioning assets offer. To tackle this limitation, we model the assets that could be an opportunity over the long run. [45]

We estimate the share of assets able to transition in a sector or sub-sector through the percentage of assets getting the highest environmental rating from Eikon, a Refinitiv Company. We use environmental score grades for about 60,000 firms across Canada, the United States, Europe and Japan to estimate the potential long-term transition of assets sold during fire sales. For instance, 19.83% of firms in the electricity sector have the highest environmental score. This implies that if Can$100 million of electricity equities are sold,

[45] Each firm is assigned to only one sector. For example, a firm generating electricity using only fossil fuel sources would be in the same bucket as a firm generating 51% of its electricity from fossil fuel sources and 49% from renewable sources. The activities in the sector might change in the future, but the initial assessment considers the sectors as constant over time.

pension funds with good liquidity positions could buy Can$19.83 million and transition this firm to the private market. Thus, the final fire sale effect is limited to a selling pressure of Can$81.17 million. The higher the percentage, the more assets that could be absorbed by entities with a long-term horizon.

Table E-1: Comparison of this study's model with Hałaj's (2018) agent-based model

<table>
<tr><th></th><th colspan="2">Deposit-taking institutions</th><th colspan="2">Life insurance companies</th><th colspan="2">Investment funds</th><th colspan="2">Pension funds</th></tr>
<tr><th>Steps in the agent-based model</th><th>Our model</th><th>Hałaj's (2018) model</th><th>Our model</th><th>Hałaj's (2018) model</th><th>Our model</th><th>Hałaj's (2018) model</th><th>Our model</th><th>Hałaj's (2018) model</th></tr>
<tr><td>Key metrics and ratios</td><td>CET1
LCR</td><td>CET1
LCR</td><td>LICAT (total and core)</td><td rowspan="9">✗</td><td>LCR</td><td>LCR</td><td>LCR</td><td rowspan="9">✗</td></tr>
<tr><td>Interbank lending</td><td>✓</td><td>✓</td><td>✗</td><td>✗</td><td>✗</td><td>✗</td></tr>
<tr><td>Intersectoral lending</td><td>✓</td><td>✗</td><td>✗</td><td>✗</td><td>✗</td><td>✓</td></tr>
<tr><td>Fire sales</td><td>Based on sector/ sub-sector, asset type and quantile. Consider effects on credit rating.</td><td>Common calibra-tion</td><td>Based on sector/ sub-sector, asset type and quantile. Consider effects on credit rating.</td><td>Based on sector/ sub-sector, asset type and quantile. Consider effects on credit rating.</td><td>Common calibra-tion</td><td>Based on sector/ sub-sector, asset type and quantile. Consider effects on credit rating. Allow some buying pressure.</td></tr>
<tr><td>Funding shock</td><td>✓</td><td>✓</td><td>✓</td><td>✗</td><td>✗</td><td>✗</td></tr>
<tr><td>Business similarity</td><td>✓</td><td>✓</td><td>✓</td><td>✗</td><td>✗</td><td>✗</td></tr>
<tr><td>Cross-holding (equity)</td><td>✓</td><td>✗</td><td>✓</td><td>✓</td><td>✗</td><td>✓</td></tr>
<tr><td>Cross-holding (debt)</td><td>✓</td><td>✓</td><td>✓</td><td>✓</td><td>✓</td><td>✓</td></tr>
<tr><td>Performance-flow nexus</td><td>✗</td><td>✗</td><td>✗</td><td>✓</td><td>✓</td><td>✗</td></tr>
</table>

Note: CET1 is Common Equity Tier 1 ratio, LCR is liquidity coverage ratio, LICAT is Life Insurance Capital Adequacy Test.

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