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Climate-Related Risks and Opportunities for Portfolio Managers: A Literature Review

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Commissioning and Purpose of Research

The research for this report was commissioned by CalPERS, the largest public pension fund in the United States, to help it better understand the potential impact of environmental, social, and governance factors on long-term value creation and effective risk management within its investment portfolio. As a result, the research and outputs of this project were tailored to CalPERS' needs but intended also to draw larger lessons applicable for universal asset owners, especially ones that are intergenerational and fiduciaries to their members. The work was completed in June 2024.

EXECUTIVE SUMMARY

Portfolio managers and asset owners face pressure from beneficiaries, clients, regulators, and risk assessment professionals to manage extensive and complex climate-related risks. The framework, literature review and discussion presented in this report, in combination with the accompanying database, are intended to help institutional investors and asset owners understand climate-related risks to their portfolios in order to develop climate-related risk management strategies.

This report constructs a taxonomy of 28 climate-related financial risks from the perspective of portfolio managers. The categories in the taxonomy are inherently interrelated; climate-related risks do not neatly fall in a specific category of risk and many risks may have two or more dimensions, depending on whether there are regional, sectoral, or other specificities. Different studies may categorize similar risks in different ways. Accordingly, this framework is meant to provide an analytical framework to support investors when evaluating the relevance and interaction of various climate-related risks.

Importantly, this report does not offer specific advice on the interpretation or analysis of the climate-related risk research presented herein. This scoping study identifies, summarizes and categorizes relevant literature; it does not verify or endorse the accuracy, precision or completeness of the underlying literature or the results summarized herein, and does not endorse any of the third-party findings or perspectives discussed throughout this report. Indeed, this study, and the accompanying database, contain a number of studies that reach contradictory and inconclusive findings. Reliance should not be placed on the views or information expressed herein when taking any specific investment decision or choosing an investment strategy.

Also notably, this study focuses on the identification, implications and management of climate-related financial risks. It does not attempt to broadly assess the economic or financial risks that climate change poses to society, or to assess academic literature aimed at financial policymakers. It also does not include literature on the impacts of financial decision-making and investments on climate-related outcomes, nor on investment opportunities from the energy transition – both of which are increasingly relevant for institutional investors, as well.

The structure of this report is as follows: Section 1 introduces this report. Section 2 briefly summarizes the landscape of literature addressing climate-related financial risks, and outlines the methodology used to assemble this study and the associated database of references. Section 3 categorizes this literature, and identifies key themes, research areas, and subtopics. This section first summarizes three broadly recognized categories of climate risk, provides an overview of 28 "climate risk research areas" identified by this report, and then discusses recent representative research in each risk area.

Finally, Section 4 summarizes the conclusions of this scoping study. This report is accompanied by two Annexes: Annex I provides a taxonomy of climate-related portfolio risks, and summarizes the 28 climate-related "risk research areas" identified in this scoping study. Annex II provides additional detail about the research methodology discussed in Section 2.

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1. INTRODUCTION

On November 13, 2023, CalPERS, the California Public Employee Retirement System, debuted a new, and ambitious, strategy for considering climate change throughout its portfolio. This plan is designed to speed the alignment of CalPERS' investments with a "net zero" economy, "where carbon emissions from investments are evenly balanced with carbon reductions."[1] To do so, CalPERS' "new effort will commit $100 billion toward climate solutions by 2030 and ensure corporate accountability through the sale of investments that do not have a credible plan to reduce carbon emissions."[2] This ambitious commitment reflects both the significant risks and enormous opportunities that the increasing exigency of climate change presents to institutional investors.[3]

Investors rely on sophisticated research from governments, academics, and industry participants to understand the climate change impacts of their investment decisions, address climate-related portfolio risks, and identify opportunities in the climate transition. This scoping study represents the culmination of efforts by a team of faculty and researchers at Columbia University to support the ongoing efforts of CalPERS and other climate-conscious investors by building a database of literature addressing climate-related risk from the perspective of institutional investors. This report summarizes the database-building process, and reviews, categorizes, and summarizes the landscape of research around climate-related financial risks.

The field of climate-related financial scholarship is growing rapidly in response to the increasing exigency of climate change. As such, this scoping study does not represent a comprehensive summary of the entire field—such a summary would be unwieldy and immediately outdated. Instead, this report, and the accompanying database, provide a vertical slice through the scholarship addressing climate-related financial risk that captures both the extent of climate-related risk research and key scholarly debates. In doing so, this study creates a taxonomy of climate-related financial risk, largely drawn from the Basel Committee on Banking Supervision's seminal paper, "Climate-related Risk Drivers and Their Transmission Channels,"[4] adapted and supplemented to address the concerns of institutional investors.

The framework, literature review, and discussion presented in this report, in combination with the accompanying database, are intended to help institutional investors and asset owners to understand climate-related risks to their portfolios and interpret, develop, and evaluate competing climate-related risk strategies. Importantly, this report does not offer specific advice on the interpretation or analysis of the climate-related risk research presented herein. This scoping study identifies, summarizes and categorizes relevant literature; it does not verify or endorse the accuracy, precision or completeness of the underlying

[1] Press Release, CalPERS Announces $100 Billion Net Zero Pledge and New Climate Accountability Measures, CALPERS (Nov. 13, 2023), https://www.calpers.ca.gov/page/newsroom/calpers-news/2023/calpers-announces-100-billion-net-zero-pledge-and-new-climate-accountability-measures.
[2] *Id*.
[3] Wess Venteicher, Tanya Snyder, & Blanca Begert, *California's Pensions are Getting Greener*, POLITICO (Nov. 13, 2023), ("Inflation Reduction Act incentives, green mandates and the disasters wrought by increasingly extreme weather are changing the economic landscape, creating new opportunities to earn money on climate solutions and new risks of ignoring climate change, said Peter Cashion, [CalPERS'] head of sustainable investments.").
[4] BANK FOR INTERNATIONAL SETTLEMENTS, BASEL COMMITTEE ON BANKING SUPERVISION, CLIMATE-RELATED RISK DRIVERS AND THEIR TRANSMISSION CHANNELS (2021), https://www.bis.org/bcbs/publ/d517.pdf.

literature or the results summarized herein, and does not endorse any of the third-party findings or perspectives discussed throughout this report. Indeed, this study, and the accompanying database, contain a number of studies that reach contradictory and inconclusive findings. Reliance should not be placed on the views or information expressed herein when taking any specific investment decision or choosing an investment strategy.

This report develops a framework that is designed to help institutional investors and asset owners understand climate-related risks to their portfolios and interpret, develop, and evaluate competing climate-related risk strategies. This study is narrowly focused on literature that is relevant to portfolio managers focused on optimizing risk-adjusted returns for their beneficiaries and, to a lesser extent, stakeholders that interface with these decision-makers. It does not attempt to broadly assess the economic or financial risks that climate change poses to society, or to assess academic literature aimed at financial policymakers. It also does not include literature on the impacts of financial decision-making and investments on climate-related outcomes, nor on investment opportunities from the energy transition – both of which are increasingly relevant for institutional investors, as well. A significant body of scholarship which is oriented towards the global societal challenge of directing resources to combatting, and adapting to, climate change has been excluded from this literature review.

This report proceeds in three sections. Section 2 briefly summarizes the landscape of literature addressing climate-related financial risks, and outlines the methodology used to assemble this study and the associated database. Section 3 categorizes this literature, and identifies key themes, research areas, and subtopics. This section first summarizes three broadly recognized categories of climate risk, and then provides an overview of 28 "climate risk research areas" identified by this report, and then discusses recent representative research in each risk area. Finally, Section 4 summarizes conclusions from this scoping study. This report is accompanied by two Annexes: Annex I provides a taxonomy of climate-related portfolio risks, and summarizes the 28 climate-related "risk research areas" identified in this scoping study. Annex II provides additional detail about the research methodology discussed in Section 2.

2. METHODOLOGY

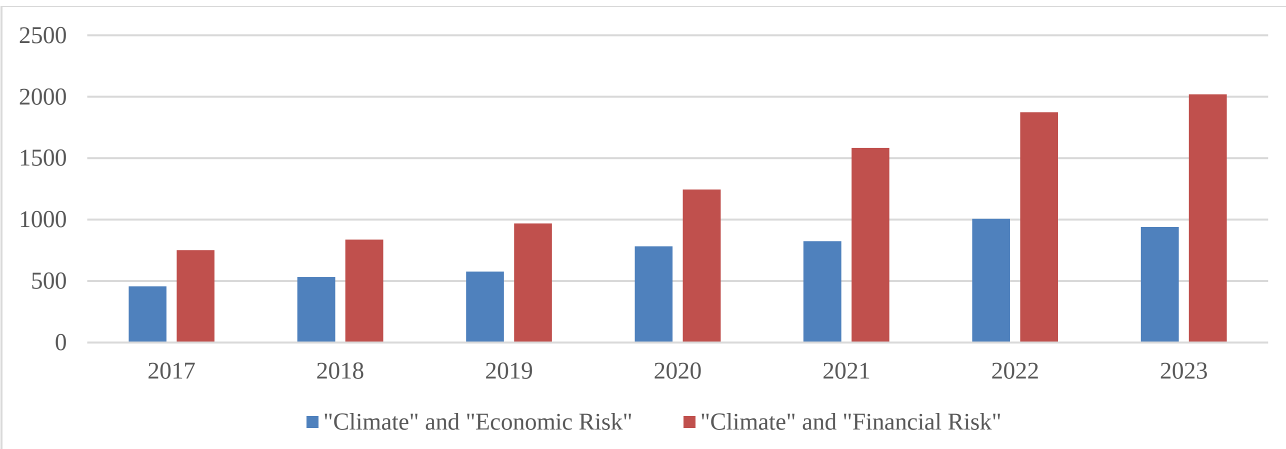
The goal of this project was to develop a functional and up-to-date database of climate-related financial literature, and to provide a review of climate-related financial risks and opportunities. This database and review can then be used by CalPERS employees to develop portfolio-level climate strategies, and to assess, understand, and engage with the climate policies of CalPERS' external asset managers, portfolio companies, and external advisors. This review focuses on literature addressing climate-related risks from the perspective of financial institutions, investors, and asset owners.

We identified relevant literature through a three-phase process. First, our research team selected four key scoping papers produced by financial industry regulators that attempt to provide comprehensive overviews of climate-related risks to the financial sector. Next, we developed "research trees" consisting of the sources reviewed and cited by those regulators as significant. Throughout this process, our team categorized the identified literature into 28 climate risk research areas. Finally, we supplemented this initial dataset with targeted searches within CLIO, Columbia University's academic database of more than 862 million publications. The methodology underlying each phase of this process is explained at length in this section.

2.1 The Scale of Climate-Related Financial Literature

To give some idea of the scope of potentially relevant literature, a simple keyword search of CLIO for English-language scholarly publications identified 15,122 publications tagged with the keywords "climate" and "financial risk", and 8,951 tagged with the keywords "climate" and "economic risk." Of these publications, more than half (9,975 for "financial risk" and 5,344 for "economic risk") were published since January 1, 2017, and approximately 25% (4,590 for "financial risk" and 2,271 for "economic risk") were published since January 1, 2022. Analysis of annual publications shows a consistent growth in publications addressing climate-related economic or financial risk (see *Table 1* below). While these simple searches and raw numbers are neither comprehensive nor particularly tailored, they demonstrate the scale and rapid growth of climate-related risk literature.[5]

Table 1: English-Language Scholarly Publications Addressing Climate-related Investment Risk[6]



2.2 Scoping Methodology

Given the volume of potentially relevant literature, this scoping study required a highly tailored research methodology intended to:

1. Identify scholarly literature around the economic impacts of climate change that would be highly relevant to CalPERS' decision-making;
2. Contain a significant and representative portion of the universe of relevant literature;
3. Categorize resources in a way that supports further detailed analysis; and
4. Ensure that resources are available to support CalPERS' work at the strategic, portfolio, and investment levels.

[5] In practice these numbers may understate the actual growth in climate-related risk literature, as CLIO is an actively maintained database and there may be delays between an article's publication and its inclusion in the database.
[6] These sample searches were conducted on June 5, 2024. CLIO is an actively maintained database, and searches using identical terms that are conducted at different times may reflect slightly different results as sources become available or unavailable.

As an initial step, this project established a research cut-off of 2017. This cut-off date was based on work by the Financial Stability Board (FSB), an international organization of states and NGOs that "monitors and makes recommendations about the global financial system."[7] In 2017 a committee of the FSB, the Task Force on Climate-related Financial Disclosures (TCFD), published "recommendations for disclosing clear, comparable and consistent information about the risks and opportunities presented by climate change," along with standardized disclosure frameworks for conducting climate risk assessments at the company level.[8] The TCFD's frameworks and standardized terminology are "highly influential," and have been "specifically mentioned in or incorporated into the laws and regulations of multiple jurisdictions."[9] Adopting a cut-off date of 2017 allows database users to take advantage of the increasingly standardized terminology around climate-related risk, while still capturing the majority of potentially relevant sources.

Following this decision, this paper's literature review methodology has proceeded through three phases: (1) scoping, (2) risk area identification, and (3) supplemental asset class searches.

2.2.1 Phase 1: Scoping via "Key Papers."

An initial review of the literature identified four "key papers" to serve as starting places:

(1) A 2021 review paper by the Basel Committee on Banking Supervision, "*Climate-related Risk Drivers and Their Transmission Channels*;"[10]

(2) A 2020 report by the Market Risk Advisory Committee of the U.S. Commodity Futures Trading Commission (CFTC), "*Managing Climate Risk in the U.S. Financial System*;"[11]

(3) A 2022 analytical paper published by the European Central Bank and European Systemic Risk Board, "*The Macroprudential Challenge of Climate Change*,"[12] and

(4) A 2023 paper by the United Nations Environment Programme's Financial Initiative, "*The 2023 Climate Risk Landscape*."[13]

These documents were identified as "key papers" for several reasons. First, each was recently published by a government agency or intergovernmental organization charged with broadly assessing or regulating financial risk. Next, each key paper identifies and categorizes the economic impacts of climate change.

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[7] *About the FSB*, FSB (Nov. 16, 2020), https://www.fsb.org/about/.
[8] FINANCIAL STABILITY BOARD, RECOMMENDATIONS OF THE TASK FORCE ON CLIMATE-RELATED FINANCIAL DISCLOSURES i (2023), https://assets.bbhub.io/company/sites/60/2020/10/FINAL-2017-TCFD-Report-11052018.pdf [hereinafter TCFD RECOMMENDATIONS].
[9] MARTIN LOCKMAN, MODELLING CLIMATE LITIGATION RISK FOR (RE)INSURERS 12, SABIN CENTER FOR CLIMATE CHANGE LAW (July 18, 2023), https://scholarship.law.columbia.edu/sabin_climate_change/201.
[10] BANK FOR INTERNATIONAL SETTLEMENTS, BASEL COMMITTEE ON BANKING SUPERVISION, CLIMATE-RELATED RISK DRIVERS AND THEIR TRANSMISSION CHANNELS (2021), https://www.bis.org/bcbs/publ/d517.pdf [hereinafter BASEL COMMITTEE REPORT].
[11] REPORT OF THE CLIMATE-RELATED MARKET RISK SUBCOMMITTEE, MARKET RISK ADVISORY COMMITTEE OF THE U.S. COMMODITY FUTURES TRADING COMMISSION, MANAGING CLIMATE RISK IN THE U.S. FINANCIAL SYSTEM (2023), https://www.cftc.gov/sites/default/files/2020-09/9-9-20%20Report%20of%20the%20Subcommittee%20on%20Climate-Related%20Market%20Risk%20-%20Managing%20Climate%20Risk%20in%20the%20U.S.%20Financial%20System%20for%20posting.pdf [hereinafter CFTC CLIMATE RISK REPORT].
[12] EUROPEAN CENTRAL BANK/EUROPEAN SYSTEMIC RISK BOARD PROJECT TEAM ON CLIMATE RISK MONITORING, THE MACROPRUDENTIAL CHALLENGE OF CLIMATE CHANGE (2022), https://www.esrb.europa.eu/pub/pdf/reports/esrb.ecb.climate_report202207~622b791878.en.pdf.
[13] DAVID CARLIN ET AL., THE 2023 CLIMATE RISK LANDSCAPE, UNEP (2023), https://www.unepfi.org/themes/climate-change/2023-climate-risk-landscape/#:~:text=UNEP%20FI%27s%202023%20Climate%20Risk,on%20dozens%20of%20individual%20tools.

Finally, each key paper develops these categorizations with particular attention towards understanding climate-related risk to investors and financial institutions. Together, these factors mean that the four key papers represent a strong foundation for understanding the landscape of climate-related risks and opportunities facing CalPERS, a regulated financial institution with a complex global portfolio of investments.

2.2.2 Phase 2: Identifying Climate Risk Research Areas.

After the completion of Phase 1, our team began to build a database from the sources cited within the four key papers. This process of building "research trees" from the key sources allowed our team to both (1) identify scholarly publications that risk regulators consider particularly relevant, and (2) develop a more nuanced and detailed understanding of the categories of climate risk research. This resulted in a database of 107 sources.

The process of identifying and categorizing sources resulted in a list of "climate risk research areas." These climate risk research areas are largely drawn from the 2021 Basel Committee Report, supplemented by categories in the 2020 CFTC Climate Risk Report. While together these two reports provide a relatively holistic overview of the landscape of climate risk research, two additional risk research areas were added after consultations with CalPERS and a review of the literature: biodiversity and deforestation. This review ultimately identified 28 distinct (but overlapping) climate risk research areas, ranging from "geographic heterogeneity" to "consumer sentiment" to "liability risk." Each climate risk research area is discussed at length in Section 3 of this paper.

2.2.3 Phase 3: Supplementing Risk Research with Asset Class-Specific Searches.

Finally, Phase 3 supplemented this literature review with asset class-specific searches, to ensure that the database and literature review contained literature that was particularly responsive to CalPERS' needs. This supplemental review focused on four asset classes and investment areas that CalPERS identified as high priorities: (1) Global Fixed Income, (2) Private Equity, (3) Real Estate and Real Assets, and (4) Sustainable Investment.

These asset class-oriented searches were conducted within CLIO through a three-part net of search terms for each asset class using (1) an anchor term for each asset class, (2) 33 primary keywords, and (3) asset class-specific filter terms.

Anchor Terms: Each class was given a designated "anchor term" to identify literature specifically studying the impact of climate change on that asset class. This anchor term was used to limit each search. For example, the supplemental literature review for private equity used the anchor term "private equity."[14]

Primary Keywords: Each anchor term was combined with a set of 33 primary keywords: the 28 climate risk research areas identified in Phase 2, supplemented with five more generic keywords: "climate change," "risk," "financial risk," "economic risk," and "climate transition." Where a climate risk research area used

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[14] This resulted in a total set of five anchor terms for the four investment areas; initial searches revealed that the universe of potentially relevant literature in the "Real Estate and Real Assets" space required two anchor terms—"infrastructure" and "real estate." *See* Annex II: Supplemental Review Methodology.

highly specific terminology that eliminated all results, a more generic term was substituted on a search-by-search basis (for example, "legal heterogeneity" was frequently replaced by the more generic term "legal"). Each combination of anchor terms and primary keywords was searched independently.

Filter Terms: The simple combination of anchor terms and primary keywords frequently resulted in an unmanageable number of results. For example, the combination of the anchor term "real estate" and the keyword "physical risk" returns more than 3,700 articles. To permit manual review of the most relevant sources, the authors developed a set of "filter terms" for each category. Filter terms for each asset class were developed from a list of potential research questions provided by CalPERS, which are elaborated upon in Annex II to this paper. CalPERS' real estate team, for example, were particularly interested in understanding the role that adaptation strategy played in real estate investment risk. Adding the filter terms "climate change" and "adapt" to the search for "real estate" and "physical risk" returns only 485 relevant sources, which could then be reviewed manually. As a general rule, at least 50 sources were manually reviewed for each possible combination of anchor term and keyword, although significantly more sources were reviewed for some keyword combinations that produced a large number of highly relevant results.[15]

This manual review resulted in a universe of between 25-30 highly relevant sources for each of the four priority asset classes.[16] These supplemental sources were added to the database, bringing the total number of database sources to 221, and were integrated into this report's discussion of specific "climate risk research areas." Annex II to this report outlines the full methodology and search terms used for each supplemental search.

3. KEY CLIMATE RISK RESEARCH AREAS

Throughout Phases 1 and 2 of the database building process, the Columbia research team identified 28 separate areas of climate-related financial risk research. This section provides an overview of the 28 climate risk research areas, and discusses recent representative research in each risk area. For the ease of the reader, these risk research areas are grouped into nine categories: (1) economic impact of physical risks, (2) climate-related market dynamics, (3) climate-related capital dynamics, (4) climate-related industry dynamics, (5) legal and policy risk, (6) climate-adjacent physical impacts, (7) analytic and strategic considerations, (8) climate risk mitigants, and (9) climate-related key performance indicators.

It is essential to emphasize that the nine research categories and 28 risk research areas discussed in this section do not have firm boundaries. These separate categories permit readers to focus on different subsets of literature and meaningly identify risk considerations among the broad universe of climate-related risk literature. However, many of these risk areas are deeply interrelated, and almost all of the climate research reviewed for this report addresses multiple climate risk research areas. The 28 climate risk research areas are instead designed to assist financial sector actors like pension funds in identifying and assessing comparable categories of climate risk research.

[15] While this description implies that more than 8,000 individual sources were manually reviewed for this paper, in practice the number was much smaller. Some anchor/keyword combinations produced fewer than 50 sources without additional filtering, and many sources appeared in more than one search process.
[16] Unsurprisingly, a significant number of sources identified in the Phase 3 review had previously been captured by Phases 1 and 2 of the review.

3.1. Types of Climate Risk

Before discussing more nuanced areas of climate risk research, it is important to first discuss three broadly recognized categories of climate-related risk: (1) physical risk, (2) transition risk, and (3) liability risk. These widely-referenced categories of risk do not represent discrete "climate risk research areas" for the purposes of this report; they are instead broad descriptive categories that cut across climate risk literature.

In the context of climate-related financial risk, "**physical risk**" refers to changes in weather and climate, or extreme weather-related events, that lead to economic costs and financial losses.[17] While many sectors of the economy face direct physical risks to their production, distribution, and supply chains, the severity of these risks will vary depending on the physical exposure of assets, infrastructure, and populations relevant to the sector.[18] These risks can come in the form of short-term weather events causing immediate economic losses, or long-term gradual effects from changing climates that affect economies or asset values. For example, in the agricultural sector, a 2017 study published in the Proceedings of the National Academy of Sciences estimated that "each degree-Celsius increase in global mean temperature would, on average, reduce global yields of wheat by 6%, rice by 3.2%, maize by 7.4%, and soybeans by 3.1%," with "highly heterogeneous" impacts across different crops and geographical areas.[19]

Companies also face financial risks associated with "**transition risk**"— economic costs and financial losses related to the process of adjusting our society towards a low-carbon economy.[20] This process can include changes in public policies, technological innovation, or investor and consumer sentiment. Transition risks can be particularly significant in industries, regions, or economies that are forced to undertake a haphazard or disorderly transition to a low-carbon economy,[21] and can impact both economic activity and asset valuation.[22] One transition risk is the risk of assets that utilize outdated or disfavored technology losing their economic value and becoming "stranded." The 2020 CFTC Climate Risk Report identifies a number of climate-related transitions, including shifts in climate policy, technology or consumer preferences, that may lead to asset stranding and capital stranding.[23] For example, a 2020 analysis by the International Energy Agency estimated that between $250 billion and $1.2 trillion of then-current investments in fossil fuel companies risked becoming stranded by the transition to low-emission power sources, depending on emission reduction pathways and fossil fuel industry responses.[24]

Some taxonomies divide all climate risk into "physical risk" or "transition risk," but others identify a third category: "**liability risk**." Liability risk refers to economic risk arising from "climate change litigation and other legal action, such as regulatory enforcement proceedings, fines, and penalties" associated with the

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[17] *See* BASEL COMMITTEE REPORT at v, 7.
[18] CFTC CLIMATE RISK REPORT at 11.
[19] Chuang Zhao et al., *Temperature Increase Reduces Global Yields of Major Crops in Four Independent Estimates, Proceedings of the National Academy of Sciences* (Aug. 15, 2017), https://doi.org/10.1073/pnas.1701762114.
[20] *See* BASEL COMMITTEE REPORT at vi.
[21] CFTC CLIMATE RISK REPORT at 19–22.
[22] *Id.* at 32–33.
[23] CFTC CLIMATE RISK REPORT at 11, 32.
[24] INTERNATIONAL ENERGY AGENCY, THE OIL AND GAS INDUSTRY IN ENERGY TRANSITIONS: INSIGHTS FROM IEA ANALYSIS 100 (2020) https://www.iea.org/reports/the-oil-and-gas-industry-in-energy-transitions.

climate-related act or omissions of an entity.[25] While some frameworks, including the TCFD's taxonomy of "Climate-Related Risks, Opportunities, and Financial Impact,"[26] categorize liability risk as a subset of transition risk, an increasing body of scholarship discusses climate-related liability as an independent set of risks that are tied to, but not coterminous with, physical and transition risks. Some recent scholarship has attempted to categorize and quantitatively model liability risk based on the factual allegations underlying climate-related claims.[27] Other frameworks have divided liability risks for private entities into *ex ante* or *ex post* categories, based on whether the liability risk arises from a materialized real-world harm (*ex post liability*) or a failure to manage, disclose, or properly represent risks that has not yet resulted in harm (*ex ante liability*).[28]

While climate liability risk often involves novel legal theories or factual circumstances, and "has proven particularly resistant to quantitative modelling,"[29] it is already having a significant economic impact in some sectors. For example, in 2019 PG&E, a publicly traded utility company, declared bankruptcy after its equipment caused a series of wildfires in northern California between 2017 and 2018 that, several studies suggest, were made "more likely to occur and more damaging" by climate change.[30] At the time of its bankruptcy, PG&E "estimated that its wildfire related liabilities could exceed [USD] $30 billion," excluding "potential punitive damages, fines and penalties, or damages related to future claims."[31]

3.2. Economic Impact of Physical Risks

A large amount of research into climate-related financial risks looks at the impact of "**acute physical risks**." This research attempts to quantify the economic costs and financial losses associated with the increasing severity and frequency of extreme climate change-related weather events like "lethal heatwaves, floods, wildfires and storms."[32] A significant body of research has developed that attempts to assess the impact of climate risk on portfolios of real assets and real estate in particular.[33] The 2020 CFTC Climate Risk Report

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[25] *See* SARAH BARKER, JOSHUA DELLIOS, & ELLIE MULHOLLAND, LIABILITY RISK AND ADAPTATION FINANCE 5, UNITED NATIONS ENVIRONMENT PROGRAMME'S FINANCE INITIATIVE (2021), https://www.unepfi.org/wordpress/wp-content/uploads/2021/04/UNEPFI-Climate-Change-Litigation-Report-Lowres.pdf [hereinafter LIABILITY RISK AND ADAPTATION FINANCE].
[26] *See* TCFD RECOMMENDATIONS at 8, Fig. 1.
[27] *See* MARTIN LOCKMAN, MODELLING CLIMATE LITIGATION RISK FOR (RE)INSURERS 6–7 SABIN CENTER FOR CLIMATE CHANGE LAW (July 18, 2023), https://scholarship.law.columbia.edu/sabin_climate_change/201. (categorizing climate litigation as "mitigation claims," arising out of a defendant's contributions to climate change, "adaptation claims," arising out of a defendant's failure to consider climate risks, and "governance and regulatory claims," arising out of a defendant's climate-related breach of established regulations and legal duties) [hereinafter MODELLING CLIMATE LITIGATION RISK FOR (RE)INSURERS].
[28] *See* LIABILITY RISK AND ADAPTATION FINANCE at 7.
[29] MODELLING CLIMATE LITIGATION RISK FOR (RE)INSURERS at 2.
[30] JOHN J. MACWILLIAMS, SARAH LA MONICA, & JAMES KOBUS, PG&E: MARKET AND POLICY PERSPECTIVES ON THE FIRST CLIMATE BANKRUPTCY 10, CENTER ON GLOBAL ENERGY POLICY (2019), https://www.energypolicy.columbia.edu/wp-content/uploads/2019/08/PGE-CGEP_Report_111722.pdf.
[31] *Id*. at 9.
[32] BASEL COMMITTEE REPORT at v, 6.
[33] *See* Jim Clayton *et al., Climate Risk and Real Estate Prices: What Do We Know?*, 47 JOURNAL OF PORTFOLIO MANAGEMENT 75 (2021) (reviewing the literature that assesses the price impacts of physical climate change risks on real estate prices); Jamilu Iliyasu *et al.*, *Pricing Environmental Amenities and Climate Change Risks in Real Estate Market*, 28 ENVIRONMENTAL MODELING & ASSESSMENT 999 (2023); *see also* Mark Wescot *et al.*, *Be Prepared: Exploring Future Climate-Related Risk for Residential and Commercial Real Estate Portfolios*, JOURNAL OF ALTERNATIVE INVESTMENTS (Summer 2020), at 24; Zella Ann Conyers, Richard Grant, & Shouraseni Sen Roy, *Sea Level Rise in Miami Beach: Vulnerability and Real Estate Exposure*, 71 THE PROFESSIONAL GEOGRAPHER 278 (2019), https://doi.org/10.1080/00330124.2018.1531037. *See also*, Markus Baldauf, Lorenzo

recognized that the valuation of some assets, such as commercial and residential real estate, is closely linked to the physical characteristics of those assets, and that acute physical risks such as wildfires or flooding can dramatically affect their value.[34] Recent studies have shown that neglecting to account for acute physical risks within firm risk assessment models can result in investors underestimating portfolio value at risk by up to 82%.[35] Similarly, a 2019 study in the Journal of Econometrics suggests that equity investors are "underreacting to climate-change risks" in countries with an increasing propensity toward droughts, an acute physical risk associated with climate change.[36] This underreaction is reflected in relatively poor country-level returns on food stocks in increasingly drought-prone countries.[37]

Another strand of research looks at the impact of "**chronic physical risks**." Chronic physical risks represent "longer-term gradual shifts of the climate" that create economic costs and financial losses through phenomena like rising temperatures, changes in precipitation, and rising sea levels, among others.[38] These trends pose significant risks across large and diverse swathes of the economy. For example, a 2018 report from the California Department of Insurance documented a broad array of climate risks to California's economy, ranging from lost tourism revenue in California's winter sports industry caused by warmer winters[39] to broad infrastructure damage caused by degrading ocean and forest ecosystems removing natural barriers to storm surges and fires.[40] This research either identifies new risks and opportunities or focuses on market responses to previously identified risks. In 2022, for example, quantitative research focused on U.S. municipal bonds concluded that the market was increasingly pricing exposure to sea level rise into municipal bond pricing; the authors found that "one standard deviation (approximately ten percentage point) increase in the fraction of [an issuer school district's] properties exposed to six feet of sea level rise is accompanied by a 5.3 basis point . . . increase in municipal bond credit spreads."[41]

3.3. Climate-Related Market Dynamics

Another area of climate risk research studies the reactions of investors, consumers, and counterparties to climate change. One line of research focuses on the impact of "**investor sentiment**," and attempts to assess how investors' awareness and expectations with respect to climate change are incorporated into investment decisions.[42] Some of this research examines the willingness of certain "impact investors" or "ESG-

Garlappi, & Constantine Yanellis, *Does Climate Change Affect Real Estate Prices? Only If You Believe in It*, 33 REVIEW OF FINANCIAL STUDIES 1256 (2020), https://doi.org/10.1093/rfs/hhz073 (finding that the price impact of sea level rise on residential property values was tied to the community's level of acceptance of climate change); Quyen Nguyen *et al.*, *Price Recovery After the Flood: Risk to Residential Property Values from Climate Change-related Flooding*, 66 AUSTRALIAN JOURNAL OF AGRICULTURAL AND RESOURCE ECONOMICS 532 (2022), https://doi.org/10.1111/1467-8489.12471.

[34] CFTC CLIMATE RISK REPORT at 16–17.

[35] Giacomo Bressan et al., *Asset-level Climate Physical Risk Assessment is Key for Adaptation Finance*, SSRN (Feb. 17, 2023), http://dx.doi.org/10.2139/ssrn.4062275

[36] Harrison Hong, Frank Weikai Li, & Jiangmin Xu, *Climate Risks and Market Efficiency*, 208 JOURNAL OF ECONOMETRICS 265, 280 (2019), https://doi.org/10.1016/j.jeconom.2018.09.015 .

[37] *Id*.

[38] BASEL COMMITTEE REPORT at v, 7.

[39] EVAN MILLS ET AL., TRIAL BY FIRE: MANAGING CLIMATE RISKS FACING INSURERS IN THE GOLDEN STATE 8, CALIFORNIA DEPARTMENT OF INSURANCE (2018), https://www.law.berkeley.edu/wp-content/uploads/2018/09/Trial-by-Fire-September-2018.pdf.

[40] *Id.* at 15, 59.

[41] Paul Goldsmith-Pinkham et al., *Sea Level Rise Exposure and Municipal Bond Yields* 2, Jacobs Levy Equity Management Center for Quantitative Financial Research Paper (November 9, 2022), http://dx.doi.org/10.2139/ssrn.3478364

[42] BASEL COMMITTEE REPORT at 8.

motivated investors" to accept lower financial returns for nonpecuniary benefits, leading to lower costs of capital for companies funded by impact investors.[43] In addition to studying the nature of investor sentiment, some branches of the literature focus on the impacts of such sentiment around climate-related risk. One 2021 study of U.S. shareholder proposals, for example, found both that companies with greater amounts of environmental shareholder activism, especially by institutional investors, were more likely to release climate risk information, and that companies that release climate risk information following activist pressure tend to "achieve a higher stock market valuation post disclosure."[44] Research into investor sentiment may also show that some markets fail to incorporate, or fully reject, assessments of climate change risk. For example, a great deal of research has focused on understanding and quantifying "investors' relative confidence in fossil fuel stocks" in the face of climate policy trajectories and the energy transition.[45]

Other climate risk research focuses on "**consumer sentiment**," broadly defined as changes in consumption behavior in response to climate change.[46] Consumer sentiment can induce lifestyle changes, activity reduction, activity substitution, or activity adoption. A great deal of climate research around consumer sentiment has assessed consumer perceptions of the climate impact of their consumption and consumer willingness to voluntarily adopt lower-emissions lifestyles.[47] Consumer sentiment can also be reflected in consumer adaptations to physical hazards, technological changes, or policies associated with climate change. For example, a 2020 study of coastal home prices in Florida showed that homes located in regions where a higher proportion of inhabitants deny the existence of climate change sell for about 7% more than homes located in areas that acknowledge climate change.[48]

Another heavily studied area of climate risk surrounds "**reputational risk**" arising from climate-related perceptions of an entity by its "customers, counterparties, shareholders, investors, debt-holders, market analysts, other relevant parties or regulators" that may affect that entity's ability to maintain business relationships and access funding.[49] Entities face both direct reputational risk based on their own activities and indirect reputational risk, based on the activities of their clients and counterparties. Reputational risk studies vary significantly in granularity, from market-wide surveys to assessments of local reputation. For example, one 2022 study of "environmental reputational risk" found that U.S. banks with "poor environmental reputation[s]," based on weighted ESG data, were "more likely to experience declining branch-level deposits the following year in counties exposed to severe climate change risks."[50]

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[43] *See, e.g.*, Lasse H. Pedersen, Shaun Fitzgibbons, Lukasz Pomorski, *Responsible Investing: The ESG-Efficient Frontier*, 142 JOURNAL OF FINANCIAL ECONOMICS 572 (2021) https://doi.org/10.1016/j.jfineco.2020.11.001; Brad M. Barber, Adair Morse, Ayako Yasuda, *Impact Investing*, 139 JOURNAL OF FINANCIAL ECONOMICS 162 (2021), https://doi.org/10.1016/j.jfineco.2020.07.008.
[44] Caroline Flamer, Michael Toffel, & Kala Viswanathan, *Shareholder Activism and Firms' Voluntary Disclosure of Climate Change Risks*, 42 STRATEGIC MANAGEMENT JOURNAL 1850, https://doi.org/10.1002/smj.3313.
[45] *See, e.g.*, J.F. Mercure *et al.*, *Macroeconomic Impact of Stranded Fossil Fuel Assets*, 8 NATURE CLIMATE CHANGE 558 (2018), https://doi.org/10.1038/s41558-018-0182-1.
[46] BASEL COMMITTEE REPORT at 8–9.
[47] *See*, e.g., John Thøgersen, *Consumer Behavior and Climate Change: Consumers* Need Considerable Assistance, 42 CURRENT OPINION IN BEHAVIORAL SCIENCES 9 (2021), https://doi.org/10.1016/j.cobeha.2021.02.008 (reviewing literature on consumer behavior and climate change).
[48] Markus Baldauf, Lorenzo Garlappi, & Constantine Yanellis, *Does Climate Change Affect Real Estate Prices? Only If You Believe in It*, 33 REVIEW OF FINANCIAL STUDIES 1256, 1258 (2020), https://doi.org/10.1093/rfs/hhz073.
[49] *Basel Framework 30.29*, BASEL COMMITTEE ON BANKING SUPERVISION (Dec. 15, 2019), https://www.bis.org/basel_framework/chapter/SRP/30.htm; *see also* BASEL COMMITTEE REPORT at 32 (noting the relevance of the "reputational risk" framework for climate risk assessments).
[50] Daewoung Choi, Yong Kyu Gam & Hojong Shin, *Environmental Reputation and Bank Liquidity: Evidence from Climate Transition*, 50 JOURNAL OF BUSINESS FINANCE & ACCOUNTING 1274–1304 (2022), https://doi.org/10.1111/jbfa.12669.

3.4. Climate-Related Capital Dynamics

Some climate risk research areas are targeted towards understanding the impacts of climate change on the flows of capital and valuation of assets. This research operates at a number of different scales, from firm-level credit assessments to broad theoretical work into macroeconomic stability. One such research area focuses on "**credit risk**," the risk that climate change or associated transition risks will reduce the ability of a borrower to repay or service debt, or reduce the ability of a lender to "recover the value of a loan in the event of a default" due to declining collateral values.[51] Credit risk is issuer-specific (either for corporate, sovereign, or trans-national issuers). A 2018 empirical study commissioned by the United Nations Environment Programme estimated that exposure to climate risk has increased the average cost of debt for a set of developing countries "by 117 basis points . . . translated into more than USD 40 billion in additional interest payments in the past 10 years on government debt alone."[52] Credit risk can also vary between portfolio compositions and locations. For example, the 2020 CFTC Climate Risk Report notes that small banks in the Midwest of the United States "hold proportionately more of certain types of agricultural loans that could be affected by climate impacts," such as reduced crop yields and disrupted agricultural production.[53] Following severe flooding in the Midwest in 2019, bankers reported to the Federal Reserve of Chicago that 69% of their borrowers "were at least moderately affected by extreme weather events."[54]

Another climate risk research area, "**market risk**," addresses the impact of climate change on financial asset values. This research includes assessing risks of "downward price shocks and an increase in market volatility in traded assets" where climate risk is not yet incorporated into prices, and studying "breakdown[s] in correlations between assets, reducing the effectiveness of hedging" and making it difficult for financial institutions and investors to manage their risks.[55] The 2020 CFTC Climate Risk Report found that financial assets most likely to be impacted by climate risks included assets tied to (1) real property, (2) infrastructure, (3) companies whose business is affected by climate-related risks, (4) coverage providers such as insurers and reinsurers, and (5) government revenue streams.[56] There is a vast and growing body of literature around market risk, addressing sectors, products, and assets ranging from fossil fuel reserves[57] to food stocks.[58]

Finally, a third area of research into climate-related capital dynamics focuses on "**liquidity risk**"—the impact of climate change on firms' and institutions' access to stable sources of funding that affects their ability to meet their obligations when they come due.[59] Climate risk drivers can impact a bank's liquidity risk directly by constraining their ability to raise funds or liquidate assets, or indirectly by affecting

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[51] BASEL COMMITTEE REPORT at 11.
[52] Bob Buhr et al., *Climate Change and the Cost of Capital in Developing Countries*, IMPERIAL COLLEGE BUSINESS SCHOOL & SOAS UNIVERSITY OF LONDON (2018), https://eprints.soas.ac.uk/26038/1/ClimateCostofCapital_FullReport_Final.pdf.
[53] CFTC CLIMATE RISK REPORT at 34.
[54] *See* David Oppendah, *AgLetter: August 2019*, FED. RESERVE BANK OF CHICAGO (2019), https://www.chicagofed.org/publications/agletter/2015-2019/august-2019.
[55] BASEL COMMITTEE REPORT at 15.
[56] CFTC CLIMATE RISK REPORT at 31.
[57] J.F. Mercure et al., *Macroeconomic Impact of Stranded Fossil Fuel Assets*, 8 NATURE CLIMATE CHANGE 558 (2018), https://doi.org/10.1038/s41558-018-0182-1.
[58] *See generally* Harrison Hong, Frank Weikai Li, & Jiangmin Xu, *Climate Risks and Market Efficiency*, 208 JOURNAL OF ECONOMETRICS 265 (2019), https://doi.org/10.1016/j.jeconom.2018.09.015 .
[59] BASEL COMMITTEE REPORT at 18–19.

customer demand. A wide array of interacting physical and transition risks can threaten market liquidity, causing "a cascade of liquidity shortfalls."[60] A 2023 empirical study of 23 developing market banks concluded that banks domiciled in countries with higher levels of physical or transition risks "are likely to experience more liquidity pressures."[61] At the firm level, a 2022 analysis of banks in 56 countries from 1995 to 2012 using the Notre Dame Global Adaptation Initiative's climate risk measurement variables found that a bank's liquidity creation is negatively impacted by its climate sensitivity and exposure to climate risk, particularly in larger banks, while positively impacted by its jurisdiction's "adaptive capacity" to adjust to the impacts of climate change.[62]

3.5. Climate-Related Industry Dynamics

Several areas of climate risk research focus on impacts to specific industries or business operations. **"Operational risk"** involves "the risk of loss resulting from inadequate or failed internal processes, people and systems or from external events."[63] Climate change can impact operational risk through "changes in human and institutional behaviors," changes in economic metrics like credit risk and market risk, and direct physical impacts to infrastructure and supply chains.[64] For example, a 2021 paper examining the propagation of climate impacts through international production networks found that climate-driven "weather shocks" like heating and flooding had significant financial impacts on supply chains, and resulted in customers "adapt[ing] their supply-chain organizations" towards "replacement suppliers with lower expected supply chain risks."[65]

Another risk research area, "**sectoral risk**," examines the impact of climate change on specific sectors or industries.[66] The various physical risks, transition risks, and liability risks associated with climate change present different risks and opportunities to different sectors, and as a result industries will face significantly different adaptation needs and economic outcomes. The 2020 CFTC Climate Risk Report found that the "agriculture and ecosystem services," "infrastructure," and "commercial and residential real estate" sectors along with sectors particularly dependent on human health and labor output, were particularly vulnerable to climate-related physical risks, while energy industry companies and financial market participants faced unique transition risks.[67] These impacts will be driven by different climate change risks; agriculture faces

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[60] *See* Paola D'Orazio, Jessica Reale, & Pham Anh Duy, *Climate-Induced Liquidity Crises: Interbank Exposures and Macroprudential Implications*, CHEMNITZ ECONOMIC PAPERS, NO. 059 (2023), http://hdl.handle.net/10419/272332.

[61] Qiaoqi Lang, Feng Ma, Nawazish Mirza, & Muhammad Umar, *The Interaction of Climate Risk and Bank Liquidity: An Emerging Market Perspective for Transitions to Low Carbon Energy*, 191 TECHNOLOGICAL FORECASTING AND SOCIAL CHANGE 122480 (2023), https://doi.org/10.1016/j.techfore.2023.122480 .

[62] Chien-Chiang Lee, Chih-Wei Wang, Bui Tien Thinh, & Zhi-Ting Xu, *Climate Risk and Bank Liquidity Creation: International Evidence*, 82 INTERNATIONAL REVIEW OF FINANCIAL ANALYSIS 102198 (2022), https://doi.org/10.1016/j.irfa.2022.102198.

[63] BASEL COMMITTEE REPORT at 19; *see also* Nahiomy Alvarez, Alessandro Cocco, & Ketan B. Patel, *A New Framework for Assessing Climate Change Risk in Financial Markets*, CHICAGO FED. LETTER NO. 448 (Nov. 2020), https://www.chicagofed.org/publications/chicago-fed-letter/2020/448 (defining "operational risk" as "the risk of loss resulting from failed processes, systems, or practices").

[64] *See generally* Grimwade, Michael, *How Climate Change May Impact Operational Risk*, 17 JOURNAL OF OPERATIONAL RISK 41 (June 1, 2022), *available at SSRN*: https://ssrn.com/abstract=4155494.

[65] Norma M. C. Pankratz & Christoph Schiller, *Climate Change and Adaptation in Global Supply-Chain Networks*, EUROPEAN CORPORATE GOVERNANCE INSTITUTE – FINANCE WORKING PAPER NO. 775/2021 (June 25, 2021), http://dx.doi.org/10.2139/ssrn.3475416.

[66] *See, e.g.*, BASEL COMMITTEE REPORT at 2 (noting that "business models and exposures can increase the severity of any climate-related risk impact . . . because certain economic sectors will have greater sensitivities to acute climate-related physical risks or to the transition to a low-carbon economy").

[67] CFTC CLIMATE RISK REPORT at 13–23.

risks from physical climate impacts such as heat waves impacting livestock or farm workers,[68] the infrastructure industry faces shortened asset lifespans and "degradation in operational viability" due to increased physical risks,[69] and the real estate industry faces both physical risks to their operations and threats to their asset valuations and rental revenues.[70] This research can be highly relevant to investors like pension funds; a 2017 study of portfolio equity holdings in the U.S. and the E.U. found that approximately 45.2% of the equity holdings of insurance and pension funds were invested in five sectors (fossil fuels, utilities, energy-intensive sectors, transport, and housing) that are highly impacted by climate policy.[71]

Yet another climate risk research area, "**technology**," looks at risks and opportunities associated with technological changes with the potential to generate, accelerate, slow, or disrupt the transition towards a low-carbon economy, or the impact of technology on climate adaptation.[72] This research largely, but not exclusively, focuses on transition risk. Technologies that increase energy efficiency, for example, can compete with preexisting technologies, leading to losses in affected industries that have invested in outdated technologies. These technological changes can have significant second-order impacts, as devalued investments in outdated technologies or assets ("stranded capital") results in losses throughout affected economies.[73] A 2021 paper in Energy Economics attempted to quantify the exposure of various sectors and countries to capital stranding. The paper concluded that a decline in the fossil fuel sector shows "the strongest potential to create capital stranding in other sectors," but that some unexpected sectors "like real estate and public administration rank among the most affected [sectors] by global fossil stranding."[74] Technology risk can also come from the introduction of climate-resiliency into the marketplace. Climate-resilient infrastructure and products, such as new climate-resilient crops,[75] can benefit early adopters while causing non-adapting competitors to lose market share.

A small set of technology-related papers identified by this supplemental literature review attempt to chart the path of the energy transition, and assess its impact on different sectors and asset classes under different climate scenarios.[76] One significant 2023 study published in Nature Communications develops a model to forecast the global and regional deployment of energy technologies.[77] The study finds that, even without any further policy support for renewable energy technology, the system cost of "a global irreversible solar tipping point may have passed where solar energy gradually comes to dominate global electricity markets, without any further climate policies."[78] The study further notes that declining costs in developed markets

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[68] *Id*. at 13–14.
[69] *Id*. at 14–16.
[70] *Id.* at 16–17.
[71] Stefano Battiston *et al.*, *A Climate Stress-Test of the Financial System*, 7 NATURE CLIMATE CHANGE 283 (2017). https://doi.org/10.1038/nclimate3255.
[72] BASEL COMMITTEE REPORT at 8.
[73] *See, e.g.*, *See* J. Curtin *et al.*, *Quantifying Stranding Risk for Fossil Fuel Assets and Implications for Renewable Energy Investment: A Review of the Literature*, 116 RENEWABLE AND SUSTAINABLE ENERGY REVIEWS (2019), https://doi.org/10.1016/j.rser.2019.109402.
[74] Louison Cahen-Fourot et al., *Capital Stranding Cascades: The Impact of Decarbonisation on Productive Asset Utilisation*, 103 ENERGY ECONOMICS 105581 (2021), https://doi.org/10.1016/j.eneco.2021.105581.
[75] *See* Maricelis Acevedo *et al.*, *A Scoping Review of Adoption of Climate-Resilient Crops by Small-Scale Producers in Low- and Middle-Income Countries*, 6 NATURE PLANTS 1231 (2020), https://doi.org/10.1038/s41477-020-00783-z
[76] *See, e.g.*, Luca Bongiorno *et al.*, *Climate Scenario Analysis for Pension Schemes: A UK Case Study*, 27 BRITISH ACTUARIAL JOURNAL e6, 2 (2022), https://doi.org/10.1017/S1357321721000106 ("explor[ing] how climate scenario analysis can be used for forward-looking assessment of the risks and opportunities for defined benefit pension schemes and other financial institutions.")
[77] Femke J. M. M. Nijsse *et al.*, *The Momentum of the Solar Energy Transition*, 14 NATURE COMMUNICATIONS 6542 (2023), https://doi.org/10.1038/s41467-023-41971-7.
[78] *Id.* at 1.

have an "international spillover" effect, which "implies that developing countries could become realistic markets for solar energy even when the capacity of their governments to implement climate policies remains limited."[79] This phenomena suggests that some of the most pessimistic climate transition scenarios, which assume that renewable energy will remain relatively expensive and coal usage will increase, may already be "highly improbable."[80] Other literature emphasizes that private finance for energy transition projects may be significantly limited in developing markets,[81] and the structure and strength of public-private partnerships may be crucial for deploying private finance for energy transition projects in less developed markets.[82]

3.6. Legal and Policy Risk

Two climate risk research areas focus on understanding the intersection of legal and political risk with climate change. Research around "**policy risk**" investigates potential risks and uncertainties associated with government climate policies that may impact business operations, investments, and financial markets.[83] For example, a 2020 study tracked in detail "investors' reactions to each of the three steps in the development of a German climate policy proposal known as the 'climate levy'" that started as a tax on certain CO_2 emissions from "power generating units older than 20 years"[84] and "was subsequently turned into a compensation mechanism paying individual lignite-fired power plants for phasing out," which was in turn challenged on the basis that it might violate E.U. law.[85] The study concluded that investors in affected German firms initially priced in policy risk, but "[did] not believe that they [would] be financially affected" because they assumed that the government would adopt some compensation mechanism.[86] Studies in this area assess the impact of potential climate policies on private investment decisions,[87] and often highlight opportunities for policy intervention where apparent market failures have led to underinvestment in climate-resilient businesses.[88] One recurrent theme in this literature is that private equity investments are most

[79] *Id*. at 3.
[80] *Id*. at 2.
[81] *Id*. at 5.
[82] Abdulrasheed Isah et al., *Financing Renewable Energy: Policy Insights From Brazil and Nigeria*, 13 ENERGY, SUSTAINABILITY, & SOCIETY (2023), https://doi.org/10.1186/s13705-022-00379-9; *see also* Joisa Dutra & Antonio Barbalho, *The Convergence of Business Models and Long-Term Financing in the Energy Transition*, 18 COMPETITION AND REGULATION IN NETWORK INDUSTRIES 256 (2017), https://doi.org/10.1177/1783591718784743 (assessing the role that new energy industry business models, like distributed renewable energy generation, may play in shaping financing structures).
[83] BASEL COMMITTEE REPORT at 13–14.
[84] Suphi Sen & Marie-Theres von Shickfus, Climate Policy, *Stranded Assets, and Investors' Expectations*, 100 JOURNAL OF ENVIRONMENTAL ECONOMICS AND MANAGEMENT 3 (2020), https://doi.org/10.1016/j.jeem.2019.102277.
[85] *Id.* at 18.
[86] *Id*.
[87] *See, e.g.*, Hyoungkun Park & Jong Dae Kim, *Transition Toward Green Banking: Role of Financial Regulators and Financial Institutions*, 5 ASIAN JOURNAL OF SUSTAINABILITY AND SOCIAL RESPONSIBILITY (2020), https://doi.org/10.1186/s41180-020-00034-3 (assessing the role of various monetary policy instruments on green investment decisions); Dhruba Purkayastha & Runa Sarkar, *Getting Financial Markets to Work for Climate Finance*, 27 JOURNAL OF STRUCTURED FINANCE 27 (2021), https://dx.doi.org/10.3905/jsf.2021.1.122 (assessing policy levers to mobilize private capital towards "green projects").
[88] For example, one recent study of European companies finds that energy efficient firms do not generally have better access to finance than similarly situated inefficient firms, and credits this to the difficulty private investors face in incorporating energy efficiency into financing decisions without clear policy signals. *See* Philipp-Bastian Brutscher, Pauline Ravillard & Gregor Semieniuk, *Do Energy Efficient Firms Have Better Access to Finance?*, 42 ENERGY JOURNAL 6 (2023), https://doi.org/10.5547/01956574.42.6.pbr.

benefitted by government support structures that provide some measure of policy stability.[89] A comprehensive survey of policy-oriented climate investment literature finds that unstable or uncertain climate policies like changing tax credits can lead investors to demand higher returns, "which often make the projects themselves unviable."[90] The 2022 Inflation Reduction Act, a U.S. law that has been hailed as a landmark embodiment of the policy response to climate pressures, has significant implications for investments in the power sector.[91]

Other research focuses on "**legal heterogeneity**," or variations in legal frameworks and regulations between jurisdictions.[92] Understanding these legal variations can be significant to assessing climate-related risk and opportunity across many areas. For example, the United Nations Environment Programme's 2023 Global Climate Litigation Report documents "a growing number of cases" that target private sector companies for their contributions to climate change, for their failure to adapt to climate change, or for violating laws, regulations, or legal duties related to climate change.[93] However, a 2023 survey of climate litigation risk models suggests that jurisdictional differences in legal systems can significantly impact the likelihood that private sector companies will face climate change-related lawsuits.[94]

3.7. Climate-Adjacent Physical Impacts

Two more climate risk research areas, "deforestation" and "biodiversity," represent climate-adjacent physical impacts. Although these risk research areas fall outside of the climate risks discussed in the 2021 Basel Committee Report and the 2020 CFTC Climate Risk Report, they are frequently discussed alongside other climate risks and have been identified by CalPERS as significant areas of interest.

One branch of research focuses on the intersection of finance and "**deforestation**," "practices or processes that result in the conversion of forested lands for non-forest uses," often through deliberate clearing or destruction.[95] Deforestation, together with agriculture and other changes in land use, is responsible for around a quarter of global greenhouse gas emissions.[96] Alongside legal and regulatory risk, research in this area suggests that firms engaged in deforestation can face significant financial impacts from associate reputational risk. For example, banks that decide to finance projects or companies responsible for

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[89] For example, a 2023 study of government support for the renewable energy sector found that policies like tax incentives, which "entail greater policy uncertainty" than other incentives like R&D support or price guarantees, had a negative impact on the level of private equity investments in the sector. *See* Dina Azhgaliyeva, John Beirne & Ranjeeta Mishra, *What Matters for Private Investment in Renewable Energy?*, 23 CLIMATE POLICY 71, 83 (2023), https://doi.org/10.1080/14693062.2022.2069664.
[90] Sarah Hafner, Olivia James & Aled Jones, *A Scoping Review of Barriers to Investment in Climate Change Solutions*, 11 SUSTAINABILITY 3201(2019), https://doi.org/10.3390/su11113201, at 13.
[91] John E T Bistline et al., *Power Sector Impacts of the Inflation Reduction Act 2022* Environ. Res. Lett. 19 014013 (2024) https://iopscience.iop.org/article/10.1088/1748-9326/ad0d3b/pdf.
[92] *See generally* CFTC CLIMATE RISK REPORT at 1–6 (discussing the scope of global climate action and variations in policy between jurisdictions).
[93] U.N. ENVIRONMENT PROGRAMME, GLOBAL CLIMATE LITIGATION REPORT: 2023 STATUS REVIEW 90 (July 27, 2023), https://www.unep.org/resources/report/global-climate-litigation-report-2023-status-review.
[94] *See* MARTIN LOCKMAN, MODELLING CLIMATE LITIGATION RISK FOR (RE)INSURERS 36–37, SABIN CENTER FOR CLIMATE CHANGE LAW (July 18, 2023), https://scholarship.law.columbia.edu/sabin_climate_change/201.
[95] *Vocabulary Catalogue: Climate Change Terms*, U.S. ENVIRONMENTAL PROTECTION AGENCY (Sept. 9, 2013), https://sor.epa.gov/sor_internet/registry/termreg/searchandretrieve/glossariesandkeywordlists/search.do.
[96] INTERGOVERNMENTAL PANEL ON CLIMATE CHANGE, IPCC SPECIAL REPORT ON CLIMATE CHANGE, DESERTIFICATION, LAND DEGRADATION, SUSTAINABLE LAND MANAGEMENT, FOOD SECURITY, AND GREENHOUSE GAS FLUXES IN TERRESTRIAL ECOSYSTEMS Ch. 1-2 (Aug. 7, 2019), https://www.ipcc.ch/site/assets/uploads/2019/08/Fullreport-1.pdf.

"extensive deforestation" face exposure to reputational risks,[97] which can materialize as losses of customers and deposits.[98] The advent of deforestation-related regulation in the UK and EU is likely to affect agro-industrial issuers in Brazil.[99] Deforestation can also worsen the prevalence and severity of physical risks related to climate change. A 2021 climate modelling project found that "large-scale deforestation of the Amazon rainforest will greatly magnify the risk of exposure to extreme heat associated with climate change on local and regional scales,"[100] which can lead to economic losses based on the physical risk mechanisms described earlier in this survey.[101]

Other research focuses on the intersection of finance and "**biodiversity**," "the variability among living organisms from all sources including terrestrial, marine, and other aquatic ecosystems and the ecological complexes of which they are a part," including "diversity within species, between species, and of ecosystems."[102] In 2020, the World Economic Forum ranked biodiversity loss and ecosystem collapse as one of the top five threats society will face in the next decade, with $44 trillion of economic value generation being moderately or highly dependent on nature and its services.[103] Biodiversity and ecosystem degradation can harm businesses by impacting operations, supply chains, and markets. A 2022 study assessing global exposure to biodiversity risk estimates that 21% of the world's largest publicly listed companies (totaling 20% of the total publicly listed enterprise value) are "materially exposed" to biodiversity risk by various measures.[104]

3.8. Analytic and Strategic Considerations

One widely explored set of research areas focuses on risk transmission, propagation, and magnification within markets and economies. While much of this literature is targeted towards risk regulators and heavily regulated financial sector entities like banks, research generated in these areas may be particularly useful for analytic or strategic exercises like developing portfolio-level climate hedging strategies.

"**Microeconomic transmission channels**" refer to the mechanisms through which climate risks affect individual counterparties, potentially resulting in the transmission of climate-related financial risk.[105] These risks can materialize through damage to a firm or fund's counterparties, the infrastructure of the firms or

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[97] *See* PIETRO CALICE, FEDERICO DIAZ KALAN, & FARUK MIGUEL, NATURE-RELATED FINANCIAL RISKS IN BRAZIL, WORLD BANK GROUP (Aug. 2021), https://pdfs.semanticscholar.org/8fb9/a3306ceb37db15b9d31f674a54f15bb35428.pdf (quantifying the exposure of the Brazilian banking sector to biodiversity loss).
[98] *See* Daewoung Choi, Yong Kyu Gam & Hojong Shin, *Environmental Reputation and Bank Liquidity: Evidence from Climate Transition*, 50 JOURNAL OF BUSINESS FINANCE & ACCOUNTING 1274–1304 (2022), https://doi.org/10.1111/jbfa.12669.
[99] Susan Cesar de Oliveira et al. *The European Union and United Kingdom's deforestation-free supply chains regulations: Implications for Brazil*, 217 ECOLOGICAL ECONOMICS (2024), https://doi.org/10.1016/j.ecolecon.2023.108053.
[100] Alves de Oliveira, B.F., Bottino, M.J., Nobre, P. *et al. Deforestation and climate change are projected to increase heat stress risk in the Brazilian Amazon*, 2 COMMUNICATIONS EARTH & ENVIRONMENT 207 (2021). https://doi.org/10.1038/s43247-021-00275-8.
[101] See *supra* Section 3.2 (discussing research around physical risks).
[102] CONVENTION ON BIODIVERSITY Art. 2, 1760 U.N.T.S. 79 (1992), *available at* https://www.cbd.int/convention/articles/?a=cbd-02.
[103] WORLD ECONOMIC FORUM, NATURE RISK RISING: WHY THE CRISIS ENGULFING NATURE MATTERS FOR BUSINESS AND THE ECONOMY 8 (Jan. 2020), https://www3.weforum.org/docs/WEF_New_Nature_Economy_Report_2020.pdf.
[104] Sergio Henrique Carvalho, Theodor Cojoianu & Francisco Ascui, *From Impacts to Dependencies: A First Global Assessment of Corporate Biodiversity Risk Exposure and Responses*, 32 BUSINESS STRATEGY AND THE ENVIRONMENT 2600–2614 (2022).
[105] BASEL COMMITTEE REPORT at 11.

funds themselves, or through risks to physical and financial assets such as machinery or stocks and bonds.[106] Large and unpredicted levels of climate change-related defaults, for example, would propagate economic losses throughout the economy via microeconomic transmission channels. A great deal of literature in this area focuses on microeconomic risk transmission resulting from asset devaluation. For example, a 2020 study suggests that the probability of default by leveraged investors in corporate and sovereign bond portfolios is highly susceptible to variations in underlying climate transition scenarios, and "[c]hoosing the wrong scenario could lead to a massive underestimation of losses."[107] Significantly less literature addresses the transmission of climate risk through contracts and counterparty risk.

"**Macroeconomic transmission channels**," in contrast, refer to the mechanisms through which climate risk affects macroeconomic factors, such as labor productivity and economic growth, which in turn may have an impact on entities by affecting the economy in which they operate.[108] Macroeconomic transmission channels are increasingly studied by central banks and financial system risk regulators. A 2022 report by the Bank of England, for example, documented both physical and transition risks that can be transmitted through macroeconomic channels. Physical risks like extreme weather can influence key economic variables, such as output and inflation, by damaging a country's physical and infrastructure capital, causing displacement or migration, or disrupting supply chains.[109] Likewise, transition risks like changing climate policies can lead to price fluctuations or the reallocation of economic activity toward sectors that are less carbon-intensive.[110] In 2020 a paper published by the Banque de France proposed a modelling framework to assess the impact of several climate transition scenarios on "key macroeconomic and financial variables," including GDP.[111] The study estimated that the United States and Europe risk a 2-3% reduction of real GDP in a "delayed transition scenario" and a real GDP reduction of between 6-7% in a "sudden transition scenario," as compared to an "orderly transition scenario."[112]

Another climate risk research area, "**geographic heterogeneity**," assesses variations in climate-related financial risks across and within jurisdictions based on differences in economies, markets, financial systems, and physical risks.[113] Investors with similar portfolios can be subject to varying levels of financial risk depending on where the assets are located. For example, projections assessing the impact of a transition away from fossil fuels suggest that fossil fuel-producing jurisdictions will face wildly different impacts to their GDPs and employment levels.[114] Consumer sentiment also varies with geographic heterogeneity, as consumers in different markets behave differently, face different regional exposure to physical risks, and

[106] *See* DANIEL ROMERO, JUAN CARLOS SALINAS, & JAQUELINE TALLEDO, CLIMATE RISK STRESS TEST: IMPACT OF CLIMATE CHANGE ON THE PERUVIAN FINANCIAL SYSTEM, PERU'S SUPERINTENDENCIA DE BANCA, SEGUROS Y ADMINISTRADORAS PRIVADAS DE FONDOS DE PENSIONES (Dec. 2022), https://www.sbs.gob.pe/Portals/0/jer/DDT_ANO2022/DT 03 2022.pdf (assessing the exposure of Peru's financial system to climate risks).
[107] Stefano Battison & Irene Monasterolo, *The Climate Spread of Corporate and Sovereign Bonds* 1, (July 1, 2020), available at SSRN: https://ssrn.com/abstract=3376218.
[108] BASEL COMMITTEE REPORT at 10, 19.
[109] MARILENA ANGELI ET AL., CLIMATE CHANGE: POSSIBLE MACROECONOMIC IMPLICATIONS, BANK OF ENGLAND (Oct. 21, 2022), https://www.bankofengland.co.uk/quarterly-bulletin/2022/2022-q4/climate-change-possible-macroeconomic-implications.
[110] *Id.*
[111] Thomas Allen et al., *Climate-Related Scenarios for Financial Stability Assessment: an Application to France*, BANQUE DE FRANCE WORKING PAPER NO. 774 (July 2020), https://publications.banque-france.fr/sites/default/files/medias/documents/wp774.pdf.
[112] *Id*. at 31.
[113] BASEL COMMITTEE REPORT at 25–26.
[114] J.F. Mercure et al., *Macroeconomic Impact of Stranded Fossil Fuel Assets*, 8 NATURE CLIMATE CHANGE 558 (2018), https://doi.org/10.1038/s41558-018-0182-1.

receive significantly different benefits from different climate adaptation technologies.[115] An example of geographic heterogeneity is the differential impact of carbon border adjustment mechanisms for corporate issuers in certain emerging markets.[116]

"**Financial amplifiers**" are another climate risk research area that has attracted significant attention from financial risk regulators. Financial amplifiers are phenomena where interactions within the economy have the potential to increase the impact of climate-related financial risks.[117] A 2020 report by the Financial Stability Board (FSB) highlighted that "[t]he materialization of physical or transition risks, and their effects on institutions and markets, could give rise to 'feedback loops' within the financial system, or between the financial system and the real economy," which interact in ways that amplify the effects on the economy.[118] The FSB's report identified several possible mechanisms that could act as financial amplifiers for climate risk, like negative growth-suppressing feedback loops associated with reductions in bank lending or insurance availability.[119] Some recent research in this area has attempted to identify and quantify climate-related financial amplifiers by modelling specific shocks to economic systems. One 2023 study published by the European Central Bank, for instance, analyzed the impact of a disorderly climate transition "on banks, funds, and insurance companies simultaneously," and identified associated "price shocks for bond and stock markets" and increases to "corporate and household probability of default . . . and loss given default.[120] "The reactions of these institutions to the initial shocks, combined with their interconnectedness, amplify the system's overall losses."[121] Despite these attempts, it is difficult to assess the significance of such amplification mechanisms, "partly . . . because there has not yet been a climate-related shock of a magnitude sufficient to trigger amplification mechanisms."[122]

Another important area of climate risk research investigates "**risk driver interactions**"—interactions between climate related risks that can "create additional uncertainty and be accretive," and may introduce "tipping points and non-linearity" into risk models.[123] Although physical and transition risks are often treated in isolation, in practice these climate risk research areas interact, and interactions between risks can lead to "new, complex cascade effects that cannot be captured by physical or transition risks separately."[124] For example, a study that repeatedly surveyed the same 275 Australian farmers over a five-year period found an interesting interaction between consumer sentiment, firm behavior, and physical risk. Farmers with an increased exposure to climate risk (based on the physical characteristics and financial health of their farms) were "more likely to agree that climate change posed a risk," more likely to take adaptation actions

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[115] *See, e.g.*, Saptarshi Das, Eric Wilson, & Eric Williams, *The Impact of Behavioral and Geographic Heterogeneity on Residential-Sector Carbon Abatement Costs*, 231 ENERGY AND BUILDINGS 110611 (Jan. 15, 2021), https://doi.org/10.1016/j.enbuild.2020.110611.

[116] Bong-Kyung Cho et al. *Implications of the Carbon Border Adjustment Mechanism on South Korean Industries: Challenges and Policy Recommendations* 444 JOURNAL OF CLEANER PRODUCTION (2024), https://doi.org/10.1016/j.jclepro.2024.141278.

[117] BASEL COMMITTEE REPORT at 26–27.

[118] FINANCIAL STABILITY BOARD, THE IMPLICATIONS OF CLIMATE CHANGE FOR FINANCIAL STABILITY (Nov. 23, 2020), https://www.fsb.org/wp-content/uploads/P231120.pdf.

[119] *Id*. at 20–25.

[120] Tomasz Dubiel-Teleszynski et al., *System-Wide Amplification of Climate Risk*, EUROPEAN CENTRAL BANK (2023), https://www.ecb.europa.eu/pub/financial-stability/macroprudential-bulletin/html/ecb.mpbu202206_2~1bec56088f.en.html.

[121] *Id*.

[122] FINANCIAL STABILITY BOARD, THE IMPLICATIONS OF CLIMATE CHANGE FOR FINANCIAL STABILITY (Nov. 23, 2020), https://www.fsb.org/wp-content/uploads/P231120.pdf.

[123] BASEL COMMITTEE REPORT at 26.

[124] PATRICK BOLTON ET AL., THE GREEN SWAN: CENTRAL BANKING AND FINANCIAL STABILITY IN THE AGE OF CLIMATE CHANGE 78, BANQUE DE FRANCE (Jan. 2020), https://www.bis.org/publ/othp31.pdf.

to reduce that risk, and subsequently more likely to "reduce their stated climate change risk perceptions" in subsequent surveys.[125] "Conversely, farmers who were originally deniers were more likely to undertake somewhat riskier farm production decisions," and subsequently to perceive climate change as more of a risk.[126]

3.9. Climate Risk Mitigants

Five climate risk research areas focus on understanding behaviors, strategies, and technologies that can be used to mitigate climate-related financial risk. The first of these, "**hedging opportunities**," focuses on the use of financial instruments to protect against climate-related financial losses by making compensating transactions.[127] These hedging opportunities can take the form of a number of climate-related derivative instruments like "ESG futures," "carbon derivatives," or "water derivatives."[128] A 2018 paper focused on supply chain risk, for instance, proposed that product manufacturers can use "weather index-based financial instruments" to mitigate financial risk resulting from adverse weather conditions on the retail and supply chain level.[129] Similarly, a 2022 study published by the U.S. Federal Reserve Board used market reactions to a German carbon tax proposal in 2019 to examine climate-related hedging strategies. The study found that, while stocks with high ESG scores did not perform any better than their low-score counterparts, "the carbon intensity of a firm is a robust predictor of the reaction of stock prices to the unexpected increase in the carbon tax," and concluded that investors should consider both carbon footprints and ESG weightings in designing climate risk hedges.[130]

Other research focuses on the use of "**insurance**" designed to mitigate the financial impacts of climate change-related events and risks.[131] A broad array of insurance policies and insurance-like products are available to mitigate climate change-related risk, including insurance-linked securities like parametric catastrophe bonds.[132] However, the viability of insurance hedging strategies depends on the availability of relevant and affordable policies, and insurance has historically covered only a fraction of losses from natural catastrophes.[133] Despite gaps, in some markets, insurance has been effective at mitigating both direct climate-related physical risks as well as associated indirect credit risks for lenders and investment funds. For instance, the aftermath of Hurricane Katrina led to an overall reduction in household debt due to large payouts from government flood-insurance programs.[134] Additionally, a 2019 study published by the Federal Reserve Bank of Chicago found that due to the prevalence of insurance and other post-disaster payments, "the high levels of flooding after Hurricane Harvey in 2017 lead to modest increases in auto loan balances,

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125 Sarah Ann Wheeler, Céline Nauges, & Alec Zuo, *How Stable are Australian Farmers' Climate Change Risk Perceptions? New Evidence of the Feedback Loop Between Risk Perceptions and Behaviour*, 68 GLOBAL ENVIRONMENTAL CHANGE 102274 (2021), https://doi.org/10.1016/j.gloenvcha.2021.102274.
126 *Id.*
127 BASEL COMMITTEE REPORT at 31.
128 *Id.*
129 Xavier Brusset & Jean-Louis Bertrand, *Hedging Weather Risk and Coordinating Supply Chains*, 64 JOURNAL OF OPERATIONS MANAGEMENT 41-52 (2018), https://doi.org/10.1016/j.jom.2018.10.002.
130 Marcelo Ochoa, Matthias Paustian, & Laura Wilcox, *Do Sustainable Investment Strategies Hedge Climate Change Risks? Evidence from Germany's Carbon Tax* 40, FINANCE AND ECONOMICS DISCUSSION SERIES 2022-073, BOARD OF GOVERNORS OF THE FEDERAL RESERVE SYSTEM, https://doi.org/10.17016/FEDS.2022.073.
131 BASEL COMMITTEE REPORT at 29–30.
132 *Id.* at 30.
133 *Id.*
134 CFTC CLIMATE RISK REPORT at 38.

but moderate decreases in mortgage balances," and overall "did not hurt consumers' credit access."[135] However, climate risks have strained traditional insurance markets. In response to hurricane-driven losses, the insurance sector has increasingly turned to catastrophe bonds, securities that pay the issuer when a predefined disaster risk is realized, to spread their risk to the broader market.[136] Insurance can also be used to protect against certain transition risks, as well as physical risks. For instance, since 2022 several companies have begun to "develop, sell, and underwrite policies that protect the buyers of [greenhouse gas emissions] offsets against risks like invalidation, third-party negligence and fraud."[137]

Another branch of climate risk research looks at "**firm behavior and business models**," broadly defined as actions taken by companies and organizations to reduce their climate-related risks and contribute to climate mitigation efforts.[138] Firm-level climate risks are highly varied, and individual firms and business models face a wide array of physical and transition risks associated with climate change. In light of this diversity of risks, a great deal of research has focused on building firm-level risk assessment frameworks that allow behavior and business models to be adjusted on a firm-by-firm basis, both internally and throughout their supply and customer networks.[139] Other recent research focuses on identifying effective responses to specific climate-related risks. For example, a 2019 study assessed the impact of climate-driven temperature anomalies on firm earnings, and concludes that firm diversification of business segments and markets "significantly mitigate[s] the negative impact of warmer regional climates."[140]

A significant amount of research in this area studies the impact of physical risk adaptation on the value of investments in real estate and infrastructure.[141] A persistent theme throughout this research is that, across various markets, private sector developers face significant challenges in integrating climate "resilience" metrics or other proactive adaptation strategies into construction practices.[142] One interview-based study focused on the Netherlands finds that private developers generally perceive that the economic benefits of adaptation "are much more intangible and long-term than the costs,"[143] and that private sector climate

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[135] Daniel Hartley, Eleni Pakis, Ben Weintraut, *Flooding and Finances: Hurricane Harvey's Impact on Consumer Credit*, CHICAGO FED. LETTER NO. 415 (2019), https://www.chicagofed.org/publications/chicago-fed-letter/2019/415.
[136] Andy Polacek, *Catastrophe Bonds: A Primer and Retrospective*, CHICAGO FED. LETTER NO. 405 (2018), https://www.chicagofed.org/publications/chicago-fed-letter/2018/405.
[137] MARTIN LOCKMAN, MODELLING CLIMATE LITIGATION RISK FOR (RE)INSURERS 28–29, SABIN CENTER FOR CLIMATE CHANGE LAW (July 18, 2023), https://scholarship.law.columbia.edu/sabin_climate_change/201.
[138] BASEL COMMITTEE REPORT at 28–29.
[139] *See, e.g.*, Sanjay Patnaik & Kira Fabrizio, *A New Framework for How Firms Can Manage Climate Risks*, CENTER ON REGULATION AND MARKETS WORKING PAPER #7, BROOKINGS (Apr. 2023), https://www.brookings.edu/wp-content/uploads/2023/04/A-new-framework-for-how-firms-can-manage-climate-risks-FINAL.pdf
[140] Artur Hughon & Kelvin Law, *Impact of Climate Change on Firm Earnings: Evidence from Temperature Anomalies* 16–17 (January 24, 2019), *available at*: http://dx.doi.org/10.2139/ssrn.3271386.
[141] *See* Hans Vrensen, Dennis Schoenmaker, Julia Wein, *Managing Climate Change-Related Risks in Global Real Estate*, 23 REAL ESTATE ISSUES 1 (2020); *see also* CARBON RISK REAL ESTATE MONITOR (n.d.), https://www.crrem.eu/; *but see* Emmanuel M.N.A.N. Attoh *et al.*, *Making Physical Climate Risk Assessments Relevant to the Financial Sector–Lessons Learned from Real Estate Cases in the Netherlands*, 37 CLIMATE RISK MANAGEMENT 100447 (2022), https://doi.org/10.1016/j.crm.2022.100447, at 3 (suggesting that real estate managers and investors struggle to integrate asset-specific assessments of vulnerability into portfolio-level risk models, since these assessments require assessing the impacts of specific design decisions on asset-level exposure to climate risks).
[142] *See* Margaret H. Kurth *et al.*, *Defining Resilience for the U.S. Building Industry*, 47 BUILDING RESEARCH & INFORMATION 480 (2019), https://doi.org/10.1080/09613218.2018.1452489; Afshin Pourmokhtarian *et al.*, *Construction and Climate Change; Challenges and Opportunities: A Case Study of the Northeast U.S.*, 1218 IOP CONFERENCE SERIES: MATERIALS SCIENCE AND ENGINEERING 012046 (2022) (focused on the northeastern United States);
[143] Niek ten Brinke *et al.*, *Mainstreaming Climate Adaptation into Urban Development Projects in the Netherlands: Private Sector Drivers and Municipal Policy Instruments*, 22 CLIMATE POLICY 1155, 1165 (2022), https://doi.org/10.1080/14693062.2022.2111293.

adaptation practices are often driven by "professional" motivations like reputation rather than perceptions that adaptation will increase the short-term sale value of projects.[144] In response to these challenges, a number of researchers have built models to evaluate real asset adaptation options.[145]

Another important subset of the literature surrounding firm behavior and business models focuses on governance and investment strategies for so-called "universal owners." In the context of this literature, the phrase "universal owners" refers to broadly diversified owners like pension funds and insurance companies, whose portfolios mirror the economy "such that they have a long-term interest in the health of the economy as a whole, as opposed to the relative performance of one firm over another."[146] As a result, a significant amount of scholarship argues that these investors are incentivized to reduce intra-portfolio externalities like climate change by reducing emissions at their source.[147] Recent research targeted towards institutional "universal owners" has focused on devising frameworks for pricing these externalities and engaging in "systematic stewardship" around them.[148]

Zooming out to a macroeconomic level, another strand of climate risk research focuses on the effect of "**financial system behavior**," actions or measures taken by the financial system to address climate-related risks.[149] Such actions could include implementing risk management strategies, incorporating climate-related factors into financial regulations, promoting responsible finance practices, and supporting the transition to a low-carbon economy.[150] Financial system responses to climate risk have varied considerably between jurisdictions; while some low-income countries have adopted prudential instruments to channel investment towards green sectors, high-income countries have lagged behind in prudential regulation of climate risk.[151] A large amount of research in this area examines how existing financial system risk controls, like capital requirements for banks, might be adapted to incorporate climate risk.[152] To supplement this work, many regulators are supporting research designed to more rigorously assess the financial system's exposure to economic risk from specific sectors.[153]

[144] *Id*. at 1158.
[145] *See* Dolores Luigi *et al.*, *Financial Impacts of the Energy Transition in Housing*, 14 SUSTAINABILITY 4876 (2022), https://doi.org/10.3390/su14094876; *see also* Manasvini Thiagarajan, Galen Newman, & Shannon Van Zandt, *The Projected Impact of a Neighborhood-Scaled Green-Infrastructure Retrofit*, 10 SUSTAINABILITY 3665 (2018) (assessing the impact and cost-effectiveness of property- and neighborhood-level green infrastructure projects in lieu of conventional stormwater management systems); Lisa L. Greenwood *et al.*, *Partnering for Climate Resilience: Exploring the Maturity of Private-Sector Efforts in the Great Lakes Region*, 15 SUSTAINABILITY 14105 (2023), https://doi.org/10.3390/su151914105 (assessing the prevalence and effectiveness of private sector climate resilience efforts)
[146] Madison Condon, *Externalities and the Common Owner*, 95 WASHINGTON LAW REVIEW 66–67 (2020).
[147] *Id*. at 6.
[148] *See* Jeffrey N. Gordon, *Systematic Stewardship*, 47 JOURNAL OF CORPORATION LAW 627, 658–60 (2022).
[149] This research area overlaps with, but is distinguished from, research into the *characteristics* of particular financial systems that make them vulnerable to, or resilient against, climate-related risks. Such research is characterized in Section 3.8 under the heading of "macroeconomic transmission channels." In practice, however, individual studies and policy papers often discuss these issues together.
[150] *See generally* BASEL COMMITTEE REPORT (broadly addressing climate risks to the international financial system and potential responses).
[151] Paola D'Orazio, Lilit Popoyan, *Fostering Green Investments and Tackling Climate-Related Financial Risks: Which Role for Macroprudential Policies?* 160 ECOLOGICAL ECONOMICS 25 (2019), https://doi.org/10.1016/j.ecolecon.2019.01.029.
[152] *See, e.g.*, Ivana Baranović et al., *The Challenge of Capturing Climate Risks in the Banking Regulatory Framework: Is There a Need for a Macroprudential Response?*, EUROPEAN CENTRAL BANK (2021), https://www.ecb.europa.eu/pub/financial-stability/macroprudential-bulletin/html/ecb.mpbu202110_1~5323a5baa8.en.html.
[153] *See* EUROPEAN CENTRAL BANK/EUROPEAN SYSTEMIC RISK BOARD PROJECT TEAM ON CLIMATE RISK MONITORING, CLIMATE-RELATED RISK AND FINANCIAL STABILITY (2021), https://www.ecb.europa.eu/pub/pdf/other/ecb.climateriskfinancialstability202107~87822fae81.en.pdf

A final climate risk research area focused on mitigants looks at "**negative emissions**." In the context of climate change, negative emissions refer to measures aimed at removing GHGs from the atmosphere.[154] The International Energy Agency points to three broad categories of negative emissions strategies: nature-based solutions, such as afforestation and reforestation; enhanced natural processes, such as increasing carbon content in soil or adding biochar to soils; and technological solutions including carbon capture and storage technologies.[155] Some research in this area has attempted to understand the economic impact of negative emissions strategies. For example, one 2019 study assessed cost-effectiveness of afforestation as a negative emissions technology under various estimated values for CO_2 sequestration, considering associated costs like monitoring costs and opportunity costs.[156] Another 2020 study assessed the impacts and implications of adopting direct air capture technology to meet the Paris Agreement's "1.5 °C end-of-century temperature increase goal."[157] The study concluded that this deployment of direct air capture technology may also exacerbate demand for energy and water and lead to significant increases in staple food crop prices, particularly in the Global South.[158]

3.10. Climate-Related Key Performance Indicators (KPIs)

Finally, three climate risk research areas address ways to measure and report climate-related risks and activities, and examine mechanisms to incentivize emissions reductions or climate adaptation. The first of these risk areas, "**metrics**," focuses on developing measurements, tools, and processes to analyze a firm's or activity's contribution to climate change or exposure to climate change risk.[159] Climate-related metrics have proliferated in recent years. However, the 2020 CFTC Climate Risk Report emphasized that, while voluntary disclosure frameworks are useful, "in the aggregate these frameworks identify more than 165 potentially "material" metrics, an overwhelmingly large number for many financial institutions."[160] One persistent theme in the literature surrounding climate-related metrics is that the materiality of different "sustainability" or "ESG" indicators can vary significantly between sectors and financial products, and that topline metrics that combine several environmental, social, or governance measurements may hide significant differences between such factors.[161] There can also be significant variations in the quality of

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[154] *See* CFTC CLIMATE RISK REPORT at 78 (discussing the role of negative emissions technologies and the importance of understanding the cost and availability of such technologies).
[155] Sara Budinis, *Going Carbon Negative: What Are the Technology Options?*, INTERNATIONAL ENERGY AGENCY (Jan. 31, 2020), https://www.iea.org/commentaries/going-carbon-negative-what-are-the-technology-options.
[156] Jonathan C. Doelman et al., *Afforestation for Climate Change Mitigation: Potentials, Risks, and Trade-Offs*, 26 GLOBAL CHANGE BIOLOGY 1039 (2020), https://doi.org/10.1111/gcb.14887.
[157] Jay Fuhrman et al., *Food–Energy–Water Implications of Negative Emissions Technologies in a +1.5 °C Future*, 10 NATURE CLIMATE CHANGE 920, 924 (2020), https://doi.org/10.1038/s41558-020-0876-z.
[158] *Id*. at 924–26.
[159] *See* CFTC CLIMATE RISK REPORT at 88–92 (assessing the landscape of climate disclosure standards and evaluating various disclosure metrics).
[160] CFTC CLIMATE RISK REPORT at 60.
[161] *See, e.g.*, Lutfi Abdul Razak; Mansor Ibrahim, & Adam Ng, *Which Sustainability Dimensions Affect Credit Risk? Evidence from Corporate and Country-Level Measures*, 13 JOURNAL OF RISK & FINANCIAL MANAGEMENT 316 (assessing "the financial materiality of sustainability issues across different industries" with respect to credit risk); Caterina Di Tommaso, Maria Mazzuca, *The stock price of European insurance companies: What is the role of ESG factors?*, 56 FINANCIAL RESEARCH LETTERS 104017 (2023) (examining the market impact of announcements of ESG upgrades and downgrades on the stock of insurance companies, and finding that "that the environmental pillar score is the most important factor for investors, with a greater reaction to a downgrade in this score than to the social or governance pillars," perhaps because the insurance sector is particularly exposed to climate risk); Guido Giese, Linda-Eling Lee; Dimitris Melas, Zoltán Nagy, Laura Nishikawa, *Foundations of ESG Investing:*

disclosures, even applying a consistent metric. For instance, the dominant framework for quantifying a firm's impact on global greenhouse gas emissions was established by the Greenhouse Gas Protocol (GHG Protocol), an international organization that issues standards categorizing emissions into three "scopes": (1) "scope 1": the direct emissions of a company, (2) scope 2: the emissions associated with electricity purchased by a company, and (3) scope 3: the emissions associated with the activities of the company, but not produced from sources owned or controlled by the company, like emissions caused by the company's suppliers or sold products.[162] The GHG Protocol's framework is increasingly accepted, and has either been or is in the process of being incorporated into public securities disclosure requirements in major markets around the world. Some recent research, however, has criticized the GHG Protocol's accounting mechanisms as providing room for reporting companies to reduce their reported emissions without reducing real-world emissions.[163] Other research has attempted to build independent climate risk metrics in a variety of ways, either examining objective measures such as the geographic distribution of firms' operations[164] or more subjective measures like analysis of firms' own statements about their exposure to climate risk.[165] Some recent research has even focused on meta-analyses of climate risk metrics, comparing and assessing tools designed to derive corporate climate risk metrics.[166]

Another climate risk research area focuses on "**reporting**," processes and procedures for collecting and publishing KPI metrics.[167] Corporate climate reporting has been the focus of a significant amount of international attention. As previously discussed, the TCFD has been one of the most influential actors in setting internationally accepted climate-related financial reporting standards for private companies.[168] As discussed above, the Greenhouse Gas Protocol has been highly influential in establishing "comprehensive global standardized frameworks to measure and manage greenhouse gas (GHG) emissions from private and public sector operations, value chains and mitigation actions."[169] The growing consensus around the need for climate-related risk reporting has led to secondary research examining the quality of climate disclosures, as well as their presence or absence.[170] Other research in this area investigates the causes and effects of investor demands for climate risk reporting. One 2021 paper, for example, examined the stated and revealed preferences of institutional investors, finding (1) that many institutional investors have a strong demand for

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How ESG Affects Equity Valuation, Risk, and Performance, JOURNAL OF PORTFOLIO MANAGEMENT, July 2019, at 69 (examining the transmission channels that connect ESG characteristics to financial value).

[162] *See generally* GHG PROTOCOL INITIATIVE, THE GREENHOUSE GAS PROTOCOL: A CORPORATE ACCOUNTING AND REPORTING STANDARD, WORLD RESOURCES COUNCIL FOR SUSTAINABLE DEVELOPMENT AND WORLD RESOURCES INSTITUTE (2015), https://ghgprotocol.org/sites/ default/files/standards/ghg-protocol-revised.pdf.

[163] *See* Jack Arnold *et al.*, *Transferred Emissions are Still Emissions: Why Fossil Fuel Asset sales Need Enhanced Transparency and Carbon Accounting*, COLUMBIA CENTER ON SUSTAINABLE INVESTMENT & SABIN CENTER ON CLIMATE CHANGE LAW (2023), https://scholarship.law.columbia.edu/sustainable_investment/14/ (highlighting ways that GHG accounting mechanisms incentivize emissions transfers, rather than emissions reductions).

[164] *See* Elsa Allman, *Pricing Climate Change Risk in Corporate Bonds*, 23 JOURNAL OF ASSET MANAGEMENT 596 (Nov. 2022).

[165] *See* Zacharias Saunter *et al.*, *Firm-Level Climate Change Exposure*, 78 JOURNAL OF FINANCE 1449 (June 2023), https://doi.org/10.1111/jofi.13219.

[166] *See* Julia Anna Bingler & Chiara Colesanti Senni, *Taming the Green Swan: a Criteria-Based Analysis to Improve the Understanding of Climate-Related Financial Risk Assessment Tools*, 22 CLIMATE POLICY 356 (2022), https://doi.org/10.1080/14693062.2022.2032569.

[167] *See* CFTC CLIMATE RISK REPORT at iv–v (discussing the growth in climate-related corporate reporting and needs for increased risk reporting).

[168] FINANCIAL STABILITY BOARD, RECOMMENDATIONS OF THE TASK FORCE ON CLIMATE-RELATED FINANCIAL DISCLOSURES (2023), https://assets.bbhub.io/company/sites/60/2020/10/FINAL-2017-TCFD-Report-11052018.pdf.

[169] *What is the GHG Protocol*, GREENHOUSE GAS PROTOCOL (n.d.), https://ghgprotocol.org/about-us.

[170] *See, e.g.*, Annabelle Braasch & Patrick Velte, *Climate Reporting Quality Following the Recommendations of the Task Force on Climate-Related Financial Disclosures: A Focus on the German Capital Market*, 31 JOURNAL OF SUSTAINABLE DEVELOPMENT 926 (2023).

climate disclosures, (2) that disclosure demand by climate-conscious investors is "affected by climate-specific disclosure costs and benefits," and (3) that the equilibrium disclosure level of any one firm is set by both investor demand and regulatory pressure.[171]

A final climate risk research area focuses on "**incentives**." In the context of climate risk research, the study of incentives refers to research into structuring incentives to encourage firms, sectors, portfolio companies, or entire economies to engage in emissions reductions or climate change adaptation activity.[172]

Research in this area often looks at ways that incentive mechanisms built into financial instruments or firm governance can incorporate broadly recognized climate metrics as accurate and easily understood proxies for firm-level emissions reduction or climate adaptation. For example, recent research examines ways in which sustainability-linked bonds (SLBs) integrating the European Union's taxonomy of sustainable financial activities as "technical screening criteria" could encourage emission reductions in issuers.[173] Other research on SLBs discusses risk-neutral pricing models for SLBs based on market and firm perceptions of the likelihood that an issuer will hit its SLB targets.[174] Other work focused on incentive KPIs examines situations in which environmentally motivated investors can effectively leverage their investments to encourage companies to adopt incentive KPIs. A recent paper examining opportunities for institutional investor engagement across asset classes suggests that institutional investors have the most leverage to push for climate action through equity investments when they threaten to exit their investment in advance of seasoned equity offerings, "when the company is looking for fresh capital."[175] That same study suggests that "the absolute largest impact can be achieved on debt markets," by threatening to deny new debt "unless the issuer commits to linking the fresh capital to sustainability performance," with significant coupon step-up rates associated with missed sustainability targets.[176]

4. CONCLUSION

Across the world, financial sector actors and asset owners face pressure from beneficiaries, clients, regulators, and risk assessment professionals to manage extensive and complex climate-related risks and to adapt their portfolio management strategies to the increasing exigency of climate change. This scoping study provides a taxonomy of climate-related financial risks to help institutional investors assess, interpret, and evaluate competing climate risk frameworks. This scoping study, and the accompanying database, identify 28 discrete areas of climate-related financial risk research, divided into nine overarching categories. While several of these risk categories overlap, and most discrete research or risk evaluation projects will

[171] Emirhan Ilhan et al., *Climate Risk Disclosure and Institutional Investors*, 36 REVIEW OF FINANCIAL STUDIES 2617 (July 1, 2023), https://doi.org/10.1002/sd.2430.
[172] *See* CFTC CLIMATE RISK REPORT at 112–113 (discussing mechanisms to structure existing financial instruments to incentivize "improved environmental performance").
[173] *See* Gregor Vulturis, Aaron Maltais, & Kristina Forsbacka, *Sustainability-Linked Bonds – Their Potential to Promote Issuers' Transition to Net-Zero Emissions and Future Research Directions*, JOURNAL OF SUSTAINABLE FINANCE & INVESTMENT (Feb. 2022), https://doi.org/10.1080/20430795.2022.2040943.
[174] *See* Ulf Erlandsson et al., *Notes on Risk-Neutral Pricing of SLBs and Step-Down Structures* (Oct. 25, 2022), available on SSRN: https://papers.ssrn.com/sol3/papers.cfm?abstract_id=4258897.
[175] Andreas G.F. Hoepner & Fabiola I. Schneider, *Exit vs Voice vs Denial of (Re)(Entry: Assessing Investor Impact Mechanisms on Corporate Climate Transition*, (Aug. 2022), available on SSRN: https://papers.ssrn.com/sol3/papers.cfm?abstract_id=4193465.
[176] *Id*.

straddle multiple risk areas, the 28 risk research areas and nine categories represent conceptually different strands of climate risk assessment, each of which can be relevant to financial sector actors like pension funds. Decisionmakers assessing climate-related financial risk frameworks can use the taxonomy contained in this report to assess the adequacy of a framework's inputs, metrics, and variables.

It is important to emphasize that this study emphatically does *not* suggest that all climate risk frameworks must consider, or explicitly incorporate, variables from all 28 climate risk research areas. However, credible strategies to assess climate-related risks should reflect conscious decisions to incorporate or exclude specific categories of climate-related financial risk. When institutional investors are evaluating competing climate-related risk models, the taxonomy in this scoping study should provide an analytical foundation against which to test climate risk models. The taxonomy provided by this paper should prompt evaluators to ask questions like:

> "Which risk research area(s) is this variable trying to encompass?"
>
> "How is this variable proxying for this identified climate risk?" and
>
> "Which risk research areas have been excluded from this model, and why?"

Armed with a theoretical understanding of the scope and scale of climate-related financial risks, analysts will be better able to evaluate options to combat them.

ANNEX I –Taxonomy of Climate-Related Portfolio Risks

This Annex provides a taxonomy of climate-related portfolio risks, and summarizes the 28 climate-related "risk research areas" identified in this scoping study. This Annex is provided for ease of reference only; for a full discussion of each risk research area, please see the relevant section main report.

Climate-Related Risk Research: A Taxonomy	
Category of Climate-Related Risk	**Climate Risk Research Area**
1. Economic Impact of Physical Risks	**1.1** Acute physical risks
	1.2 Chronic physical risks
2. Climate-Related Market Dynamics	**2.1** Investor sentiment
	2.2 Consumer sentiment
	2.3 Reputational risk
3. Climate-Related Capital Dynamics	**3.1** Credit risk
	3.2 Market risk
	3.3 Liquidity risk
4. Climate-Related Industry Dynamics	**4.1** Operational risk
	4.2 Sectoral risk
	4.3 Technology
5. Legal and Policy Risk	**5.1** Policy risk
	5.2 Legal heterogeneity
6. Climate-Adjacent Physical Impacts	**6.1** Deforestation
	6.2 Biodiversity
7. Analytic and Strategic Considerations	**7.1** Microeconomic transmission channels
	7.2 Macroeconomic transmission channels
	7.3 Geographic heterogeneity
	7.4 Financial amplifiers
	7.5 Risk driver interactions
8. Climate Risk Mitigants	**8.1** Hedging opportunities
	8.2 Insurance
	8.3 Firm behavior and business models
	8.4 Financial system behavior
	8.5 Negative emissions
9. Climate-Related Key Performance Indicators (KPIs)	**9.1** Metrics
	9.2 Reporting
	9.3 Incentives

Risk Research Area	Definition
1. Economic Impact of Physical Risks	
1.1 Acute physical risks	The economic costs and financial losses associated with the increasing severity and frequency of extreme climate change-related weather events.
1.2 Chronic physical risks	The economic costs and financial losses that arise from gradual and persistent climate-related phenomena.
2. Climate-Related Market Dynamics	
2.1 Investor sentiment	Investors' awareness and expectations with respect to climate change.
2.2 Consumer sentiment	Changes in consumption behavior in response to climate change.
2.3 Reputational risk	Studies the impact of different constituencies' climate-related perceptions of an entity may affect that entity's ability to maintain business relationships and access funding.
3. Climate-Related Capital Dynamics	
3.1 Credit risk	The risk that climate change or associated transition risks will reduce the ability of a borrower to repay or service debt, or reduce the ability of a lender to recover from a defaulted debtor due to declining collateral values.
3.2 Market risk	The impact of climate change on financial asset values.
3.3 Liquidity risk	The impact of climate change on firms' and institutions' access to stable sources of funding that affects their ability to meet their obligations when they come due.
4. Climate-Related Industry Dynamics	
4.1 Operational risk	Risk associated with damage to, or failures of, an organization's resources, human capital, or internal processes and systems.
4.2 Sectoral risk	The impact of climate change on specific sectors or industries.
4.3 Technology	Risks and opportunities associated with technological changes with the potential to generate, accelerate, slow, or disrupt the transition towards a low-carbon economy, or the impact of technology on climate adaptation.
5. Legal and Policy Risk	
5.1 Policy risk	Potential risks and uncertainties associated with government climate policies that may impact business operations, investments, and financial markets.

Risk Research Area	Definition
5.2 Legal heterogeneity	Variations in legal frameworks and regulations between jurisdictions.
6. Climate-Adjacent Physical Impacts	
6.1 Deforestation	The conversion of forested land to non-forested-land, often through deliberate clearing or destruction.
6.2 Biodiversity	"[T]he variability among living organisms from all sources including terrestrial, marine, and other aquatic ecosystems and the ecological complexes of which they are a part," including "diversity within species, between species, and of ecosystems."[177]
7. Analytic and Strategic Considerations	
7.1 Microeconomic transmission channels	Mechanisms through which climate risks affect individual counterparties, potentially resulting in the transmission of climate-related financial risk.
7.2 Macroeconomic transmission channels	Mechanisms through which climate risk affects macroeconomic factors, such as labor productivity and economic growth, which in turn may have an impact on entities by affecting the economy in which they operate.
7.3 Geographic heterogeneity	Variations in climate-related financial risks across and within jurisdictions based on differences in economies, markets, financial systems, and physical risks.
7.4 Financial amplifiers	Phenomena where interactions within the economy have the potential to increase the impact of climate-related financial risks.
7.5 Risk driver interactions	Interactions between climate related risks, particularly when such interactions introduce uncertainty and non-linearity into climate risk models.
8. Climate Risk Mitigants	
8.1 Hedging opportunities	The use of financial instruments to protect against climate-related financial losses by making compensating transactions.
8.2 Insurance	The use of a particular category of traditional financial instrument, insurance, to mitigate the financial impacts of climate change-related events and risks.
8.3 Firm behavior and business models	The range of actions that can be taken by companies and organizations to reduce their climate-related risks and contribute to climate mitigation efforts.

[177] CONVENTION ON BIODIVERSITY Art. 2, 1760 U.N.T.S. 79 (1992), *available at* https://www.cbd.int/convention/articles/?a=cbd-02.

Risk Research Area	Definition
8.4 Financial system behavior	Actions or measures taken by the financial system to address climate-related risks.
8.5 Negative emissions	Measures aimed at removing GHGs from the atmosphere.
9. Climate-Related Key Performance Indicators (KPIs)	
9.1 Metrics	Measurements, tools, and processes to analyze a firm's or activity's contribution to climate change or exposure to climate change risk.
9.2 Reporting	Processes and procedures for collecting and publishing KPI metrics.
9.3 Incentives	Tools to encourage firms, sectors, portfolio companies, or entire economies to engage in emissions reductions or climate change adaptation activity.

ANNEX II – Supplemental Review Methodology

This scoping study was, in part, designed to support the ongoing efforts of CalPERS and other climate-conscious investors by building a database of literature addressing climate-related risk from the perspective of institutional investors. To ensure that this database contained information relevant to the day-to-day work of investment professionals, the Columbia team solicited questions from and initiated conversations with four practice groups and asset classes within CalPERS: (1) Sustainable Investments, (2) Real Estate and Real Assets, (3) Private Equity, and (4) Global Fixed Income. These conversations resulted in a large set of climate-related investment research questions, which were condensed into seven core inquiries and used to develop and shape supplemental searches that added to the underlying research database.

This Annex lists the seven inquiries that shaped this supplemental review, and identifies the search terms that were used in response to these questions. For a full review of the methodology of these supplemental literature reviews, see Section 2.2.3 of the accompanying scoping study.

1. CLIMATE INVESTMENT QUESTIONS

Sustainable Investments:

(1) What are the implications of integrating climate-related metrics into portfolio management practices?

Real Estate, Real Assets, and Infrastructure:

(1) How can physical and transition risk be assessed, quantified, and mitigated, in real asset portfolios

(2) What are the implications of energy transition scenarios for investments in real assets?

Private Equity:

(1) How are climate-related metrics associated with economic outcomes for private equity investments?

(2) How can private equity investors shape firms through engagement, divestment, or other capital allocation decisions?

Global Fixed Income:

(1) How can investors effectively assess and manage climate change transition risk within a fixed income portfolio?

(2) To what extent do green bond covenants, issuer characteristics, and other conditions influence green bond yields as compared to non-green bonds?

2. SUPPLEMENTAL SEARCH TERMS

Search Type	Function	Terms Used	
Anchor Term(s)	One anchor term was used in each search to define the scope of the overall search	***Sustainable Investments***	(1) “ESG”
		Real Estate, Real Assets, and Infrastructure	(1) “infrastructure,” (2) “real estate”
		Private Equity	(1) “private equity”
		Global Fixed Income	(1) “fixed income”

<table>
<tr><th>Search Type</th><th>Function</th><th colspan="2">Terms Used</th></tr>
<tr><td>Primary Keywords</td><td>Each primary keyword was searched in combination with each anchor term. Searches returned all sources that contained these “keywords” in their text.</td><td colspan="2">(1) “physical risk,” (2) “transition risk,” (3) “liability risk,” (4) “acute physical risk,” (5) “chronic physical risk,” (6) “investor sentiment,” (7) “consumer sentiment,” (8) “reputational risk,” (9) “credit risk,” (10) “market risk,” (11) “liquidity risk,” (12) “operational risk,” (13) “sectoral risk,” (14) “technology,” (15) “policy risk,” (16) “legal heterogeneity,” (17) “deforestation,” (18) “biodiversity,” (19) “microeconomic transmission channels,” (20) “macroeconomic transmission channels,” (21) “geographic heterogeneity,” (22) “financial amplifiers,” (23) “risk driver interactions,” (24) “hedging opportunities,” (25) “insurance,” (26) “firm behavior and business models,” (27) “financial system behavior,” (28) “negative emissions,” (29) “climate change,” (30) “risk,” (31) “financial risk,” (32) “economic risk,” (33) “climate transition”</td></tr>
<tr><td rowspan="4">Filter Terms</td><td rowspan="4">Filter terms were used to narrow search results, as necessary, to obtain a universe of highly relevant documents that could be manually searched. Searches returned all sources that contained selected “filter terms” in their text.</td><td>Sustainable Investments</td><td>(1) “performance,” (2) “return,” (3) “volatility,” (4) “systematic risk,” (5) “risk-adjusted return,” (6) “climate”</td></tr>
<tr><td>Real Estate, Real Assets, and Infrastructure</td><td>(1) “adaptation,” (2) “energy transition,” (3) “resilience,” (4) “scenario,” (5) “invest,” (6) “climate”</td></tr>
<tr><td>Private Equity</td><td>(1) “capital,” (2) “impact,” (3) “fund,” (4) “divestment,” (5) “return,” (6) “ESG”</td></tr>
<tr><td>Global Fixed Income</td><td>(1) “transition,” (2) “green bond,” (3) “yield,” (4) “returns,” (5) “metrics”</td></tr>
</table>